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Abstract The massive *Ulva (U.) prolifera* bloom in the Yellow Sea was first observed and reported in summer of 2008. After that, the green tide event occurred every year and influenced coastal areas of Jiangsu and Shandong provinces of China. Satellite remote sensing plays an important role in monitoring the floating macroalgae. In this paper, *U. prolifera* patches are detected from quasi-synchronous satellite images with different spatial resolution, i.e., Aqua MODIS (Moderate Resolution Imaging Spectroradiometer), HJ-1A/B (China Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting), CCD (Charge-Coupled Device), Landsat 8 OLI (Operational Land Imager), and ENVISAT (Environmental Satellite) ASAR (Advanced Synthetic Aperture Radar) images. Two comparative experiments are performed to explore the *U. prolifera* monitoring abilities by different data using detection methods such as NDVI (Normalized Difference Vegetation Index) with different thresholds. Results demonstrate that spatial resolution is an important factor affecting the extracted area of the floating macroalgae. Due to the complexity of case II sea water characteristics in the Yellow Sea, a fixed threshold NDVI method is not suitable for *U. prolifera* monitoring. A method with adaptive ability in time and space, e.g., the threshold selection method proposed by Otsu (1979), is needed here to obtain accurate information on the floating macroalgae.

Keywords *Ulva prolifera*, the Yellow Sea, MODIS, CCD, OLI, SAR, NDVI

1 Introduction

Since the summer of 2008, when the massive *Ulva (U.) prolifera* bloom in the Yellow Sea was first observed and reported, the green tide event has become a regular phenomenon in this region (Hu and He, 2008; Sun et al., 2008; Liu et al., 2009, 2013; Xu et al., 2014). As a species widely distributed in the Yellow Sea and the East China Sea, *U. prolifera* is also known as *Enteromorpha prolifera* (Huang, 2001; Shimada et al., 2009; Keesing et al., 2011). Although *U. prolifera* is non-toxic, the green algae bloom is considered a type of marine disaster because it

usually breaks out suddenly and causes environmental damage and economic loss (Liu et al., 2009; Qiao et al., 2009; Shimada et al., 2009; Pang et al., 2010). Thus it is necessary to monitor the occurrence, distribution, and development of green macroalgae bloom in the Yellow Sea effectively for dealing with this disaster. Satellite remote sensing has proven to be a valuable tool for real-time *U. prolifera* bloom monitoring in a large spatial scale.

The spectral characteristics of *U. prolifera* are distinct from that of surrounding sea water in the visible and infrared bands, which makes the macroalgae detectable by optical satellite imagery. Based on MODIS (Moderate Resolution Imaging Spectroradiometer) images with spatial resolution of 250 m, Hu and He (2008) and Liu et al. (2009) analyzed the massive *U. prolifera* bloom which affected Qingdao coastal waters during the 2008 Olympic Games using the NDVI (Normalize Difference Vegetation Index) method. With the same kind of data and method, Keesing et al. (2011) studied the annual and intra-annual patterns of the green tides during 2007–2009. Latterly, Hu (2009) proposed a novel method, namely the floating algal index (FAI) method for *U. prolifera* monitoring from MODIS images. Using this method and 7 years of MODIS data from 2007 to 2013, Xu et al. (2014) investigated the interannual variability of the *U. prolifera* bloom in the Yellow Sea and discussed its origin. Similarly, Shi and Wang (2009) presented a normalized difference algae index (NDAI) to monitor the *U. prolifera* from MODIS images. More recently, other kinds of optical satellite data with higher spatial resolution were also used for detection of the green macroalgae bloom. Using Landsat 5 TM (Theme Mapper) or Landsat 7 ETM (Enhanced Theme Mapper) images with 30 m spatial resolution, both Hu et al. (2010) and Xing et al. (2011) found small *U. prolifera* patches that are not visible in MODIS images.

Compared to optical satellite images which are influenced by cloud cover, microwave data have all-day and all-weather observing capability, which makes them a good supplement for *U. prolifera* observation. Monitoring of the floating green macroalgae in the microwave bands depends on its unique backscattering features. For example, Li et al. (2011) analyzed the distribution of *U. prolifera* patches in the Yellow Sea from RADARSAT-1 SAR (Synthetic Aperture Radar), ENVISAT (Environmental Satellite) ASAR (Advanced SAR) and ALOS (Advanced Land Observing Satellite), and PALASAR (Phased Array type L-band SAR) data with 30 m resolution. Cui et al. (2012) compared the difference in *U. prolifera* monitoring ability based on an ENVISAT ASAR image and two optical images from MODIS and HJ-1A/B (China Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting) CCD (Charge-Coupled Device).

Satellite remote sensing data play an important role in monitoring *U. prolifera* bloom in the Yellow Sea. But there are still many open questions. In this region, the concentrations of phytoplankton, sediment, and zooplankton are different in coastal waters and offshore, which makes the spectrum characteristic of the sea water very different from that of Case I sea water. In this case, what is the difference between quantitative monitoring results of the floating macroalgae from different types of satellite data? Which method is more appropriate for effective *U. prolifera* monitoring in this area?

To address these questions, the *U. prolifera* imaging abilities of different satellite sensors are compared in this article. Two groups of quasi-synchronous satellite images with different spatial resolution and working bands are selected to extract the area of the macroalgae in the Yellow Sea with different methods. These multi-source data, as well as the monitoring methods, are described in Section 2. The comparison results are presented and discussed in Section 3. Section 4 concludes our findings.

2 Data and methodology

2.1 Satellite data

To compare the *U. prolifera* monitoring ability of multi-source data, we searched satellite images of the Yellow Sea during summer of 2007–2014 and selected two groups of quasi-synchronous satellite images on 28 June 2008 and 24 June 2013, respectively. They are three types of optical remote sensing data from Terra/Aqua MODIS, HJ-1A/B CCD, and Landsat 8 OLI (Operational Land Imager), and a microwave image from ENVISAT ASAR. The basic information of these data is listed in Table 1. As shown in the two MODIS images (Fig. 1), massive *U. prolifera* accumulated in the Northern Yellow Sea. The macroalgae arrived at the coastal areas of Qingdao, Shandong province on 28 June 2008 and moved northward to Qingdao coastal waters on 24 June 2013.

Table 1 Basic information of satellite images

Date	Time (UTC)	Satellite/sensor	Spatial resolution/m	Swath/km
2013.6.24	5:20	Aqua/MODIS	250	2,330
	2:12	HJ-1A/B/CCD	30	360
	2:38	Landsat 8/OLI	30	185
2008.6.28	5:05	Aqua/MODIS	250	2,330
	1:55	ENVISAT/ASAR	30	100

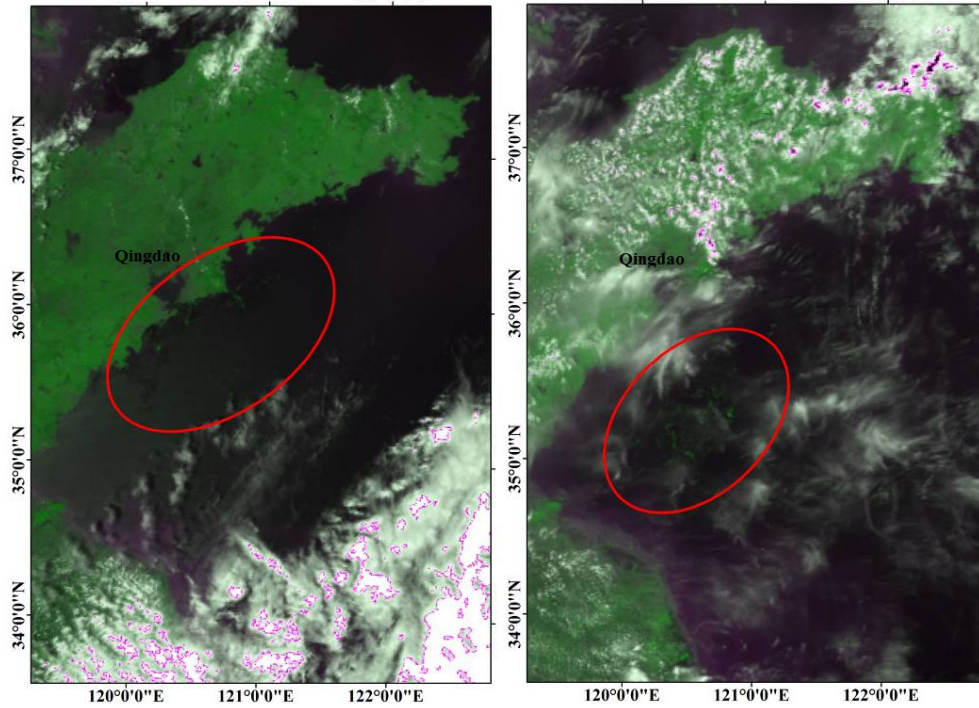


Fig. 1 Aqua MODIS RGB (1, 2, 1 bands) images of the *U. prolifera* bloom in the Yellow Sea acquired at 5:05 UTC on 28 June 2008 (a) and 5:20 UTC on 24 June 2013 (b). The floating macroalgae are shown as green patches (marked with red circles) on the images.

Based on the multi-source images listed in [Table 1](#), two comparative tests (CTs) are carried out for *U. prolifera* monitoring. In CT 1, three types of optical images of the green algae bloom in the northern Yellow Sea (Fig. 2) acquired on 24 June 2013 were chosen. In CT 2, we selected MODIS and ASAR images of the algae bloom in Qingdao coastal areas on 24 June 2013 (Fig. 3). In the monitoring process, in order to reduce errors introduced by growth, disappearance, or movement of the macroalgae, we selected several sub-regions with similar and independent algae patterns in each group of satellite images [based on human-computer interaction](#) (Cui et al., 2012). For each group of satellite data, images were acquired within 3 hours and the pattern of *U. prolifera* bloom changed little during the time span. Therefore, the *U. prolifera* patch in each corresponding sub-region is regarded as the same patch and its area is calculated and compared. For Figs. 2 and 3, we selected 6 and 5 sub-regions for comparison, respectively.

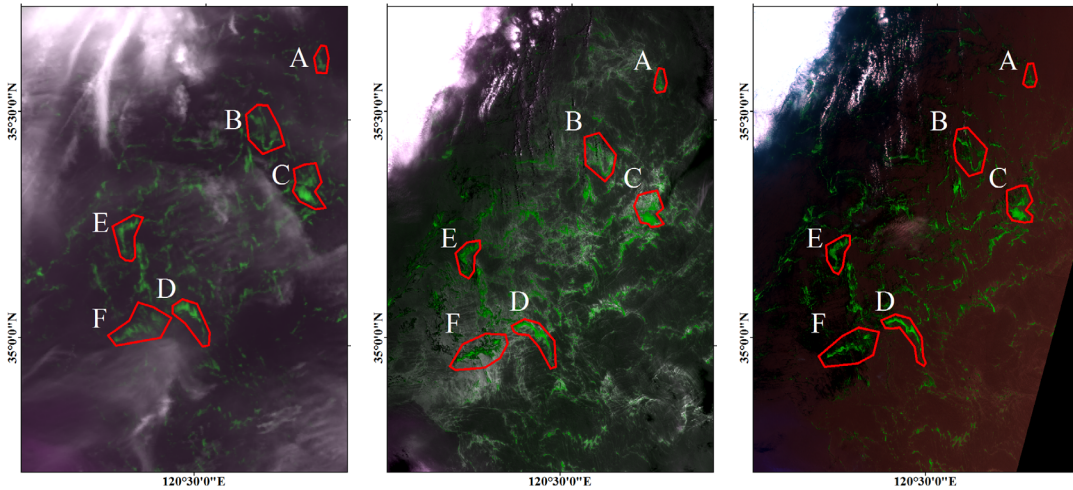


Fig. 2 Sub-images of three quasi-synchronous optical satellite images of *U. prolifera* bloom in the northern Yellow Sea. (a) Aqua MODIS image acquired at 5:20 UTC on 24 June 2013; (b) HJ-1A/B CCD image acquired at 2:12 UTC on 24 June 2013; (c) Landsat 8 OLI image acquired at 2:38 UTC on 24 June 2013. The 6 sub-regions A–F are marked with red polygons.

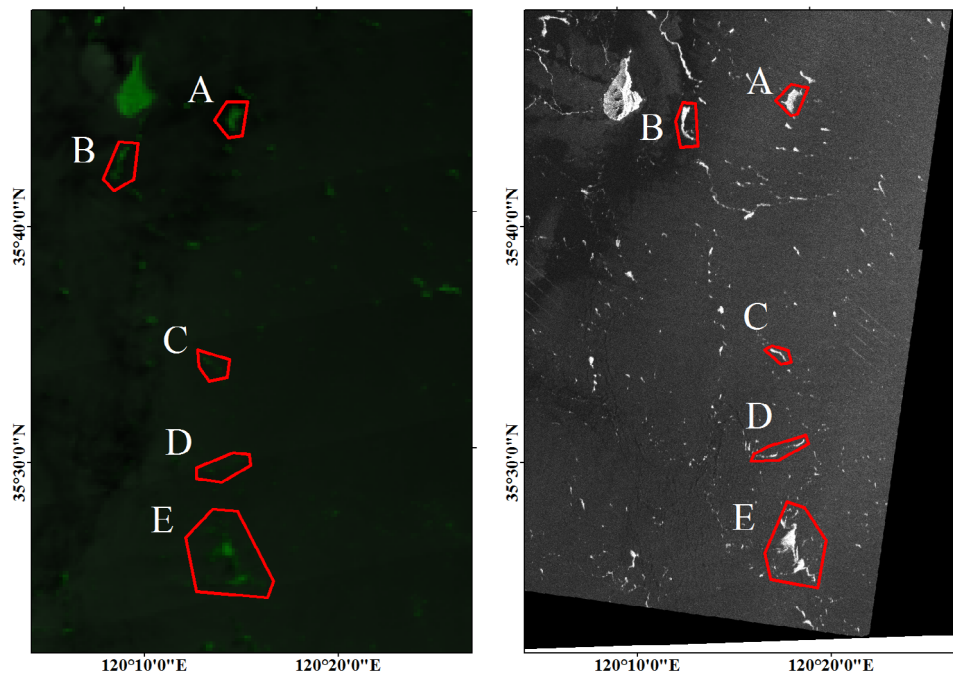


Fig. 3 Sub-images of *U. prolifera* bloom in Qingdao coastal areas: (a) Aqua MODIS image acquired at 5:05 UTC on 28 June 2008; (b) ENVISAT ASAR image acquired at 1:55 UTC on 28 June 2008. The 5 sub-regions A–E are marked with red polygons.

2.2 *U. prolifera* monitoring method

Because the spectral characteristics of *U. prolifera* in the visible and infrared bands are much like that of the land vegetation, most methods for monitoring this kind of algae from optical satellite data are based on the “red edge” phenomenon of the vegetation spectrum. In this study, we adopt

the NDVI method, which was widely used for *U. prolifera* monitoring (Hu and He, 2008; Liu et al., 2009; Keesing et al., 2011; Cui et al., 2012). The index is defined as

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}), \quad (1)$$

where NIR and R denote radiance in near infrared (NIR) and red bands, respectively. A threshold of NDVI must be selected to segment the image for the extraction of *U. prolifera* patches.

Monitoring of the green algae bloom from SAR images depends on the difference of the normalized radar backscattering cross section (NRCS) between *U. prolifera* and sea water. NRCS of the floating macroalgae is higher than that of the surrounding sea water, which makes the algae patches brighter in the SAR image (Fig. 3(b)).

The extraction of *U. prolifera* information in the Yellow Sea relies on the result of satellite image segmentation. And the image segmentation depends on the selection of a segmentation threshold (T), which is related to the difference of the radiance or NRCS between *U. prolifera* and sea water in optical or SAR images. But this difference varies greatly with the environment. Theoretically, the image pixels of positive NDVI value are treated as green vegetation. However, the Yellow Sea water is usually case II water (Ren and Zhao, 2002), which has large amounts of phytoplankton and suspended matter. In this case most water pixels will be classified as *U. prolifera* if we segment optical images with an NDVI threshold of 0, which will make the calculated area of the green algae much larger than the truth. Therefore, some researchers adjusted the threshold above 0 and used other fixed values. Since the selection of the fixed value is usually influenced by human-computer interaction and varies in different studies, the monitoring results of the *U. prolifera* from the same satellite image will also be different.

In this study, we use a nonparametric and unsupervised method which was proposed by Otsu (1979) (hereafter named OTSU method) and widely used in the field of image segmentation (Xu et al., 2011) to automatically determine the threshold for distinguishing the *U. prolifera* and sea water. The optimal threshold is selected by the discriminant criterion to maximize the separability of the resultant classes in gray levels. The procedure is very simple, utilizing only the zeroth- and the first-order cumulative moments of the gray-level histogram. Once the pixels covered by the floating macroalgae are discriminated from that of water, i.e., the pixel values of the floating macroalgae are higher than that of water, the area is calculated by multiplying pixel area and the number of algae pixels. For optical images, the NDVI threshold with fixed values of 0, 0.1, and 0.2 is also used to investigate the influence of the threshold selection on *U. prolifera* monitoring results. For all optical images, FLAASH (Fast Line of Sight Atmospheric Analysis of Spectral Hyper-cubes) atmospheric correction is conducted before image segmentation (Cooley et al., 2002).

3 Results and discussion

3.1 Comparative test 1

Using the NDVI method with different segmentation thresholds (0, 0.1, 0.2, and that determined by the OTSU method, hereafter named OTSU threshold), the areas of 6 *U. prolifera* patches in

sub-region A–F are calculated from MODIS, HJ-1 A/B CCD, and Landsat 8 OLI images on 24 June 2013, respectively. The results are listed in [Table 2](#).

As an example, [Figs. 4–6](#) show the green algae monitoring results in region F on OLI and MODIS images, respectively. One can see the areas calculated by NDVI with a small threshold ($T=0$) are too large. Due to the complexity of the characteristics of case II water in the Yellow Sea, almost all the pixel NDVI values of the optical image are positive. Thus the calculated areas with $T=0$ are almost the whole area of the sub-region, and many sea water pixels are classified as *U. prolifera*. If the threshold is too large (e.g., $T=0.2$), however, some of the *U. prolifera* cannot be detected. For any type of the optical images, the detecting results using **OTSU threshold** are always better and more accurate. From the figures, we can also see that the spatial resolution is an important factor affecting the *U. prolifera* monitoring result. Some small patches in CCD or OLI images are not shown in MODIS images, indicating satellite data with high spatial resolution is more suitable for describing the distribution of *U. prolifera* bloom in the Yellow Sea. In the process of observing *U. prolifera* pattern with multi-source remote sensing data, spatial resolution is a primary factor to be considered.

Table 2 Area (km²) of *U. prolifera* patches extracted from optical satellite images on 24 June 2013

Sensor	Spatial resolution/m	NDVI Method	Area/km ²					
			Region A	Region B	Region C	Region D	Region E	Region F
HJ-1A/B	30	$T=0$	13.50	62.60	44.86	51.86	34.17	83.12
CCD		$T=0.1$	5.15	25.93	35.09	25.53	18.10	33.55
		$T=0.2$	3.03	11.58	16.86	14.20	12.04	18.80
		OTSU T	3.37	11.34	11.97	10.45	10.88	15.06
Landsat 8	30	$T=0$	13.66	62.24	45.66	42.38	21.53	43.43
OLI		$T=0.1$	4.63	22.23	26.97	19.59	15.48	29.10
		$T=0.2$	3.89	18.14	20.78	15.43	13.63	24.53
		OTSU T	3.71	16.28	17.22	13.00	12.70	23.67
Aqua	250	$T=0$	8.50	45.19	48.69	33.94	29.69	57.63
MODIS		$T=0.1$	6.13	32.63	38.19	24.13	22.50	37.19
		$T=0.2$	4.75	22.63	31.25	17.81	16.44	19.63
		OTSU T	5.88	28.75	27.38	16.50	18.00	35.00

'OTSU T' denotes the threshold is determined by OTSU method.

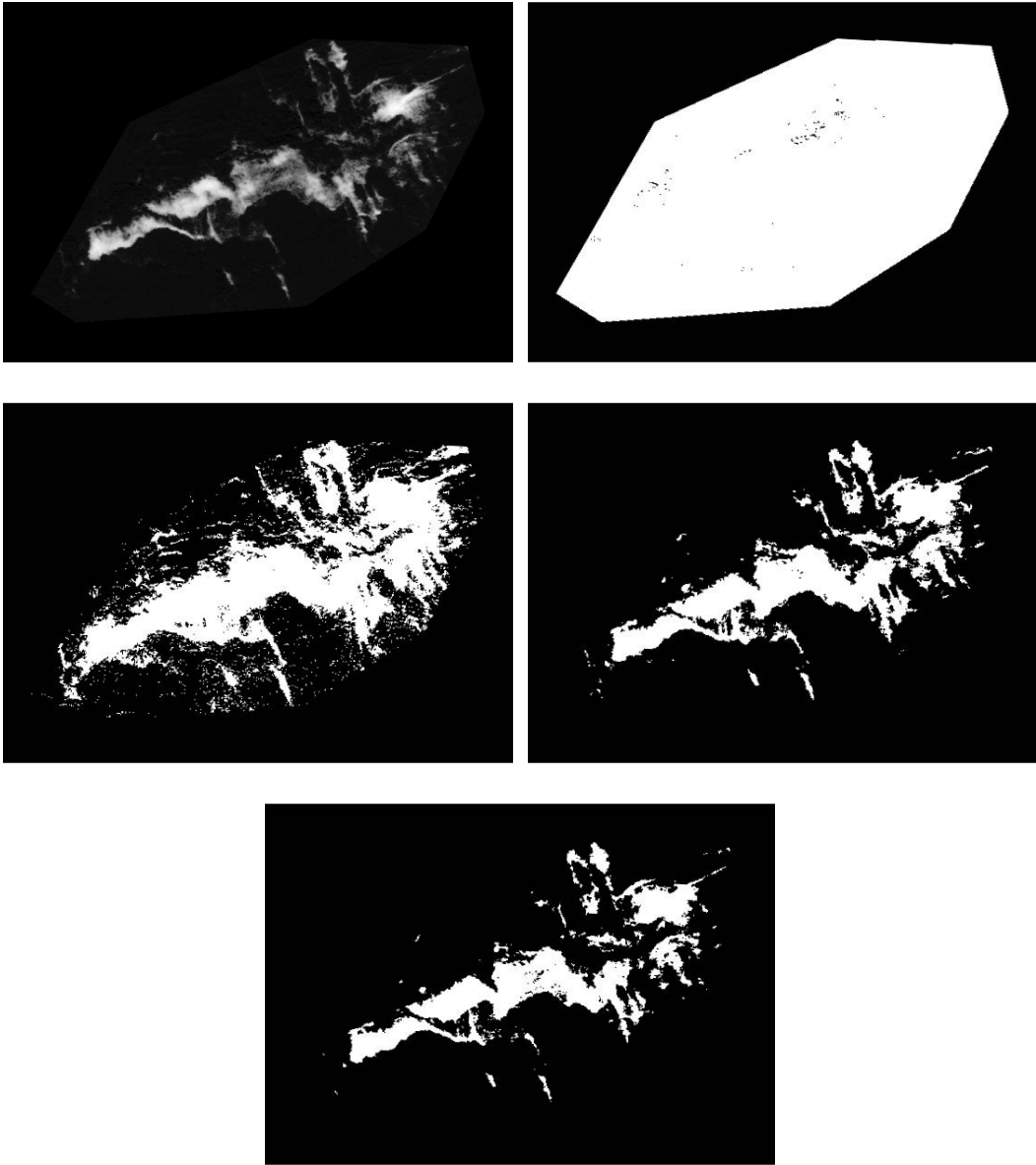
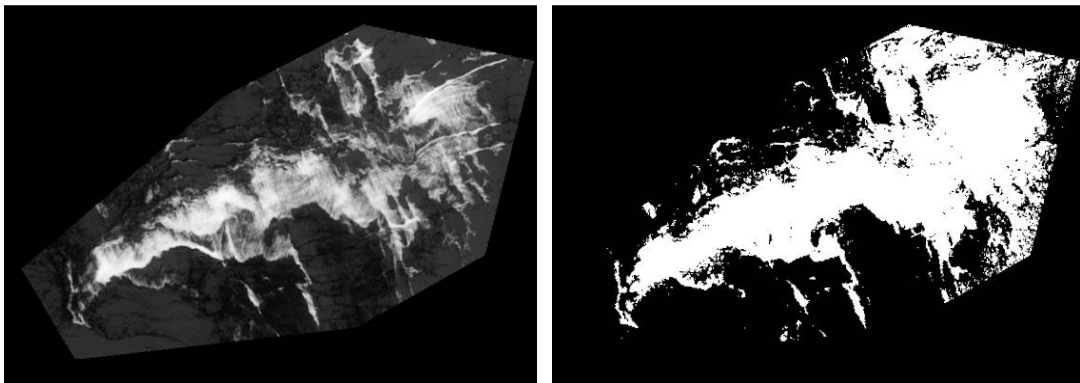


Fig. 4 The *U. prolifera* monitoring results in sub-region F on HJ-1A/B CCD image: (a) NDVI image, (b) detected *U. prolifera* (white color pixels) using NDVI method with $T=0$, (c) $T=0.1$ (d) $T=0.2$, and (e) OTSU threshold.



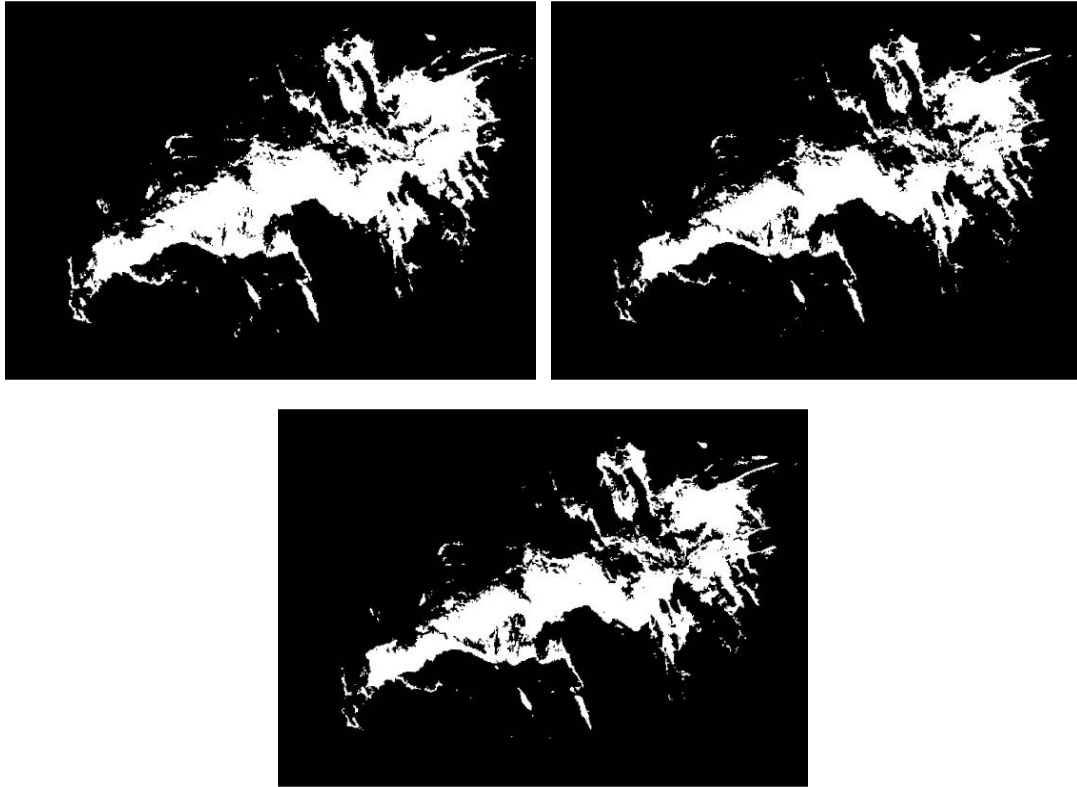
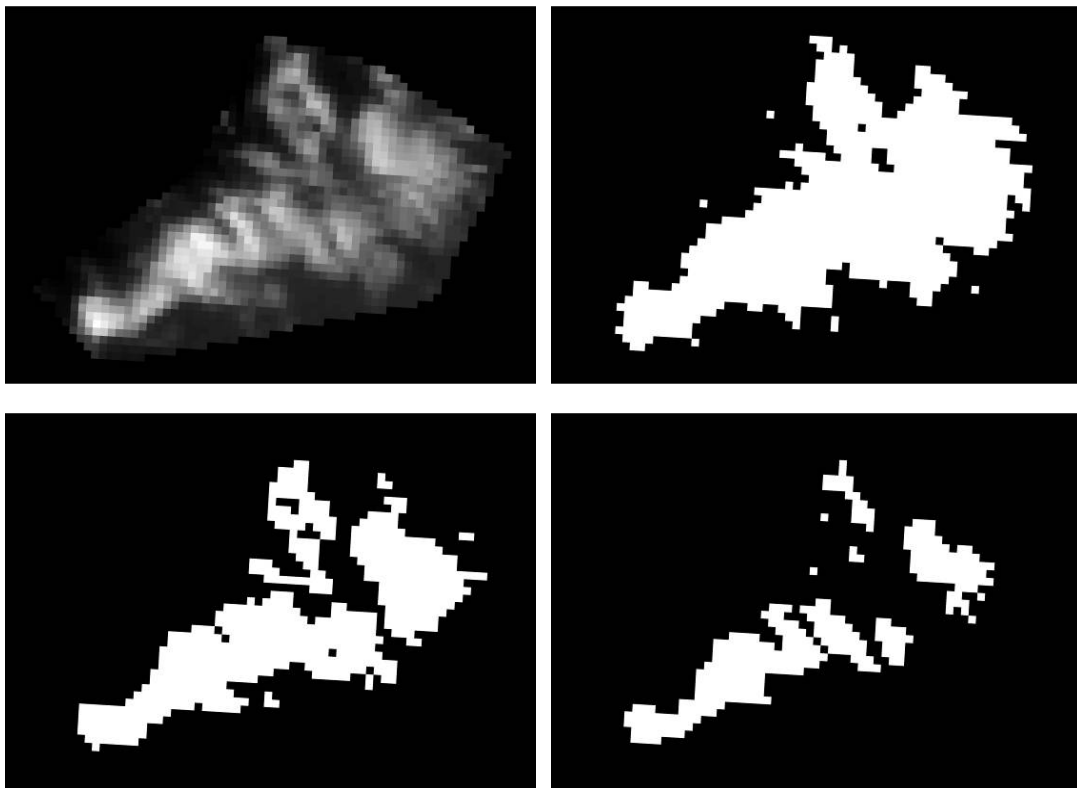


Fig. 5 The *U. prolifera* monitoring results in sub-region F on Landsat 8 OLI image: (a) NDVI image, (b) detected *U. prolifera* (white color pixels) using NDVI method with $T=0$, (c) $T=0.1$ (d) $T=0.2$, and (e) OTSU threshold.



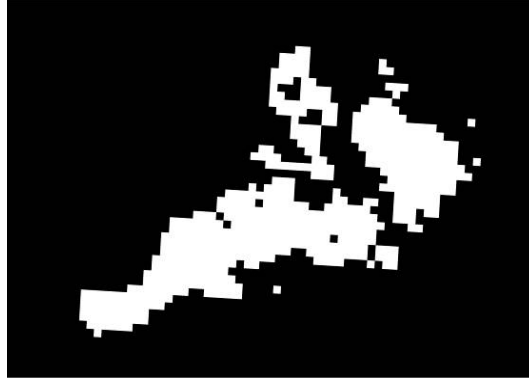


Fig. 6 The *U. prolifera* monitoring results in sub-region F on Aqua MODIS image: (a) NDVI image, (b) detected *U. prolifera* (white color pixels) using NDVI method with $T=0$, (c) $T=0.1$ (d) $T=0.2$, and (e) OTSU threshold.

The areas of floating macroalgae extracted from optical sensors with different spatial resolution using the NDVI method with OTSU threshold are compared in Fig. 7. In general, the area extracted from MODIS image with 250 m resolution is about 1.5–2.5 times that extracted from CCD or OLI image with 30 m resolution (Table 3). This result is similar to that presented by Cui et al. (2012), indicating again that the spatial resolution is a key factor influencing the *U. prolifera* observation.

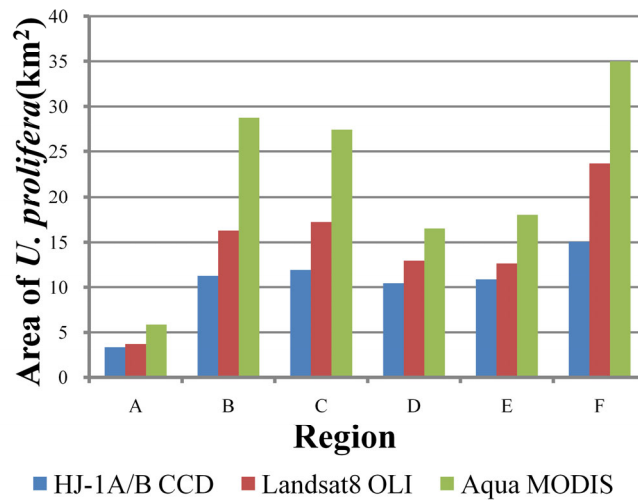


Fig. 7 Comparison of *U. prolifera* area (km²) calculated from HJ-1A/B CCD, Landsat8 OLI, and Aqua MODIS images in region A–F using NDVI method with OTSU threshold.

Table 3 Ratio between macroalgae areas extracted from Aqua MODIS and that from HJ1-A/B CCD and Landsat 8 OLI images using NDVI method with OTSU threshold

Area ratio	Region A	Region B	Region C	Region D	Region E	Region F
MODIS/CCD	1.7	2.5	2.3	1.6	1.7	2.3
MODIS/OLI	1.6	1.8	1.6	1.3	1.4	1.5

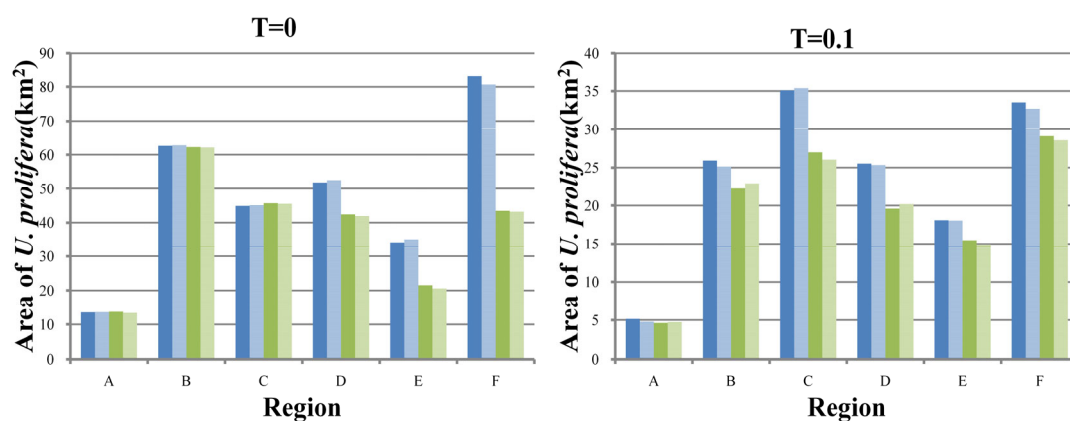
As we compare the areas computed from CCD and OLI images, we found that there is also a difference even if the two sensors have the same spatial resolution. As shown in Table 4, the average difference in 6 sub-regions is 32.7% and the differences in regions B, C, and F are

relatively large. Considering that the time interval between the two images is within half an hour, this difference might be primarily caused by the difference in sensors themselves (e.g., the configuration of sensor bands).

Table 4 Area (km²) of *U. prolifera* patches extracted from HJ1-A/B CCD and Landsat 8 OLI images with the same spatial resolution (30 m) using NDVI method with OTSU threshold. The difference in the table is the percentage of the area difference divided by the area from CCD

	Region A	Region B	Region C	Region D	Region E	Region F
HJ-1A/B CCD/ km ²	3.37	11.34	11.97	10.45	10.88	15.06
Landsat 8 OLI/ km ²	3.71	16.28	17.22	13.00	12.70	23.67
Difference/%	10.1	43.6	43.8	24.4	16.8	57.2

Cui et al. (2012) pointed out that the difference in *U. prolifera* monitoring results with different sensors is mainly because of the difference in spatial resolution. In their study, they resampled an HJ-1A/B CCD image on 5 June 2009 to 250 m resolution. The calculated algae areas in sub-regions are similar to that from quasi-synchronous MODIS image, with the average difference of 14% (ranging from 1% to 50% in different sub-regions). In this study, we carried out similar experiments by resampling the HJ-1A/B CCD and Landsat 8 OLI images to 250 m spatial resolution using the nearest neighbor method. The areas of *U. prolifera* patches extracted from the resampled images are compared with that from original images in Fig. 8. One can see the results are much different from that of Cui et al. (2012). No matter what NDVI threshold (fixed or OTSU threshold) we selected, the difference between the areas calculated from images before and after resample is not obvious. This difference from Cui et al. (2012) might be because the sub-regions Cui et al. (2012) selected are too small. These regions correspond to dozens or hundreds of pixels in the raster images. While extracting the area of the macroalgae, they selected an NDVI threshold by means of human-computer interaction, which may influence the monitoring results. As shown in Table 2, a small change in threshold will cause great change in area calculation. Especially for the data with 250 m spatial resolution, the difference may be only a few pixels. As our study shows, the influence of spatial resolution on the results of *U. prolifera* monitoring seems mainly embodied in original spatial resolution. The resampled images might retain more characteristics of original images. Whether fixed or OTSU NDVI threshold is used, the monitoring results will be similar to that from the original images.



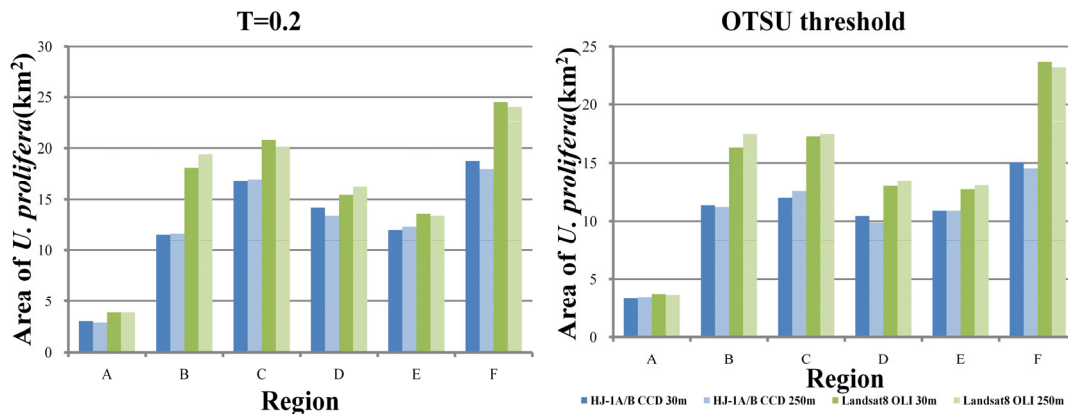
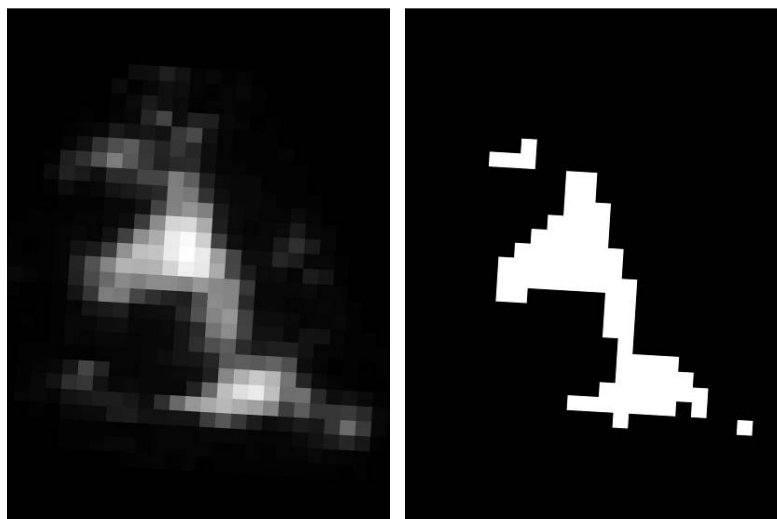


Fig. 8 Area of *U. prolifera* patches calculated from HJ-1A/B CCD and Landsat 8 OLI images before (resolution of 30 m) and after resample (resolution of 250 m) using NDVI method with (a) $T=0$, (b) $T=0.1$, (c) $T=0.2$, and (d) OTSU threshold.

3.2 Comparative test 2

In CT 2, for a MODIS image on 28 June 2008, the area of floating macroalgae was calculated by NDVI with the OTSU threshold. For quasi-synchronous ENVISAT ASAR data, we calculated the area by segmentation of the Normalized Radar Backscatter Cross Section (NRCS) image using the threshold also determined by the OTSU method. As an example, Figs. 9(b) and 9(d) show the detection results in sub-region E on MODIS and ASAR images, respectively. The SAR image with higher spatial resolution of 30 m also captured some small algae patches not shown on MODIS image. The areas extracted in 5 sub-regions are listed in Table 5, in which the area extracted from resampled ASAR image with resolution of 250 m is also shown. We can see MODIS detected areas of *U. prolifera* patches are 1.5–3 times that extracted from the original ENVISAT ASAR image with 30 m resolution, which is correlated with the different spatial resolution of the sensors. Note that unlike optical sensors, SAR cannot detect macroalgae suspended beneath the sea surface, which may make the areas extracted from SAR data a little smaller than that from optical images of the same resolution. The resampling of ASAR data does not affect the monitoring result much, similarly to the conclusion in CT 1. Therefore, we believe the results in this study are credible.



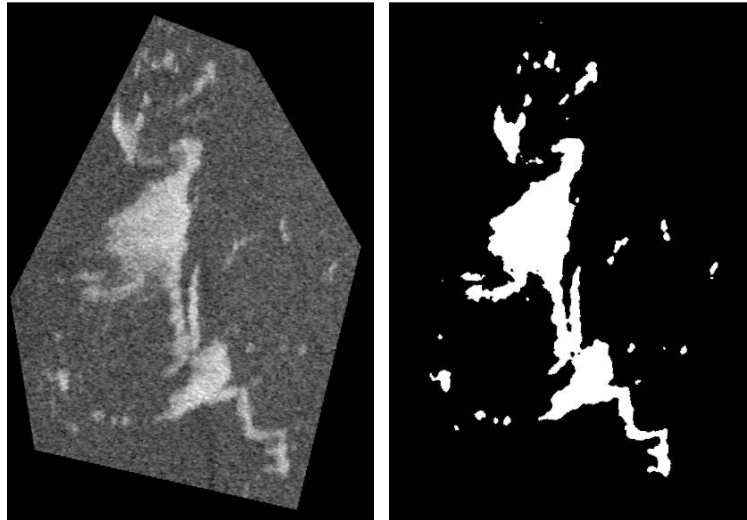


Fig. 9 The *U. prolifera* monitoring results in sub-region E on MODIS and SAR images acquired on 28 June 2008: (a) MODIS NDVI image, (b) detected *U. prolifera* (white color pixels) from MODIS using NDVI method with OTSU threshold, (c) SAR NRCS image, (d) detected *U. prolifera* (white color pixels) from SAR using OTSU threshold.

Table 5 Area (km²) of *U. prolifera* patches extracted from Aqua MODIS and ENVISAT ASAR images on 28 June 2008

Sensor	Spatial Resolution/m	Area/km ²				
		Region A	Region B	Region C	Region D	Region E
ENVISAT	30	0.86	0.91	0.22	0.38	2.88
ASAR	250 (After resampling)	1.06	1.13	0.31	0.44	3.31
Aqua MODIS	250	1.94	1.75	0.63	1.25	4.94

4 Conclusions

Based on two groups of quasi-synchronous satellite data with different spatial resolution, i.e., three images from optical sensors Aqua MODIS, HJ-1A/B CCD, and Landsat 8 OLI, and one image from microwave sensor ENVISAT ASAR, we conducted two comparative experiments to estimate the *U. prolifera* monitoring abilities in the Yellow Sea. For optical data, we used the NDVI method with different thresholds for image segmentation. The components of the Case II water in the Yellow Sea are complex, resulting in instability of the spectrum. In this case, visual interpretation itself cannot meet the accuracy requirement of *U. prolifera* monitoring. Image segmentation using a NDVI with fixed threshold is not suitable as well. In this study, we use the nonparametric and unsupervised method proposed by Otsu (1979) to automatically determine the threshold for segmentation. Results show that the floating macroalgae can be detected more accurately using this adaptive method, indicating that the monitoring results based on the characteristics of satellite images are more close to the truth when we know little about the study area.

In general, the macroalgae areas extracted from MODIS image with 250 m spatial resolution are 1.5–3 times that from CCD or OLI or ASAR image with 30 m spatial resolution, and high-resolution data can detect some small algae patches not shown on the MODIS image, meaning that the spatial resolution of satellite images is an important factor influencing the monitoring results. Even if the sensors have the same spatial resolution, the extracted algae areas are a little different, which might be primarily caused by the difference in sensor band configuration or aerosol optical properties (Cui et al., 2012).

For effective detection and warning of a massive *U. prolifera* bloom, satellite data with high spatial resolution (tens of meters) and short revisiting period (e.g., CCD) are preferable. The microwave data such as SAR images are a good supplement due to its all-weather and all-day monitoring capability. For tracking the origin of the floating macroalgae in the Yellow Sea and observing the movement of the massive bloom, wide swath data (e.g., MODIS) are also needed (Xu et al., 2014).

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References

- Cooley T, Anderson G P, Felde G W, Hoke M L, Ratkowski A J, Chetwynd J H, Gardner J A, Adler-Golden S M, Matthew M W, Berk A, Bernstein L S, Acharya P K, Miller D, Lewis P (2002). FLAASH, a MODTRAN4-based atmospheric correction algorithm, its application and validation. *Geoscience and Remote Sensing Symposium, IGARSS'02*, 3: 1414–1418
- Cui T, Zhang J, Sun L, Jia Y, Zhao W, Wang Z, Meng J (2012). Satellite monitoring of massive green macroalgae bloom (GMB): Imaging ability comparison of multi-source data and drifting velocity estimation. *Int J Remote Sens*, 33(17): 5513–5527 [doi:10.1080/01431161.2012.663112](https://doi.org/10.1080/01431161.2012.663112)
- Hu C (2009). A novel ocean color index to detect floating algae in the global oceans. *Remote Sens Environ*, 113(10): 2118–2129 [doi:10.1016/j.rse.2009.05.012](https://doi.org/10.1016/j.rse.2009.05.012)
- Hu C, He M (2008). Origin and offshore extent of floating algae in Olympic sailing area. *Eos Trans AGU*, 89(33): 302–303 [doi:10.1029/2008EO330002](https://doi.org/10.1029/2008EO330002)
- Hu C, Li D, Chen C, Ge J, Muller-Karger F E, Liu J, Yu F, He M (2010). On the recurrent *Ulva prolifera* blooms in the Yellow Sea and East China Sea. *Journal of Geophysical Research*, 115(C5) [doi:10.1029/2009JC005561](https://doi.org/10.1029/2009JC005561)
- Huang Z (2001). *Marine Species and Their Distribution in China's Seas*. Malabar: Krieger Pub Co, 1–599
- Keesing J K, Liu D Y, Fearnas P, Garcia R (2011). Inter- and Intra-annual patterns of *Ulva prolifera* green tides in the Yellow Sea during 2007–2009, their origin and relationship to the expansion of coastal seaweed aquaculture in China. *Mar Pollut Bull*, 62(6): 1169–1182 [doi:10.1016/j.marpolbul.2011.03.040](https://doi.org/10.1016/j.marpolbul.2011.03.040)
- Li Y, Liang G, Yu S M, Chen P (2011). Selection of microwave remote sensing data of monitoring of *Enteromorpha prolifera* disaster. *Marine Environmental Science*, 30(5): 739–742 (in Chinese)

- Liu D, Keesing J K, He P, Wang Z, Shi Y, Wang Y (2013). The world's largest macroalgal bloom in the Yellow Sea, China: formation and implications. *Estuar Coast Shelf Sci*, 129: 2–10 [doi:10.1016/j.ecss.2013.05.021](https://doi.org/10.1016/j.ecss.2013.05.021)
- Liu D, Keesing J K, Xing Q, Shi P (2009). World's largest macroalgal bloom caused by expansion of seaweed aquaculture in China. *Mar Pollut Bull*, 58(6): 888–895 [doi:10.1016/j.marpolbul.2009.01.013](https://doi.org/10.1016/j.marpolbul.2009.01.013)
- Otsu N A (1979). A threshold selection method from gray –level histograms. *IEEE Trans Syst Man Cybern*, 9(1): 919–926
- Pang S, Liu F, Shan T, Xu N, Zhang Z, Gao S, Chopin T, Sun S (2010). Tracking the algal origin of the *Ulva* bloom in the Yellow Sea by a combination of molecular, morphological and physiological analyses. *Mar Environ Res*, 69(4): 207–215 [doi:10.1016/j.marenvres.2009.10.007](https://doi.org/10.1016/j.marenvres.2009.10.007)
- Qiao F, Dai D, Simpson J, Svendsen H (2009). Banded structure of drifting macroalgae. *Mar Pollut Bull*, 58(12): 1792–1795 [doi:10.1016/j.marpolbul.2009.08.006](https://doi.org/10.1016/j.marpolbul.2009.08.006)
- Ren J, Zhao J (2002). Progress and prospect of ocean color remote sensing in case 2 waters. *Advance in Earth Sciences*, 17(3): 363–371 (in Chinese)
- Shi W, Wang M (2009). Green macroalgae blooms in the Yellow Sea during the spring and summer of 2008. *Journal of Geophysical Research*, 114, C12010 [doi: 10.1029/2009JC005513](https://doi.org/10.1029/2009JC005513)
- Shimada S, Yokoyama N, Arai S, Hiraoka M (2009). Phylogeography of the genus *Ulva* (Ulvophyceae, Chlorophyta), with special reference to the Japanese freshwater and brackish taxa. Nineteenth International Seaweed Symposium. Springer Netherlands, 2: 529–539
- Sun S, Wang F, Li C, Qin S, Zhou M, Ding L, Pang S, Duan D, Wang G, Yin B, Yu R, Jiang P, Liu Z, Zhang G, Fei X, Zhou M (2008). Emerging challenges: massive green algae blooms in the Yellow Sea. *Nature Proceedings*, hdl: 10101/npre.2008.2266.1.
- Xing Q, Zheng X, Shi P, Hao J, Yu D, Liang S, Liu D, Zhang Y (2011). Monitoring “green tide” in the Yellow Sea and the East China Sea using multi-temporal and multi-source remote sensing images. *Spectroscopy and Spectral Analysis*, 31(6): 1644–1647 (in Chinese)
- Xu Q, Zhang H, Ju L, Chen M (2014). Interannual variability of *Ulva prolifera* blooms in the Yellow Sea. *Int J Remote Sens*, 11–12: 1–15
- Xu X, Xu S, Jin L, Song E (2011). Characteristic analysis of Otsu threshold and its applications. *Pattern Recognit Lett*, 32(7): 956–961 [doi:10.1016/j.patrec.2011.01.021](https://doi.org/10.1016/j.patrec.2011.01.021)