Large invasion of floating aquatic plants in the Río de la Plata estuary!

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ABSTRACT

The La Plata basin is the second major hydrographical basin of South America and the fifth largest in the world. The massive development of floating plants in floodplain lakes and wetlands in the upper Middle Paraná river is important both environmentally and socio-economically. Drifting aquatic vegetation represents an important biomass, mobilized by flood pulses and climatic factors, and its drift moves organic matter, insects and other organisms in the ecological system. Aquatic plant detachments drift downstream arriving in small amounts to the Río de la Plata (RdP) every year, but huge temporary invasions have been observed in the RdP every 10 or 15 years associated to massive floods. Since late December 2015, heavy rains, driven by a strong El Niño, have increased river levels in the La Plata basin provoking a large temporary invasion of aquatic plants from January to April 2016. This event caused significant disruption of human activities via clogging of drinking water intakes in the estuary, blocking of ports and marinas and introducing dangerous animals from faraway wetlands into the city. Quantifying and mapping invasive plant species is important for efficient management and implementation of mitigation measures. This paper evaluates the ability of high-resolution multi-spectral imagery like Sentinel-2, Landsat-8, PROBA-V, and MODIS-250m, for mapping the large aquatic hyacinth (*Eichhornia crassipes*) invasion in the RdP that started in January 2016. Indices using bands that take into account chlorophyll-a absorption in the red band and the reflectance in the near-infrared and short-wave infrared bands are tested and validated using field measurements.

INTRODUCTION

Water hyacinth (*Eichhornia crassipes*) is a free-floating macrophyte native to Lower Amazonia, Brazil that forms dense mats on the surface of slow-moving waterways and backwaters. In floodplain wetlands aquatic macrophytes play a crucial role since they take part in life cycles of several other species providing food, nesting sites, refuge, etc., and can also interact with other factors modifying some physical and chemical characteristics of the environment, such as the transparency of water, sedimentation rates, etc. (Marchetti et al. 2013). On the other hand, massive proliferation of the invasive water hyacinth might represent a significant threat to recreation, fisheries, and wildlife resources, and ecological processes of freshwater ecosystems, like in lake Victoria in East Africa (Fusilli et al. 2013), the Río Grande River (Everitt et al. 2003) and in California's Sacramento–San Joaquin River Delta (Cohen and Carlton,1998) in the United States, amongst others.

Mapping of aquatic plants and estimation of their surface extent are crucial to the efficient management and implementation of mitigation measures. This information can be derived accurately with fine resolution remote sensing products like the high resolution imagery provided by Sentinel-2/MSI (10 m) and Landsat-8/OLI (30 m) systems, but their low observation frequency and narrow swath hinder their ability to continuously monitor and quantify the extent of floating vegetation. Meanwhile coarser resolution sensors, like MODIS (250 m), OLCI (300 m), and PROBA-V (100 m) provide a wider view and higher data frequency, but at the expense of spatial details. Different indexes have been developed to detect floating aquatic vegetation using remote sensing data that make use of their strong near infrared (NIR) reflectance similar to that of land vegetation (Gower et al. 2006; Hu, 2009; Shi and Wang , 2009; Keesing et al. 2011; Alawadi 2010).

In the Paraná river floodplain (Argentina) (Fig. 1) floating aquatic vegetation represents an important biomass, mobilized by flood pulses and climatic factors, and its drift moves organic matter, insects and other organisms in the ecological system. Aquatic plant detachments drift downstream arriving in small amounts to the Río de la Plata (RdP) every year, but huge temporary invasions have been observed in the RdP every 10 or 15 years. In mid-January 2016 the coast of Buenos Aires became covered with large mats of the aquatic hyacinth *Eichhornia crassipes*. This abnormal event was related to unusually heavy rains that occurred in Southern South America at the end of 2015 associated to a strong El Niño that flooded the rivers that feed into the Río de la Plata. The rain and floods raised water levels of the floodplains along the Paraná river and swept floating plants into the main river waterway (Fig. 1b). This large temporary invasion of aquatic plants that occurred from January to end of April 2016 caused significant disruption of human activities via clogging of drinking water intakes in the estuary, blocking of ports and marinas and introducing dangerous animals from faraway wetlands into the city.
The objective of the present study is to assess the unusual invasion of *Eichhornia crassipes* in the Río de la Plata in a multi-mission perspective. The ability of high-resolution multi-spectral imagery like Sentinel-2, Landsat-8, PROBA-V, and MODIS-250m, for mapping the large aquatic hyacinth invasion in the turbid waters of RdP was evaluated.

STUDY AREA

La Plata basin is the second largest basin in South America after the Amazon and the fifth largest in the world (UNESCO, 2007). It drains to the Atlantic Ocean at around 34° S through the Paraná and Uruguay rivers (Fig. 1). The Paraná river supplies most of the sediment load reaching the Río de la Plata estuary, most of which originates in Bermejo river, amongst the most turbid rivers of the world (~8,000 g m^{-3}). It also drains around 79% of the discharged water which annual mean value is ~22,500 m^3 s^{-1}, but can reach up to ~90,000 m^3 s^{-1} and can be as low as ~7,800 m^3 s^{-1} in association with the ENSO cycle (Robertson and Mechoso, 1997; Jaime et al., 2003). The Paraná-Paraguay fluvial corridor starts in tropical latitudes (Pantanal in Brazil), runs through subtropical regions and ends in the Río de la Plata estuary, located in a temperate region. It's the main surface water collector of the basin which presents high extensions of wetlands characterized by a regime of drought and flood pulses (Neiff and Malvárez, 2004). This bio-geographical corridor constitutes an effective route for passive or active migration of flora and fauna from tropical to temperate zones (Bó 2006). The main water collectors (Paraguay and Paraná) present branched watersheds over complex flood plains (Inventario de los humedales de Argentina, 2013). The end portion of the Paraná-Paraguay fluvial corridor is characterized as a wetland macrosystem (Neiff et al. 1994), the Paraná Delta where the Paraná river converges with the Uruguay river into the Río de la Plata estuary. This large funnel shape estuary has significant social, ecological and economical importance for the countries on its shores, Argentina and Uruguay. The capital cities of both countries (Buenos Aires and Montevideo) and a number of harbours, resorts and industrial centres are located on its margins and influence zone. The estuary constitutes the main source of drinking water for the millions of inhabitants in the region, for whom it is also an important recreational area.

FLOATING VEGETATION INDEXES

Two indexes were tested in this study for their ability to detect floating vegetation in the turbid waters of RdP. The first is the Normalized Difference Vegetation Index (NDVI), developed originally as an index of land vegetation density or greenness, but also used to delineate floating algae from nearby waters (Hu 2009), defined as

$$NDVI = \left[R_{rc}(NIR) - R_{rc}(RED)\right] / \left[R_{rc}(NIR) + R_{rc}(RED)\right] \quad (1)$$

where R_{rc} is the Rayleigh-corrected reflectance and the RED and NIR are the spectral bands indicated in Table 1 for each sensor. The second is the floating algal index (FAI), developed to detect enhanced reflectance in the NIR (Hu et al. 2010), and defined as

$$FAI = R_{rc}(NIR) - R_{rc}(RED) - \left[R_{rc}(SWIR) + R_{rc}(RED) \times (\lambda_{NIR} - \lambda_{RED}) / \lambda_{SWIR} - \lambda_{RED})\right] \quad (2)$$

where λ_{band} is the central wavelength in each band (RED, NIR, SWIR) corresponding to each sensor (Table 1). The FAI is calculated as the difference between R_{rc} in the NIR and the baseline reflectance derived from the linear interpolation between the red and SWIR bands (see spectra in Fig. 2). In this study, the presence of floating vegetation was defined when the index was positive.

DATA

Satellite data

Satellite data with different spatial and temporal resolutions covering the RdP region from the January-April 2016 period were used in the present study (Table 1). MODIS-Aqua L1A images were downloaded form the NASA Ocean Color web site (http://oceancolor.gsfc.nasa.gov), Landsat-8/OLI and Sentinel-2/MSI data from USGS EarthExplorer (http://earthexplorer.usgs.gov), and PROBA-V 100 m data through the VITO Earth Observation Product Catalogue (http://www.vito-eodata.be).

Rayleigh-corrected reflectance (R_{rc}) at all bands was obtained using different freely available software for the different sensors: MODIS data was processed using SeaDAS (version 7.02), while OLI, and MSI data were processed using ACOLITE v.20160520.1 software (http://odnature.naturalsciences.be/remsem/software-and-data/acolite). PROBA-V imagery was processed using a modified version of ACOLITE that is not yet publicly available. RGB "true-color" images were also generated for each sensor using the corresponding red (R), green (G) and blue (B) band of each sensor (see Fig. 3). It should be noted that given that PROBA-V lacks a band in the green region, so the RGB is made from Red-NIR (835 nm)-Blue instead.

Land and cloud masking was performed using first a classification scheme and then an isolation criteria. Each pixel was classified as a) water, b) land or floating vegetation, and c) cloud and cloud shadow if:

a) R_{rc}(SWIR) / R_{rc} (RED) < 0.03
b) FAI > 0
c) max(R_{rc}(VIS)-min(R_{rc}(VIS)) * max(R_{rc}(VIS)) < 0.0002 & min(R_{rc}(VIS))>0.15

Then, the neighboring pixels of each pixel with FAIT > 0 (b) are evaluated to determine if they correspond to land or floating vegetation. A window of 300 m, i.e. with different pixel size for each senor (e.g. 30 x 30 for S2 and 10 x 10 for L8) centered at the flagged pixel is analyzed and is flagged as floating vegetation if pixels flagged as water are found in at least two of the eight main directions, otherwise the pixel is flagged as land. Finally, every pixel flagged as floating vegetation that is spatially connected to land/cloud pixels is flagged as land/cloud: this prevents that coastline and cloud edges to be erroneously flagged as floating vegetation.

Field data

Surface reflectance measurements were made on a dense mat of aquatic hyacinth during the invasion on January 28, 2016, from a pier located in the city of Tigre, to the north of Buenos Aires city and close to the Paraná Delta. Two Trios-RAMSES hyperspectral spectroradiometers, measuring radiance and downwelling irradiance, were mounted on a home-made frame. Zenith angle of the sea-viewing radiance sensor was 40° and the azimuth angle from the sun was ~135°. Spectral reflectance (ρ) was calculated by dividing π times the upwelling radiance by the downwelling irradiance.

RESULTS AND DISCUSSION

Detection of Floating Vegetation

Surface reflectance from *Eichhornia crassipes* mats collected close to Buenos Aires during the floating vegetation invasion in January showed a marked increase in the NIR and a peak in the green regions of the spectra (green spectra in Fig. 1e). The mean spectra of more than 50 field measurements collected in the RdP turbid waters are shown in black for comparison.

The two vegetation indices, NDVI and FAI, have been applied to images with different resolutions and visually compared with their corresponding RGB images to assess the ability of each index to detect the aquatic hyacinth invasion in the RdP. As an example, the different indexes applied to a MODIS image acquired on 21 April 2016 are shown in Fig. 2, where pixels are flagged if NDVI or FAI > 0. Systematically, NDVI identified as floating vegetation less pixels (N=2696) compared to FAI (N=9998) and the visual analysis indicated that NDVI was more conservative while FAI identified the pixels that an observer would identify as "greenish" or vegetation-containing pixels. However, false positives were obtained in the most turbid region of the estuary (brown pixels in Fig. 2c). A spectral analysis of pixels in this region for moderate to high turbid waters does not show a peak in the NIR band (blue spectra in Fig. 2). However, where the maximum turbidity is known to occur (Punta Piedras) reflectance is very high in the NIR (high amount of particles) and lower in the red and SWIR bands (high water absorption) thus presenting a peak in the NIR which is erroneously interpreted as a floating vegetation pixel by the FAI (brown spectra in Fig.2). In order to avoid the false positive in the most turbid waters, a threshold on the red band was determined by examination of several images. Only pixels with positive FAI and Rayleigh-corrected reflectance in the red band with values less than 0.09 were considered to contain floating vegetation. Considering this threshold, from the 9998 pixels classified as floating vegetation (green pixels in Fig. 2b), 6205 are classified as floating vegetation(green pixels in Fig. 2c) and 3793 pixels were misclassified using FAI (brown pixels in Fig. 2c). It is the modified floating algal index in turbid waters (FAIT) that will be used in the following analysis.

Impact of spatial resolution

A time series of MODIS-Aqua FAIT images was generated for the period 1 January - 31 May 2016. Due to cloud cover only 74 images were used, from which only 26 showed the presence of floating vegetation. The first and last images with detection of floating vegetation were acquired on 15 January and 22 April 2016 respectively. It's worth noting that between the 8 and 15 January there were no cloud-free images of the region, thus no exact date of the first detected floating vegetation can be determined. The first observations of floating vegetation

arriving to the coast of Buenos Aires were made on 16 January 2016 and the arrival of big masses was not continuous, but in pulses after strong rains.
Less images were available for the higher spatial resolution sensors due to their reduced temporal resolution. Available images were often covered by clouds. The detection capability of different high resolution imagers was analyzed and compared to MODIS-Aqua imagery acquired the same day. Given the large extension of the estuary and the different coverage of the sensors (the swaths of the high spatial resolution sensors cover only part of the estuary), the analysis was restricted to the upper estuary region which includes the Paraná Delta and the coast of Buenos Aires city (Fig. 3). In general, higher resolution imagers were able to detect a larger area covered by floating vegetation and also could resolve finer scale features that were lost in the coarser MODIS resolution images (250 m). Several large patches of floating vegetation have been identified on 22 April 2016 by PV and MODIS sensors. Considering the same sub-region in both images (dashed squares in Fig. 3) the surface covered by the floating vegetation (calculated multiplying the number of flagged pixels times the nominal surface of the pixel) for PV (100 m) and MODIS-Aqua (250 m) was relatively similar: 90.8 and 117.8 km^2 respectively. In turn, L8 captured fine scale patches on 24 February, 2016. For the same sub-area, the covered surface detected with L8 (30 m) was 12.5 km^2 while MODIS-Aqua (250 m) mapped one third of this area, 4.1 km^2. Finally, on the S2 image on 9 February, 2016 small patches (0.31 km^2) were detected, while using MODIS-Aqua (250 m) no floating vegetation was detected. Part of the differences between images from different sensors are expected due to the difference in time of the satellite overpasses, but mainly due to the reduction of the spectral contrast caused by the reduced spatial resolution. The example above clearly shows this: the reduction in the mapped area is more pronounced as the spatial resolution increases. To assess this effect S2-MSI data (10 m) was spatially averaged to coarser grids and spectra were extracted from S2 data and averaged over spatial windows corresponding to different resolutions. Fig. 4 shows S2-MSI data (9 February 2016) over a patch of floating vegetation, spatially averaged to 30, 100, 300 and 1100 m, and the corresponding spectra and FAIT values. This figure clearly shows the loss in spectral contrast as a result of a reduced spatial resolution thus limiting the capability of the coarser resolution sensors to detect floating vegetation.

Detection of other floating organisms in the RdP

The FAIT index proposed in this study is a refinement of the FAI proposed by Hu (2009) which takes into account the highly reflective waters in the RdP that also show elevated reflectance in the NIR leading to a misclassification of very turbid waters as floating vegetation. The analysis of MODIS-Aqua derived FAIT images from 2015 showed an unexpected patch of FAIT>0 in the Uruguay coast in January 2015. The MODIS and L8 RGB images confirmed the presence of a large green patch close to the Uruguay capital (Montevideo) which looked like a surface bloom (Fig. 5). In January, local authorities alerted the population to the presence of a cyanobacteria bloom in Montevideo and Canelones beaches. In different parts of the coasts of RdP cyanobacteria blooms (being *Microcystis spp.* and *Anabaena spp.* the most common species) have been detected since 1982, mainly in Summer, and have been related to high concentration of nitrogen and phosphorous. Along the Uruguay coast these compounds come from fertilizers which are drained mainly from the Negro and Uruguay rivers. Ideal conditions for bloom development in the coastal area are low water salinity (due to increased rains and thus increased waters drained from rivers), high temperatures, and low winds. Landsat-8 images from the January 2015 period have been analyzed (Fig. 5). The FAIT flag was set only in part of the observed green waters. An increase in the NIR reflectance in these type of blooms has already been associated to surface scum of cyanobacteria (Hu et al. 2010, Qi et al. 2010, Shen et al. 2015). Therefore, the cyanobacteria scum could not be spectrally distinguished from the aquatic hyacinth with neither MODIS nor L8 bands and both are flagged using FAIT. In turn, green waters located closed to the cyanobacteria scum, but not classified using FAIT, have a peak in the green band, but could not be spectrally distinguished from clearer waters using neither MODIS nor L8 (Fig. 5).

CONCLUSIONS

The FAIT allowed the identification and mapping of the large aquatic hyacinth (*Eichhornia crassipes*) invasion in the RdP that started in January 2016. However, this index detects floating vegetation in general and thus cannot be used to differentiate floating water plants, like the aquatic hyacinth, from cyanobateria scum. In order to differentiate them higher spectral resolution is needed, for example bands at and around ~620 nm would be useful given the characteristic pigment present in cyanobacteria cells called phicocyanin (PC), a phycobiliprotein that has a local absorption peak at ~620 nm. Qi et al. (2014) has already proposed an algorithm using MERIS 620 nm band to estimate PC blooms, in which both cyanobacteria cells and scum were detected and considered as bloom.

Daily 250m MODIS images allowed us to identify the period when the floating vegetation lasted and to make a coarse quantification of its extension. However, higher spatial resolution sensors allowed to detect finer scale features and to have a better quantification of floating vegetation extent. It has been shown that a reduction in the spatial resolution and the associated reduction in the spectral contrast causes a reduction in the amount of floating vegetation identified.

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Table 1. List of the satellites used in this study, their spatial resolution, the bands used in the floating algal indexes (bandwidth), swath and revisit time.

	Spatial Resolution (m)	*RED (nm)*	*NIR (nm)*	*SWIR (nm)*	*Swath (km)*	*Revisit*
MODIS	250[1] & 500[2]	645[1] (50)	859[1] (250)	1240[2] (20)	2,330	Daily
PROBA-V	100	658 (82)	834(121)	1610 (89)	517	5 days
Landsat-8	30	655 (50)	865 (40)	1650 (100)	180	8 or 16 days
Sentinel-2	10	665 (30)	865 (20)	1610 (90)	290	10 days

[1] Band with 250 m resolution; [2] Band with 500 m resolution

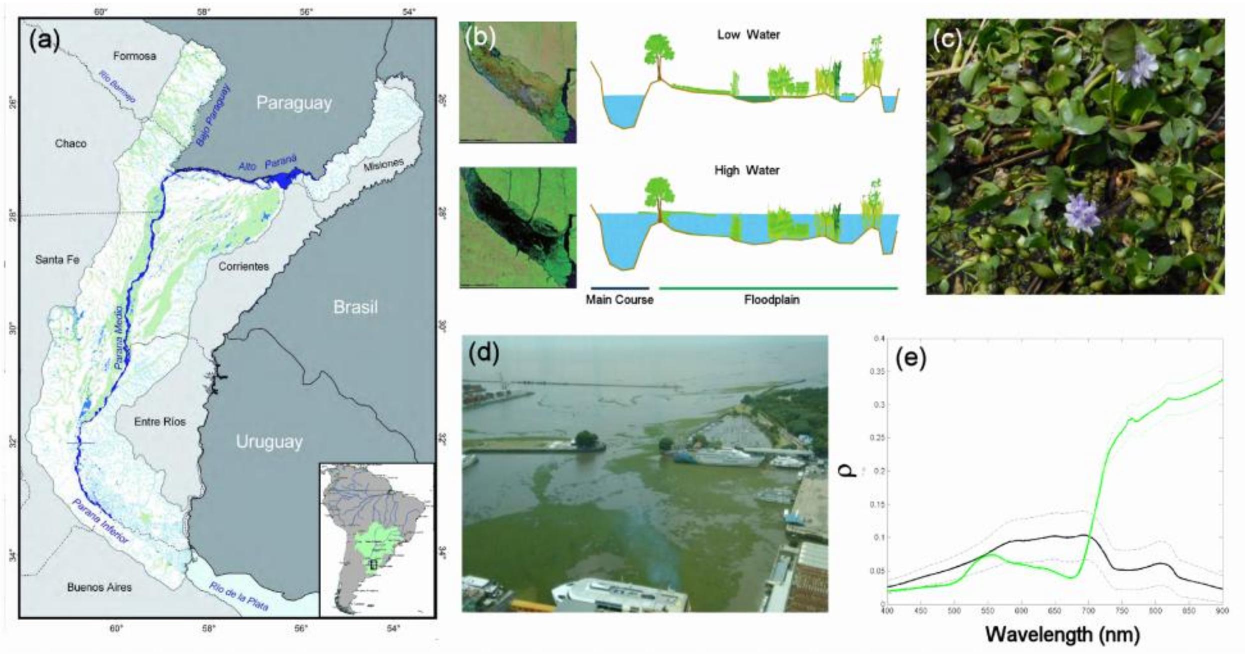

Fig. 1 (a) Location of the Paraná-Paraguay fluvial corridor and RdP estuary; (b) schematic representation of low and high water conditions that can be found in the floodplain; (c) floating water hyacinth *Eichhornia crassipes*; (d) a passenger ferry terminal invaded by water hyacinth; (e) Surface reflectance of water hyacinth mats (green) collected in Jan 2015 and RdP turbid waters (black) collected in previous cruises. Thick lines represent the mean of ~10 and >50 measurements from *Eichhornia crassipes* and turbid waters of RdP, respectively. Dashed lines correspond to one standard deviation.

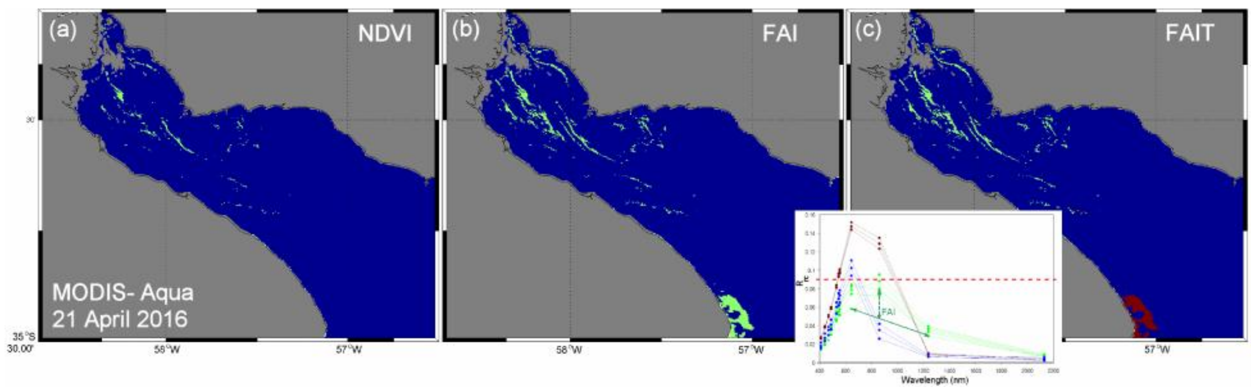

Fig. 2. Maps of positive floating vegetation indexes calculated over a MODIS-Aqua acquired on MA 21 April, 2016. (a) NDVI>0 N= 2696; (b) FAI> 0 (N=9998); (c) FAIT>0 & R_{rc}(RED)>0.09 N=6205. Spectra of pixels flagged as floating vegetation (green), pixels in moderate to high (blue) and in the highest (brown) turbid waters in the estuary are also shown.

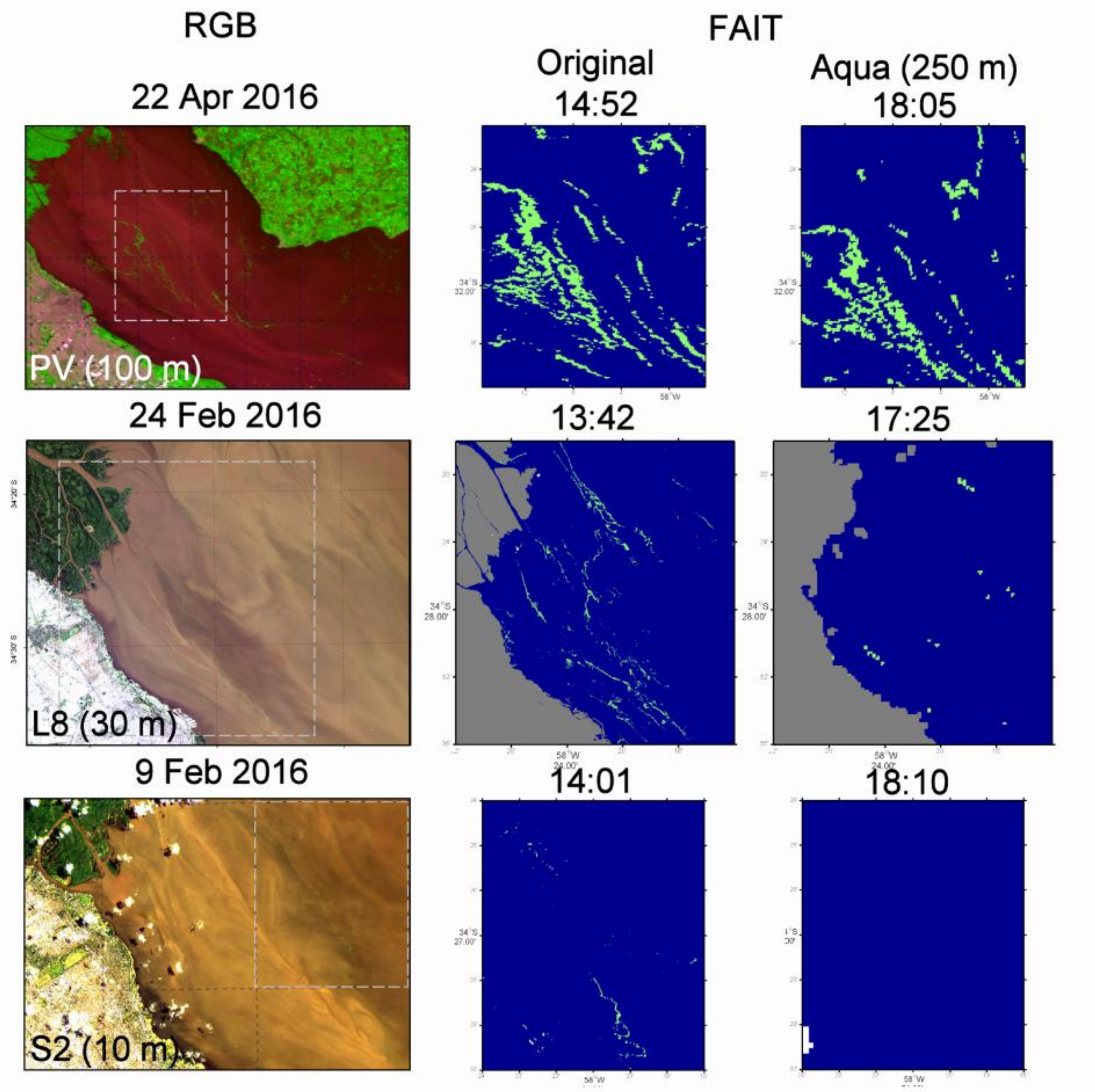

Fig. 3 True-color red-green-blue (RGB) images from PV (R=650, G=835, B=470), L8 (R=655, G=561, B=443) and S2 (R=664, G=560, B=444), FAIT flagged subset of each image (dashed squares in RGB) and from the same day MODIS-Aqua image. The acquisition date and time (GMT) of each image is indicated.

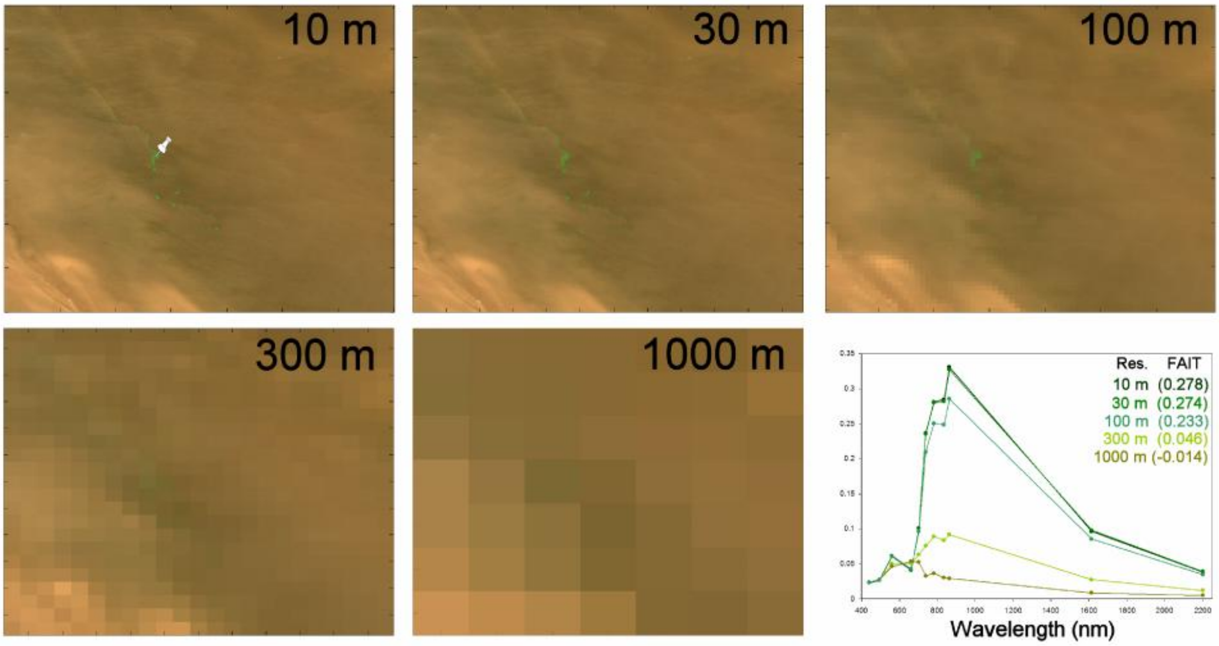

Fig. 4. S2-MSI data on 9 February 2016 over a patch of floating vegetation (upper left) and spatially averaged to 30, 100, 300 and 1000 m pixel size. Corresponding spectra of the original S2 green pixel and the arithmetic mean value of 3x3, 9x9, 29x29 and 99x99 pixel boxes and the corresponding FAIT value (lower right).

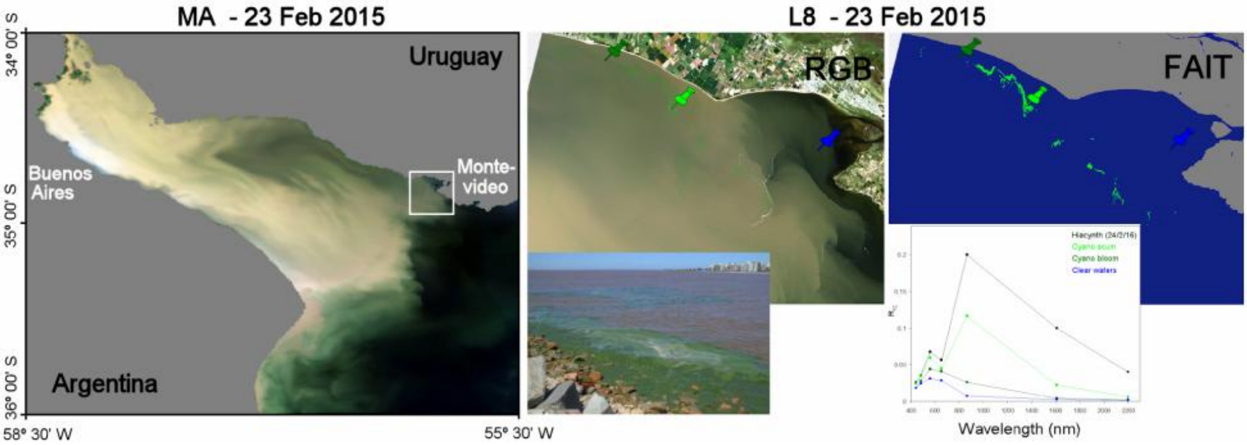

Fig. 5 L8 Cyanobacteria bloom (Microsystis spp.) along the Uruguay coast. MODIS-Aqua and L8-OLI RGB images and the FAIT flagged L8 image on 23 February 2015. Spectra of clear waters, cyanobacteria bloom and scum as well as from floating vegetation detected on a L8 image on 24 February 2016 are also shown.