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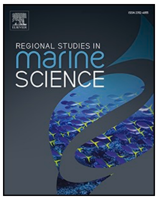

Harmful Algal Blooms on the Portuguese coast: Cross-checking events with remote sensing ocean colour data for coastal management

Helena Monteiro [a,c,*], Priscila Goela [a,b], Raquel Pinto [c,d], Sónia Cristina [a]

[a] *CIMA—Centre for Marine and Environmental Research/ARNET-Aquatic Research Network, Universidade do Algarve, Campus de Gambelas, Faro 8005-139, Portugal*
[b] *S2AQUA - Collaborative Laboratory, Association for a Sustainable and Smart Aquaculture, EPPO-IPMA, Av. Parque Natural da Ria Formosa, s/n, 8700-194, Portugal*
[c] *FCUP - Faculty of Sciences of the University of Porto, Rua do Campo Alegre, s/n, Porto 4169-007, Portugal*
[d] *CIIMAR, Interdisciplinary Center for Marine and Environmental Research, Terminal de Cruzeiros de Leixões, Av. General Norton de Matos, s/n, Matosinhos 4450-208, Portugal*

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ABSTRACT

Phytoplankton plays a vital role in marine ecosystems, serving as a primary food source for a diverse array of organisms, including commercially important bivalves, crustaceans, and fish. However, in some situations, the proliferation of algae can cause serious economic losses for aquaculture, fishing, and tourism and have major environmental and human health impacts. Increases in the occurrence of toxic phytoplankton blooms in Iberian waters have been reported. Earth Observation (EO) can provide important information about the spatial and temporal distribution and the destination of blooms, with scales not available for conventional monitoring techniques. The present work aims to take advantage of public databases (Harmful Algae Event Database (HAEDAT)) to relate ocean colour data, also publicly available, (Copernicus Marine Environmental Monitoring Service (CMEMS)) with the detection of the occurrence of harmful algal blooms (HABs). From the analysis of the HAEDAT database, it was possible to observe that in Portugal, from 1987 to 2020, there were 669 HABs events, with Diarrhetic Intoxication by Shellfish (DSP) syndrome. The images were extracted from multiple ocean colour sensors (2017–2020) for periods coinciding with DSP HABs events in recent years to identify patterns in the development of HAB toxins and to assist in coastal management. Having in account the HAB events analysed (12), was observed a weak but significant correlation between the datasets when the comparison was between the biotoxin concentration and its 14th day precedent Chlorophyll *a* (Chl *a*) concentration ($r_{Spearman}$=0.15). These results show how EO data relate to regular bivalve toxin monitoring programs on the Portuguese coast and are useful for future integration in modelling tools. Other than being useful for coastal water quality assessment and management, these results also reinforce the importance of maintaining existing monitoring programs on a regular basis, especially as some types of HABs may not be easily distinguishable by EO.

1. Introduction

At the heart of marine ecosystems, phytoplankton fulfils a crucial role as the primary sustenance for a wide range of organisms, among them commercially significant bivalves, crustaceans, and fish. They also drive nutrient and carbon cycling and play critical roles in global biogeochemical processes and climate regulation. In most cases, phytoplankton blooms are beneficial for aquaculture and wild fishing. However, in some situations the proliferation of algae, the so-called Harmful Algal Blooms (HABs), have negative effects, causing negative impacts on human health and significant economic losses (for example, aquaculture, tourism) (Pettersson and Pozdnyakov, 2013).

Increases in the occurrence of some toxic phytoplankton blooms and the appearance of species never mentioned in Iberian waters have been reported, which may be related to the increased use of coastal waters for aquaculture, anthropogenic eutrophication, and the transport of toxic microalgae in the ballast waters of ships (Borbor-Cordova et al., 2019; Pettersson and Pozdnyakov, 2013).

In Portugal, HAB events in coastal regions are common and, depending on its originating microphytoplankton species (cells size > 200 m), might have seasonal recurrence. Diarrhetic Shellfish Poisoning (DSP) toxin producing dinoflagellates such as *Dinophysis* spp. have been

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* Corresponding author at: CIMA—Centre for Marine and Environmental Research/ARNET-Aquatic Research Network, Universidade do Algarve, Campus de Gambelas, Faro 8005-139, Portugal.
E-mail address: up201804360@up.pt (H. Monteiro).

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Fig. 1. Study areas in the Portuguese coast (The Iberian Peninsula image contains modified [Cristina, 2022] Sentinel-3 OLCI [01–03–2016] image, processed by ESA and the other two satellite images containing modified [Cristina, 2022] Sentinel-2B Level 2 A data [24–02–2020], processed by the European Space Agency (ESA)).

referred as the most common HAB forming communities observed in Iberian coasts, in particular the species *Dinophysis acuta* and *Dinophysis acuminata*, and are known for causing shellfish harvesting closures from late spring to autumn (Broullón et al., 2020; Escalera et al., 2010; Moita et al., 2006, 2016). Other phytoplankton groups such as the dinoflagellate *Gymnodinium catenatum* and the diatom *Pseudo-nitzschia* spp., which are associated with Paralytic Shellfish Poisoning (PSP) and Amnesic Shellfish Poisoning (ASP) toxins, respectively, have also been observed several times in coastal regions of Portugal (Pitcher et al., 2010).

Given its deleterious impacts on the coastal activities and livelihood (aquaculture offshore, beach tourism, etc), there has been an effort at the national and international levels to implement and increment HAB event monitoring programs. The Harmful Algae Event Database (HAEDAT) is a meta-database compiled by the UNESCO Intergovernmental Oceanographic Commission (IOC), where information regarding harmful algal events, on a global scale, is available (http://haedat.iode.org/index.php). The events recorded in HAEDAT have caused impacts or consequences such as water discoloration, toxin bioaccumulation on seafood above regulatory levels, marine life threatening, within others, in such a way that conducted to management actions by the country authorities where these events have been reported (Hallegraeff et al., 2021). For Portugal, the HAEDAT records information regarding 669 HAB events, from 1987 up till 2020, in coastal and estuarine areas.

Earth Observation (EO) could provide important insights regarding the spatial, and temporal spread and fate of the blooms, with scales not available for the conventional monitoring techniques (Gokul et al., 2019). Optical sensors on board satellites, the so-called ocean colour (OC) sensors, typically capture algal bloom presence through the retrieval of Chlorophyll *a* (Chl*a*), which is a ubiquitous pigment in phytoplankton cells, and for that reason are used as a *proxy* for phytoplankton biomass abundance. However, although providing a synoptic scale of the events, the use of OC remote sensing (OCRS) tool is challenging with certain HABs, either because the causing harmful phytoplankton species does not bloom in the top of the optical layers of the water column or either because the harmful impacts are felt even when low numbers of harmful phytoplankton cells are present (e.g.: toxin producing HABs) (IOCCG, 2021). In the latter case, the concentrations of Chl*a* estimated by OCRS might not be, on its own, an adequate proxy for those HABs, and other related factors should be evaluated together, such as the ecological succession dynamic into regional phytoplankton communities.

The combination of the release of recent data in public sources both on HABs occurrences and concentration of toxins with the availability of OCRS Chl*a* data for those regions might allow for interesting scientific comparisons within this topic, and thus capitalizing the investment on regular monitoring programs and EO platforms. Thus, the aim of this work is to take advantage of publicly available databases – HAEDAT and Copernicus Marine Environmental Monitoring Service (CMEMS), integrating EO with official monitoring programs data, to evaluate its feasibility and usefulness to assess and recognize patterns in the frequency of HAB events in the Portuguese coast.

2. Material and methods

This study focuses on the analysis of recent data, due to the increased availability of OCRS data, particularly since the deployment of Sentinel missions in 2015, as well as the online accessibility of Portuguese Institute of the Sea and Atmosphere (IPMA) biotoxin monitoring data from the same year.

2.1. HAEDAT database

The HAEDAT (IOC-UNESCO, 2022) was analysed from 1987 to 2020,

Table 1
Maximum DSP toxin concentration measured for each event, and attributed levels of colours corresponding to the 4 stages of registered concentration of biotoxins for each event (green – minima to red – maxima). The legal concentration threshold for DSP biotoxins in Portugal is 160 µg OA equiv/kg, according to current legislation.

Region	Event	Maximum DSP toxin concentration (µg OA equiv/kg)	🟩	🟨	🟧	🟥
Setúbal (L6)	01st June to 30th June 2017	334	[0;83.5[	[83.5;167[	[167;250.5[	[250.5;334[
	24th September to 02nd November 2018	152	[0;38[	[38;76[	[76;114[	[114;152[
Aljezur (L7a)	29th May to 28th August 2019	550	[0;137.5[	[137.5;275[	[275;412.5[	[412.5;550[
	04th September to 02nd November 2020	354	[0;88.5[	[88.5;177[	[177;265.5[	[265.5;354
Sagres-Offshore (L7c1)	27th June to 04th October 2018	550	[0;137.5[	[137.5;275[	[275;412.5[	[412.5;550[
	07th May to 03rd July 2020	352	[0;88[	[88;176[	[176;264[	[264;352[
Porto de Mós (L7c2)	12th June to 29th September 2017	390	[0;97.5[	[97.5;195[	[195;292.5[	[292.5;390[
	01st May to 25th May 2018	550	[0;137.5[	[137.5;275[	[275;412.5[	[412.5;550[
	27th June to 04th October 2018	550	[0;137.5[	[137.5;275[	[275;412.5[	[412.5;550[
	04th September to 04th December 2020	524	[0;131[	[131;262[	[262;393[	[393;524[
Faro (L8)	02nd January to 31st August 2017	550	[0;137.5[	[137.5;275[	[275;412.5[	[412.5;550[
	28th December to 07th January 2020	524	[0;131[	[131;262[	[262;393[	[393;524[

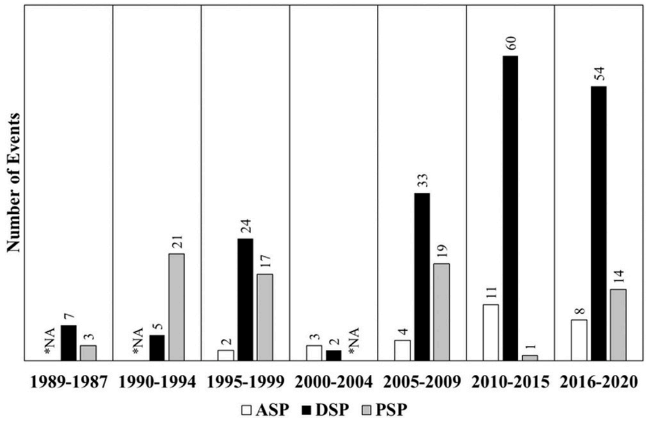

Fig. 2. The number of events registered at HAEDAT for Portuguese coast, from 1987 to 2020, and respective syndromes (*NA - Data Not Available).

to find out which HABs events (classified according to the produced toxins) have occurred more frequently in Portugal. HAEDAT is classified into "events'' that lead to management actions or cause any negative economic impact or have different ecological consequences. In this database, events are divided according to general information (event name, event year, event date, monitoring program, among others), location, and date (i.e., quarantine start date, quarantine end date, latitude, longitude, region, etc.), type of microalgae (causative species name, etc.), type of toxin and the detected toxicity and harmful effects. This information can also include discoloration of the water, accumulation of biotoxins in various seafood, the abundance of harmful algae, all which could result in a ban on harvesting seafood or other seafood or in the prohibition of beaches and any other event in which both animal and human life may be negatively affected.

Table 2
The number of HAB events organized by species, HAB syndrome, and the number of quarantine days, from 1987 until 2020 (*NA - Not Available, data that is not available).

		Causative Species	Number of Events	Minimum and Maximum Numbers of Days of Quarantine
HAB Associated Syndrome	**ASP (28 events)**	***Pseudo-nitzschia spp.***	15	5–117
		Pseudo-nitzschia australis	5	10
		Pseudo-nitzschia seriata	3	6–52
		Not specify	5	*NA
	DSP (185 events)	***Dinophysis spp.***	26	23–365
		Dinophysis acuminata	94	5–318
		Dinophysis acuta	15	6–284
		Dinophysis caudata	2	29–241
		Dinophysis fortii	2	25–132
		Dinophysis sacculus	4	*NA
		Not specify	42	*NA
	PSP (75 events)	***Gymnodinium catenatum***	56	8–180
		Alexandrium minutum	1	* NA
		Not specify	18	*NA

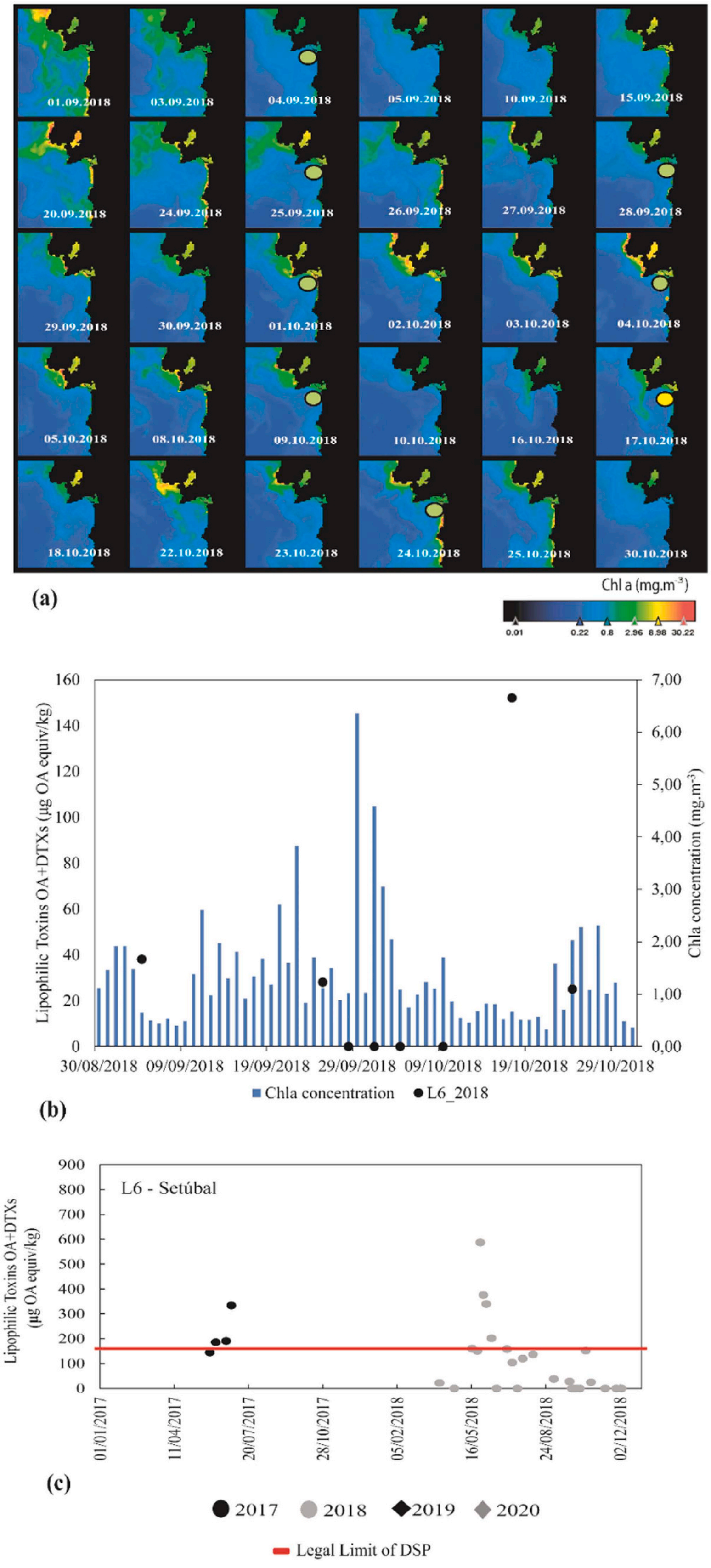

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Fig. 3. **(a)** Satellite Chl*a* images timeline matching the period of an event recorded in HAEDAT, (24th September - 2nd November 2018), covering the period from 30th August to 24th October 2018, for Setúbal (L6) region. The DSP toxin producing community was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification). **(b)** Concentration of Chl*a* retrieved from satellite observations *versus* the concentration of Lipophilic Toxins during the registered DSP event. **(c)** DSP biotoxin concentrations (μg OA equiv / Kg), taken from the IPMA, between January 2017 until December 2020. The red line represents the maximum legal biotoxin concentration, from which the ban on bivalve harvesting in the area is triggered.

2.2. *Ocean Colour remote sensing satellite images and biotoxin concentration data*

The years between 2017 and 2020 were selected to observe eventual relationships between the satellite retrieved Chl*a* concentration and the occurrence of biotoxins. Considering the dates and locations where the HABs events occurred, a total of five areas were investigated: one in the west coast (Setúbal (L6)) and four in the south coast (Aljezur (L7a), Sagres - Offshore (L7c1), Porto de Mós (L7c2) and Faro (L8)) (Fig. 1).

The satellite observations of Chl*a* concentration corresponding to this period were downloaded from the CMEMS (https://doi.org/10.48670/moi-00289), the marine component of the Copernicus Programme of the European Union and were used Atlantic Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, daily Level 4 (L4) (product identification: OCEANCOLOUR_ATL_BGC_L4_MY_009_118) satellite observations. The Chl*a* concentration satellite images are from multiple ocean colour sensors (SeaWiFS, MODIS-Aqua, MERIS, VIIRS-SNPP & JPSS1, OLCI-S3A & S3B) with a 1 km of resolution using the regional OC5 Chl-a algorithm (Colella et al., 2022). The daily L4 satellite images give us a complete gap-free dataset based on a space-time interpolation to provide a “cloud free” observations. The satellite images were processed under the Sentinel Application Platform (SNAP) software version 7.0.0.

After compiling the images, by areas and dates, and analysing the Chl*a*, the images were organized and compared with the biotoxin concentration data in bivalve tissues, collected in these study areas, available online through the National Bivalve Mollusc Monitoring System (https://www.ipma.pt/pt/bivalves/biotox/), from the Marine Biotoxins Laboratory of the IPMA. For each area, the bivalve species with the highest concentration of biotoxin were considered: in the case of the regions of Setúbal (L6) and Faro (L8) the species that presented the highest biotoxin concentration was *Donax trunculus*, and for the regions of Aljezur (L7a), Sagres - Offshore (L7c1) and Porto de Mós (L7c2), *Mytilus spp.* was the chosen species.

2.3. *Criteria for HABs biotoxin dynamics assessment with Chla image timelines*

A colour scale code was conceived to facilitate the comparison between the satellite images and the evolution of HAB events on the selected areas of the Portuguese coast. This colour scale code was designed to signal the initiation, development, maximum, and termination of the HAB events in the gathered OCRS images timelines during HAB events identified in HAEDAT, which are represented in the figures as coloured dots in the IPMA areas where samples were collected (Figs. 3–7). The satellite Chl*a* images timeline matching the period of an event recorded in HAEDAT, in some cases, have an extended duration in time once some events prevailed during several months. In these, there were selected Chl*a* satellite images each 4 days and, during high concentration of biotoxins, there were selected the day of the high concentration and the day before and after that date.

The criteria for the colour code consisted in attributing four levels of colours, from green to red scale, comprehending the 4 stages of concentration of biotoxins (obtained from IPMA) associated with these HAB events. For each HAB event, the maximum biotoxin concentration was registered, and the colour code stages were defined based on this value as follows: colour green was assigned for biotoxin concentration from the limit of quantification (LOQ) to ¼ of the maximum toxin concentration, the colour yellow was assigned to biotoxin concentrations from ¼ -½ of the maximum toxin concentration of the event, orange colour for the concentrations between ½ - ¾ of the maximum toxin concentration and red colour was assigned for the days where concentrations were equal or exceeded ¾ of the maximum concentration. For example, in a HAB event that registered a maximum of 550 mg OA equiv/kg (micrograms of okadaic acid equivalents per kilogram), the green rank was attributed from LOQ-137.5 mg OA equiv/kg, the yellow rank was from 137.5 to 275 mg OA equiv/kg, the orange rank was from 275 to 412.5 mg OA equiv/kg, and the red rank was chosen for days where DSP biotoxin values were above 412.5. In fact, for several sampling days, 550 mg OA equiv/kg was the highest numeric concentration ceiling for biotoxin concentration provided in IPMA reports, and higher values found were only referred to be exceeding this threshold. For this reason, in this work, even when exceeding values were numerically reported, 550 mg OA equiv/kg has still been considered as the maximum (Table 1).

After setting the boundaries for the colour codes, the coloured dots were displayed on the timeline figures in the matching dates (Figs. 3–7). When absolutely matching dates between biotoxin data collection and satellite imagery were not possible, the biotoxin concentration values were retained up till two days after or before the satellite image data.

2.4. *Statistical analysis*

All the statistical analyses were done with the software IBM® SPSS® Statistics Version 28.0.1.0 (142) (IBM Corp. Released, 2021).

All the variables studied (Chl*a*, quantity of toxins, number of dinoflagellate cells) were checked for distribution normality with a Levene’s statistical test.

To test the differences in the distribution of the values of Chl*a*, quantity of toxins and dinoflagellates between sampling sites and throughout the years, a Kruskall-Wallis test was done.

A correlation of Spearman/Kendall was performed to detect if the values of toxins and dinoflagellates were related to the levels of Chl*a*. Several data matrixes were tested by enhancing the day delay between the toxins or dinoflagellates and the values of toxins. The data matrixes tested ranged from 0 days of delay to 14 days of delay. This analysis was done to analyse the number of days between the registration of higher values of Chl*a* and higher values of dinoflagellates and toxins.

3. Results

3.1. *HAEDAT analysis*

The HAEDAT database was explored to analyse the number of HAB events in the coastal regions of Portugal and understand which HAB types are more likely to impact public health and marine economic activities in the study area (Table 1). It was observed that, by far, DSP has been the most common HAB syndrome causing impacts in the coastal regions of Portugal, with a total of 185 DPS related HAB events registered in the last three decades (33 years), followed by PSP associated HAB event, with 75 events in the same time window (Fig. 2). Conversely, ASP related HAB event only registered a total of 28 events during the considered period.

Dinophysis acuminata was the most prevalent DSP HAB causative

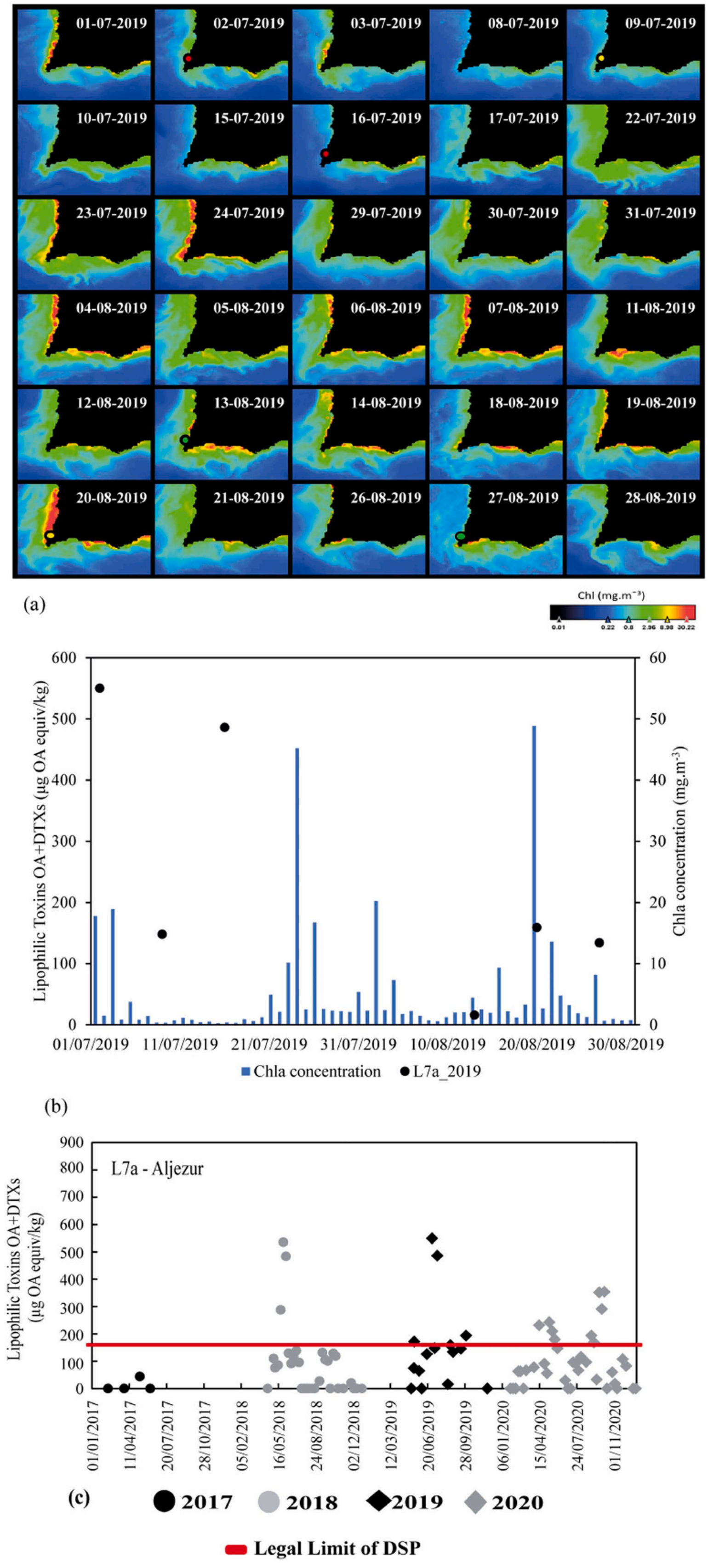

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Fig. 4. **(a)** Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (29th May - 28th August 2019) for Aljezur (L7a) region, covering the period from 1st July to 30th August 2019. The DSP toxin producing class was Dinophyceae. Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification). **(b)** Concentration of Chl*a* retrieved from satellite observations *versus* the concentration of Lipophilic Toxins during the registered DSP event. **(c)** DSP biotoxin concentrations (μg OA equiv / Kg), taken from the IPMA, between January 2017 until December 2020. The red line represents the maximum legal biotoxin concentration, from which the ban on bivalve harvesting in the area is triggered.

species, followed by *Dinophysis acuta* (Table 2), which is in accordance with previous literature (Broullón et al., 2020; Escalera et al., 2010; Moita et al., 2006, 2016). *Pseudo-nitzschia* appears as the only ASP HAB impacts causative genus in Portugal, while *Gymnodinium catenatum* is, by far, the most common PSP HAB impact causative species, as previously reported by Pitcher et al. (2010).

In terms of quarantine periods, DSP associated with HAB events are the ones causing a heavier impact on the aquaculture harvesting activities in coastal regions of Portugal, with registered events causing up till 1 year of bivalve harvesting interdictions.

These results indicate that DSP associated to HAB events in Portugal are ones that impact the most the marine activities in the coastal area and are more likely to cause negative health impacts, and for this reason, the subsequent analysis of HAB events with remote sensing satellite images will be focused on DSP HAB events.

When analysed in temporal terms (Fig. 2), it is visible an increase in the number of reported DSP and ASP associated to HAB events registered in the Portuguese coast from 1987 until 2020, with this enhancement being more pronounced from 2010 onwards. According to Hallegraeff et al. (2021), the increase in reported HAB events in HAEDAT indicates to be more related to the increase in monitoring efforts related to the intensification of the aquaculture industry, and its increased demand for HAB toxin control, than to a real increase in HAB events. The availability of OCRS data has also increased in the last decade, more particularly since Sentinel missions' deployment (from 2015 onwards) moreover, IPMA biotoxin monitoring data has also been made available online since 2015, which means that focusing on more recent data seemed the most reasonable research strategy for the specific objective of this study.

3.2. Chla satellite timelines of HAB events

The blooms that occurred between the years 2017–2020 were analysed, given the possibility of extracting Chl*a* concentration satellite images from multiple ocean colour sensors, with a reasonable number of matching HAB events, as registered in HAEDAT and IPMA.

Next, the results obtained for the different study areas, between 2017 and 2020 are presented.

3.2.1. Setúbal (L6) study area

In HAEDAT, a DSP event for the region of Setúbal (L6) from 24th September to 2nd November 2018, associated with *Dinophysis acuminata,* was registered. From the Fig. 3 **(a)** it was possible to observe that increased concentrations of Chl*a* in the second half of September until the beginning of October, where values of Chl*a* higher than 2 mg.m^{-3} were recorded in several days (Fig. 3 **(b)**). The concentrations of Chl*a* dropped until the 20th of October, and right after an increase in Chl*a* was once again observed.

Regarding the biotoxin concentration values, the higher values of DSP toxins were only observed at the middle of October (16th), and on the 24th of October the DSP toxins was already low again (Fig. 3 **(c)**). From the comparison between the two sets of data, is possible to infer that the levels of DSP biotoxins were not temporally matching Chl*a* maximums in this study area, and the elevated values of biotoxin concentration in the area were only registered at the least more than 15 days after the increases in the concentration of Chl*a*.

In the previous year, HAEDAT also registered a DSP toxin bloom formation in the same region (from 1st June to 30th June 2017, with the high levels of DSP toxins being attributed to a *Dinophysis caudata* bloom. A similar analysis was performed, and it was possible to observe that the Chl*a* concentration increased in the beginning of May (**Appendix A - Fig. A.1.**), whereas high concentration of biotoxin was only registered on 6th June. It was also observed that even when Chl*a* concentrations dropped, biotoxin concentrations remained high.

3.2.2. Aljezur (L7a) study area

In this southern region, a DSP toxin event was registered at HAEDAT from 29th May to 28th August 2019, associated with Dinophyceae class. It was possible to observe that the toxin producing communities were persistent, according to biotoxin concentration data, during the analysed period (Fig. 4 **(c)**). Here, it was possible to observe that the tendency of increase in Chl*a* concentrations coincided temporally with the registered high concentration of biotoxin (Fig. 4).

In the same study area, another event took place from 4th September to 2nd November 2020, according to HAEDAT, associated with *Dinophysis caudata*. When the same analysis was performed, an increase in the concentrations of Chl*a* was observed from the 4th of September onwards (**Appendix A - Fig. A.2.**). Regarding biotoxin concentrations were high on 8th of September (169 μg OA equiv/kg) (Fig. 4 **(c)**), showing once again that the increase in Chl*a* concentration and the high concentrations of biotoxins was temporally close and thus revealing a different trend than the one observed in the Setúbal (L6) study area.

3.2.3. Sagres - Offshore (L7c1) study area

At HAEDAT, there was a DSP toxin producing event, associated with *Dinophysis acuminata*, registered from 27th June to 4th October 2018. From the Fig. 5 **(a)** it is possible to observe that Chl*a* increased on the 16th of June, decreasing considerably until 22nd of June, and remaining low until the 3rd of July (Fig. 5 **(b)**).

Increased biotoxin concentrations were observed from the 25th of June until the end of the first half of July, with values around 550 μg OA equiv/kg (Fig. 5 **(c)**). When comparing Chl*a* with biotoxin concentrations, it was possible to observe that the high DSP levels were not matching temporally the increasing in Chl*a*: concentration of DSP toxin remained low on 18th June (after increased Chl*a*) and the higher values on 25th June were observed after decrease in Chl*a* concentration, suggesting a delay between the increasing of the two parameters.

Another DSP event was recorded in the same area at HAEDAT, associated with *Dinophysis* spp., from 7th May to 3rd July 2020. Although biotoxin concentrations were much lower than in the first example, it was also observed (**Appendix A - Fig. A.3.**) that the increase in biotoxin concentration was only observed 20 days after the Chl*a* concentration started to increase on 26th April 2020 (> 8 mg.m^{-3}) while the concentration of biotoxins only increased on May 18 th (142 μg OA equiv/kg) (Fig. 5 **(c)**).

3.2.4. Porto de Mós (L7c2) study area

In HAEDAT, a DSP event for the region of Porto de Mós (L7c2), from 1st May to 25th May 2018, associated with *Dinophysis acuminata,* was registered. From Fig. 6, it is possible to observe that Chl*a* increased in the beginning of May. Regarding the biotoxin concentration values, the higher values of DSP toxins were also observed at the beginning of May (2nd), and on the 25th of May, the DSP toxin levels were already low again (Fig. 6 **(c)**). This is another case where biotoxin producing phytoplankton communities were present when maximum Chl*a* values were registered.

In the same study area, another two events took place from June 12th

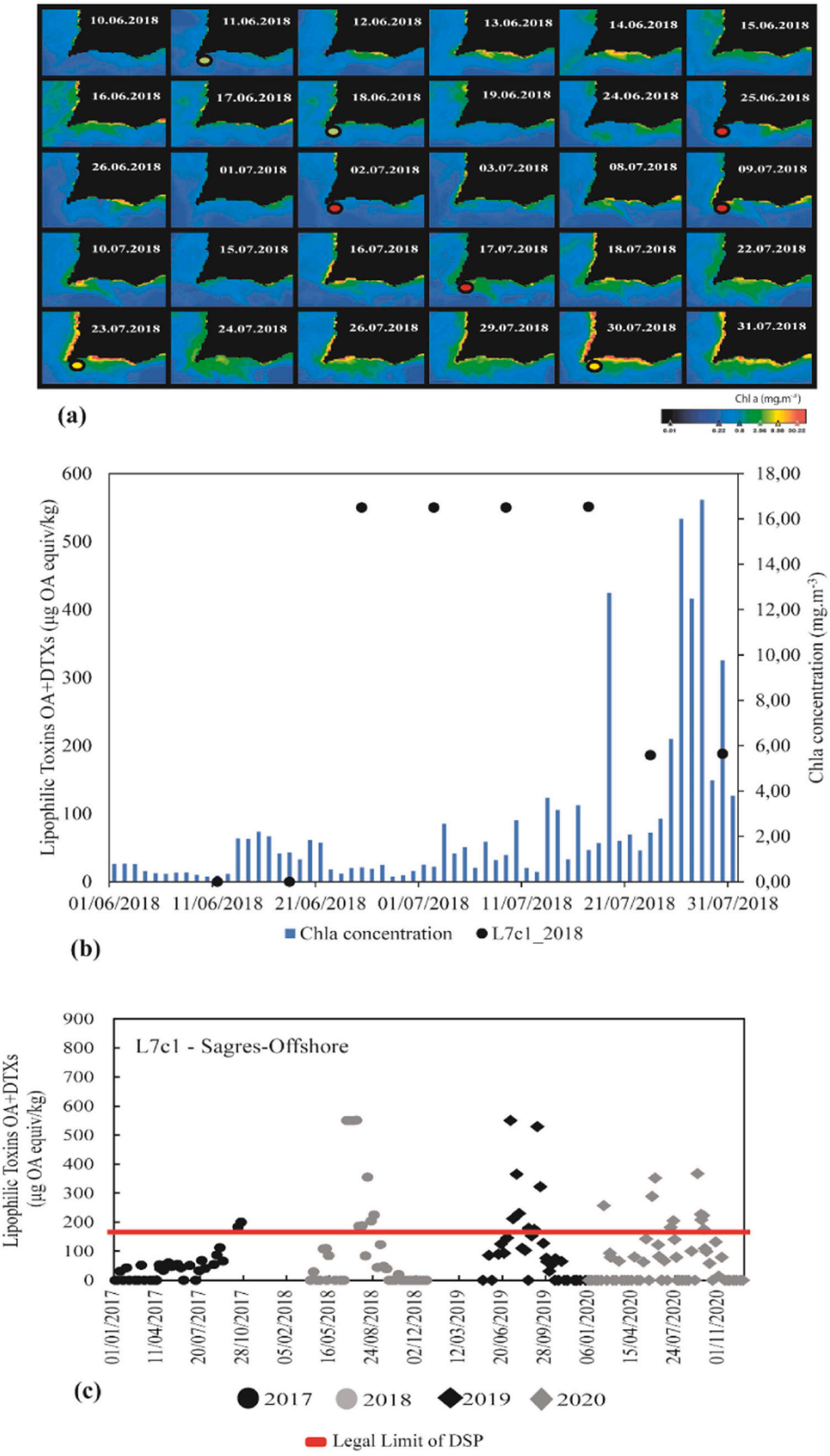

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Fig. 5. **(a)** Satellite Chl*a* images timeline matching the period of a DSP event recorded in HAEDAT (27th June - 4th October 2018) for Lagos region, covering the period from 13th June to 19th July 2018, for the most offshore zone (Sagres- Offshore - L7c1). The DSP toxin producing species was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification). **(b)** Concentration of Chl*a* retrieved from satellite observations *versus* the concentration of Lipophilic Toxins during the registered DSP event, where 550 mg OA equiv/kg has still been considered as the maximum for attributing the colour code to the assigned event. **(c)** DSP biotoxin concentrations (µg OA equiv / Kg), taken from the IPMA, between January 2017 until December 2020. The red line represents the maximum legal biotoxin concentration, from which the ban on bivalve harvesting in the area is triggered.

to September 29th, 2017, and from 27th June to 4th October 2018, both also associated with *Dinophysis acuminata*, according to HAEDAT. For both events, when the same analysis was performed, an increase in the concentrations of Chl*a* was observed, from the 25th of July 2017 onwards in the first event (**Appendix A - Fig. A.4**), and from the 13th of July 2018 onwards in the second one (**Appendix A - Fig. A.5**). Regarding the increase of biotoxin concentrations, it was observed that these were also temporally coincident with the maximums of Chl*a* concentrations, for both periods, revealing the same trend as the one observed in the Aljezur (L7a) study area (Fig. 6 **(c)**).

Contrastingly, for another event in Porto de Mós (L7c2) region, recorded in HAEDAT from 4th September to 4th December 2020, (**Appendix A - Fig. A.6**), also associated with *Dinophysis acuminata*, a delay between the increase Chl*a* concentrations and the appearance of the first toxin producing species was observed. This reveals a different trend comparing to the other events observed in this study area: the Chl*a* concentrations increase on 15th of August, while high biotoxin concentrations were only registered on 31st of August (Fig. 6 **(c)**). Note that, in this case, the analysis was performed from the middle of August onwards, once biotoxin levels (IPMA database) started to increase before the event date registered in HAEDAT.

3.2.5. *Faro (L8) study area*

At HAEDAT, there was a DSP event associated to a *Dinophysis caudata* bloom, observed from 2nd January to 31st August 2017, in the study area (L8). For the main objective of this work, a specific period of satellite images of this bloom period was observed – between April and May (Fig. 7). Within this period, it is possible to observe that the Chl*a* concentration were high in the beginning of April 2017. Throughout the second half of April the Chl*a* concentrations decrease and on 1st May it increased again.

When the biotoxin concentrations are analysed together, it can be observed that these were low in the 3rd April, but high on 17th of April, remaining high until mid-May (Fig. 7 **(c)**), which means that, once again, the increased concentrations of Chl*a* were not matching temporally the registered high concentrations of DSP biotoxin, suggesting a delay between the appearance of the toxic community and the Chl*a* concentration increase.

Another DSP toxin event, associated to Dinophyceae class, was observed according to IPMA data, 28th December 2019–7 th January 2020, although not mentioned in HAEDAT, where the same trend of delay between the detection of toxins associated with DSP syndrome and the increase of Chl*a* in the satellite imagery is also visible. (**Appendix A - Fig. A.7**). In this case, the maximum Chl*a* concentrations were observed in the beginning of December 2019 (**Appendix A - Fig. A.7**), where DSP toxin concentration levels were low, but, conversely, high concentrations of DSP toxins were observed in the end of the month and in the beginning of January, when concentrations of Chl*a* were already decreasing (Fig. 7 **(c)**).

3.3. *Statistical relationship between Chla and biotoxin concentrations*

Prior to the analysis of the statistical relationship between Chl*a* and biotoxin concentrations in this study, each of the datasets was inspected in terms of variability between study regions and interannual differences.

Chl*a* concentration did not followed a normal distribution (Levene test, $p<0.05$), even after several transformations (e.g. log10, sen, arcsen, sqrt) and so nonparametric analysis were followed. A Kruskall-Wallis test was conducted, revealing significant differences between study regions ($p<0.05$), except between production zones L7c1 and L7c2 and between L8 and L6 (pair-wise method). Similarly, Chl*a* concentrations also differ in terms of interannual comparison (significant differences within the several years from 2017 to 2020) (Kruskall-Wallis test, $p<0.05$).

Similar statistical analysis was performed to evaluate differences between study regions and within different years from 2017 to 2020 in terms of registered biotoxin concentrations. Pairwise comparisons revealed significant differences between the biotoxin concentrations in different regions (Kruskall-Wallis test, $p<0.05$), namely between L6 and L7c2, L6 and L7c1, L6 and L8, L7a and L8, and finally between L7c2 and L8. In terms of interannual comparison, significant differences were found between all years ($p<0.05$), except between 2017 and 2018 (Pairwise test).

The next step was to correlate biotoxin and Chl*a* concentration. Spearman non-parametric analysis was used once most of the variables were not normally distributed. Both direct and lagged correlations were analysed, i.e., both correlation between biotoxin levels and Chl*a* concentration registered for the same day, and to the correlation with up till 14 previous days prior to registered biotoxin concentration. Although weak, significant correlation between the datasets was only observed when the comparison was between the biotoxin concentration and its 14th day precedent Chl*a* concentration ($r_{Spearman}$=0.15).

4. Discussion

This study followed an opportunistic strategy, crossing data obtained from public and freely available databases on HAB events and ocean colour data to elicit the agreement, or not, between the increase of satellite retrieved Chl*a* concentrations with the registers of toxin producing events in the coastal regions of Portugal.

HAEDAT has been successfully delivering an outstanding collection of harmful algal events records at the global level, extending back to 1770 (IOC-UNESCO, 2022). In HAEDAT, data is organized in an intuitive way and its access has no major software requirements, which is surely one of the greatest advantages, especially for present and future studies on HAB and its relationship with climate change, given the synoptic scale now available. Having such a comprehensive dataset available enables easier and effective comparisons with oceanographic data from other sources, which is particularly useful in complex phenomena such as the urge, development and fate of HABs in coastal areas, provided that prior attention is given to the particular conditions that each particular HAB event was documented and registered.

The use of remote sensing has been recurrently mentioned as a valuable tool to monitor and forecast HABs, and to understand fully the spatial and temporal impacts of such events in the coastal regions (Guan et al., 2022; Khan et al., 2021; Wolny et al., 2020). Notwithstanding, toxin producing species do not always bloom at the surface or are rarely the dominant organism in a phytoplankton community (as *Dinophysis* spp.). With those, the efficiency of using remotely sensed Chl*a* concentration as the main indicator for HABs can be significantly decreased, and multiparametric approaches are suggested to be used (Maguire

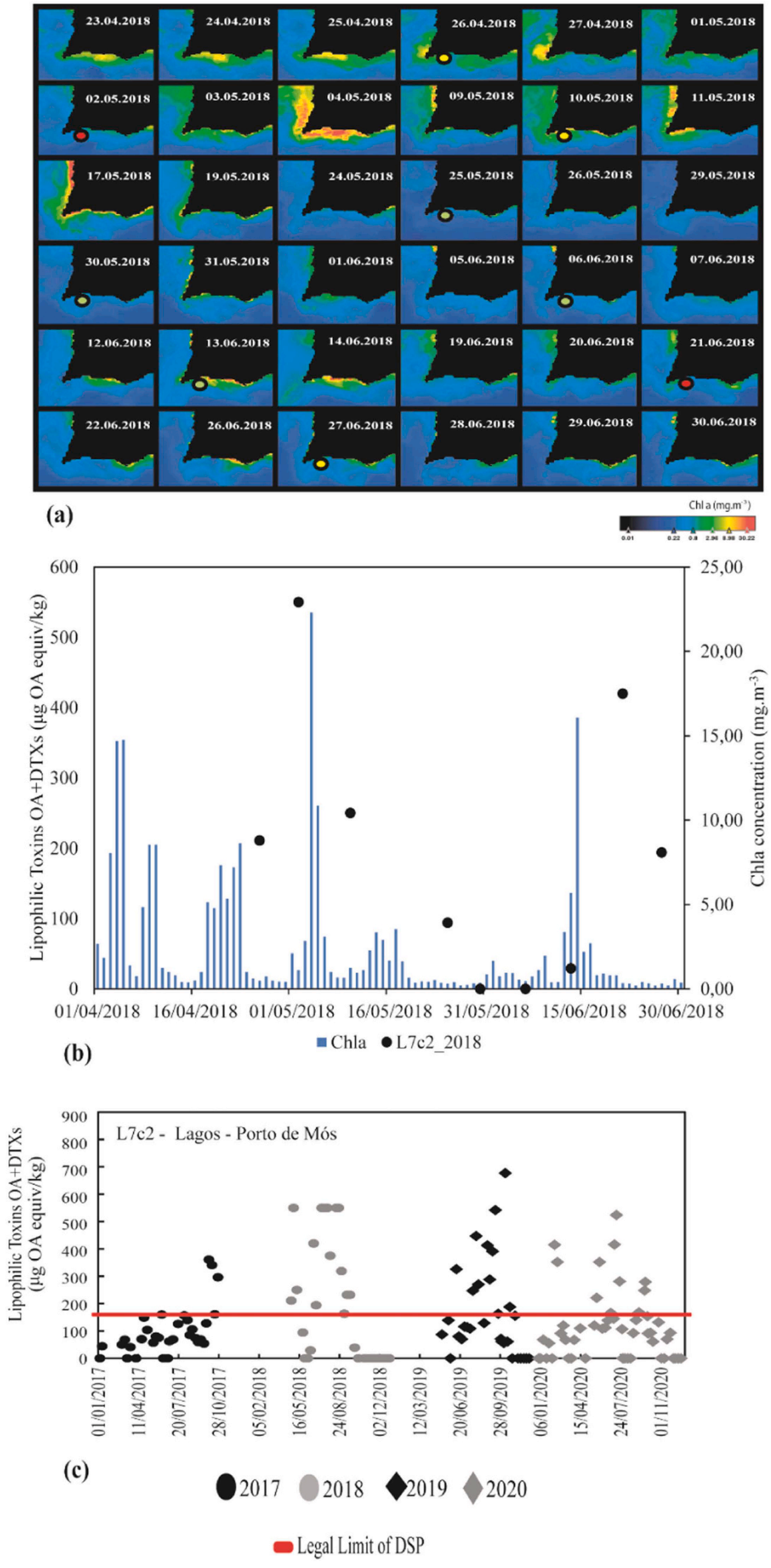

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Fig. 6. **(a)** Satellite Chl*a* images timeline matching the period of a DSP event recorded in HAEDAT (1st May 2018–25th May 2018) for Lagos region, covering the period from 21st April to 17th June 2018, for the most interior region (Porto de Mós -L7c2). The DSP toxin producing species was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification). **(b)** Concentration of Chl*a* retrieved from satellite observations *versus* the concentration of Lipophilic Toxins during the registered DSP event. **(c)** DSP biotoxin concentrations (μg OA equiv / Kg), taken from the IPMA, between January 2017 until December 2020. The red line represents the maximum legal biotoxin concentration, from which the ban on bivalve harvesting in the area is triggered.

et al., 2016). Notwithstanding, this study chose to focus on these two datasets – biotoxin and Chl*a*, to test the feasibility of using only remote sensing data with direct evidence undesirable effects of toxic phytoplankton assemblages – biotoxin concentration. Despite recognizing the relevance of comprehensively incorporating other environmental and phytoplankton assemblage parameters to infer and predict toxin release in coastal areas, this study seeks to verify if the use of practical and available data would be of advantage in management practices and day-to-day decision-making processes on coastal economical activities on Portuguese coastal area e.g. offshore aquaculture.

In Portugal, most HAB events that cause impacts and require local management actions is the toxin producing species, toxin namely DSP, rather than high algal biomass proliferation events. For that reason, the sole use of OCRS Chla as a proxy should be taken carefully in the development of monitoring programs. This study was conducted having this idea in the background. The effort was direct towards evaluating the usefulness of Chl*a* concentration to serve as a proxy of HABs in this region, namely by observing its relationship with the appearance of toxin producing species and, if no direct relation was found, to search for evidence of patterns between the two factors. The latter is based on the already existent knowledge of the local succession of phytoplankton communities, and its relationship with upwelling related temperature anomalies, which is the main factor that drives the phytoplankton dynamics in this region, and where, typically, diatoms dominance is observed during nutrient enrichment and decrease of sea surface temperature (SST) caused by upwelling, followed several occasions by dinoflagellate blooms during subsequent upwelling-relaxation conditions with an increase of SST and water mass more stratified (Danchenko et al., 2022; Escalera et al., 2010; Smayda and Trainer, 2010; Trainer et al., 2010). Some studies also suggest that low temperature and high salinities can be related with *Dinophysis* blooms too (Dhib et al., 2013; Diaz et al., 2016).

In this study, in several events, the increase in Chl*a* concentration is not matching temporally the high DSP biotoxins levels registered, mainly in the regions of Setúbal (L6) (from 1st June to 30th June 2017, and from 24th September to 2nd November 2018), of Sagres - Offshore (L7c1) (from 27th June to 4th October 2018, and from 7th May to 3rd July 2020), and Faro (L8) (from 2nd January to 31st August 2017, from 28th December 2019–7 th January 2020). Contrastingly, in the regions of Aljezur (L7a) and Porto de Mós (L7c2), it was observed that the increase in biotoxin concentration might have coincided temporally with the increase in Chl*a*, for most of the periods. A certain delay (a few days) between the increase in Chl*a* and DSP levels is to be expected, given that the Chl*a* concentration is a direct reflection of the proliferation of phytoplankton cells in bloom conditions, but toxin levels are measured in filter-feeding bivalve tissue that has accumulated toxin producing phytoplankton cells after the increase of those in the water column. This study also shows weak but statistically significant evidence that a high value of biotoxin concentrations might be preceded of high concentrations of Chl*a* (14 days of lag). But more studies will be necessary to prove this observation. Discrepancies due to the lower frequency of *in situ* sampling for toxin levels determination than the frequency of satellite images are also to be expected, especially in such an opportunistic approach, where no combined data collection schemes were upfront defined. However, the length of the delays observed (or not) between toxin levels and the increase in Chl*a* concentration might also be explained at the light of what is already known about the dynamics of HABs species in eastern boundary upwelling systems, as the case of Portuguese coast, as discussed below.

All the 12 DSP events here analysed were associated with blooms of *Dinophysis* genus, including six directly related with the species *Dinophysis acuminata* (Setúbal (L6) event in 2017, all events in Sagres - Offshore (L7c1) and all events in Porto de Mós (L7c2)), three with the species *Dinophysis caudata* (Setúbal (L6) event in 2018, Aljezur (L7a) event in 2020, and Faro (L8) event in 2017), and the three remain where associated with several species within the Dinophyceae class (Aljezur (L7a) event in 2019 and Faro (L8) event in 2020). According to Trainer et al. (2010), *D. Acuminata* tend to bloom in two conditions in eastern boundary upwelling systems: between moderate pulses of upwelling (coexisting with diatoms) and accumulating during downwelling periods, at the end of the summer. This might explain why in this study, in the *Dinophysis acuminata* events registered towards the end of summer (where the typical seasonal upwelling period relaxes (Fiúza et al., 1982; Danchenko et al., 2019), the DSP toxins are only observed a period after maximums of Chl*a* (delays of 2–4 weeks), while the DSP toxins levels from *Dinophysis acuminata* blooms happening during the summer or spring (seasons typically associated with upwelling) might match maximums of Chl*a*, and are probably coinciding with diatom blooms that tend to dominate in upwelling periods, causing an increase on Chl*a* concentration. The exception is the *Dinophysis acuminata* event in Sagres-Offshore (L7c1) during the summer of 2018, where, although happening during the upwelling period, the toxic dinoflagellate seems to have developed after the diatom growth (higher Chl*a* concentration). This might be mostly since upwelling, even in a study area with a defined upwelling season as the Portuguese coast, is "*intermittent, cyclical and embedded within bloom cycles as event-scale physical intrusions*" (Smayda and Trainer, 2010), which means that, even during summer, several upwelling relaxation periods might occur (Danchenko et al., 2019), where dinoflagellates species such as *Dinophysis acuminata* may bloom after upwelling diatom bloom maximum.

Regarding *Dinophysis caudata* blooms, all events here analysed that showed DSP toxins levels were not matching temporally the increase in Chl*a* concentration as shown by OCRS images, which suggests that, probably, these events were also happening in upwelling relaxation periods.

The results from this study reveal that the prediction of HABs in the coastal zones is complex, especially when only freely available monitoring databases are used. It might be a challenge to understand how the algal blooms are triggered, and to predict and prepare for their occurrence, in terms of time, location, duration, distribution, and the dynamics of their dominant species (Shen et al., 2019). The use of OCRS to monitor algal blooms is a valuable method that provides a synoptic view and allows continuous monitoring of the algal blooms, on a large temporal and spatial scale, as was shown by this study. However, the inclusion of such data in forecasting models should have in account the typical succession of phytoplankton in the study area and the respective delays between Chl*a* maximums and DSP toxins levels increasing, rather than only rely on the temporally matching relationship between Chl*a* and HABs. The inclusion of other data in such models, such as wind forcing, currents, nutrients and temperature is also recommendable in this specific study area, given the existent relationship between the development of HABs and the upwelling events.

Other resources/techniques might also be taken in consideration to be used together OCRS, as the case of the use of machine learning (ML), that have been developed as a tool in recent years for predicting or forecasting algal blooms (Lee and Lee, 2018; Yi et al., 2018). Its

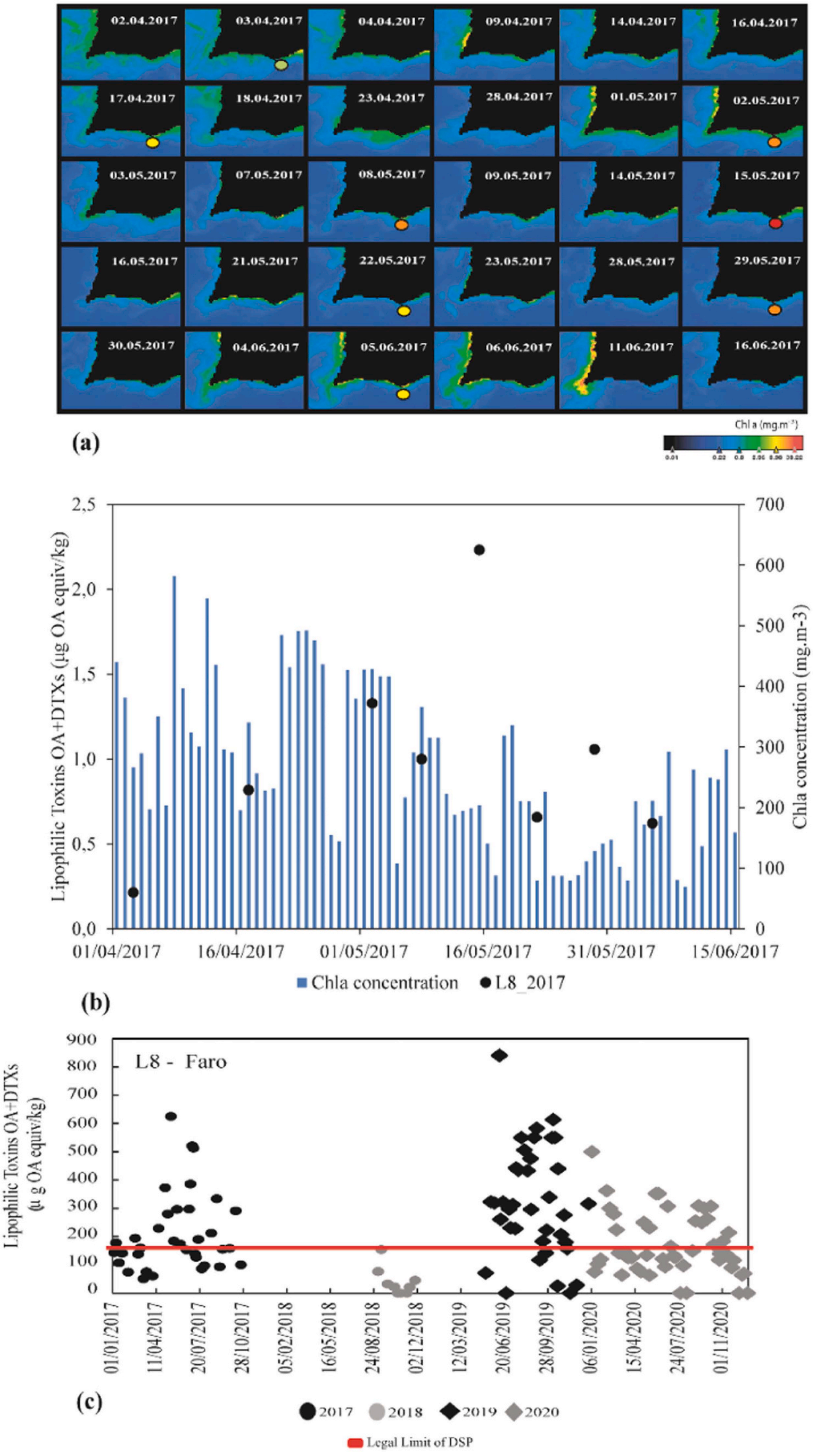

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Fig. 7. **(a)** Satellite Chl*a* images timeline matching the period of a DSP event recorded in HAEDAT (2nd January - 31st August 2017) covering the period from 1st April to 31st May 2017, for Faro (L8) region. The DSP toxin producing species was *Dinophysis caudata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification). **(b)** Concentration of Chl*a* retrieved from satellite observations *versus* the concentration of Lipophilic Toxins during the registered DSP event. **(c)** DSP biotoxin concentrations (μg OA equiv / Kg), taken from the IPMA, between January 2017 until December 2020. The red line represents the maximum legal biotoxin concentration, from which the ban on bivalve harvesting in the area is triggered.

advantage to analyse a vast amount of data and to learn about it, extracting important patterns from the datasets and providing insights into specific problems or hypothesis in a fraction of a second (Lee and Lee, 2018; Lary et al., 2018), especially when the available data is complex, intricated and when biogeochemical and physical causes of an event are not completely clear (Muttil and Chau, 2006).

5. Conclusions

This work explored the applicability of OCRS images provided by EO platforms to study the occurrence and spatial dispersion of HABs on the Portuguese coast.

In general, when comparing the levels of biotoxins associated with the presence of the genus *Dinophysis* (potentially causative of DSP syndrome) with the Chl*a* satellite images, it is observed that, while in some cases there is a clear correspondence between the two types of variables, these phytoplanktonic toxin-producing species not always coincided with episodes of high concentrations of Chl*a*, and sometimes a delay between the concentrations of Chl*a* and the biotoxicity present in the bivalves was observed. These discrepancies might be related to measurement intrinsic characteristics, limitations in math-up data availability due to the opportunistic approach adopted in this study and on the HABs dynamics in boundary upwelling systems as the case of Portuguese coast.

Future studies should include the extraction of spectral signature data (remote sensing reflectance (Rrs)) from the satellite images, to study possible significant changes in the optical properties of water associated with changes in phytoplankton communities. This will be particularly relevant in the case of successions into the phytoplankton communities with a significant presence of potentially harmful phytoplankton groups.

These findings reinforce the importance of maintaining existing monitoring programs on a regular basis, especially as some types of HABs may not be easily distinguishable by EO and have also the potential to be used as complementary tools for coastal water quality assessment and management.

CRediT authorship contribution statement

Helena Monteiro: Investigation, Formal analysis, Resources, Writing – original draft, Visualization. **Priscila Goela:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Project administration, Supervision. **Raquel Pinto:** Formal Analysis. **Sónia Cristina:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Project administration, Supervision, Funding acquisition.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

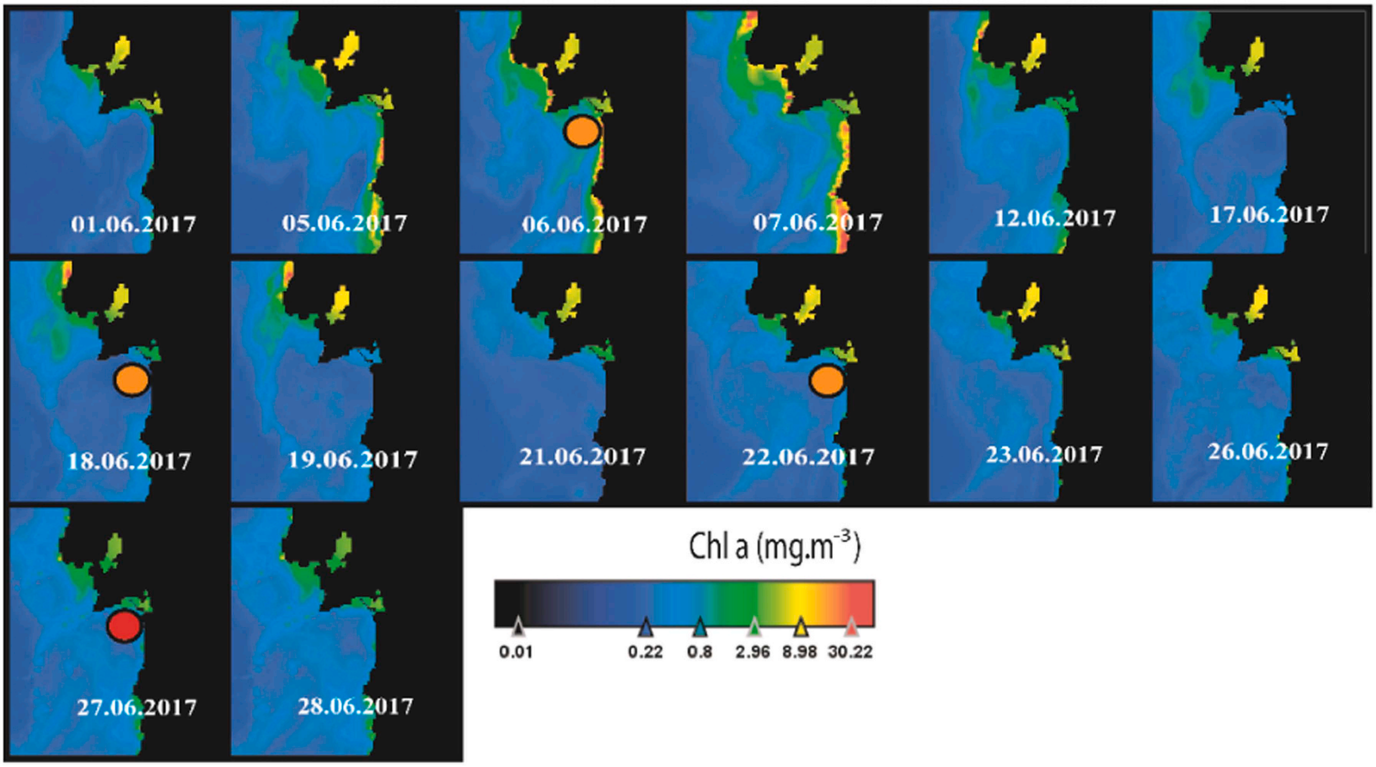

Fig. A.1. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (1st June - 30th June 2017), for Setúbal (L6) region, covering the period from 1st June to 28th June 2017. The DSP toxin producing community was *Dinophysis caudata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

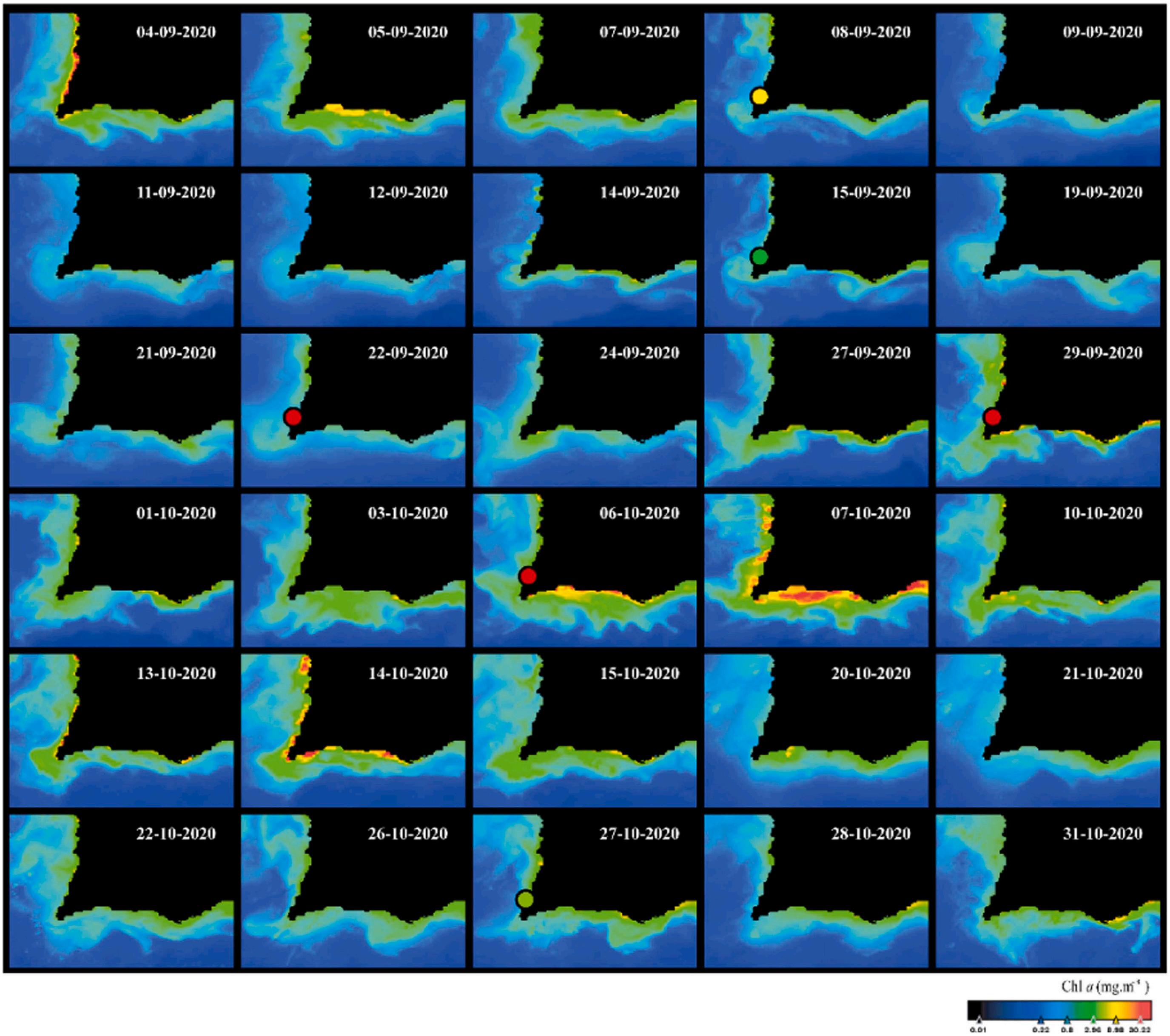

Fig. A.2. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (4th September - 2nd November 2020), for Aljezur region (L7a), covering the period from 4th September to 31st October 2020. The DSP toxin producing community was *Dinophysis caudata*. Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

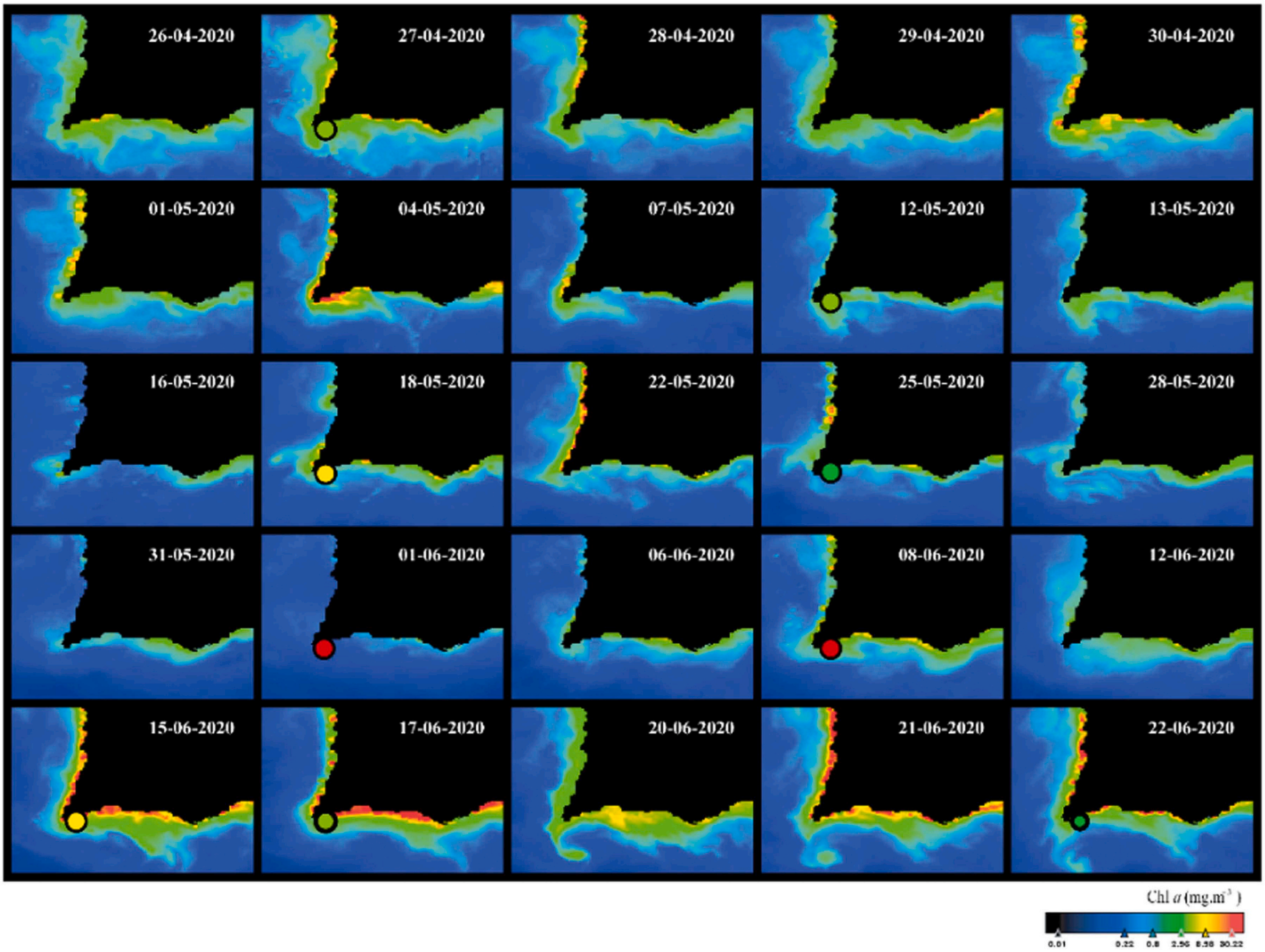

Fig. A.3. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (7th May - 3rd July 2020) for Lagos region covering the period from 26th April to 22nd June 2020, for the most offshore zone (Sagres - Offshore - L7c1). The DSP toxin producing community was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

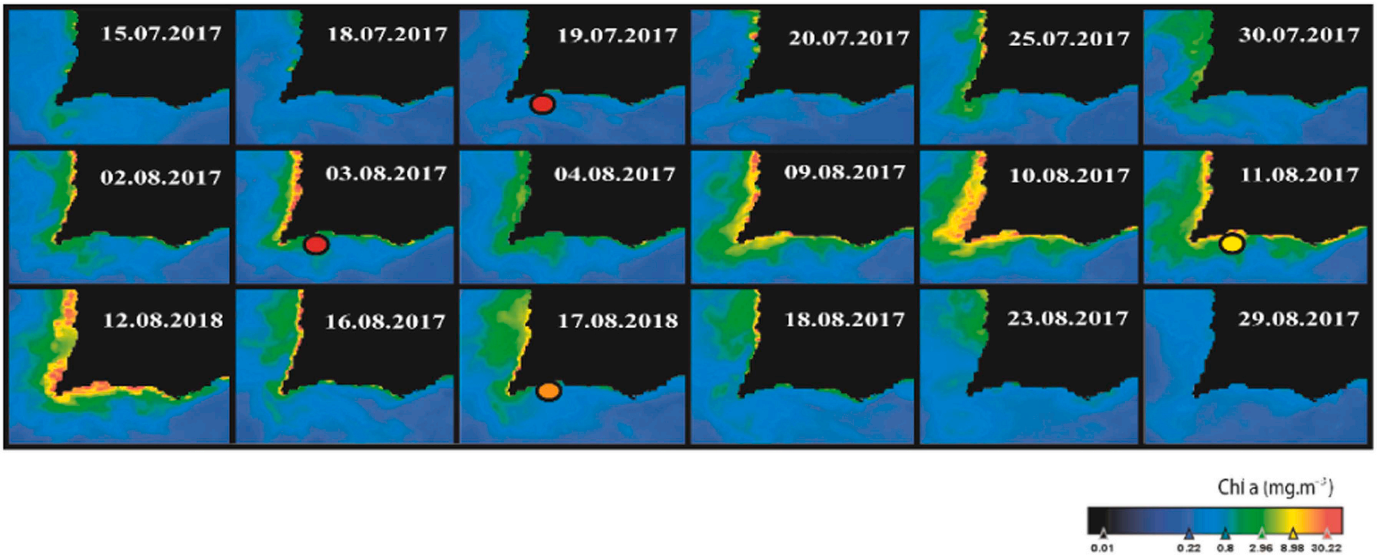

Fig. A.4. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (12th June - 29th September 2017) for Porto de Mós region, covering the period from 15th July to 29th August 2017, for the most interior region (Porto de Mós -L7c2). The DSP toxin producing community was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

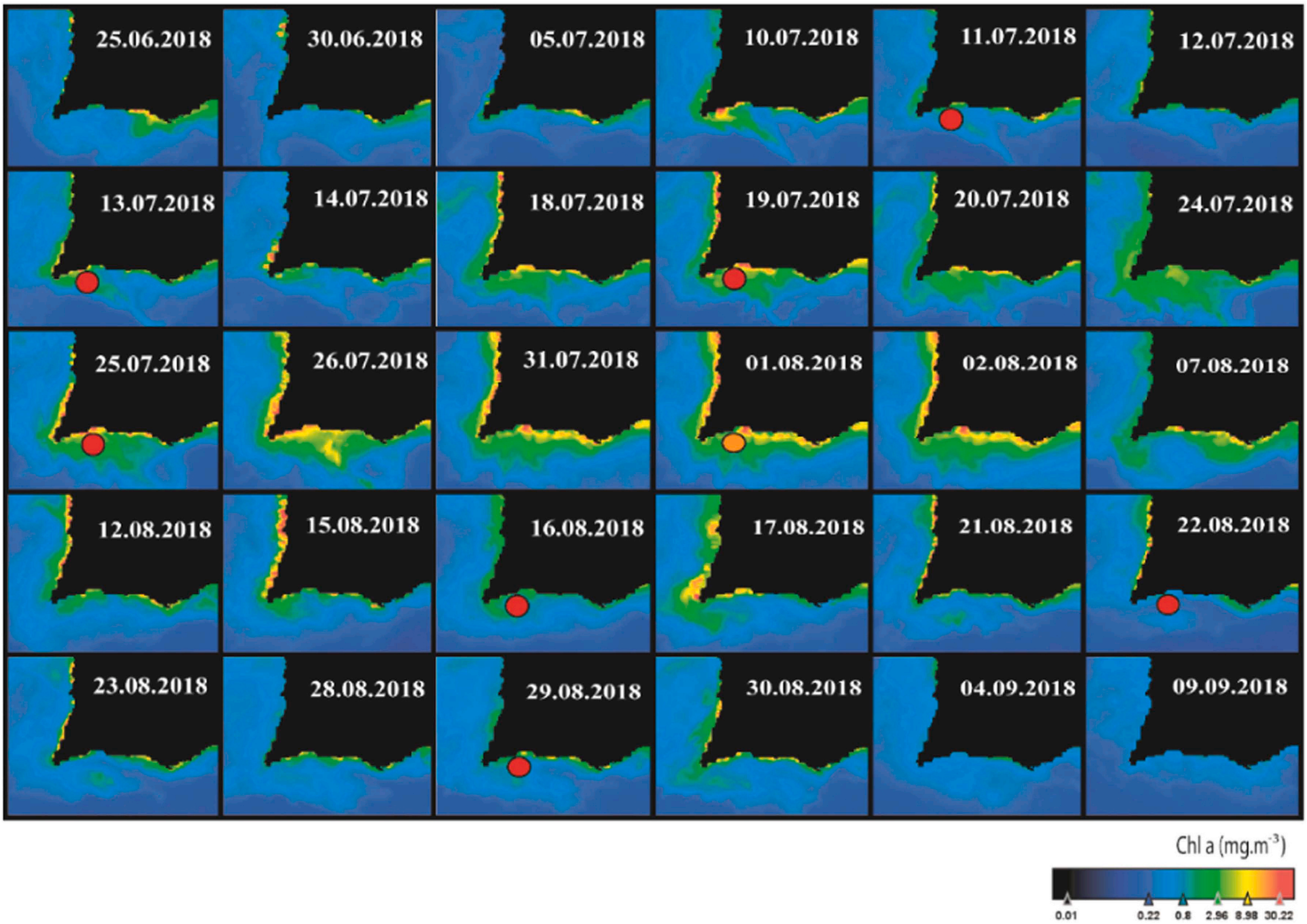

Fig. A.5. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (27th June - 4th October 2018) for Porto de Mós region, covering the period from 25th June to 9th September 2018 for the most interior region (Porto de Mós -L7c2). The DSP toxin producing community was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

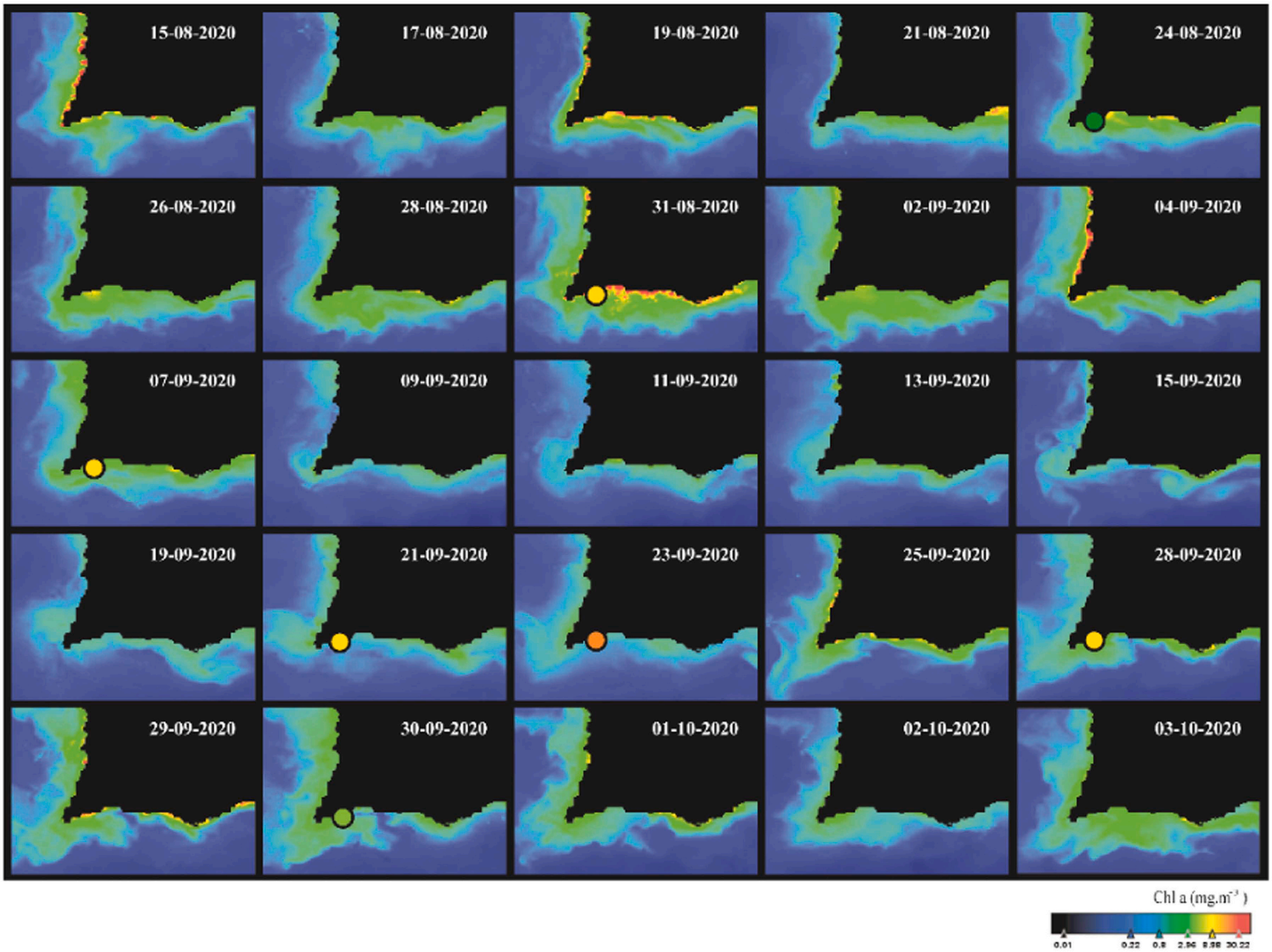

Fig. A.6. Satellite Chl*a* images timeline matching the period of an DSP event recorded in HAEDAT (4th September - 4th December 2020) for Lagos region, covering the period from 15th August to 3rd October 2020, for the most interior region (Porto de Mós -L7c2). The DSP toxin producing community was *Dinophysis acuminata.* Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

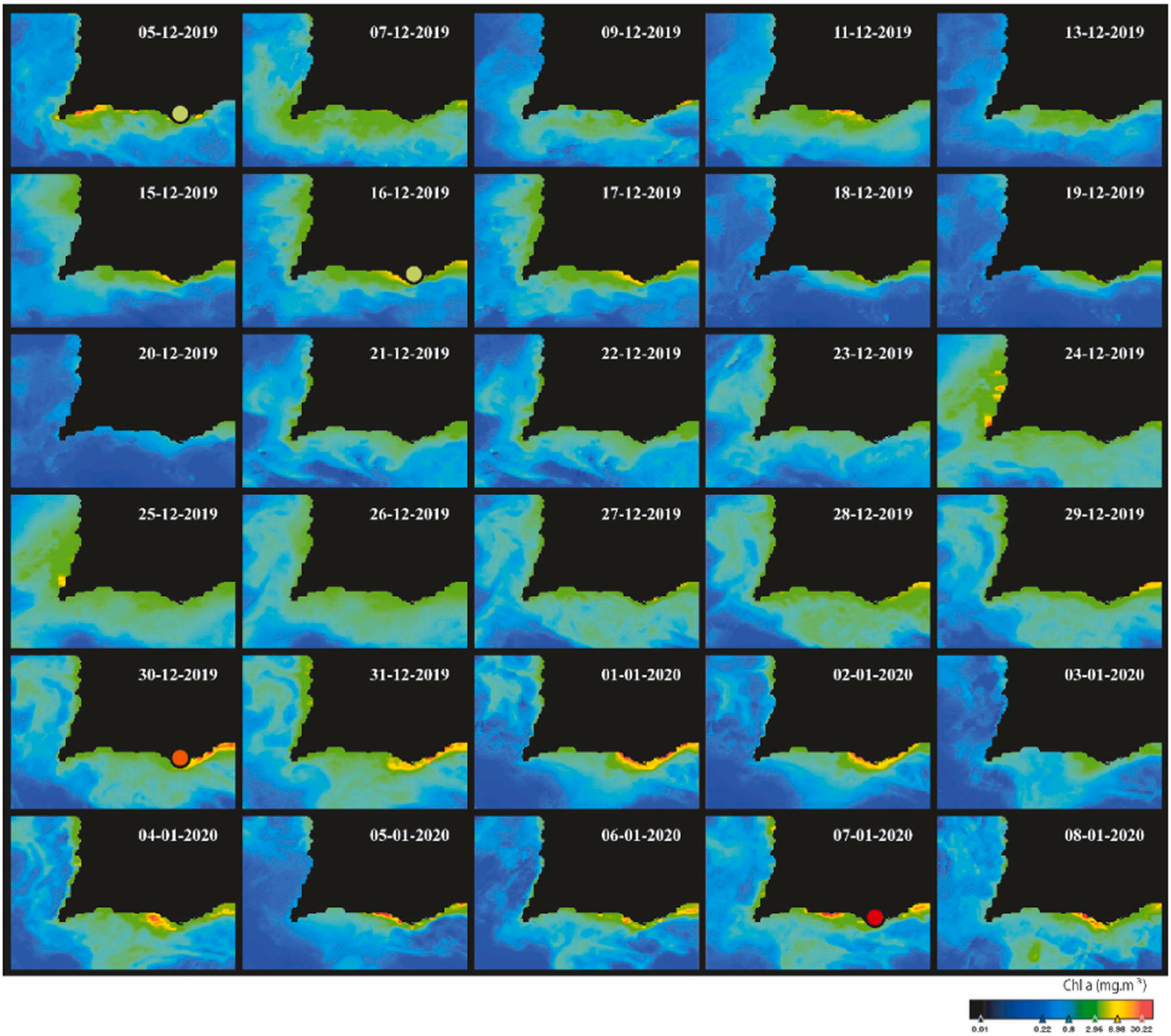

Fig. A.7. Satellite Chl*a* images timeline matching the period of an DSP event recorded in IPMA (28th December 2019–7 th January 2020), for Faro region (L8), covering the period from 5th December 2019–8 th January 2020. The DSP toxin producing community was Dinophyceae class. Each dot is showing how toxin levels vary during the event, in terms of its relative concentration to the maximum attained during the whole event (maximum-red to minimum-green, please see Section 2.3 for further clarification.

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