European
Commission

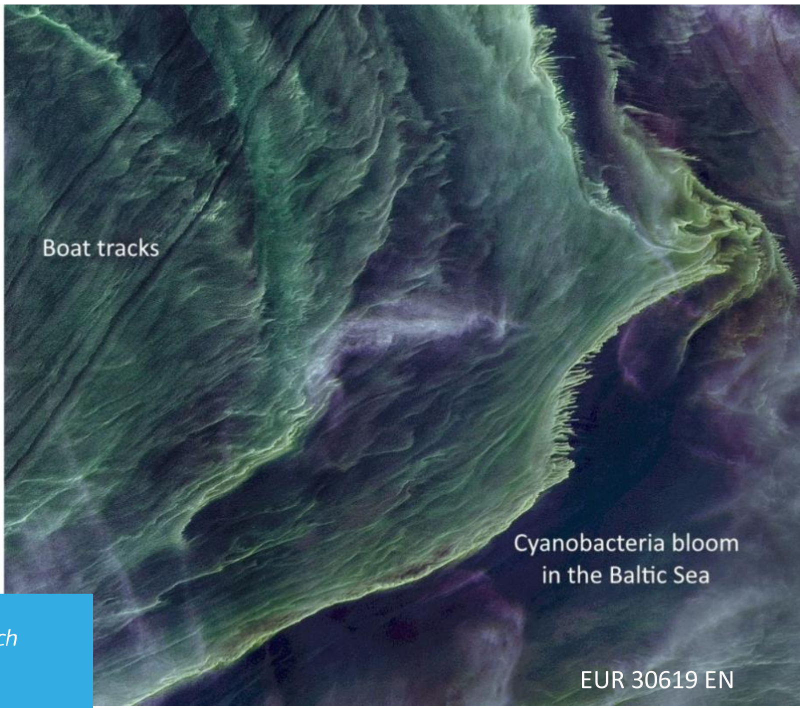
JRC TECHNICAL REPORT

Pelagic habitats under MSFD D1: current approaches and priorities

An overview of approaches
towards D1C6 assessment

Magliozzi Chiara, Druon Jean-Noël, Palialexis Andreas, Artigas Luis Felipe, Boicenco Laura, González-Quirós Rafael, Gorokhova Elena, Heyden Birgit, McQuatters-Gollop Abigail, Varkitzi Ioanna

2021



Joint
Research
Centre

EUR 30619 EN

This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact Information
Name: Jean-Noël Druon
Address: Directorate D – Sustainable Resources,
Unit D.02 Water and Marine Resources,
Via Fermi 2749,TP 051, 21027 Ispra (VA) Italy
Email: jean-noel.druon@ec.europa.eu
Tel: +39 0332 78 6468

EU Science Hub
https://ec.europa.eu/jrc

JRC123960

EUR 30619 EN

PDF ISBN 978-92-76-30988-8 ISSN 1831-9424 doi:10.2760/942589

Luxembourg: Publications Office of the European Union, 2021

© European Union, 2021

The reuse policy of the European Commission is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Except otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated. For any use or reproduction of photos or other material that is not owned by the EU, permission must be sought directly from the copyright holders.

All content © European Union, 2021

Front page images:
The left image of the Adriatic Sea was collected by the Aqua-MODIS ocean colour sensor on July 20, 2018 (source: NASA, https://oceancolor.gsfc.nasa.gov/gallery/580/).
The right image presents cyanobacteria slicks covering the surface of the Baltic Sea west of Estonia on July 15, 2017. The linear slices through the slicks were created by passing boats. These data were collected by the OLI sensor on Landsat 8 (source: NASA, https://oceancolor.gsfc.nasa.gov/gallery/545/).

How to cite this report: Magliozzi, C., Druon, J.-N., Palialexis, A., Artigas, L. F., Boicenco, L., González-Quirós, R., Gorokhova, E., Heyden, B., McQuatters-Gollop, A., Varkitzi, I., Pelagic habitats under MSFD D1: current approaches and priorities, EUR 30619 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-30988-8, doi:10.2760/942589, JRC123960

Contents

Abstract

This report reviews the current situation as regards to the Marine Strategy Framework Directive (MSFD) Descriptor 1 (Biodiversity) for pelagic habitats and serves as a basis for a workshop with Member States experts and scientists that will be held on March 9-10 2021. Recommendations are in the concluding section.

Pelagic habitats cover the 71% of Earth's surface and play an essential role in regulating temperature on land, producing oxygen and food. They are also a management challenge where the alterations of their physical, chemical and biological characteristics negatively impact their ecosystem functioning and services (e.g. provisioning services). To address these challenges, the MSFD has required the assessment of pelagic habitats against environmental targets to reach Good Environmental Status (GES). A key step in the pelagic habitat assessment is a thorough understanding of its physical, chemical and biological processes and the drivers that underlie the spatiotemporal variability in its ecologically relevant ecosystem components.

However, pelagic assessments to date have not sufficiently addressed the functional and structural characteristics of pelagic habitats processes, which is limiting our ability to inform on their environmental status and to disentangle the anthropogenic drivers. This report evaluates previously published work on pelagic habitats assessments considering the actions and targets to meet the MSFD requirements.

To do this, the report (i) summarises the main drivers of variation in pelagic habitat characterization; (ii) reviews the common empirical approaches used to assess pelagic habitats, the advantages, and challenges; and finally (iii) exposes a set of recommendations for characterising pelagic habitats in EU waters. Since the pelagic habitats are made of a highly dynamic fluid, appropriate spatiotemporal scales regarding data and methods must be considered to assess their GES. This applies in particular to the selected indicators to propose the effective and quantifiable GES targets that need to be reached.

1 Introduction

The pelagic realm is the largest ecosystem on Earth, important habitat in itself, it induces a wide range of physical and biological conditions that are crucial for the health and survival of billions of people. It is intensively impacted by human activities: overfishing, different types of pollution, mining and invasive species introduction have impaired the natural exchange of energy, mass and nutrients between pelagic and benthic habitats and caused the loss of essential habitat functions (Halpern et al., 2015; Maes et al., 2020).

The cumulative effect of all these changes suggests that there has never been a more pressing moment to assess the status of pelagic ecosystems and protect them. This is the commitment of the Marine Strategy Framework Directive (MSFD), which aims to “achieve or maintain good environmental status in the marine environment” (Directive (EC) 2008/56, 2008). The MSFD incorporates pelagic habitats in Descriptor 1 (Biodiversity) (Commission Decision (EU) 2017/848, 2017), hereafter referred to as GES Decision) and requires their assessment and monitoring against environmental targets leading to Good Environmental Status (GES). Understanding the environmental status of pelagic habitats is of fundamental interest because humans depend on their ecosystem services (Culhane et al., 2018). However, the utilization of these insights in practice is still limited by EU Member States (MS). While it makes intuitive sense to manage the pressures that affect the stability and resilience of pelagic habitats, it is unclear which actions should follow for this goal (Dickey-Collas et al., 2017). Key steps of the pelagic habitat assessment flow include selecting the habitat elements, assigning state and pressure indicators and establishing the thresholds at region or subregion scale (Walmsley et al., 2018). The selection of habitat elements enables identifying the most ecologically relevant ecosystem components and to determine key anthropogenic pressures, whereas the indicators and the thresholds maximize pelagic assessment and monitoring (European Commission, 2020).

However, the focus on pelagic habitats is still not specific enough to support the ecological mechanisms that underlie the resilience and functioning of these ecosystems. The key question is how the sets of criterion elements (what to assess) and indicators (how to assess it) reflect the functional and structural characteristics of pelagic habitats and inform on their environmental status. This report provides an overview of approaches and priorities for pelagic habitats’ assessments in view of actions and targets to meet the MSFD requirements.

1.1 What are pelagic habitats?

Interactions between physical and biological systems underpin ecosystem functioning in pelagic habitats (Würtz, 2010). The physical system refers to the whole water column where the movement of water masses occurs (Hyrenbach *et al.,*2000). The spatial extent and properties of the water masses vary on daily to decadal time scales, and create changing pelagic habitats at local, regional and basin scales (Kolodziejczyk *et al.,* 2019). Vertical and horizontal gradients of temperature, salinity, density, light, particles and dissolved nutrients drive major environmental heterogeneity within the pelagic habitat and lead to a mosaic of different ecological responses from site-specific interactions (Fenberg & Rivadeneira, 2019; Macpherson, 2002). The physical system has profound effects on the distribution and movements of pelagic communities that constitute the biological system (Hernández-León et al., 2020; Thabet et al., 2018). Pelagic habitats support lifeforms from sub-microns (i.e. bacterioplankton, phytoplankton and zooplankton) to several meters (i.e. cetaceans) (Würtz, 2010) that account for the 50% of global primary production (e.g. phytoplankton, Sathyendranath *et al.* (2019)), cover all trophic levels (e.g. primary producers, primary and secondary consumers) and regulate water physical and chemical conditions (e.g. carbon sequestration and micronutrient pumping, Hernández-León *et al.* (2020)). Perhaps one of the best-known examples of interaction between pelagic physical and biological systems is production of atmospheric O_2 (Field *et al.*, 1998), climate regulation (i.e. dimethylsulfoniopropionate, Vallina (2007)), carbon sequestration (Martin et al., 2011) and fluxes of matter and energy (Kiko et al., 2017). Many ocean ecosystem services are indeed mediated by plankton species, both phyto- and zooplankton, and therefore used to track temporal and spatial environmental changes (e.g. Essential Ocean Variables, Essential Climate Variables, Miloslavich *et al.* (2018), Bax *et al.*(2019)), shifts at higher trophic levels (Schwarz et al., 2013), and top-down and bottom-up pressures (Roff*et al.*, 1988; Howarth *et al.*, 1999; Prowe *et al.*, 2012).

The holistic nature of the physical and biological system implies that adverse changes in pelagic features might put the continued provision of ecosystem functioning and services at risk (Culhane et al., 2018). A spatial understanding of the major hydrographic processes and biological responses is therefore needed to account for changes and identify the appropriate scale of analysis for managing the assessment of pelagic habitats.

A definition of pelagic habitats in the context of the MSFD is given in the next section.

1.2 D1C6 criterion and definitions

Pelagic habitats are part of Descriptor 1 of the MSFD, which states “Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions”.

Pelagic habitats are specifically addressed in a dedicated theme with criterion D1C6 of the GES Decision: “**The condition of the habitat type, including its biotic and abiotic structure and its functions** (e.g. its typical species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), **is not adversely affected due to anthropogenic pressures**”. **D1C6 must be assessed as “extent of habitat adversely affected in square kilometres (km^2) and as a proportion (percentage) of the total extent of the habitat type.**

The criterion definition contains attributes that require further specifications:

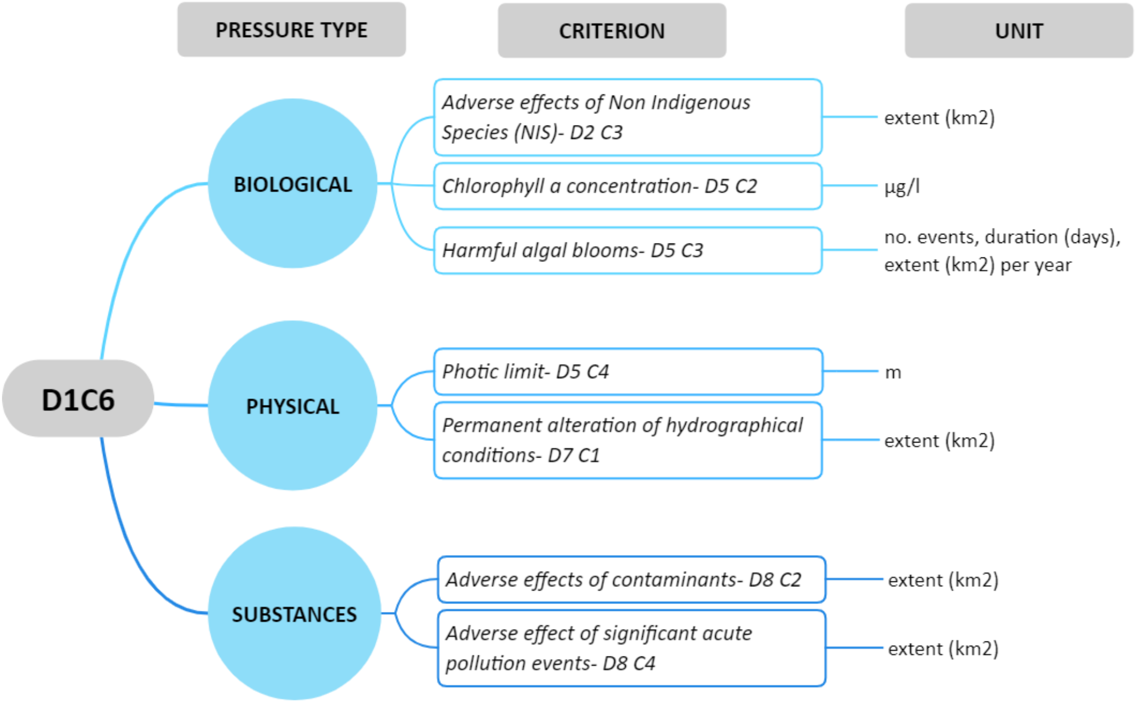
“habitat type”: the GES Decision **specifies four broad habitat types, i.e. variable salinity, coastal, shelf and oceanic/beyond shelf.** Variable salinity refers to “retained for situations where estuarine plumes extend beyond waters designated as Transitional Waters under Directive 2000/60/EC”, and coastal to “shall be understood on the basis of physical, hydrological and ecological parameters and is not limited to coastal water as defined in Article 2(7) of Directive 2000/60/EC”. MS by regional and subregional cooperation can select additional habitat types, if meeting the following criteria (GES Decision):

- scientific criteria: e.g. representative of the ecosystem (e.g. high biodiversity), specific anthropogenic pressure, extent, and species.
- practical criteria: e.g. monitoring viability and costs, timeseries.

“biotic and abiotic structure”: the biotic structure refers to the habitat “species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species”. The abiotic structure is not defined by the GES Decision but, in this report it refers to the physical system of the pelagic habitats, such as the abiotic factors that affect the living organisms.

“anthropogenic pressures”: the adverse effects from pressures assessed by the MSFD pressure Descriptors 2, 5, 7, 8 and criteria (i.e. D2C3, D5C2, D5C3, D5C4, D7C1, D8C2 and D8C4) (Figure 1).

Figure 1. Scheme of the anthropogenic pressures listed in the GES Decision and linked to D1C6. The criteria are grouped by three main pressures as in the MSFD Guidance Document 14 for Articles 8, 9, and 10 (European Commission, 2019), and their units reported as in the GES Decision.



1.3 Gaps and policy needs

Accurate delineation and characterization of pelagic habitats types and quantification of biological responses to pelagic environmental factors are key step to assess the potential effects of anthropogenic pressures in this realm and stating whether GES has been achieved. However, characterizing pelagic habitats is difficult because the temporal dimensions and process interactions underlying ecological responses are not fully characterized (Alvarez-Berastegui et al., 2014). To delineate the spatial structure and quantify biological changes, we need comprehensive insights into how different pelagic processes interact across temporal scales (Kavanaugh et al., 2014).

This report provides a baseline to discuss two main MSFD assessment questions:

i) **what is the best approach for spatial characterization of pelagic habitats considering major physical, chemical and biological processes and how different pressures affect the condition of the ecosystem?**

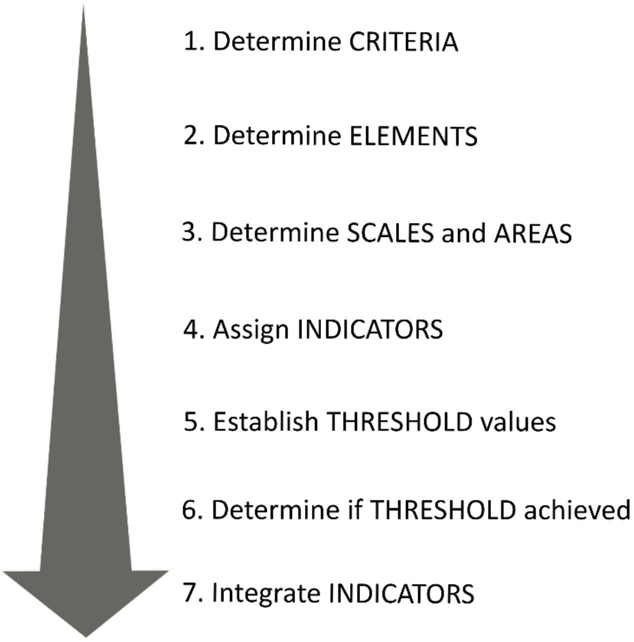
ii) **what are the existing indicators, their links to anthropogenic pressures, and the trade-offs between data availability and quality?**

There is primarily a need for **identifying driving factors and underlying processes** of the elements to be used when determining pelagic habitat GES (Article 9(1) (European Commission, 2020), Figures 2, Step 2, and Figure 3). To date, the use of broad habitat types (GES Decision) has been suggested to determine pelagic elements for assessment at a particular spatial scale (e.g. variable salinity, coastal, shelf, and oceanic/beyond shelf), which limits our understanding of the potential physical factors and processes driving biological responses at temporal scales.

The second step is the **provision of metrics reflecting status and pressures on pelagic habitats** (GES Decision), which requires more detailed information on where and how the distribution, taxonomic and functional descriptors of pelagic biota vary over time (Figure 2, Step 4, 5). Our understanding of the processes underlying pelagic habitat status is mainly based on phytoplankton and zooplankton indicators, often without consideration of the effects of changing spatial scales at which the environmental gradients are calculated. The lack of thresholds that reflect longitudinal and latitudinal changes at regional scales humpers our ability to identify anthropogenic pressures controlling GES of pelagic habitats and emphasizes the need to combine the analysis of pelagic biota to pressure gradients.

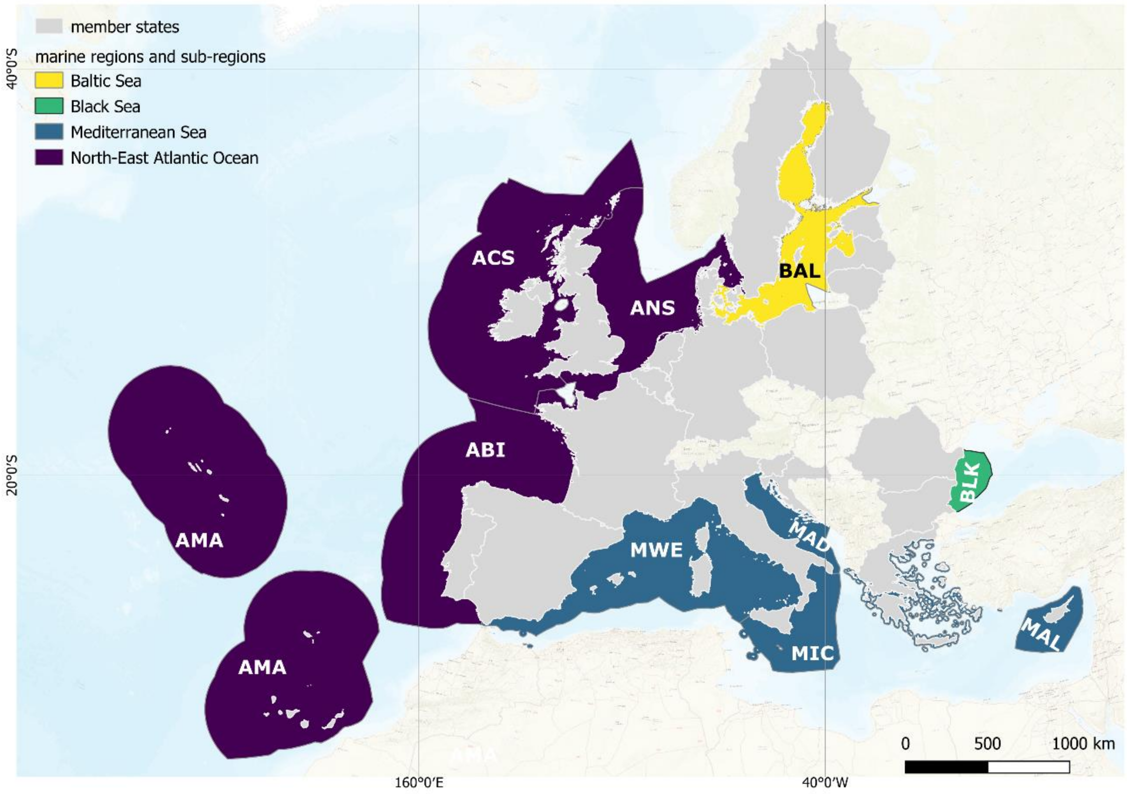
Finally, the need for representative pelagic habitat metrics requires data (Varkitzi et al., 2018). Different techniques have been used to depict biological responses to pelagic environments (Varkitzi *et al.*, 2018). However, to interpret variation of biota in terms of pressures, consideration of **all sources of uncertainty related to methods, available time-series and baselines is essential** (Smit et al., 2021). While several indicators at regional and national scale exist, their methods greatly depend on operability (i.e. data quality) and accessibility (i.e. classification and protocols) (Lombard et al., 2019); a better understanding on how datasets length and reference periods influence the interpretation and reliability of the results is needed (Bedford, Ostle, Johns, Budria, et al., 2020; Rombouts et al., 2019).

Figure 2. Assessment flow for Descriptor 1, pelagic habitats. Modified from Common Implementation Strategy 17 (Walmsley et al., 2018)**.** 'Criteria' indicates the subject to be assessed, i.e. pelagic habitats, 'Elements' refers to the essential characteristics of the criterion to be evaluated, i.e. coastal, shelf, oceanic, variable salinity, 'Scales and Areas' indicates the subdivision of the region or subregion to assess, and 'Indicators' supplies synoptic information about the Elements to allow the criterion assessment. Steps 5 and 6 indicate the approaches, by threshold value, to estimate the extent of the Elements that is adversely affected. Finally, Step 7 integrates the methodologies from indicator to GES.



1. Determine CRITERIA
2. Determine ELEMENTS
3. Determine SCALES and AREAS
4. Assign INDICATORS
5. Establish THRESHOLD values
6. Determine if THRESHOLD achieved
7. Integrate INDICATORS

Figure 3. Map displaying the marine regions and sub-regions of the Baltic Sea (BAL), North-East Atlantic Ocean (Greater North Seas (ANS), Bay of Biscay and the Iberian Coast (ABI), Celtic Seas (ACS), Macaronesia (AMA)), Mediterranean Sea (Western Mediterranean Sea (MWE), Adriatic Sea (MAD), Aegean- Levantine Sea (MAL), Ionian Sea and the Central Mediterranean Sea (MIC)) and Black Sea (BLK) regions. Marine areas shown in each subregion represent the areas of MS marine waters in which pelagic habitats are relevant (additional areas where the seabed falls under MSFD are not shown). (Map created using QGIS 3.16.0 software. Contains Esri basemap).



Box 1. Summary of EU member States' (MS) 2018 reports on D1C6.

The analysis and evaluation of Articles 8, 9, 10 of the MS 2018 reports to assess the criterion D1C6 of the MSFD underscored the need to:

- Cooperate between MS to harmonise the GES definition
- Establish a coherent set of criterion elements (e.g. habitat types) that reflect the spatiotemporal condition of the pelagic habitat
- Set indicators and methodology over the criterion elements to inform on the pressures at (sub)-regional scale
- Develop quantitative targets for each indicator to reach GES

Regarding Article 8: Four 'broad habitat types' (i.e. variable salinity, coastal, shelf, oceanic /beyond shelf) were reported by 10 MS. Coastal and shelf habitat types were reported across all marine regions (Baltic Sea (BAL), North-East Atlantic Ocean (NEA), Mediterranean Sea (MED), Black Sea (BLK). Four MS also reported on 'other pelagic habitats' that includes parameters and metrics on phytoplankton and zooplankton. MED region is poorly represented. MS often reported the indicators or parameters in place of the criterion elements. Most of the reported parameters and indicators are primarily used for eutrophication and food web assessments. Habitat assessments and threshold values change largely across marine regions. GES was defined 'achieved' by five out of 13 MS reporting on Art. 8 while the majority indicated that it is expected to be achieved later than 2020. The pressures referred to a list of general possible pressures affecting the habitats and were not specific to the indicator estimates.

Regarding Article 9: Nineteen MS reported on Art. 9. GES descriptions were poor and often not informative. The definition lacked quantitative information on methods, thresholds, and integration rules.

Regarding Article 10: Fifteen MS reported on Art. 10. The descriptions of targets poorly reported on the status and gaps to achieve GES or referred to relevant direct anthropogenic pressures. Progresses on the pressures by indicator were not assessed quantitatively

The main objectives of this report are to: i) briefly summarise the main drivers of variation in pelagic habitat characterization (Section 2); ii) review the common empirical approaches that are used to assess D1C6, with special focus on the limitations of these methods in terms of capturing spatial and temporal variability and possibility of broader applications (Section 3); and finally iii) expose a set of recommendations (Section 4).

2 Complexity of pelagic habitat characterisation

2.1 Spatiotemporal variability of the pelagic habitat processes

The pelagic environment includes a continuum of mixing and transport depending on the interaction of multiple drivers acting on different spatial and temporal scales (Barbara et al., 2016). Pelagic physical processes vary spatially with seabed features (e.g. high productivity for seamounts upwelling) and major currents and fronts, and temporally with, for example, wind-driven upwelling (Hyrenbach et al., 2000). As a result, biota responses would depend on and vary with these hydrographic factors (Bode et al., 2019).

In the MSFD, pelagic habitat types are identified horizontally by considering the distance from shore. The four broad habitat types cover two main zones: i) the neritic, which includes variable salinity and coastal habitats, and ii) the oceanic, which extents away from coast and refers to the shelf and oceanic/beyond shelf habitats (GES Decision). This is a common approach when classifying pelagic ecosystems (Roff, 2013), it requires focusing on specific mechanisms that underlie GES and thus support concrete outcomes (McQuatters-Gollop, 2012). To date, different hydro-biogeochemical models exist that describe the pelagic habitats across European marine regions (i.e., Baltic Sea, North-East Atlantic Ocean, Mediterranean Sea, Black Sea).

These models focused predominantly on hydro-biogeochemical changes at multidecadal scales, e.g. density stratification (Tett et al., 2007; van Leeuwen et al., 2015), reflecting the regions' hydrodynamics, monitoring programmes (e.g., HELCOM COMBINE, HELCOM (2017a)), or productivity-based (UNEP, 2013).

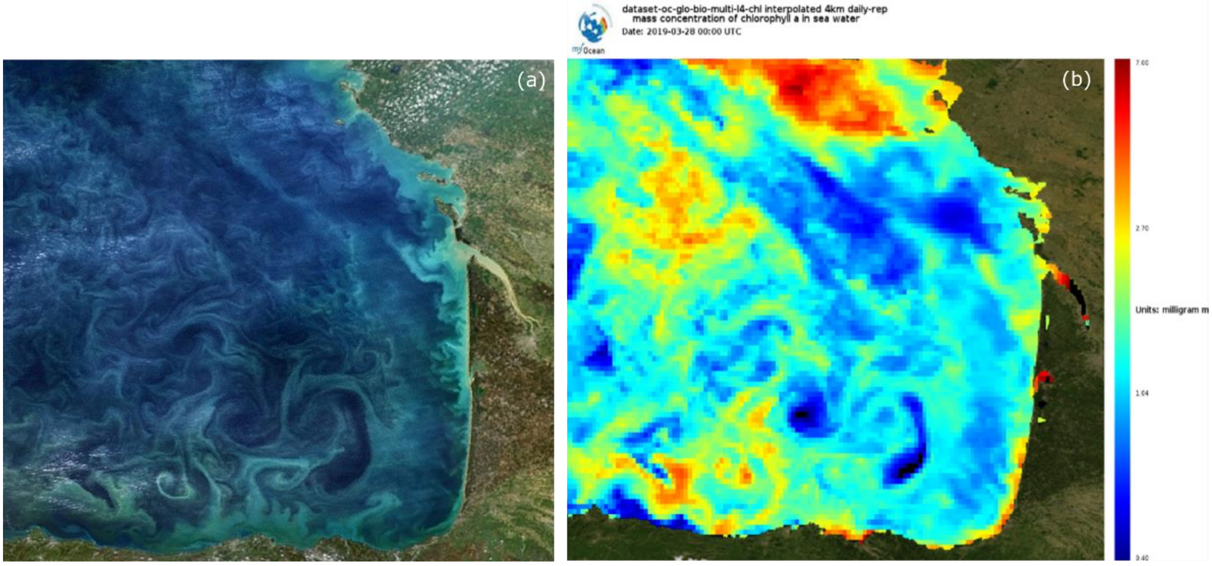
For example, in the North-East Atlantic Ocean (e.g. North Sea, English Channel), 51-year modelled hindcast provide core and distinct physical regimes that are used to characterize stable pelagic features in the OSPAR assessment area (van Leeuwen et al., 2015). As these models aim at identifying the overall remarkable features at pelagic sites, it is difficult to investigate areas of high interannual variability (van Leeuwen et al., 2015). The 29% of North Sea is currently not defined by a stable stratification regime (van Leeuwen et al., 2015). Recent developments in OSPAR to define assessment areas for eutrophication based on environmental conditions considering physical (depth, salinity, stratification), chemical (nutrients) and biological factors (phytoplankton dynamic: biomass (satellite-derived chlorophyll-a) and primary production) might also be applicable for pelagic habitat in future assessments.

In the Baltic Sea, pelagic habitats are assessed at HELCOM sub-basins scales (HELCOM, 2013a). These sub-basins reflect the HELCOM COMBINE (HELCOM, 2017a) monitoring programme and are further divided into coastal and offshore areas to account for Water Framework Directive (WFD; Directive (EC) 2000/60, 2000) water types and freshwater-driven pressures (i.e., eutrophication, HELCOM (2017a). The assessments of D1C6 at these units showed that there is a need for improving the spatial and temporal coverage of data from *in-situ*, satellite and ship-of-opportunity (HELCOM, 2018a). It is essential to consider to what degree pelagic dynamics (both spatial and temporal) should be captured to match the specific questions of the MSFD, to what extent the sampling stations are representative of wider regions and how different methods are able to represent these dynamics.

In the Mediterranean Sea, satellite-derived chlorophyll-a (Chl-a) has been proposed to classify pelagic habitat types in the epipelagic layer (0-200 m) (UNEP, 2013). This classification includes coastal and oceanic areas, and ephemeral pelagic features, such as upwellings and fronts. As chlorophyll-a is satellite-based, the spatiotemporal variability of these habitats can be monitored and used as a proxy of pelagic biodiversity (e.g. phytoplankton biomass) to regions with insufficient *in-situ* data (Hu et al., 2019; Papenfus & Schaeffer, 2020). Environments where productivity may mostly occur in the subsurface layer (i.e., below one optical depth), and consequently not seen by satellite optical sensors, are generally considered to be substantially less productive than when occurring near the surface because of the exponential decrease of light with increasing depth. Indeed, areas where a subsurface chlorophyll-a maximum occurs may characterize oligotrophic environments.

In the Black Sea temporal and spatial investigations of the physical mixing in the upper mixed layer allowed setting the production levels and evaluating phytoplankton biomass (BSIMAP, 2017). However, despite the improvement of resolution, frequency and turbidity interference corrections, challenges still exist to use satellite chlorophyll-a in areas of the Baltic and Black Seas with high content of coloured dissolved organic matter (the use of dedicated regional chlorophyll-a algorithms is needed).

Figure 4. Comparison of pseudo-real colour image (RGB composite) at 4 km resolution of the Bay of Biscay for 28 March 2019 (a) and the equivalent chlorophyll-a field (b) (range from 0.4 to 7 mg/m3). Note the mesoscale and sub-mesoscale productivity induced by currents in the coastal and oceanic areas. (a): VIIRS (source: Ocean Color WEB[1]); (b): Copernicus-GlobColour chlorophyll-a composite from MODIS, VIIRS-SNPP&JPSS1, OLCI-S3A&S3B sensors[2].



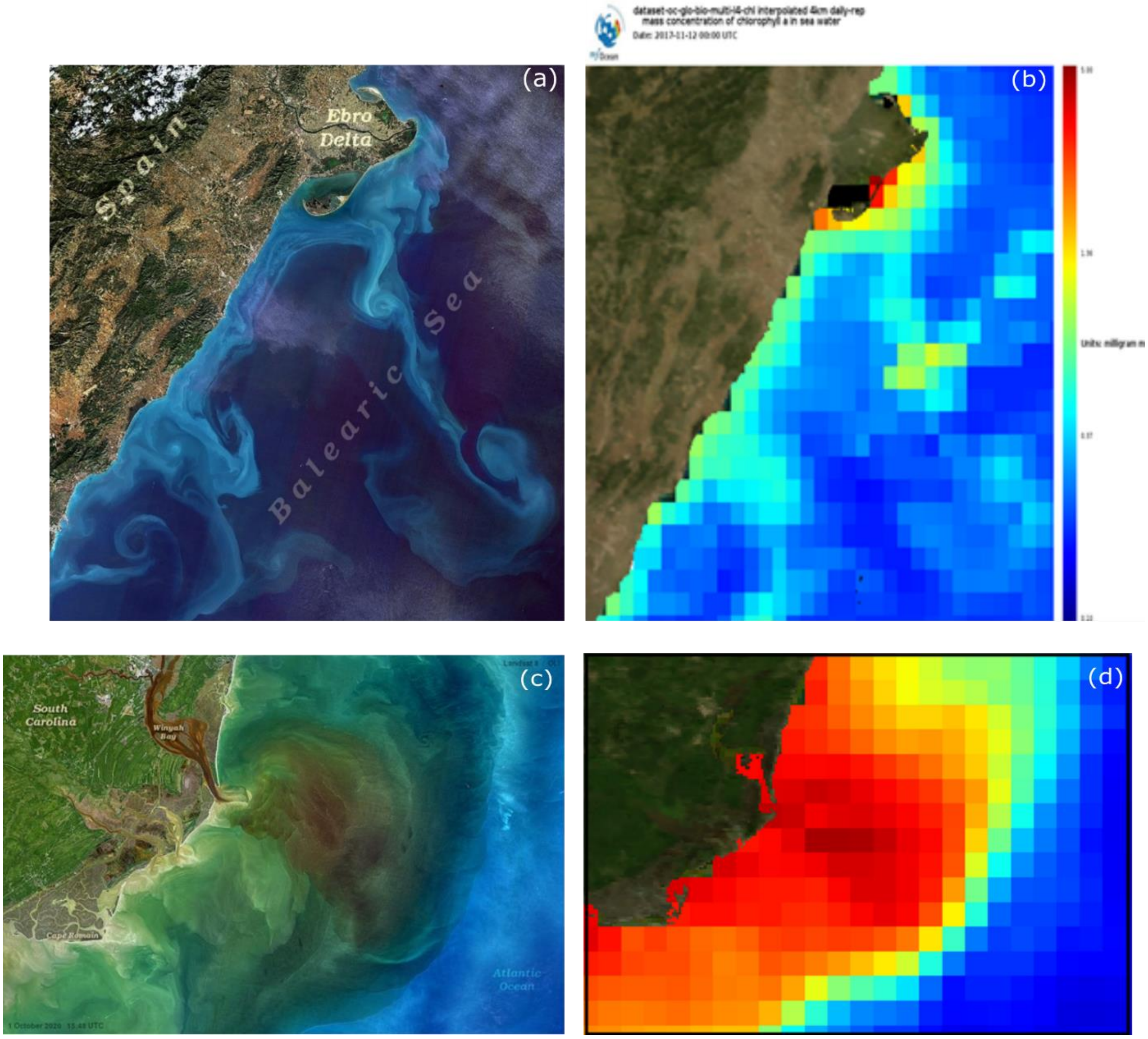
As examples of how satellite and airborne observations may horizontally capture the complexity of features of the pelagic realm, Figures 4 to 7 show daily scenes including productivity features at meso- (eddies, upwelling, river turbidity plumes) to local scale (river-induced productivity, turbidity fronts, dinoflagellate bloom). The comparison of pseudo-real colour image (RGB composite) at 4 km resolution of the Bay of Biscay (Figure 4a) and the equivalent chlorophyll-a field is proposed in Figure 4b (satellite ocean colour sensors) to enhance macro-scale processes. Figure 5 presents few examples of sub-mesoscale variability of pelagic habitats both in the coastal and oceanic areas as perceived by a high-resolution optical sensor at 30 m resolution (Landsat 8 / OLI, Figures 5a, c) and ocean colour sensors at 4 km resolution (Figures 5b, d).

---

[1] https://oceancolor.gsfc.nasa.gov/gallery/629/

[2] https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=OCEANCOLOUR_GLO_CHL_L4_REP_OBSERVATIONS_009_082

Figure 5. Examples of complex spatial distribution of coastal and shelf waters as for phytoplankton in the Ebro river area (a) at 30m resolution (Mediterranean Sea, 12/11/2017 in real colour from Landsat 8 / OLI) and corresponding chlorophyll-a content (b) at 4km resolution (Copernicus-GlobColour, 0.1-5 mg/m3) and more complex waters partially loaded of Coloured Dissolved Organic Matter (CDOM in brown) and inorganic suspended matters (in beige) discharged by rivers (c) (North Carolina, 01/10/2020, Landsat 8 / OLI) and corresponding chlorophyll-a content (d) at 4km resolution (Copernicus-GlobColour, lower image, 0.2-10 mg/m3). The Copernicus-GlobColour product is a chlorophyll-a composite from MODIS, VIIRS-SNPP&JPSS1, OLCI-S3A&S3B sensors using the OC-CCI algorithm, which is a blend of OC3, OC4, OC5 and CI algorithms depending on the water types present in a pixel.



Furthermore, Figure 6 shows an airborne multispectral 2 m-resolution transect from a river plume to offshore with a high variability of water quality features spanning from turbidity to phytoplankton and *Noctiluca scintillans* blooms. The related satellite-derived chlorophyll-a time series and horizontal field reveal that two phytoplankton blooms occurred two and five weeks before the airborne detection of the dinoflagellate *Noctiluca scintillans* bloom.

Since the MSFD requires to express the GES by proportion of sea area, these examples illustrate the necessity to account for the high variability of pelagic habitat quality.

Figure 6. An airborne multispectral observation at 2 m resolution of the Vilaine river plume area (southern Brittany, France, CASI sensor) on 10 June 1999 showing three tidal-driven fronts of turbid waters out of the estuary (1-3, inorganic suspended matter), a phytoplankton bloom area further offshore (4), a patchy distribution of *Noctiluca scintillans* (5) and shelf clearer waters (6) (figure from Druon, Loyer and Gohin (2005)).

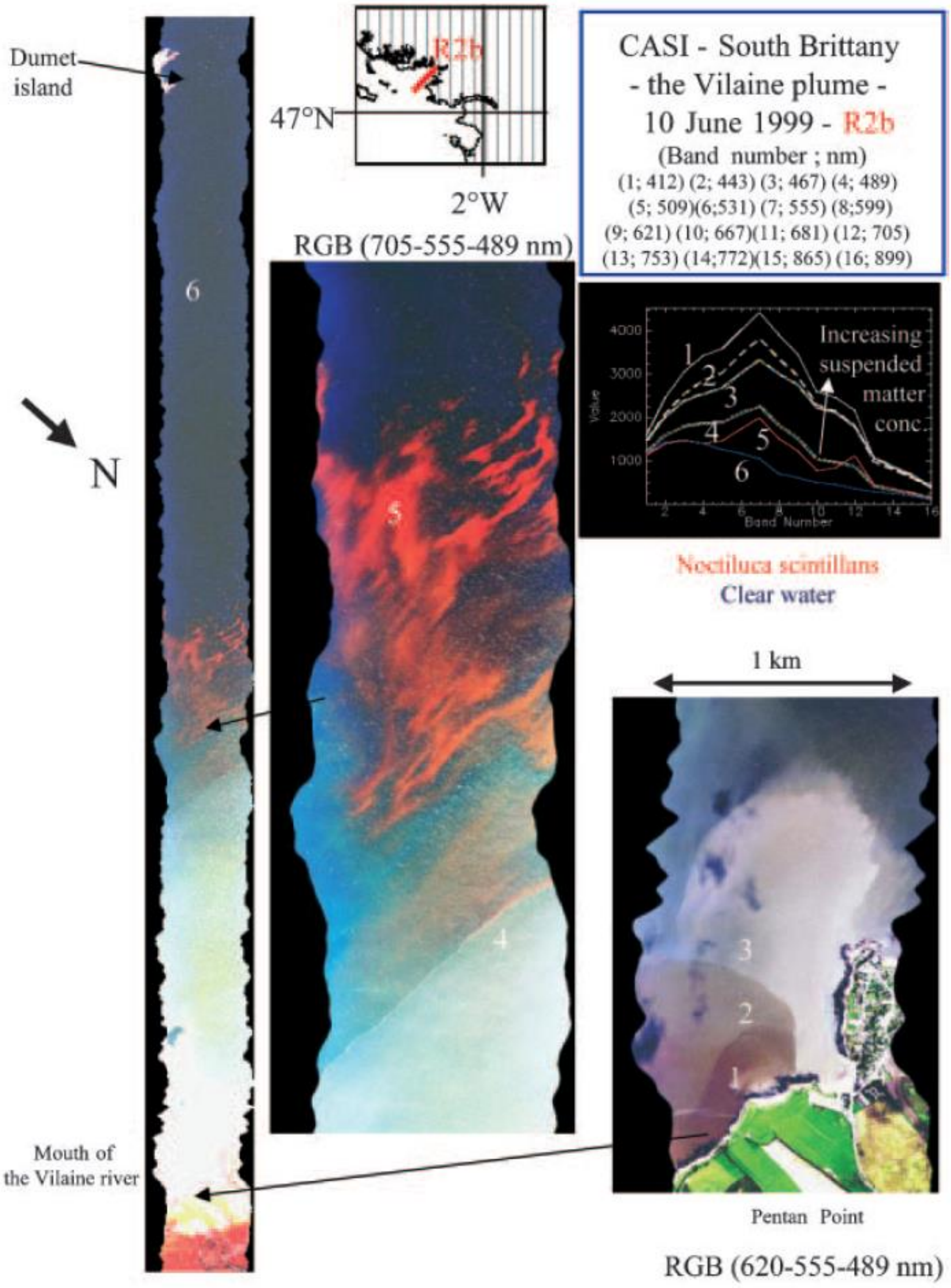
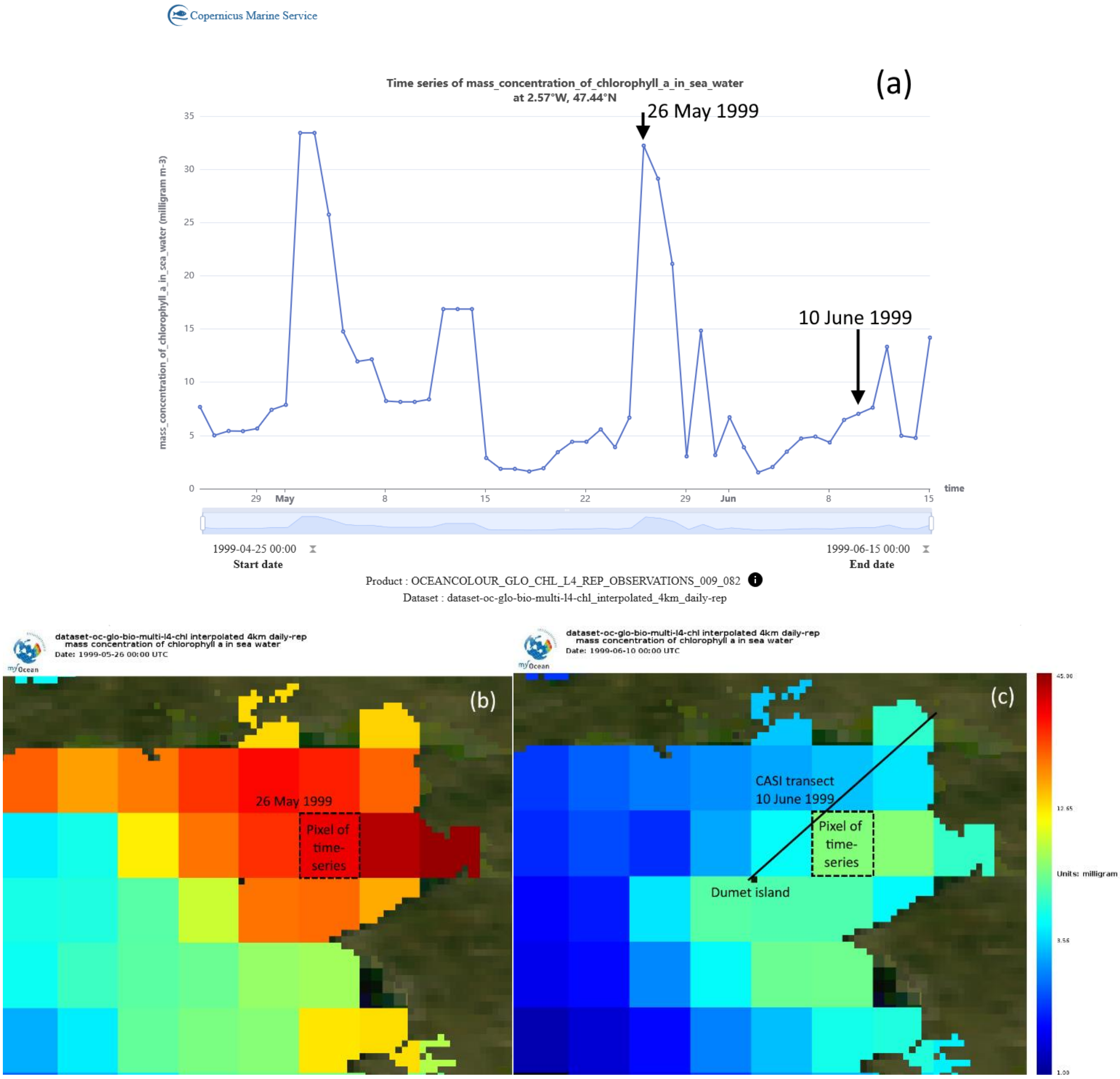


Figure 7. Corresponding satellite-derived chlorophyll-a time-series (a) and surface concentration of the Vilaine river Bay (Atlantic coast of France) 15-days before (b, 26 May 1999) and the day of the hyperspectral sampling (c, 10 June 1999) as shown in Figure 6. The bloom of *Noctiluca scintillans* sensed on 10 June 1999 was preceded by two phytoplankton blooms in the previous five weeks. Copernicus-GlobColour chlorophyll-a from SeaWiFS ocean colour sensor (range from 1 to 45 mg/m^3 for panels b and c).



Except for the MSFD, there is no explicit spatial reference to pelagic habitat types in other EU or international regulations. The Habitats Directive (Council Directive (ECC) 92/43) is however interrelated with the MSFD and identifies open sea and tidal areas, e.g., 'Estuaries', 'Coastal lagoons', 'Large shallow inlets and bays' (Annex I of the Habitat Directive), which could be tackled by the pelagic habitat criterion if including perhaps an ecohydrological dimension in addition to topographical features. Pelagic habitats are also included in the comprehensive pan-European system for habitat identification of the European Environmental Agency, the 2019 European Nature Information System (EUNIS) review[3]. The classification is hierarchical and covers the Artic, the Atlantic, the Baltic, the Black and the Mediterranean Seas. Pelagic habitats are classified in 283 types considering temporary and permanent neuston and several physico-chemical parameters (i.e., water mixing, residence time, salinity, etc.). The relative importance of hydrological drivers for the changes of the biological activity within the pelagic habitat is overall strongly influenced by different spatial and temporal scales (Totti et al., 2019). Therefore, acknowledging the relative importance of these different spatial and temporal scales, is essential to better understand and interpret the status of pelagic habitats. While the above-mentioned approaches to classify pelagic habitats have helped to better comprehend the dimensions of the pelagic system, gaps remain in linking

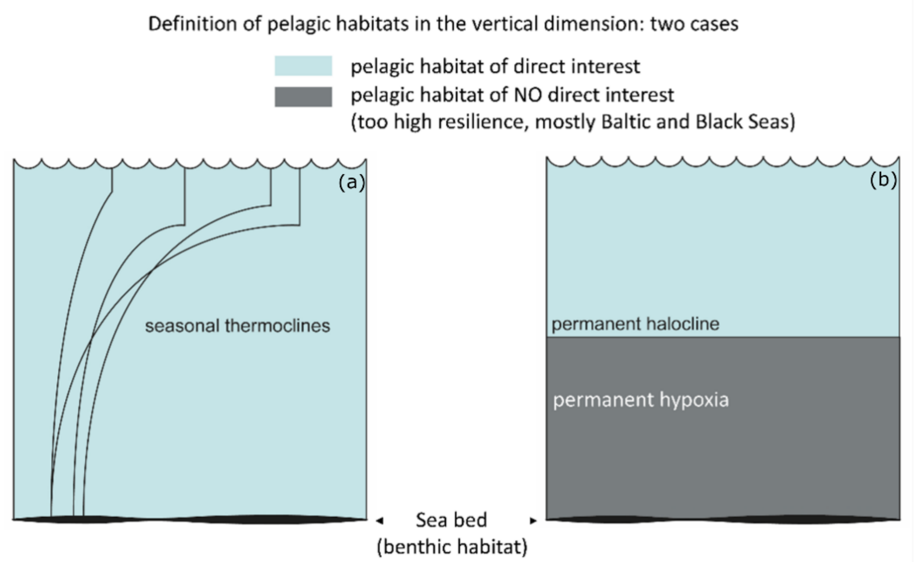
---

[3] https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification

pelagic to the physical, chemical, and biological systems for the MSFD assessment. In other words, the challenge lies in formulating conclusions about drivers and processes of pelagic habitat status across relevant spatial and temporal scales.

For example, **a vertical delimitation of pelagic habitats would consider from surface to seabed in seasonal thermoclines seas (Figure 8a) or from surface to the hypoxic layer in permanent halocline areas** (Figure 8b, e.g. the Baltic and Black Seas) where the hypoxic sub-layer is considered resilient to changes in the time scale of action of the MSFD (few years) (Figure 8b).

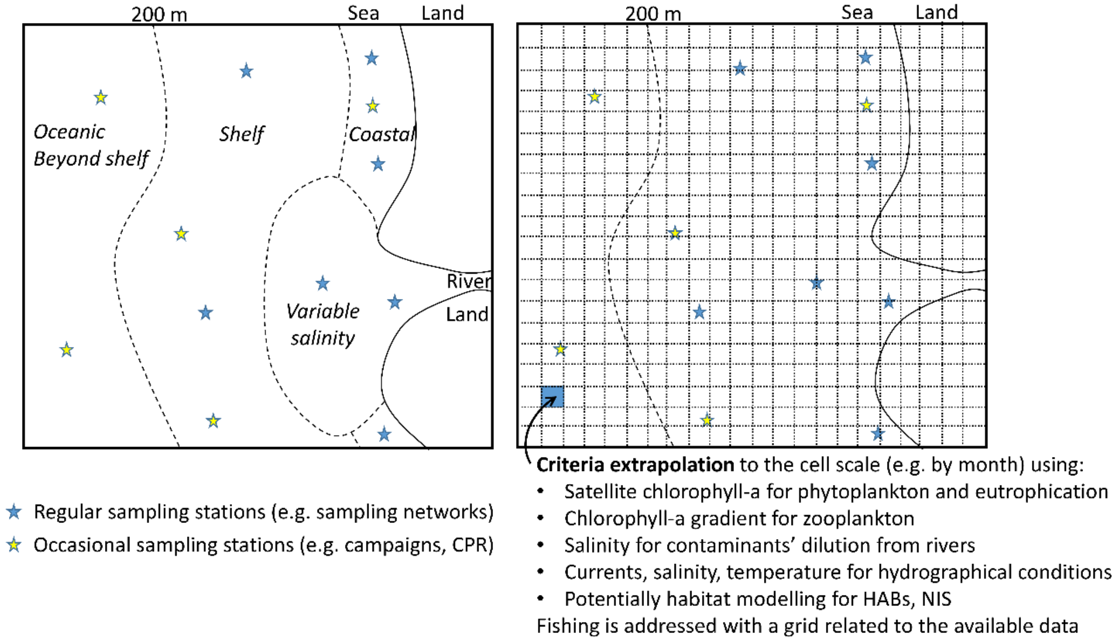
Figure 8. Vertical limits of pelagic habitats. Seas with permanent halocline and hypoxia were considered as too resilient as regards to the time scale of action of the MSFD**.**



Horizontally, the habitat types (variable salinity, coastal, shelf and oceanic/beyond shelf) as defined in the MSFD might be too simplistic (using low-frequency *in-situ* data alone) **to suitably describe the complexity of pelagic habitat changes in space and time as a result of water masses transport and mixing**. **Satellite and operational model** (e.g. Copernicus Marine Services) **data**, at the e.g. monthly or weekly time scale depending on the parameter, **might be key to extrapolate the *in-situ* observations/indicators** (e.g. harmful algal blooms) in order to better depict the spatiotemporal variability of pelagic habitats (Figure 9). To this end, the integration of *in-situ* and remote sensing data will be an important aspect to develop.

Figure 9. Comparison of (a) the simplified description of pelagic habitats as described in the MSFD (four habitat types) with a limited distribution of regular and occasional sampling stations and (b) proposal for a description at the scale of variability of the coastal and oceanic processes (continuous grid of few km) extrapolating most i*n-situ*-based criteria using environmental and operational model data such as satellite chlorophyll-a and the Marine Copernicus operational physical models (CMEMS4). [CPR: Continuous Plankton Recorder; HAB: Harmful Algal Blooms; NIS: Non-Indigenous Species]. (c) sampling frequency of *in-situ* and satellite/operational model data. Dashed arrows relate to spatiotemporal discontinuity and grey colour depicts lower absolute precision.

a- Simplified description of MSFD pelagic habitats (*types*) **b- Description** for MSFD **at the scale of** pelagic habitats' **variability**



★ Regular sampling stations (e.g. sampling networks)

☆ Occasional sampling stations (e.g. campaigns, CPR)

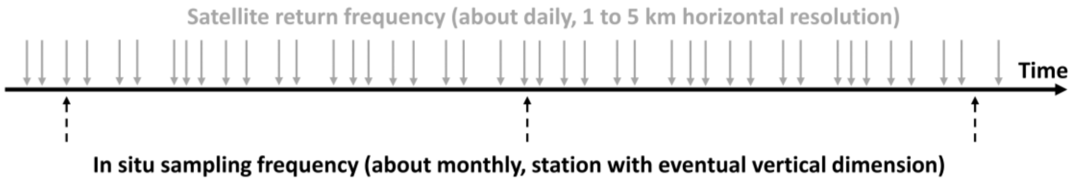
Criteria extrapolation to the cell scale (e.g. by month) using:

- Satellite chlorophyll-a for phytoplankton and eutrophication
- Chlorophyll-a gradient for zooplankton
- Salinity for contaminants' dilution from rivers
- Currents, salinity, temperature for hydrographical conditions
- Potentially habitat modelling for HABs, NIS

Fishing is addressed with a grid related to the available data

c- Typical sampling frequency & link with the spatial dimensions

(dashed arrows relates to spatiotemporal discontinuity and grey colour depicts lower absolute precision)



---

[4] https://marine.copernicus.eu/

2.2 Human pressures

Pelagic habitats are often threatened by direct and indirect human activities and associated pressures that change in intensity across the seascape (Halpern et al., 2015). The scale at which these pressures affect the biological community varies with its biological compartment, size range, ontogeny, life history and the hydrographic variables (Lefort et al., 2015). Scientific studies have identified several anthropogenic threats to the marine pelagic habitat from direct (i.e., fishing, mining, mariculture, coastal development) to indirect (i.e., climate change, invasive species, land-based pollution) (Maes *et al.*, 2020). These pressures can be acute, causing imminent loss of pelagic functions (i.e., trophic shifts Casini *et al.* (2008)) or not yet critical to their provisioning (i.e., regulated, (Beaugrand & Kirby, 2018)). As a result, the GES of pelagic habitat of a particular marine region is determined by the interaction of various seascape pressures/drivers (Figure 10) that can be classified into four main, but often strongly interlinked, categories: i) hydro-meteorological factors, ii) biological changes, iii) contaminants and litter inputs; and (iv) human physical interventions.

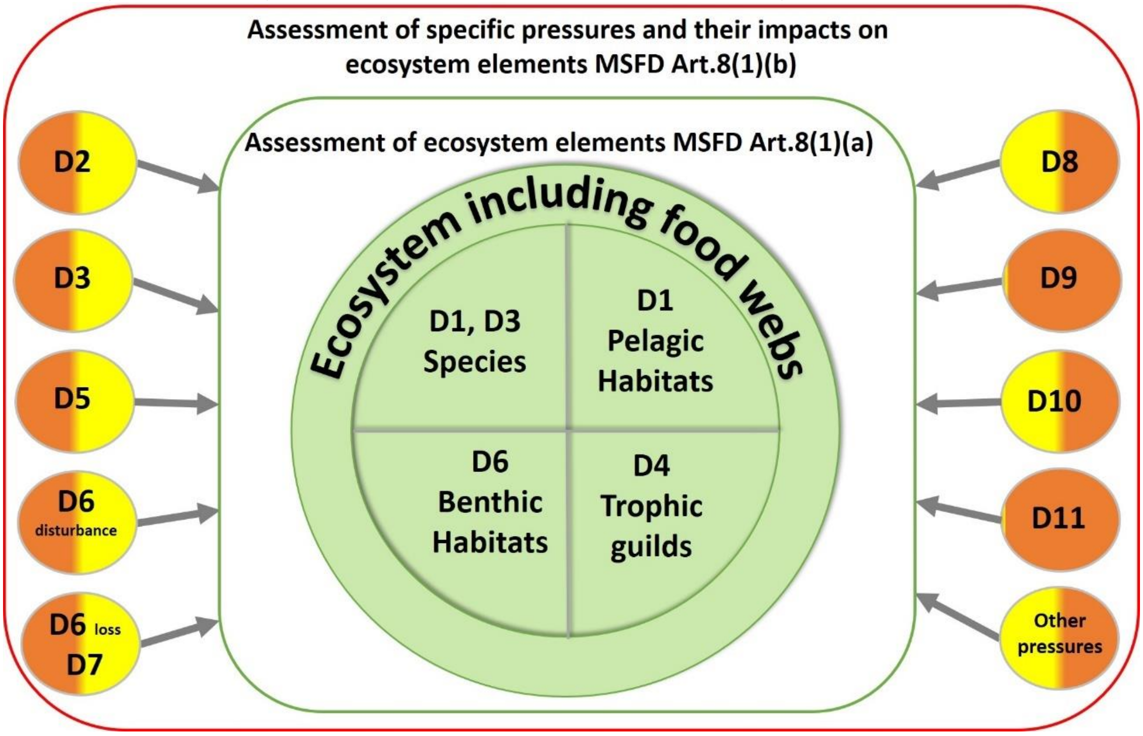
First, **hydro-meteorological conditions** are dominant drivers of pelagic habitat processes (i.e., production), both on long and short timescales (Section 1.1). Climate is the main agent of water masses movements (Bigg, 2003). It controls thermal regimes and so the atmospheric circulation that drives water mixing (Bigg, 2003). Therefore, different components, such as precipitation, evaporation, sea-ice extent, salinity, temperature, and pH are commonly included in models to estimate the hydrodynamics of the water column (Delhez et al., 2004). As a result, hydro-meteorological factors influence the availability of light, oxygen, micro- and macro- nutrients and, in turn, the ecology of the pelagic species (Würtz, 2010). Species biodiversity in the pelagic system is largely determined by the interaction between the species' niche and fluctuations in the environmental regime at local (from metres to several kilometres) and global scales (Schmidt et al., 2019). In the MSFD, this pressure category is partially accounted by Descriptor 7 and criterion D7C1 where **alterations of hydrographical conditions** (e.g. currents, salinity, temperature) associated with infrastructure development are addressed in the water column (Commission Decision (EU) 2017/848, 2017). Also, there is a strong link to the MSFD Descriptor 4 (Food Webs) and in particular with the candidate indicator Food Web -2: "Production of phytoplankton" (Kromkamp et al., 2017).

Second, the environmental status of pelagic habitat will vary as a result of ecological changes due to **invasive alien species** (Gorokhova *et al.*, 2005; Tiselius and Møller, 2017). Changes in community cascades due to strong non-selective predation can cause alterations in food web topography (Gorokhova *et al.*, 2005) and pelagic regime shifts (Casini et al., 2008; Tiselius & Møller, 2017). Furthermore, the co-invasion of species that exploit different habitats, e.g. pelagic and benthic, can have major impacts on resource use and cause indirect and cross-habitats effects (Fryxell et al., 2016). In the MSFD, it is recommended to look at the links between pelagic habitats and invasive species by considering the proportion of habitat affected by the invaders (Descriptor 2 Criterion 3). The challenge of analysing the effects of invasive species on pelagic habitats is high as relationships are multiple, non-linear and non-stationary (Bradley et al., 2019). These relationships are indeed strongly context-driven (e.g. depend on climatic conditions, geomorphic changes and ecological succession, Robinson *et al.*, 2017). Moreover, there is a difficulty in considering phytoplankton microorganisms as invasive species.

Third, **organic and inorganic environmental contaminants and litter** can have a significant impact on the pelagic biological system over short- and long-term timescales. Similar to invasive species, these effects are influenced by the geometry of the coastline, wave actions and mixing characteristics (Jones & de Voogt, 1999). The uptake of trace metals and persistent organic pollutant by primary producers can build up along the food web (e.g. biomagnification, (Jones & de Voogt, 1999)) and impair metabolic and reproductive functions of aquatic organisms (Bezerra et al., 2019). Furthermore, toxic compounds can originate from both untreated sewage and chemical discharges by industries, and can also sorb to marine litter (Caruso, 2019). In the MSFD, chronic and acute pollution is considered by the Descriptor 8 and criteria 2 and 4 but none of pelagic species are included in the descriptor indicator. Likewise, excessive nutrient loads can drive an increase in plant production and biomass and lead to eutrophication and hypoxia (Kudryavtseva et al., 2019). In such context, chlorophyll-a concentration (MSFD D5C2) and algal summer blooms (MSFD D5C3), are expected to increase and water transparency (MSFD D5C4) to decrease. As a result, monitoring of these parameters is recommended for the MSFD pelagic habitat assessment.

Finally, good environmental status of pelagic habitats can also be affected by **human physical interventions** (Salmaso & Tolotti, 2020). Even short-term environmental interventions may lead to ecological legacy effects over longer time periods (Korpinen et al., 2012). Changes in thermal and salinity regimes can occur as a product of cooling cycles, for example from nuclear power and wastewater treatment plants or from the presence of bridges and coastal dams (Korpinen et al., 2012). Likewise, underwater noise from coastal and offshore shipping or operational wind farming and oil rigs interfere with the biological community structure (Slavik et al., 2019). Increase in siltation can result from a greater sediment supply, e.g. as a result of riverine runoff, dredging, and coastal shipping (Slavik et al., 2019). In this context, the MSFD targets some of these human pressures in Descriptors 11 (underwater noise), and other human activities are required to be identified during the GES assessment (European Commission, 2019).

Figure 10. An ecosystem-based approach for the determination and assessment of GES: main elements of the ecosystem (state-based descriptors, centre) and the adverse effects of pressures (pressure-based descriptors, satellite circles, in which orange depicts pressure and yellow the impact). Note that Descriptors D2, D3, D5, D6, D7, D8 and D10 include both pressure and impact criteria in the GES Decision (Modified from European Commission 2020, Figure 8).



2.3 Conclusions: complexity of pelagic habitat characterisation

The physical, chemical and biological processes of pelagic habitats are highly variable in time and space and often characterised by feedback mechanisms due to the interactions between the seascape and human influence. This variability results in different biological responses and non-linear behaviour of the pelagic ecosystem components. A coastal area is generally characterised by highly different pelagic communities compared to the open ocean. These differences are especially pronounced in sea areas with highly fretted coasts and heterogenous geomorphology (i.e. Northern Baltic Sea). The assessment of the pelagic habitats with an improved spatiotemporal resolution requires a comprehensive understanding of the causes and symptoms of these pressures and of the underlying indicators that describe the pelagic habitat functions in the timescale of the MSFD implementation.

3 Metrics and indicators to assess the status of pelagic habitats

A range of indicators for pelagic habitats are used to monitor pelagic habitat biodiversity in seas and assess its status (Varkitzi et al., 2018). While individually these indicators are useful for analysing biodiversity changes for the scale under question, they typically address groups of pelagic communities and, therefore, are relevant to certain spatiotemporal scales. Therefore, the results of using different indicators are difficult to interpret as regards to the processes that underly biodiversity changes over multiple scales and to the harmonisation across EU marine regions (Box 1).

For the scope of the MSFD assessment, indicators should reflect a pressure-state relationship (European Commission, 2020), where pressure refers to 'at source' and 'at sea' anthropogenic activities and state to the range of environmental impacts having adverse effects on the habitat.

State and pressure indicators currently operational to GES are discussed in the following section by looking at their main characteristics, challenges and limitations.

3.1 State indicators

Various interactions at the seascape between factors described in Section 2 often result in taxonomic and functional changes of plankton communities. The most common state indicators are based on planktonic organisms' metrics (abundance, biomass, size distribution, and diversity; Table 1) because plankton:

i) form the basis of most pelagic and benthic food webs, supporting a range of key ecosystem functions (i.e. carbon sequestration) (Hernández-León et al., 2020)
ii) have short lifespans (Richardson, 2009)
iii) have temperature-dependent physiologies (Thomas et al., 2017)
iv) have a high potential for dispersal (Peijnenburg & Goetze, 2013)
v) are not commercially exploited (Richardson, 2009)
vi) have long time-series spatially and timely (especially shallow coastal system) (Lombard et al., 2019).

The analysis of plankton metrics can provide useful insight into physical hydro-climatic changes (McQuatters-Gollop, 2012; Bedford *et al.*, 2018; Bedford *et al.*, 2020) and thresholds determining good environmental state (Gorokhova et al., 2016; Varkitzi et al., 2018).

Table 1. Regional state indicators, (pre)operational to GES used to assess D1C6 criterion. 'PH' refers to Phytoplankton, 'FW' to Food Webs and 'EO' to Ecological Objectives. Marine Regions abbreviations: Baltic Sea (BAL), North-East Atlantic Ocean (NEA), Mediterranean Sea (MED), and Black Sea (BLK).

Code	Name	Metric	Region	Scale of application	Threshold value	Threshold scale	RSC
1	*Chlorophyll-a (Chl a)*	Concentration	BAL	EU	YES	REGIONAL	(HELCOM 2018b)
2	*Diatom/Dinoflagellate (Dia/Dino) Index (*)*	Biomass	BAL	EU	YES	REGIONAL	(HELCOM 2018c)
3	*Phytoplankton abundance*	Abundance	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
4	*Phytoplankton biomass*	Biomass	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
5	*Seasonal Succession of Dominating Phytoplankton Group*	Composition	BAL	EU	YES	REGIONAL	(HELCOM 2018d)
6	*PH1/FW5: Changes in Phytoplankton and Zooplankton Communities*	Abundance of lifeforms per pairs	NEA	EU	NO	REGIONAL	(OSPAR, 2018)
7	*PH2: Changes in Phytoplankton Biomass*	Biomass, Abundance of copepod	NEA	EU	NO	REGIONAL	(OSPAR, 2019a)

	and Zooplankton Abundance						
8	*PH3: Changes in Plankton Diversity*	Abundance per species or genus	NEA	EU	NO	REGIONAL	(OSPAR, 2019b)
9/10	*Indicator 1: Habitat distributional range (EO1) to also consider habitat extent as a relevant attribute.* *Indicator 2: Condition of the habitat's typical species and communities (EO1).* • *Coastal waters phytoplankton communities* • *Coastal waters zooplankton communities* • *Shelf and oceanic waters phytoplankton communities* • *Shelf and oceanic waters zooplankton communities*	Biomass, Abundance	MED	EU	NO	REGIONAL	(UNEP/MAP, 2016)
11	*Chlorophyll-a (Chl a)*	Concentration	MED	EU	YES	REGIONAL	(Commission Decision 2018/229)
12	*Zooplankton H-Shannon*	Biomass, Abundance	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
13	*Zooplankton abundance*	Abundance	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
14	*Zooplankton biomass*	Biomass	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
15	*Copepoda biomass*	Biomass	BLK	EU	YES	REGIONAL	(BSIMAP, 2017)
16	*Zooplankton Mean Size and Total Stock (MSTS) (*)*	Biomass, Abundance, Body Size	BAL	EU	YES	REGIONAL	(HELCOM 2018e)

(*) both state and pressure indicator

3.1.1 The currently used approaches

A common approach to estimate pelagic environmental status is to look for plankton community changes. In this approach, abundance, biomass and diversity are often considered as proxies for processes controlling the pelagic physical and biological systems (e.g. eutrophication). Generally, the biological community are assessed by three categories of indicators depending on the targeted taxa: phytoplankton-only (codes 1, 2, 3, 4, 5, 11; Table 1), zooplankton-only (codes 12, 13, 14, 15, 16; Table 1), and combined phyto- and zooplankton (codes 6, 7, 8, 9, 10; Table 1). There are advantages and disadvantages depending on the category and metric addressed by each indicator.

The phytoplankton-only category has indicators representing the whole or majority of phytoplankton community, i.e. Chl-a, Phytoplankton abundance, Phytoplankton biomass, Phytoplankton genus or species diversity, Seasonal succession of dominating phytoplankton, or specific taxa, i.e., Diatoms and Dinoflagellates (Dia/Dino Index) (Table 1). The phytoplankton-only group has the advantage of providing frequently basic data for the estimation of biomass on large spatial scales (e.g. satellite-derived Chl-a) with insights on the trophic level transfer efficiency (productivity fronts, Druon et al., 2019; Descriptor 4), thus providing a snap-shot of the whole autotrophic plankton community (Sammartino et al., 2018). The *in-situ* data and derived indicators can imply high costs depending on national monitoring programmes (variable sampling effort) and on temporal and spatial variability (sampling depth 0-10 m[5]). To date, these indicators have been evaluated for specific assessment units of the Baltic and Black Seas (BSIMAP, 2017; HELCOM, 2017b). The Dia/Dino Index targets the seasonal succession from diatoms to dinoflagellates in the Baltic Sea (HELCOM, 2018c) and is used as a proxy of the spring bloom magnitude. It does not require a precise quantification of the bloom and can be easily identified on the basis of the routine methods for phytoplankton sampling and analysis. Conversely, this index is limited to marine areas where diatoms and dinoflagellates occur (Klais et al., 2013). There is also an alternative to the Dia/Dino Index based on dissolved silicate consumption that is recommended when the diatom bloom is not sampled (Wasmund, 2017). However, taxonomic metrics that refer to the group level are popular because they are simple to use and the results are intuitive (Smit et al., 2021) but require high taxonomical skills.

The zooplankton-only category includes abundance, biomass, diversity and size-based indicators of the mesozooplankton community (organisms of 0.2 to 20 mm), i.e. zooplankton H-Shannon, zooplankton abundance, zooplankton biomass, Copepoda biomass and MSTS. All these indicators are regional reporting indicators in the Black Sea (BSIMAP, 2017) and MSTS (Gorokhova et al., 2016) is currently a HELCOM core indicator in the Baltic Sea (HELCOM, 2018e). The taxonomy-based metrics of mesozooplankton provide information about the relative importance of top-down and bottom-up control (e.g. zooplankton feed on phytoplankton and in turn constitute food for higher trophic levels). To this end, the MSTS indicates both fish feeding levels and grazing pressures from zooplankton on phytoplankton by considering jointly mean size of zooplankton and its biomass or abundance (Gorokhova et al., 2016). Thus, MSTS is a two-dimensional indicator representing a synthetic descriptor of zooplankton community structure and providing insights into the energy transfer efficiency in the pelagic food web (Labuce et al., 2020). However, there are limitations due to spatial and temporal variability of the monitoring stations and data availability. Consequently, research is needed to evaluate the impacts of these coverage gaps on the open sea assessment units (HELCOM, 2018e). To that regard, the satellite-derived mesozooplankton habitat (Druon et al., 2019) could provide useful complementary information as it estimates, in relative values, the phyto- to zooplankton transfer efficiency based on the observation of resilient and large productivity fronts. To be noticed, the recent successfully application of the MSTS approach to the copepod communities in the Celtic Sea, and the proposal for modifiying this indicator (Copepod Mean Size and Total Abundance; CMSTA) in association with a Plankton Imager for analysing the copepod-dominated communities outside of the Baltic Sea (Pitois et al., 2021).

Finally, the last category of combined phyto- and zoo-plankton indicators includes multimeric and multispecies indices, i.e., PH1/FW5, PH2, PH3, and a combination of indicators of habitat type and communities, i.e., Indicator 1, Indicator 2 (Table 1). Among the multimetric indicators, the PH3 "Changes in Plankton Diversity" targets both the alpha (i.e. diversity within a community) and beta (i.e. rate of change of community composition) diversity of the phytoplankton community (Rombouts et al., 2019) and aims at describing changes in its structure (composition, diversity). The assessment concept of PH3 is also intended to be used for zooplankton, but has so far only been applied in test assessments (i.e. French MSFD 2017 Environmental Assessment, Duflos et al., 2018). PH3 belongs to the category of surveillance indicator (Bedford et al., 2018) as well as PH2 that is indicative of physical hydro-climatic changes. Both these indicators have been used together with PH1/FW5 in the North-East Atlantic assessment area (OSPAR, 2017). Availability of data and sampling methods to characterise the community represent the main limitations to support the regional assessments. Research is looking to explore complementary methods to microscopic identification (e.g. flow-cytometry, image analysis, DNA barcoding) for phytoplankton and zooplankton, and to integrate that information in the index zooplankton data (OSPAR, 2019b). Among the multispecies indices, there is PH2 and PH1/FW5 (Table 1). The PH2 indicator combines taxonomic metrics of Copepoda abundance and total phytoplankton to depict changes in the energy transfer between primary and secondary producers (OSPAR, 2019a). Total copepod abundance is used in the calculation as a proxy for main zooplankton abundance, while chlorophyll-a is used as a proxy for phytoplankton biomass. Conversely, the PH1/FW5 is a functional-based indicator that considers phyto- and zooplankton lifeforms (e.g. size, motility, trophic preferences) paired with species abundances to investigate changes in the energy flow

---

[5] "The minimum requirements include sampling near surface waters, i.e. either at 1 m below the surface or a depth-integrated sample at 0–10 m. This can be accomplished by pooling samples (from bottles) from depths of 0, 2.5, 5, 7.5, and 10 m, by using a sampling tube at 0–10 m or another type of depth-integrating sampling device. It is necessary to use the same volumes of water from each depth when pooling. This sampling strategy will miss any sub-surface phytoplankton maxima deeper than 10 m."

from primary to secondary producers and to top predators (Mcquatters-Gollop et al., 2019; Tett et al., 2015). By looking at plankton traits and structure, the indicator has the advantage of depicting links to ecosystem functioning (Litchman et al., 2012) using data collected with different sampling methods and taxonomic analysis (Duflos *et al.*, 2018; McQuatters-Gollop *et al.*, 2019). Despite the inclusion of different methods, these indicators are limited by plankton-data inconsistencies (e.g. undersampling of small phytoplankton taxa, proper definition of trophic regime, different time-series length) and therefore further research is needed for implementing a more complete trait-based plankton database. Moreover, the use of complementary methods to microscopic identification of taxa is also being explored.

For the water habitat-community indicators of the Mediterranean Sea that were developed in the frame of EcAp/IMAP (UNEP, 2013), the only operational index is Chlorophyll-a concentration (Commission Decision (EU) 2018/229, 2018). The Mediterranean water types, reference conditions and boundaries have been identified for Chl-a concentrations in coastal waters, as a result of the WFD Mediterranean Geographical Intercalibration Group (Commission Decision 2018/229/EU). The MS that currently follow this classification system are Croatia, Cyprus, Greece, France, Italy, Slovenia and Spain. Many metrics for phyto- and zoo- plankton communities were shown to provide valuable insights on population dynamics (Varkitzi et al., 2018), but they are not yet operational for the D1C6 assessment, and the following phytoplankton indicators were found promising: i) size-related metrics such as the multi-metric index of size spectra sensitivity ISS-phyto for its high accuracy, low uncertainty and relatively simple sample processing; ii) diversity metrics such as Shannon-Wiener's Diversity Index for its high accuracy, iii) dominance metrics such as Berger-Parker's Dominance Index for its high accuracy, low uncertainty and focusing only on the most abundant taxa; and iv) Bloom frequency index to measure the dominance of a species during an algal bloom. A follow-up study with the large-scale testing of eight different phytoplankton metrics against different levels of stress and spatial/temporal gradients in Mediterranean sub-regions proposes a composite assessment system in pelagic habitats, i.e. the combination of Shannon's or Simpson's Diversity with Sheldon's Evenness and one of the dominance indices Berger-Parker's or McNaughton's (Francé *et al.* under revision). Particularly Shannon's or Simpson's Diversity and Sheldon's Evenness are sensitive to impacts and were less correlated with each other compared to other pairs of indices.

3.1.2 Accounting for changes: threshold methods and aggregation

The relationship between plankton communities' structure and environmental status is examined by different assessment criteria, such as value levels (e.g. baseline or reference condition, trends) and aggregation (Table 2).

Baseline condition

The assessment based on deviation from reference conditions are used for most of the indicators in Table 2 across the Baltic and Black Seas. In the Baltic, reference conditions are defined by different methods depicting environmental conditions prior to the onset of significant anthropogenic activities or pelagic systems not measurably affected by these activities. For the Dia/Dino Index, high-quality phytoplankton data from the beginning of the twentieth century (e.g. 1905-1950) was available and used to identify a historical mean value of the index and the acceptable deviation of 20% (Wasmund et al., 2017) for achieving GES. GES threshold for the Dia/Dino Index was established at 0.75 at the Kiel Bay and at 0.5 for the Eastern Gotland Basin to indicate diatom dominance over dinoflagellate community (Wasmund et al., 2017) and consequent status. Regarding the alternative Dia/Dino Index, the threshold levels were set to 0.94 and 0.84 for the Kiel Bay and Eastern Gotland Basin, respectively. But historical values are lacking in other HELCOM areas limiting the application of this indicator on regional scale.

For the indicator of 'Seasonal Succession of Dominating Phytoplankton Groups', reference seasonal growth curves and wet weight biomass data at the regional scale were set through observations after the 1980s and by expert judgment. To define reference conditions, periods of stability in long-term biomass data were determined by two approaches: i) considering yearly total biomass values ($\mu g\ l^{-1}$) and calculating five-year moving averages of their standard deviations, and ii) using a multiplicative decomposition model (HELCOM, 2018d). The thresholds values for open and coastal waters (averages among assessment units) are 0.67 and 0.65, respectively. The final GES is evaluated using the average score of the single dominant groups in the basin (HELCOM, 2018e).

Regarding the MSTS index, GES is achieved when both mean size and total stock meet specific threshold values at the scale of the assessment unit (HELCOM, 2018e). The reference periods indicate negligible eutrophication and overfishing pressures and are set by two approaches depending on the length of zooplankton time series

(Gorokhova et al., 2016). In relatively short time-series (< 12 years), mean and variance (95% confidence interval) for both parameters (size and stock) are calculated using the entire dataset, and the lower bound of the 95% confidence interval is used as the threshold value to evaluate deviations for a current observation. If time series of > 30 years are available, the reference conditions are obtained using both specific Chl-a and clupeid fish reference data at the sub-basin scale (HELCOM, 2009). In some cases, reference periods can be adopted from neighbouring areas, for which longer datasets are available. The reference conditions reflect time periods when effects of eutrophication (defined as 'acceptable' chlorophyll-a concentration) are low, whereas nutrition of zooplanktivorous fish is adequate for optimal growth. To evaluate cumulative deviations of the mean size and total stock over time, the CuSum method based on the cumulative summing of the persistent deviations from the reference mean (Manly & Mackenzie, 2003) is used. A significantly not good status is assigned when the change is persistent, and cumulative negative change exceeds 5σ difference from the threshold value.

In the Black Sea, two different approaches were adopted for developing phytoplankton and zooplankton (abundance and biomass) thresholds. For phytoplankton, thresholds are seasonal and inferred from 1961 to 2017 (e.g. Bulgaria) or from 1956 to 2010 (e.g. Romania) historical data. GES is achieved by estimating the number of pixels below the thresholds. For zooplankton, thresholds were estimated by calculating the 90th percentile from the cold and warm season for each habitat type using data from 1966 to 2014 (e.g. Bulgaria) and from 1960 to 2002 (e.g. Romania), and GES is achieved when the values are above the lower limit.

In the Mediterranean Sea, reference conditions have been identified for Chl-a by statistical analysis of data coming from the WFD sampling networks and other existing datasets, spanning over the last twenty years in some cases. Reference and GES boundaries were determined by calculating the 90th percentile and/or the geometric mean in different water types of the Mediterranean coastal waters (Varkitzi *et al.* 2018).

Trends

Trends are used in the Baltic and North-East Atlantic Regions for five indicators: Chl-a (BAL), PH1/FW5, PH2, and PH3.

Ecological targets for Chl-a and other eutrophication indicators like nutrients, Secchi depth and oxygen were derived within the HELCOM TAGREV project. The analysis of long-term trends based on the available data identified three different periods (pre-eutrophication before 1940, eutrophication period from 1940 to 1980, eutrophication stagnation period starting 1980 to present), which were used for model scenarios. Chl-a data are only available since 1970 (eutrophication period). Thresholds of Chl-a concentrations for all HELCOM sub-basins, were calculated using the estimated levels of Chl-a for 1970s and model predictions of 1900 period (considered pre-eutrophication phase in the Baltic Sea) (HELCOM, 2013b). Depending on availability, the assessment protocol may include annual averages of *in-situ* and satellite data (HELCOM, 2018b). For example, in the last HELCOM assessment (HELCOM, 2018a) satellite data from the ENVISAT MERIS mission was used to determine Chl-a concentration in open sea areas (Schroeder et al., 2007); however, integration of these data is a challenge, especially in the Baltic Sea.

In the NEA region, baseline conditions have not been set due to lack of historical data demonstrating negligible human pressures at targeted sites. PH1/FW5, PH2, and PH3 require long-term data (at least five years of data to characterise the status of the plankton community, and GES is achieved by assessing their trends and the correlation with local human pressures (OSPAR, 2018, 2019a, 2019b). For PH1/FW5 the trend evaluation comprises i) establishing starting conditions from the oldest available dataset through the community ecological envelope (i.e. a state-space of prevailing lifeform abundances), ii) mapping a recent-years dataset on the envelope to calculate the proportion of points falling inside, and finally iii) estimating statistically significant changes between periods by a chi-square calculation (OSPAR, 2018). This process is currently under revision. For PH2 and PH3 indicators, the plankton metrics are calculated for each month and across years of the whole time-series. To date the methods for trend analysis have not been yet established.

Regarding the aggregation, each indicator was developed and applied to the open sea or in the coastal areas based on the local ecological conditions and topography of the sampling sites (HELCOM, 2018a). For example, some indices were tested only in open sea units (i.e. Diatom/Dinoflagellate index in the Baltic region) or at subregional scale (e.g. PH1/FW5, PH2). As a result, they are differently aggregated within the marine region.

Two main approaches are used among the categories of Section 3.1.1 to set good environmental status threshold: baseline or reference conditions and trends.

Table 2. Analysis method and aggregation used for the operational indicators to characterise the D1C6 state. 'PH' refers to Phytoplankton, 'FW' to Food Webs and 'EO' to Ecological Objectives. Marine Regions abbreviations: Baltic Sea (BAL), North-East Atlantic Ocean (NEA), Mediterranean Sea (MED), and Black Sea (BLK).

Code	**Name**	**Assessment criteria**		**Region**
		aggregation	**analysis method**	
1	*Chlorophyll-a (Chl-a)*	17 open sea units	Deviation from baseline	BAL
2	*Diatom/Dinoflagellate Index (Dia/Dino) (*)*	Eastern Gotland Basin	Deviation from baseline	BAL
3	*Phytoplankton abundance*	Bulgaria	Deviation from baseline	BLK
4	*Phytoplankton biomass*	Bulgaria, Romania		BLK
5	*Seasonal Succession of Dominating Phytoplankton group*	14 open and coastal units	Deviation from baseline	BAL
6	*PH1/FW5: Changes in Phytoplankton and Zooplankton Communities*	North Sea and Celtic Sea (at ecohydrodynamic areas, Section 2.1), Bay of Biscay	Trend	NEA
7	*PH2: Changes in Phytoplankton Biomass and Zooplankton Abundance*	North Sea, Celtic Seas (at ecohydrodynamic areas, Section 2.1), Bay of Biscay	Trend	NEA
8	*PH3: Changes in Plankton Diversity*	at ecohydrodynamic areas, Section 2.1	Trend	NEA
9/10	*Indicator 1: Habitat distributional range (EO1) to also consider habitat extent as a relevant attribute* *Indicator 2: Condition of the habitat's typical species and communities (EO1)* • *Coastal waters phytoplankton communities* • *Coastal waters zooplankton communities* • *Shelf and oceanic waters phytoplankton communities* • *Shelf and oceanic waters zooplankton communities*	Not set	Not set	MED
11	*Chlorophyll-a (Chl-a)*	7 MS and 9 water types	Reference threshold	MED
12	*Zooplankton H-Shannon*	Bulgaria	Deviation from baseline	BLK
13	*Zooplankton abundance*	Bulgaria		BLK
14	*Zooplankton biomass*	Bulgaria, Romania		BLK
15	*Copepoda biomass*	Bulgaria, Romania		BLK
16	*Zooplankton Mean Size and Total Stock (MSTS) (*)*	17 Baltic Sea sub-basins	Deviation from baseline	BAL

(*) both state and pressure indicator

3.1.3 Methodological and policy challenges

Although state indicators are the most common methods to assess changes, there are still methodological challenges. The first one is that biodiversity is multidimensional and no single measure is sufficiently representative. As reported in Section 2.1, plankton communities are tightly linked to the spatiotemporal variability of hydrological and biogeochemical conditions in surface and in the whole water column (Bode et al., 2019).

Traditional taxonomy-based indices (e.g. abundance, diversity) have the advantage of representing the community structure and allowing comparisons between communities but require a high level of expertise in taxonomic identification (Artigas et al., 2019). Also, changes in abundance, biomass and diversity metrics may show different patterns related to differences in the lags to variations in the environmental parameters (e.g. nutrients). Moreover, these patterns are often species-specific and depend on sampling effort (Giering et al., 2019; Lugoli et al., 2012). Alternative taxon-independent indicators (i.e. MSTS, PH1/FW5) have been proposed to evaluate changes in species functional ecology (Evans et al., 2020; Fontana et al., 2017). These metrics address plankton functional traits, shifting from a focus on taxonomy to more general mechanistic process-driven patterns. However, their applicability is limited to taxonomic units that come together to a taxonomic-functional traits database. As a result, the assessment across European marine regions is highly inconsistent (and difficult to compare) in terms of the metric estimates and highly influenced by sampling effort and targeted species (Magliozzi et al., in press).

The second challenge is to assess the whole plankton community and at the spatial scale of the MSFD regions and subdivisions. In phytoplankton- and zooplankton-only indicators, part of the planktonic community is investigated, providing partial information on the community taxonomic composition and trophic interactions as a whole. Several studies have demonstrated the importance of the predator-prey relationship, thus combining phytoplankton and zooplankton species to understand the contribution of primary production to higher trophic levels (e.g. Descriptor 4) (Giering et al., 2019; Ho et al., 2020). The selection of single or combined taxa indicators often depends on the availability of monitoring data. Continuous plankton data (as well as data on environmental variables that drive biological changes) in time and space are often scarce and collected by different methods, which may not be comparable or consistent between marine regions and sub-regions (Mcquatters-Gollop et al., 2019). Plankton data availability involves two aspects: monitoring programme effort and datasets quality and accessibility (Batten et al., 2019). Long-term monitoring programmes contribute to formal MSFD biodiversity assessment (McQuatters-Gollop, 2012; McQuatters-Gollop et al., 2015).

The strengths of the Continuous Plankton Recorder (CPR) are its consistency of sampling methods (organisms counting) over 90 years, and its reduced cost. The survey has retained its core sampling techniques, while also adapting to meet policy requirements, such as by adding sensors or re-analysing stored and preserved samples with new techniques to investigate new questions (such as using molecular techiquest to look at viruses, and identifying plastics on historical samples) (Batten et al., 2019). More recent monitoring programmes are fundamently research-driven and therefore are characterised by different sampling strategies (i.e. frequencies of deployment), data series (timeseries length) and methods for taxa identification (e.g. molecular, image analysis, optical properties). The diversity of surveys’ frameworks and the lack of harmonised methodology for plankton call for European and national networks to improve operability of plankton data in both quality and processing workflow (Lombard et al., 2019). Moreover, where monitoring is not in place, advantages may come from research cruises equipped with gliders and autonomous underwater vehicles implemented with automated biological sensors to fill the spatio-temporal gaps of the water column, especially in stratified systems.

To this end, the use of satellite Chl-a to extrapolate the *in-situ* related indicators (using for example Artificial Intelligence approaches) may contribute to identify finer spatiotemporal estimates of the environmental status at regional scale. Investigating the potential link between the variability of a given indicator and the satellite-derived Chl-a (phytoplankton) or the horizontal gradient of chlorophyll-a (zooplankton) time-series (few weeks/months prior sampling) have received much attention in recent scientific discussions. Similarly, joint international projects have highlighted the interest of using high-resolution sensors to be implemented in autonomous vessels as complementary data for discrete sampling and microscopic counts (Artigas et al., 2019), with considerable potential to expand the temporal and spatial resolution of plankton analyses and intercomparisons in European marine regions (e.g. recent JERICO NEXT (2015-2019) and current JERICO S3 (2020-2024) H2020 INFRAIA projects, www.jerico-ri.eu). Finally, large datasets require the use of complex data management techniques and advanced computational skills to be analysed. There is no consensus as to the most appropriate technique to many indicators and the final choice mostly depends on the observed data (Smit et al., 2021).

3.2 Pressure indicators

While a wide range of state indicators have been used to analyse pelagic biological changes, most of these indices generate a snapshot of community status and do not provide a direct link to anthropogenic pressures. The problem is that clearer relationships between indicators and human pressures are needed to formally assess GES and are depended on the scale at which the system is studied.
Pressure-based indicators are based on specific planktonic taxa or plankton groups (Table 3).

Table 3. Regional pressure indicators, operational to GES used to assess D1C6 criterion. Marine Regions abbreviations: Baltic Sea (BAL), North-East Atlantic Ocean (NEA), Mediterranean Sea (MED), and Black Sea (BLK).

Name	Metric	Pressure	Region	Scale of application	Threshold value	Threshold scale	RSC
Cyanobacterial Bloom Index (CyaBI)	Surface accumulations, Biomass	Eutrophication	BAL	EU	YES	REGION	(HELCOM, 2018f)
Diatom/Dinoflagellate (Dia/Dino) Index (*)	Biomass	Eutrophication	BAL	EU	YES	REGION	(HELCOM, 2018c)
Noctiluca scintillans biomass	Biomass	Eutrophication	BLK	REGIONAL	YES	REGION	(BSIMAP, 2017)
Mnemiopsis leidyi biomass	Biomass	Non-indigenous species	BLK	REGIONAL	YES	REGION	(BSIMAP, 2017)
Zooplankton Mean Size and Total Stock (MSTS) (*)	Biomass, Abundance, Body Size	Overfishing, Eutrophication	BAL	EU	YES	REGION	(HELCOM, 2018e)

(*) both state and pressure indicator

3.2.1 The currently used approaches

The heterogeneity of human pressures at the scale of the MSFD assessment requires that indicators represent the biological dynamics and the main factors controlling them (European Commission, 2020). Most of these indicators were developed as a part of the WFD (Directive (EC) 2000/60, 2000) implementation, which framework gave the opportunity to improve approaches in response to eutrophication. Three indices are in fact characterised by a strong link to the eutrophication processes, i.e., CyaBI, Dia/Dino Index and *Noctiluca scintillans* biomass, and, except for the Dia/Dino Index, are already used in the assessment of the Descriptor 5 of the MSFD.

Interactions between pressures described in Section 2 may result in changes in species composition, and algae bloom frequencies and magnitude (HELCOM, 2018f). For example, CyaBI evaluates the occurrence (surface accumulation) and intensity (biomass) of cyanobacterial blooms connected to the physical variability of water movement, solar irradiance, nutrient concentrations and their ratios, and stratification (Anttila et al., 2018). Specifically, in the Baltic Sea, the CyaBI is used to assess pelagic habitats because many cyanobacteria species have been found to dominate the response to eutrophic conditions. Palaeoecological analysis of long-term historical data has demonstrated that the Baltic Sea is naturally sensitive to eutrophication and anoxic events (Bianchi et al., 2000). Coastal and open sea areas respond differently to eutrophication due to sharp topographical, geological and hydrographical variations (Rönnberg & Bonsdorff, 2004). Permanent and semi-permanent haloclines are characteristic of the Baltic Sea from south to north (Rönnberg & Bonsdorff, 2004). Under these salinity gradients, the rate of primary production increases in surface waters, and stratification occurs near the bottom, leading to regional hypoxia (Karlson et al., 2002). Cyanobacterial blooms have occurred naturally in the Baltic since the 19th century (Finni, Kononen, Olsonen, & Wallström, 2001), but their occurrence has increased during the last few decades because of eutrophication (HELCOM, 2018f) that is usually arising from excess of nutrient input of anthropogenic origin (e.g. wastewater discharges, organic pollutant, run-off of fertilizers). Consequently, the reduction of especially phosphorus loads is expected to decrease blooms of cyanobacteria, the latter being able to fix the atmospheric N2. The main advantage of the CyaBI is the combination of two aspects of algal blooms: the summer cyanobacterial surface occurrence, which integrates surface area and period of blooms estimated from remote sensing observation, and the cyanobacteria biomass that is derived from in-situ observations. Low values of CyaBI indicate high eutrophication level (HELCOM, 2018f).

Another index strongly linked to eutrophication processes is based on *Noctiluca scintillans* biomass. In the Black Sea, this species plays a key role in supplying limiting nutrients to phytoplankton by excreting NH4 + -N and PO4 3– -P (Lazăr et al., 2019). Ara et al. (2013) estimated a daily excretion of ammonia and phosphate of about 35% and 55% of the daily N and P requirement for primary production. During the spring and summer, when phytoplankton is confined in or near the surface mixed layer, a large amount of excreted nutrients by *N. scintillans* is a resource for phytoplankton growth and thus for seasonal blooms (Ara et al., 2013).

Also in the Black Sea, pressures due to the presence of non-indigenous species are addressed by the *Mnemiopsis leidyi* indicator (BSIMAP, 2017). This ctenophore is known for its competitive behaviour with planktivorous fish on zooplankton (anchovy) and for its direct predation of fish eggs and larvae (Hamer et al., 2011). Its invasion in the 1990's led to the collapse of the pelagic fisheries and a significant economic loss (Chandra & Gerhardt, 2008).

Finally, a pressure-based indicator is the MSTS (Section 3.1.1) that responds to both fishing and eutrophication pressures (HELCOM, 2018e). Research in the Baltic Sea has demonstrated a hierarchical response of zooplankton biomass to fisheries (e.g., *Sprattus sprattus*, top-down control Österblom et al.(2006)), and of zooplankton mean size to eutrophication (e.g. dominance of bacterio-picoplankton that favours small-sized zooplankton, bottom-up control). Moreover, the indicator was found to respond to eutrophication–related cyanobacteria blooms (HELCOM, 2018e).

Indicators used in the eutrophication assessment of the North-East Atlantic area, such as high Chl-a concentrations and phytoplankton indicator species (e.g. *Noctiluca scintillans*), directly resulting of nutrient enrichment, could be compared with the assessments of the PH indicators. Even if phytoplankton indicator species will only be used when a clear link to nutrient enrichment can be proven, it could be useful to align the data used in the different assessments. In addition, it will be investigated if currently derived thresholds for Chl-a based on historical model scenarios around 1900 in the eutrophication assessment can also provide guidance for thresholds of pelagic indicators using Chl-a.

Therefore, applying these pressure indicators on multiple spatiotemporal scales can provide information on the major drivers of biological changes and on practical guidance to setting targets for the MSFD GES. However, more evidence is needed to strenghten the pressure-indicator relationship.

3.2.2 Accounting for changes: threshold methods and aggregation

Plankton patterns express the variability of the environmental and human pressures and emphasise the context-specificity of the observed processes. Similarly to the state indicators (Section 3.1), the relationship between community metrics and human pressures is examined by value levels (e.g. baseline or reference condition and trends) and aggregation unit (Section 3.1.2). The indicators Dia/Dino and MSTS were already discussed in Section 3.1.

Regarding the CyaBI, long-term datasets of satellite-based (1979-2014 (Kahru et al., 2014)) and *in-situ* data (1990-2015) were analysed to identify periods of low bloom intensity by the shift detection method (Rodionov, 2004); these are periods without extensive and potentially harmful blooms but still to some extent impacted by eutrophication (HELCOM, 2018f). The shift detection approach was used on satellite data across all assessment units, and on cyanobacteria biomass data in the Bothnian Sea, for estimating the cyanobacterial surface accumulation thresholds (HELCOM, 2018f). Where the biomass data were not available, the threshold values were predicted using the lowest quartile biomass level (HELCOM, 2018f). A final threshold value was set for each CyaBI parameter and assessment unit, and their normalised average values were calculated for the final assessment (Section 3.2.1). If a threshold value could not be estimated for both satellite and *in-situ* estimates, only one threshold was used. GES is achieved for CyaBI greater than the threshold value (low eutrophication).

In the Black sea, the *Noctiluca scintillans* reference conditions and thresholds were set by statistical analysis of data from 1960-2002, as well as based on expert judgment. GES was estimated by calculating the 90th percentile for values during cold and warm season for each marine reporting unit and compared to the average of 1960-1969 (good status) period and 1977-2002 (bad status) time series. GES is achieved if at least 50% of the samples (for each season and water body) are in good status. The *N. scintillans* indicator is partially operational but would need further validation against relevant pressures. For *Mnemiopsis leidyi*, literature information are used to define GES: the average value of the species biomass must not exceed 4 g/m^3 or 120 g/m^2 (Vinogradov *et al.*, 2005).

The pressure indicators (Table 3) were developed and applied to the sub-basins in the open or coastal waters based on the local ecological conditions of the marine region (HELCOM, 2018a). As a result, some indices were tested only in open sea units (i.e., CyaBI, Diatom/Dinoflagellate index in the Baltic region), by only a few countries (e.g. in the Black Sea) and differently aggregated within one final assessment scale.

3.2.3 Methodological and policy challenges

The main limitation of the pressure-based indicators is the limited cause-effect relationships between human pressures and the communities' response (Goodsir et al., 2015). This limitation is strongly context-driven and not straightforward. These indicators also tend to focus on well-studied or area-specific taxonomic groups making them less adaptable to other marine areas. For example, in the Baltic Sea, besides the data availability limitation (e.g., satellite in CyaBI, Section 3.1.3) the CyaBI is not relevant in the Kattegat, where cyanobacteria blooms do not occur. Therefore, it would be necessary to identify and use a combination of multiple indicators specifically adapted to the assessment area to understand the local ecosystem as a whole (e.g. in temporarily or permanently stratified systems) (Rombouts et al., 2013).

Furthermore, other pressures than eutrophication indicated by the MSFD for D1C6 criterion (Section 2.2.) are not currently addressed by RSCs operational indicators (Table 3). As a result, it remains a challenge to harmonise and interpret the environmental status at regional scale. Recent promising studies used cumulative pressure- and impact-based assessment (CPIAs) as an approach to filter and prioritize linkages between human activities and pressures (Korpinen & Andersen, 2016), with a potential to characterize the non-linearity of processes (Uthicke et al., 2016).

3.3 Conclusions: state and pressure indicators

Different empirical methods exist to analyse and quantify plankton dynamics over multiple timescales, ranging from taxonomic and functional to more cause-effect based that can establish the linkage to human pressures.

The state indicators related to taxonomic metrics (abundance, biomass and diversity) are appropriate parameters to characterise regional plankton communities; however, they are not sufficient to capture the temporal variation caused by the interactions between physical drivers and human pressures due to costly *in-situ* sampling and time consuming analysis. To this end, ocean colour sensors have showed to be promising in observing small scale processes (Druon et al., 2019; Druon, 2014) as a rapid and low cost mean (Caballero et al., 2020), with a considerable potential to expand the spatial resolution of pelagic habitat indicators and support policy assessment.

Additionally, state indicators, by including functional metrics (or functional traits), are suitable to apprehend the multiple interactions between hydrological and ecological processes that drive the spatiotemporal variation of ecological communities, especially at short to medium timescales (i.e., individual blooms events to seasonal). This requires to consider complementary approaches than classical *in situ* sampling and laboratory analysis, as automated imaging and on-board optical methods in regular cruises or ship-of-opportunities.

The pressure-based indicators are essential to provide information on human activities, pressures and ecosystem components. The high spatiotemporal complexity of pelagic habitats renders challenging the delineation of specific and cumulative pressures on the ecological communities. The selection of appropriate methods to depict these non-linear relationships therefore remains challenging.

In conclusion, state and pressure-based indicators provide insights into the conditions under which biological communities exist in pelagic habitats. Knowing these conditions improve our understanding of the importance of individual changes that influence the trends of pelagic communities.

4 General conclusions and recommendations

The characterization of the environmental status of pelagic habitats, i.e., to quantify physical, chemical and biological aspects and understand their spatiotemporal scales, is important from both scientific and management perspectives. To this end, a thorough understanding of the dynamics, processes and interactions underlying pelagic system is essential. This report emphasises the **importance to account for the spatial and temporal scales of pelagic processes to infer conclusions about dominant pressures and status expressed as a proportion of sea surface area**. The main outcome of this report is a call for the future MSFD assessment of pelagic habitats that structurally combines the different methodologies, *in situ* sampling and complementary satellite-based observations, to fully capture the habitat processes and underlying pressures.

The physical and biological dynamics and processes in pelagic habitats can be observed over multiple timescales, in which different dominant factors can operate. This scale-dependency has important management implications. For example, long-term species data alone are not sufficient to assess changes in the community structure as a result of a pressure. This data does not provide *per se* information about the direct impact of single or combined pressures acting on different spatio-temporal scales (e.g. climate change, eutrophication). Therefore for this species-related data, additional information on the pressure is needed. Similarly, the identification of the thresholds requires the understanding of how long-term and mean community metrics impact the short-term community changes at a specific location at sea.

In terms of the best spatial approach for **characterizing pelagic habitat** (**Step 2**, Figure 2), the assessment would benefit from revising the classification of 'broad' and 'other' habitat types (GES Decision).

- **Vertically**, a possible approach to delimit pelagic habitats would be to consider only the part of the water column where GES status can be potentially improved within the timescale of the MSFD cycle (6 years) so that the waters below a permanent halocline and suffering permanent hypoxia are excluded (in the Baltic and Black Seas).
- **Horizontally**, given the high variability of pelagic habitats as a moving fluid that impacts the distribution of its chemical and biological components, the approach would consist in extrapolating the high-precision, low-occurrence field observation-derived indicators with the low-precision, high-occurrence satellite and/or operational model data to retrieve the main spatiotemporal features that characterize GES in term of sea surface area. This approach can include the use of medium occurrence and precision data from automated and advanced *in-situ* methods for data collection and analysis that are on board of regular or opportunity cruises, ships of opportunity, moorings and other automated platforms, e.g. JERICO-NEXT and JERICO-S3. This extrapolation of the *in situ*-based indicators using complementary spatiotemporal data is an additional step in the process and not an alternative (e.g. this is not about deriving satellite-based indicators).

For determining the appropriate scales and areas for assessment (**Step 3**, Figure 2), it is recommended to **identify the major anthropogenic pressures** affecting pelagic habitats at the marine region or subregion scale and evaluate alignment of assessment areas under different state and pressure indicators and MSFD descriptors. The MSFD indicators need to reflect clear pressure-response relationships, however the uncertainties on these relationships are higher in case of multiple pressures that act together on biological responses. Identifying magnitude, direction, and uncertainties in the pressure-response relationships for individual indicator would better characterize the nonlinearity of the community responses to anthropogenic gradients (King & Baker, 2010; Tam et al., 2017).

The **selection of indicators** (**Step 4**, Figure 2) should reflect their relevance and feasibility at large scale as regards to D1C6 GES. Monitoring networks and large-scale survey data address issues related to data availability for the current indicators. Recent methodological approaches for data collection (e.g. *in situ* automated measurements during non-dedicated surveys, moorings and fixed autonomous platforms, satellite-derived observation) and analysis (e.g. automated imaging, species identification with molecular techniques) to complement current *in-situ* sampling. More generally about indicator selection, the analysis of the effects of various pressures on key indicators shall be discussed across MSFD descriptors (e.g. D4C1, D4C2, D4C3).

Finally, the MSFD assessment requires identifying the points or thresholds at which the increase of one or multiple pressures result in abrupt changes of the pelagic habitat state (**Step 5**, **6**, Figure 2) by including abundance, biomass, diversity and productivity. Given the differences of baselines with reference periods and methods between the indicators, the threshold setting remains challenging. To this end, there is an urgent need for a more explicit framework for **coordinated threshold setting and evaluations of the uncertainties at least at regional level**, and especially for those indicators that are pan-European. The GES determination and the evaluation of related uncertainties shall be improved by approaching pelagic habitats through their spatial and temporal dynamics.

References

Alvarez-Berastegui, D., Ciannelli, L., Aparicio-gonzalez, A., Reglero, P., Hidalgo, M., & Lo, J. L. (2014). Spatial Scale , Means and Gradients of Hydrographic Variables Define Pelagic Seascapes of Bluefin and Bullet Tuna Spawning Distribution. 9(10). https://doi.org/10.1371/journal.pone.0109338

Anttila, S., Fleming-lehtinen, V., Attila, J., Alasalmi, H., Hällfors, H., Kervinen, M., & Koponen, S. (2018). Int J Appl Earth Obs Geoinformation A novel earth observation based ecological indicator for cyanobacterial blooms. International Journal Earth Observation Geoinformation, 64(June 2017), 145–155. https://doi.org/10.1016/j.jag.2017.09.007

Ara, K., Nakamura, S., Takahashi, R., Shimoto, A., & Hiromi, J. (2013). Seasonal variability of the red tide-forming heterotrophic dino fl agellate Noctiluca scintillans in the neritic area of Sagami Bay , Japan : its role in the nutrient-environment and aquatic ecosystem. Plankton and Benthos Research, 8(1), 9–30. https://doi.org/10.3800/pbr.8.9

Artigas, F., Créach V., Houliez H., Karlson B., Lizon F., Seppälä J., Wacquet G. (2019) Novel methods for automated in situ observations of phytoplankton diversity and productivity: synthesis of exploration, inter comparisons and improvements. JERICO-NEXT-WP3-D3.2, 85 pp (www.jerico-ri.eu).

Batten, S. D., Abu-alhaija, R., Chiba, S., Edwards, M., Graham, G., Jyothibabu, R., Kitchener, J. A., Koubbi, P., Mcquatters-gollop, A., Muxagata, E., Ostle, C., Richardson, A. J., & Muller-karger, F. E. (2019). A Global Plankton Diversity Monitoring Program. 6(June), 1–14. https://doi.org/10.3389/fmars.2019.00321

Bax, N. J., Miloslavich, P., Muller-karger, F. E., Allain, V., Appeltans, W., Batten, S. D., Benedetti-cecchi, L., Buttigieg, P. L., Chiba, S., Costa, D. P., Duffy, J. E., & Bax, N. J. (2019). A Response to Scientific and Societal Needs for Marine Biological Observations. 6(July), 1–22. https://doi.org/10.3389/fmars.2019.00395

Beaugrand, G., & Kirby, R. R. (2018). How do marine pelagic species respond to climate change? Theories and observations. Annual Review of Marine Science, 10, 169–197. https://doi.org/10.1146/annurev-marine-121916-063304

Bedford, J., Johns, D., Greenstreet, S., & Mcquatters-gollop, A. (2018). Plankton as prevailing conditions : A surveillance role for plankton indicators within the Marine Strategy Framework Directive. Marine Policy, 89(October 2017), 109–115. https://doi.org/10.1016/j.marpol.2017.12.021

Bedford, J., Ostle, C., Johns, D. G., Atkinson, A., Best, M., Bresnan, E., Machairopoulou, M., Graves, C. A., Devlin, M., Milligan, A., Pitois, S., Mellor, A., Tett, P., & Mcquatters-gollop, A. (2020). Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. Global Change Biology, February, 3482–3497. https://doi.org/10.1111/gcb.15066

Bedford, J., Ostle, C., Johns, D. G., Budria, A., & Mcquatters-gollop, A. (2020). The in fl uence of temporal scale selection on pelagic habitat biodiversity indicators. Ecological Indicators, 114(December 2019), 106311. https://doi.org/10.1016/j.ecolind.2020.106311

Bezerra, M. F., Lacerda, L. D., & Lai, C. T. (2019). Trace metals and persistent organic pollutants contamination in batoids (Chondrichthyes: Batoidea): A systematic review. Environmental Pollution, 248, 684–695. https://doi.org/10.1016/j.envpol.2019.02.070

Bianchi, T. S., Engelhaupt, E., Westman, P., Andrén, T., Rolff, C., & Elmgren, R. (2000). Cyanobacterial blooms in the Baltic Sea: Natural or human-induced? Limnology and Oceanography, 45(3), 716–726. https://doi.org/10.4319/lo.2000.45.3.0716

Bode, A., Álvarez, M., Ruíz-Villarreal, M., & Varela, M. M. (2019). Changes in phytoplankton production and upwelling intensity off A Coruña (NW Spain) for the last 28 years. Ocean Dynamics, 69(7), 861–873. https://doi.org/10.1007/s10236-019-01278-y

Bradley, B. A., Laginhas, B. B., Whitlock, R., Allen, J. M., Bates, A. E., Bernatchez, G., Diez, J. M., Early, R., Lenoir, J., Vilà, M., & Sorte, C. J. B. (2019). Disentangling the abundance–impact relationship for invasive species. Proceedings of the National Academy of Sciences of the United States of America, 116(20), 9919–9924. https://doi.org/10.1073/pnas.1818081116

BSIMAP. (2017). BLACK SEA INTEGRATED MONITORING AND ASSESSMENT PROGRAM List (Vol. 2022). https://ec.europa.eu/environment/marine/international-cooperation/regional-sea-conventions/bucharest/pdf/BSIMAP_2017_to_2022_en.pdf

Caballero, I., Fernández, R., Escalante, O. M., & Mamán, L. (2020). New capabilities of Sentinel-2A / B satellites combined with in situ data for monitoring small harmful algal blooms in complex coastal waters. Scientific Reports, 1–14. https://doi.org/10.1038/s41598-020-65600-1

Caruso, G. (2019). Microplastics as vectors of contaminants. Marine Pollution Bulletin, 146(April), 921–924. https://doi.org/10.1016/j.marpolbul.2019.07.052

Casini, M., Hjelm, J., Molinero, J.-C., Lovgren, J., Cardinale, M., Bartolino, V., Belgrano, A., & Kornilovs, G. (2008). Trophic cascades promote threshold-like shifts. Pnas, 106(Table 1), 197–202. https://doi.org/10.1073/pnas.0806649105

Chandra, S., & Gerhardt, A. (2008). Invasive species in aquatic ecosystems : Issue of global concern. 3(1), 1–2. https://doi.org/10.3391/ai.2008.3.1.1

Commission Decision (EU) 2018/229 (2018). Commission Decision (EU) 2018/229 of 12 February 2018 establishing, pursuant to Directive 2000/60/EC of the European Parliament and of the Council, the values of the Member State monitoring system classifications as a result of the intercalibration exercise and repealing Commission Decision 2013/480/EU (notified under document C (2018) 696) In Official Journal of the European Union (pp. 1–91). http://data.europa.eu/eli/dec/2018/229/oj

Commission Decision (EU) 2017/848. (2017). COMMISSION DECISION (EU) 2017/848 of 17 May 2017 aying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. In Official Journal of the European Union (pp. 43–74). https://doi.org/https://eur-lex.europa.eu/eli/dec/2017/848/oj

Council Directive (ECC) 92/43. (1992). COUNCIL DIRECTIVE 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. In Official Journal of the European Communities (pp. 7–49). https://doi.org/10.1039/AP9842100196

Culhane, F. E., Frid, C. L. J., Royo Gelabert, E., White, L., & Robinson, L. A. (2018). Linking marine ecosystems with the services they supply: what are the relevant service providing units? Ecological Applications, 28(7), 1740–1751. https://doi.org/10.1002/eap.1779

Delhez, É. J. M., Damm, P., De Goede, E., De Kok, J. M., Dumas, F., Gerritsen, H., Jones, J. E., Ozer, J., Pohlmann, T., Rasch, P. S., Skogen, M., & Proctor, R. (2004). Variability of shelf-seas hydrodynamic models: Lessons from the NOMADS2 Project. Journal of Marine Systems, 45(1–2), 39–53. https://doi.org/10.1016/j.jmarsys.2003.09.003

Dickey-Collas, M., McQuatters-Gollop, A., Bresnan, E., Kraberg, A. C., Manderson, J. P., Nash, R. D. M., Otto, S. A., Sell, A. F., Tweddle, J. F., & Trenkel, V. M. (2017). Pelagic habitat: Exploring the concept of good environmental status. ICES Journal of Marine Science, 74(9), 2333–2341. https://doi.org/10.1093/icesjms/fsx158

Directive (EU) 2010/60. (2010) DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy, Official Journal of the European Communities (2000). http://data.europa.eu/eli/dir/2000/60/oj

Directive (EU) 2008/56. (2008) DIRECTIVE 2008/56/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy, Official Journal of the European Union 19 (2008). http://data.europa.eu/eli/dir/2008/56/oj

Druon, J. N., Hélaouët, P., Beaugrand, G., Fromentin, J.M., Palialexis, A., & Hoepffner N. (2019). Satellite-based indicator of zooplankton distribution for global monitoring. Nature Scientific Reports 9:4732. DOI: 10.1038/s41598-019-41212-2

Druon, J. N., Loyer, S., & Gohin, F. (2005). Scaling of coastal phytoplankton features by optical remote sensors: Comparison with a regional ecosystem model. International Journal of Remote Sensing, 26(20), 4421–4444. https://doi.org/10.1080/01431160500227847

Druon, Jean-Noël. (2014). Monitoring pelagic habitats to support future EU Policies. JRC Science and Policy Report. https://doi.org/10.2788/69671

Duflos, M., Wacquet, G., Aubert, A., Rombouts, I., & Mialet, B. (2018). Évaluation de l ' atteinte du BEE des habitats pélagiques au titre du descripteur 1.

European Commission. (2017). Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. Official Journal of the European Union, 125(May), 43–74. https://doi.org/http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf

European Commission. (2019). Reporting on the 2018 update of articles 8, 9 & 10 for the Marine Strategy Framework Directive

(MSFD Guidance Document 14, October 2019 version). (Vol. 75, Issue October). https://ec.europa.eu/info/sites/info/files/swd202060final.pdf

European Commission. (2020). COMMISSION STAFF WORKING DOCUMENT Background document for the Marine Strategy Framework Directive on the determination of good environmental status and its links to assessments and the setting of environmental targets Accompanying the Report from the Comm (Vol. 53, Issue 9). https://doi.org/10.1017/CBO9781107415324.004

Evans, L. E., Hirst, A. G., Kratina, P., & Beaugrand, G. (2020). Temperature-mediated changes in zooplankton body size: large scale temporal and spatial analysis. Ecography, 581–590. https://doi.org/10.1111/ecog.04631

Fenberg, P. B., & Rivadeneira, M. M. (2019). On the importance of habitat continuity for delimiting biogeographic regions and shaping richness gradients. Ecology Letters, 22(4), 664–673. https://doi.org/10.1111/ele.13228

Field, C. B., Behrenfeld, M. J., & Randerson, J. T. (1998). Primary Production of the Biosphere : Integrating Terrestrial and Oceanic Components. Science, 281(July), 237–241. 10.1126/science.281.5374.237

Fontana, S., Thomas, M. K., Moldoveanu, M., Spaak, P., & Pomati, F. (2017). Individual-level trait diversity predicts phytoplankton community properties better than species richness or evenness. Nature Publishing Group, 12(2), 356–366. https://doi.org/10.1038/ismej.2017.160

Francé, J., Varkitzi, I., Stanca, E., Cozzoli, F., Skejić, S., Ungaro, N., Vascotto, I., Mozetič, P., Ninčević Gladan, Z., Assimakopoulou, G., Pavlidou, A., Zervoudaki, S., Pagou, K., & Basset, A (under review)). Large-scale testing of phytoplankton diversity indices for environmental assessment in Mediterranean sub-regions (Adriatic, Ionian and Aegean Seas). Ecological Indicators

Fryxell, D. C., Diluzio, A. R., Friedman, M. A., Menge, N. A., & Palkovacs, E. P. (2016). Cross-habitat effects shape the ecosystem consequences of co-invasion by a pelagic and a benthic consumer. Oecologia, 182(2), 519–528. https://doi.org/10.1007/s00442-016-3663-9

Giering, S. L. C., Wells, S. R., Mayers, K. M. J., Schuster, H., Cornwell, L., Fileman, E. S., Atkinson, A., Cook, K. B., Preece, C., & Mayor, D. J. (2019). Progress in Oceanography Seasonal variation of zooplankton community structure and trophic position in the Celtic Sea : A stable isotope and biovolume spectrum approach. Progress in Oceanography, 177(March 2018), 101943. https://doi.org/10.1016/j.pocean.2018.03.012

Goodsir, F., Bloomfield, H. J., Judd, A. D., Kral, F., Robinson, L. A., & Knights, A. M. (2015). A spatially resolved pressure-based approach to evaluate combined effects of human activities and management in marine ecosystems. ICES Journal of Marine Science, 72(8), 2245-2256. https://doi.org/10.1093/icesjms/fsv080

Gorokhova, E., Hansson, S., Hӧglander, H., and Andersen, C. M. (2005). Stable isotopes show food web changes after invasion by the predatory cladoceran Cercopagis pengoi in a Baltic Sea bay. Oecologia 143, 251–259. doi:10.1007/s00442-004-1791-0.

Gorokhova, E., Lehtiniemi, M., Postel, L., Rubene, G., Amid, C., Lesutiene, J., Uusitalo, L., Strake, S., & Demereckiene, N. (2016). Indicator properties of baltic zooplankton for classification of environmental status within marine strategy framework directive. PLoS ONE, 11(7), 1–26. https://doi.org/10.1371/journal.pone.0158326

Halpern, B. S., Frazier, M., Potapenko, J., Casey, K. S., Koenig, K., Longo, C., Lowndes, J. S., Rockwood, R. C., Selig, E. R., Selkoe, K. A., & Walbridge, S. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. Nature Communications, 6(May), 1–7. https://doi.org/10.1038/ncomms8615

Hamer, H. H., Malzahn, A. M., & Boersma, M. (2011). The invasive ctenophore Mnemiopsis leidyi : a threat to fish recruitment in the North Sea ? 33. https://doi.org/10.1093/plankt/fbq100

HELCOM (2013a) *HELCOM Monitoring and Assessment Strategy This document is a part of the 2013 HELCOM Ministerial Declaration and was adopted by the 2013 HELCOM Ministerial Meeting*.

Helcom (2013b) Approaches and methods for eutrophication target setting in the Baltic Region. Baltic Sea Environment Proceedings No. 133, Helsinki, Finland, (133), p. 134 pp.

HELCOM (2017a) *Manual for Marine Monitoring in the COMBINE programme of HELCOM*.

HELCOM (2017b) Monitoring of phytoplankton species composition , abundance and biomass, pp. 1–19.

HELCOM (2018a) HELCOM Thematic Assessment of Biodiversity 2011–2016. Available at: http://www.helcom.fi/baltic-sea-trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/.[October 2020] http://www.helcom.fi/baltic-sea- trends/holistic-assessments/state-of-the-baltic-sea-2018/reports-and-materials/

HELCOM (2018b) Chlorophyll- a. Online. [October 2020], [https://helcom.fi/wp-content/uploads/2019/08/Chlorophyll-a-HELCOM-core-indicator-2018.pdf]

HELCOM (2018c) Diatom / Dinoflagellate Index. Online. [October 2020], [https://helcom.fi/media/core%20indicators/Diatom-Dinoflagellate-index-HELCOM-pre-core-indicator-2018.pdf].

HELCOM (2018d) Seasonal succession of dominating phytoplankton groups. Online [October 2020], [https://helcom.fi/media/core%20indicators/Seasonal-succession-of-dominating-phytoplankton-groups-HELCOM-core-indicator-2018.pdf].

HELCOM (2018e) Zooplankton mean size and total stock (MSTS). [October 2020], [https://helcom.fi/media/core%20indicators/Zooplankton-mean-size-and-total-stock-HELCOM-core-indicator-2018.pdf

HELCOM (2018f) Cyanobacterial Bloom Index (CyaBI). Online [October 2020], [https://helcom.fi/media/core%20indicators/Cyanobacterial-bloom-index-HELCOM-pre-core-indicator-2018.pdf].

Hernández-León, S., Koppelmann, R., Fraile-Nuez, E., Bode, A., Mompeán, C., Irigoien, X., Olivar, M. P., Echevarría, F., Fernández de Puelles, M. L., González-Gordillo, J. I., Cózar, A., Acuña, J. L., Agustí, S., & Duarte, C. M. (2020). Large deep-sea zooplankton biomass mirrors primary production in the global ocean. Nature Communications, 11(1), 1–8. https://doi.org/10.1038/s41467-020-19875-7

Ho, P., Wong, E., Lin, F., Sastri, A. R., & García-comas, C. (2020). Progress in Oceanography Prey stoichiometry and phytoplankton and zooplankton composition in fl uence the production of marine crustacean zooplankton. Progress in Oceanography, 186(May), 102369. https://doi.org/10.1016/j.pocean.2020.102369

Howarth, R. W., Chan, F., & Marino, R. (1999). Do top-down and bottom-up controls interact to exclude nitrogen-fixing cyanobacteria from the plankton of estuaries? An exploration with a simulation model. Biogeochemistry, 46, 203–231. https://doi.org/10.1007/978-94-011-4645-6_10

Hu, C., Feng, L., Lee, Z., Franz, B. A., & States, U. (2019). Improving Satellite Global Chlorophyll a Data Products Through Algorithm Refinement and Data Recovery. Journal of Geophysical Research: Oceans, February. https://doi.org/10.1029/2019JC014941

Hunsicker, M. E., Kappel, C. V., Selkoe, K. A., Halpern, B. S., Scarborough, C., Mease, L., & Amrhein, A. (2016). Characterizing driver–response relationships in marine pelagic ecosystems for improved ocean management. Ecological Applications, 26(3), 651-663. https://doi.org/10.1890/14-2200

Hyrenbach, D. K., Forney, K. A., & Dayton, P. K. (2000). Viewpoint: Marine protected areas and ocean basin management. Aquatic Conservation: Marine and Freshwater Ecosystems, 10(6), 437–458. https://doi.org/10.1002/1099-0755(200011/12)10:6<437::AID-AQC425>3.0.CO;2-Q

Jones, K., & de Voogt, P. (1999). Persistent organic pollutants (POPs): state of the science K.C. Environmental Pollution, 100(1), 209–221. https://doi.org/10.1016/S0269-7491(99)00098-6

Kahru, M., Elmgren, R., Jolla, L., & Sciences, P. (2014). Multidecadal time series of satellite-detected accumulations of cyanobacteria in the Baltic Sea. Biogeosciences, 3619–3633. https://doi.org/10.5194/bg-11-3619-2014

Karlson, K., Rosenberg, R., & Bonsdorff, E. (2002). Temporal and Spatial Large-Scale Effects of Eutrophication and Oxygen Deficiency on Benthic Fauna in Scandinavian and Baltic Waters ‚Äì a Review. Oceanography and Marine Biology: An Annual Review 2002, January 2016, 427–489. https://doi.org/10.1201/9780203180594.ch8

Kavanaugh, M. T., Hales, B., Saraceno, M., Spitz, Y. H., White, A. E., & Letelier, R. M. (2014). Progress in Oceanography Hierarchical and dynamic seascapes : A quantitative framework for scaling pelagic biogeochemistry and ecology. Progress in Oceanography, 120, 291–304. https://doi.org/10.1016/j.pocean.2013.10.013

Kiko, R., Biastoch, A., Brandt, P., Cravatte, S., Hauss, H., Hummels, R., Kriest, I., Marin, F., McDonnell, A. M. P., Oschlies, A., Picheral, M., Schwarzkopf, F. U., Thurnherr, A. M., & Stemmann, L. (2017). Biological and physical influences on marine snowfall at the equator. Nature Geoscience, 10(November). https://doi.org/10.1038/NGEO3042

King, R. S., & Baker, M. E. (2010). Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. Journal of the North American Benthological Society, 29(3), 998–1008. https://doi.org/10.1899/09-144.1

Klais, R., Tamminen, T., Kremp, A., Spilling, K., An, W., Hajdu, S., & Olli, K. (2013). Spring phytoplankton communities shaped by interannual weather variability and dispersal limitation : Mechanisms of climate change effects on key coastal primary producers. 58(2), 753–762. https://doi.org/10.4319/lo.2012.58.2.0753

Kolodziejczyk, N., Llovel, W., & Portela, E. (2019). Interannual Variability of Upper Ocean Water Masses as Inferred From Argo Array. Journal of Geophysical Research: Oceans, 124(8), 6067–6085. https://doi.org/10.1029/2018JC014866

Korpinen, S., & Andersen, J. H. (2016). A Global Review of Cumulative Pressure and Impact Assessments in Marine Environments. Frontiers in Marine Science, 3(August), 1–11. https://doi.org/10.3389/fmars.2016.00153

Korpinen, S., Meski, L., Andersen, J. H., & Laamanen, M. (2012). Human pressures and their potential impact on the Baltic Sea ecosystem. Ecological Indicators, 15(1), 105–114. https://doi.org/10.1016/j.ecolind.2011.09.023

Kromkamp, J., Capuzzo, E., & Philippart, C. J. M. (2017). Measuring phytoplankton primary production: review of existing methodologies and suggestions for a common approach.

Kudryavtseva, E., Aleksandrov, S., Bukanova, T., Dmitrieva, O., & Rusanov, I. (2019). Relationship between seasonal variations of primary production, abiotic factors and phytoplankton composition in the coastal zone of the south-eastern part of the Baltic Sea. Regional Studies in Marine Science, 32, 100862. https://doi.org/10.1016/j.rsma.2019.100862

Labuce, A., Dimante-Deimantovica, I., Tunens, J., & Strake, S. (2020). Correction to: Zooplankton indicator-based assessment in relation to site location and abiotic factors: a case study from the Gulf of Riga (Environmental Monitoring and Assessment, (2020), 192, 2, (147), 10.1007/s10661-020-8113-9). Environmental Monitoring and Assessment, 192(7). https://doi.org/10.1007/s10661-020-08380-5

Lazăr, L., Boicenco, L., Marin, O., Culcea, O., Bișinicu, E., Timofte, F., Abaza, V., & Spînu, A. (2019). BLACK SEA EUTROPHICATION STATUS - THE INTEGRATED ASSESSMENT LIMITATIONS AND OBSTACLES. 5, 57–73.

Lefort, S., Aumont, O., Bopp, L., Arsouze, T., Gehlen, M., & Maury, O. (2015). Spatial and body-size dependent response of marine pelagic communities to projected global climate change. Global Change Biology, 21(1), 154–164. https://doi.org/10.1111/gcb.12679

Litchman, E., Edwards, K. F., Klausmeier, C. A., & Thomas, M. K. (2012). Phytoplankton niches , traits and eco-evolutionary responses to global environmental change. 470, 235–248. https://doi.org/10.3354/meps09912

Lombard, F., Boss, E., Waite, A. M., Uitz, J., Stemmann, L., Sosik, H. M., Schulz, J., Romagnan, J. B., Picheral, M., Pearlman, J., Ohman, M. D., Niehoff, B., Möller, K. O., Miloslavich, P., Lara-Lopez, A., Kudela, R. M., Lopes, R. M., Karp-Boss, L., Kiko, R., … Appeltans, W. (2019). Globally consistent quantitative observations of planktonic ecosystems. Frontiers in Marine Science, 6(MAR). https://doi.org/10.3389/fmars.2019.00196

Lugoli, F., Garmendia, M., Lehtinen, S., Kauppila, P., Moncheva, S., Revilla, M., Roselli, L., Slabakova, N., Valencia, V., Dromph, K. M., & Basset, A. (2012). Application of a new multi-metric phytoplankton index to the assessment of ecological status in marine and transitional waters. Ecological Indicators, 23, 338–355. https://doi.org/10.1016/j.ecolind.2012.03.030

Macpherson, E. (2002). Large-scale species-richness gradients in the Atlantic Ocean. Proceedings of the Royal Society B: Biological Sciences, 269(1501), 1715–1720. https://doi.org/10.1098/rspb.2002.2091

Magliozzi, C., Druon, J.-N., Boschetti, S. T., Palialexis, A. (2021, in press).Marine Strategy Framework Directive, Descriptor 1 Pelagic Habitats. Review and assessment of EU Member States' 2018 reports for Articles 8, 9 and 10. Luxembourg Publications Office of the European Union, JRC 124271.

Maes, J., Teller, A., Erhard, M., Condé, S., Vallecillo, S., Barredo, J. I., Luisa, M., Malak, D. A., Trombetti, M., Vigiak, O., Zulian, G., Addamo, A. M., Grizzetti, B., Somma, F., Hagyo, A., Vogt, P., Polce, C., Jones, A., Marin, A. I., … Santos-martín, F. (2020). Mapping and Assessment of Ecosystems and their Services : An EU ecosystem assessment. https://doi.org/10.2760/757183

Manly, B. F. J., & Mackenzie, D. I. (2003). CUSUM environmental monitoring in time and space. Environmental and Ecological Statistics, 10(2000), 231–247. https://doi.org/10.1023/A:1023682426285

Martin, P., Lampitt, R. S., Jane, M., Sanders, R., Lee, C., & Asaro, E. D. (2011). Deep-Sea Research I Export and mesopelagic particle flux during a North Atlantic spring diatom bloom. Deep-Sea Research Part I, 58(4), 338–349. https://doi.org/10.1016/j.dsr.2011.01.006

McQuatters-Gollop, A. (2012). Challenges for implementing the Marine Strategy Framework Directive in a climate of macroecological change. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370(1980), 5636–5655. https://doi.org/10.1098/rsta.2012.0401

Mcquatters-Gollop, A., Atkinson, A., Aubert, A., Bedford, J., Best, M., Bresnan, E., Cook, K., Devlin, M., Gowen, R., Johns, D. G., Machairopoulou, M., Mckinney, A., Mellor, A., Ostle, C., Scherer, C., & Tett, P. (2019). Plankton lifeforms as a biodiversity indicator for regional-scale assessment of pelagic habitats for policy. Ecological Indicators, 101(February), 913–925. https://doi.org/10.1016/j.ecolind.2019.02.010

McQuatters-Gollop, A., Atkinson, A., Aubert, A., Bedford, J., Best, M., Bresnan, E., Cook, K., Devlin, M., Gowen, R., Johns, D. G., Machairopoulou, M., McKinney, A., Mellor, A., Ostle, C., Scherer, C., & Tett, P. (2019). Plankton lifeforms as a biodiversity indicator for regional-scale assessment of pelagic habitats for policy. Ecological Indicators, 101(October 2018), 913–925. https://doi.org/10.1016/j.ecolind.2019.02.010

McQuatters-Gollop, A., Edwards, M., Helaouët, P., Johns, D. G., Owens, N. J. P., Raitsos, D. E., Schroeder, D., Skinner, J., & Stern, R. F. (2015). The Continuous Plankton Recorder survey: How can long-term phytoplankton datasets contribute to the assessment of Good Environmental Status? Estuarine, Coastal and Shelf Science, 162, 88–97. https://doi.org/10.1016/j.ecss.2015.05.010

Miloslavich, P., Bax, N. J., Simmons, S. E., Jr, D. M. C., Klein, E., Appeltans, W., & Melissa, O. A. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. February, 2416–2433. https://doi.org/10.1111/gcb.14108

OSPAR (2016). CEMP Eutrophication Monitoring Guidelines: Phytoplankton Species Composition (Agreement 2016-06)

OSPAR. (2017). Eutrophication Status of the OSPAR Maritime Area Third Integrated Report on the Eutrophication Status of the OSPAR Maritime Area.

OSPAR. (2018). OSPAR CEMP Guideline Common indicator : PH1 / FW5 Plankton lifeforms. 1–17. Online. [October 2020], [https://www.ospar.org/documents?v=39001]

OSPAR. (2019a). CEMP Guideline : PH2 “ Changes in Phytoplankton Biomass and Zooplankton Abundance ” (pp. 1–6). Online. [October 2020], [https://www.ospar.org/documents?v=40972]

OSPAR. (2019b). CEMP Guideline : PH3 Changes in Plankton Diversity. Online. [October 2020], [https://www.ospar.org/documents?v=40973]

Österblom, H., Casini, M., Olsson, O., & Bignert, A. (2006). Fish , seabirds and trophic cascades in the Baltic Sea. November. https://doi.org/10.3354/meps323233

Papenfus, M., & Schaeffer, B. (2020). Exploring the potential value of satellite remote sensing to monitor chlorophyll-a for US lakes and reservoirs.

Peijnenburg, K. T. C. A., & Goetze, E. (2013). High evolutionary potential of marine zooplankton Evolution in the Open Sea. 2765–2783. https://doi.org/10.1002/ece3.644

Pitois, S. G., Graves, C. A., Close, H., Lynam, C., Scott, J., Tilbury, J., van der Kooij, J., & Culverhouse, P. (2021). A first approach to build and test the Copepod Mean Size and Total Abundance (CMSTA) ecological indicator using in-situ size measurements from the Plankton Imager (PI). Ecological Indicators, 123, 107307. https://doi.org/10.1016/j.ecolind.2020.107307

Prowe, A. E. F., Pahlow, M., Dutkiewicz, S., Follows, M., & Oschlies, A. (2012). Progress in Oceanography Top-down control of marine phytoplankton diversity in a global ecosystem model. Progress in Oceanography, 101(1), 1–13. https://doi.org/10.1016/j.pocean.2011.11.016

Robinson, T. B., Havenga, B., van der Merwe, M., & Jackson, S. (2017). Mind the gap - context dependency in invasive species impacts: A case study of the ascidian Ciona robusta. NeoBiota, 32(1), 127–141. https://doi.org/10.3897/neobiota.32.9373

Rodionov, S. N. (2004). A sequential algorithm for testing climate regime shifts. Geophysical Research Letters, 31(May 2004), 1–5. https://doi.org/10.1029/2004GL019448

Roff, J. C., Middlebrook, K., & Evans, F. (1988). Long-term variations in North Sea zooplankton. Journal of the Marine Biological Association of the United Kingdom, 68, 143–164.

Rombouts, I., Beaugrand, G., Fizzala, X., Gaill, F., Greenstreet, S. P. R., Lamare, S., Loc, F. Le, Mcquatters-gollop, A., Mialet, B., Niquil, N., Percelay, J., Renaud, F., Rossberg, A. G., & Féral, J. P. (2013). Food web indicators under the Marine Strategy Framework Directive : From complexity to simplicity ? Ecological Indicators, 29, 246–254. https://doi.org/10.1016/j.ecolind.2012.12.021

Rombouts, I., Simon, N., Aubert, A., Cariou, T., Feunteun, E., Guérin, L., Hoebeke, M., McQuatters-Gollop, A., Rigaut-Jalabert, F., & Artigas, L. F. (2019). Changes in marine phytoplankton diversity: Assessment under the Marine Strategy Framework Directive. Ecological Indicators, 102(February), 265–277. https://doi.org/10.1016/j.ecolind.2019.02.009

Rönnberg, C., & Bonsdorff, E. (2004). Baltic Sea eutrophication: Area-specific ecological consequences. Hydrobiologia, 514(2002), 227–241. https://doi.org/10.1023/B:HYDR.0000019238.84989.7f

Salmaso, N., & Tolotti, M. (2020). Phytoplankton and anthropogenic changes in pelagic environments Along with effects mediated by many other legacy and. Hydrobiologia, 0123456789. https://doi.org/10.1007/s10750-020-04323-w

Sammartino, M., Marullo, S., Santoleri, R., & Scardi, M. (2018). Modelling the vertical distribution of phytoplankton biomass in the mediterranean sea from satellite data: A neural network approach. Remote Sensing, 10(10), 1–25. https://doi.org/10.3390/rs10101666

Sathyendranath, S., Brewin, R. J. W., Brockmann, C., Brotas, V., Calton, B., Chuprin, A., Cipollini, P., Couto, A. B., Dingle, J., Doerffer, R., Donlon, C., Dowell, M., Farman, A., Grant, M., Groom, S., Horseman, A., Jackson, T., Krasemann, H., Lavender, S., … Mélin, F. (2019). An Ocean-Colour Time Series for Use in Climate Studies : The Experience of the Ocean-Colour Climate. Sensors, September. https://doi.org/10.3390/s19194285

Schmidt, J. O., Bograd, S. J., Arrizabalaga, H., Azevedo, J. L., Barbeaux, S. J., Barth, J. A., Boyer, T., Brodie, S., Cárdenas, J. J., Cross, S., Druon, J., Fransson, A., Muller-karger, F. E., & Roffer, M. A. (2019). Future Ocean Observations to Connect Climate , Fisheries and Marine Ecosystems. 6(September), 1–18. https://doi.org/10.3389/fmars.2019.00550

Schroeder, T., Behnert, I., Schaale, M., Fischer, J., & Doerffer, R. (2007). Atmospheric correction algorithm for MERIS above case-2 waters. International Journal of Remote Sensing, 28(7), 1469–1486. https://doi.org/10.1080/01431160600962574

Schwarz, L. K., Goebel, M. E., Costa, D. P., & Kilpatrick, A. M. (2013). Top-down and bottom-up influences on demographic rates of Antarctic fur seals Arctocephalus gazella. 903–911. https://doi.org/10.1111/1365-2656.12059

Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K., & Wirtz, K. W. (2019). The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea. Hydrobiologia, 845(1), 35–53. https://doi.org/10.1007/s10750-018-3653-5

Smit, K. P., Bernard, A. T. F., Lombard, A. T., & Sink, K. J. (2021). Assessing marine ecosystem condition : A review to support indicator choice and framework development. Ecological Indicators, 121(November 2020), 107148. https://doi.org/10.1016/j.ecolind.2020.107148

Tam, J. C., Link, J. S., Large, S. I., Andrews, K., Friedland, K. D., Gove, J., Hazen, E., Holsman, K., Karnauskas, M., Samhouri, J. F., Shuford, R., Tomilieri, N., & Zador, S. (2017). Comparing apples to oranges: Common trends and thresholds in anthropogenic and environmental pressures across multiple marine ecosystems. Frontiers in Marine Science, 4(SEP). https://doi.org/10.3389/fmars.2017.00282

Tett, P., Gowen, R., Mills, D., Fernandes, T., Gilpin, L., Huxham, M., Kennington, K., Read, P., Service, M., Wilkinson, M., & Malcolm, S. (2007). Defining and detecting undesirable disturbance in the context of marine eutrophication. 55, 282–297. https://doi.org/10.1016/j.marpolbul.2006.08.028

Tett, P., Mcquatters-gollop, A., Gowen, R. J., Mcquatters-gollop, A., Tett, P., Best, M., Bresnan, E., Castellani, C., Cook, K., Forster, R., Scherer, C., & Mckinney, A. (2015). The Development of UK Pelagic (Plankton) Indicators and Targets for the MSFD (Issue December). https://doi.org/10.13140/RG.2.1.5181.1920

Thabet, R., Leignel, V., Ayadi, H., & Tastard, E. (2018). Interannual and seasonal effects of environmental factors on the zooplankton distribution in the solar saltern of Sfax (south-western Mediterranean sea). Continental Shelf Research, 165(August 2017), 1–11. https://doi.org/10.1016/j.csr.2018.06.002

Thomas, M. K., Aranguren-Gassis, M., Kremer, C. T., Gould, M. R., Anderson, K., Klausmeier, C. A., & Litchman, E. (2017). Temperature–nutrient interactions exacerbate sensitivity to warming in phytoplankton. Global Change Biology, 23(8), 3269–3280. https://doi.org/10.1111/gcb.13641

Tiselius, P., & Møller, L. F. (2017). Community cascades in a marine pelagic food web controlled by the non-visual apex predator Mnemiopsis leidyi. Journal of Plankton Research, 39(2), 271–279. https://doi.org/10.1093/plankt/fbw096

Totti, C., Romagnoli, T., Accoroni, S., Coluccelli, A., Pellegrini, M., Campanelli, A., Grilli, F., & Marini, M. (2019). Phytoplankton communities in the northwestern Adriatic Sea : Interdecadal variability over a 30-years period (1988 – 2016) and relationships with meteoclimatic drivers. Journal of Marine Systems, 193(January), 137–153. https://doi.org/10.1016/j.jmarsys.2019.01.007

UNEP/MAP. (2016). Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast and Related Assessment Criteria.

UNEP. (2013). Towards the Identification and Reference List of Pelagic Habitat Types in the Mediterranean Sea (Issue July). https://doi.org/10.4324/9780203553565

Uthicke, S., Fabricius, K., De, G., Negri, A., Smith, R., Uthicke, S., Fabricius, K., De, G., Negri, A., & Smith, R. (2016). Multiple and cumulative impacts on the GBR : assessment of current status and development of improved approaches for management Multiple and cumulative impacts on the GBR : assessment of current status and development of improved approaches for management.

Vallina, S. M. (2007). Strong Relationship Between DMS and the Solar Radiation Dose over the Global Surface Ocean. Science, 315(January), 506–509. 10.1126/science.1133680

van Leeuwen, S., Tett, P., Mills, D., & Van Der Molen, J. (2015). Journal of Geophysical Research : Oceans. Journal of Geophysical Research: Oceans, 120, 1–17. https://doi.org/10.1002/2014JC010485.

Varkitzi, I., Psarra, S., Assimakopoulou, G., Pavlidou, A., Krasakopoulou, E., Velaoras, D., ... & Pagou, K. (2020). Phytoplankton dynamics and bloom formation in the oligotrophic Eastern Mediterranean: field studies in the Aegean, Levantine and Ionian seas. Deep Sea Research Part II: Topical Studies in Oceanography, 171, 104662

Varkitzi, I., Francé, J., Basset, A., Cozzoli, F., Stanca, E., Zervoudaki, S., Giannakourou, A., Assimakopoulou, G., Venetsanopoulou, A., Mozetič, P., Tinta, T., Skejic, S., Vidjak, O., Cadiou, J. F., & Pagou, K. (2018). Pelagic habitats in the Mediterranean Sea: A review of Good Environmental Status (GES) determination for plankton components and identification of gaps and priority needs to improve coherence for the MSFD implementation. Ecological Indicators, 95(July), 203–218. https://doi.org/10.1016/j.ecolind.2018.07.036

Vinogradov, M. E., Lebedeva, L. P., Musaeva, E. I., Zas' ko, D. N., Anokhina, L. L., Sivkovich, A. E., ... & Lukasheva, T. A. (2005). Monitoring of the pelagic communities of the northeastern part of the Black Sea in 2004: macro-and mesoplankton. Oceanology, 45(3), 356-367.

Walmsley, S. F., Weiss, A., Claussen, U., & Connor, D. (2018). Guidance for Assessments Under Article 8 of the Marine Strategy Framework Directive, Integration of assessment results.

Wasmund, N. (2017). The diatom/dinoflagellate index as an indicator of ecosystem changes in the Baltic Sea. 2. Historical data for use in determination of good environmental status. Frontiers in Marine Science, 4(JUN), 1–12. https://doi.org/10.3389/fmars.2017.00153

Wasmund, N., Kownacka, J., Göbel, J., Jaanus, A., Johansen, M., Jurgensone, I., Lehtinen, S., & Powilleit, M. (2017). The diatom/dinoflagellate index as an indicator of ecosystem changes in the Baltic Sea 1. principle and handling instruction. Frontiers in Marine Science, 4(FEB). https://doi.org/10.3389/FMARS.2017.00022

Würtz, M. (2010). Mediterranean pelagic habitat: oceanographic and biological processes, an overview. In Mediterranean pelagic habitat: oceanographic and biological processes, an overview. IUCN, Gland, Switzerland, and Malaga, Spain. http://www.rac-spa. org/sites/default/files/doc_fsd/med_pelagic_habitats.pdf

List of abbreviations and definitions

BAL	Baltic Sea
BLK	Black Sea
BSC	Black Sea Commission (Bucharest Convention)
EcAp/IMAP	Ecosystem Approach/ Integrated Monitoring and Assessment Programme
EU	European Union
GES	Good Environmental Status
HELCOM	Helsinki Commission (Helsinki Convention)
JRC	Joint Research Centre
JERICO S3	Joint European Research Infrastructure of Coastal Observatories: Science, Service, Sustainability
JERICO NEXT	Joint European Research Infrastructure of Coastal Observatories: Novel European eXpertise for coastal observaTories
MED	Mediterranean Sea
MS	Member States
MSFD	Marine Strategy Framework Directive
OSPAR	OSPAR Commission (Oslo-Paris Convention)
RSC	Regional Sea Convention
WFD	Water Framework Directive
UNEP-MAP	Barcelona Convention

List of boxes

List of figures

List of tables

KJ-NA-30619-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office
of the European Union

doi:10.2760/942589

ISBN 978-92-76-30988-8