OSPAR COMMISSION

Pelagic Habitats Thematic Assessment

OSPAR

QUALITY STATUS REPORT 2023

2023

OSPAR's Quality Status Report 2023

Pelagic Habitat Thematic Assessment

OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. The Contracting Parties are Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Convention OSPAR

La Convention pour la protection du milieu marin de l´Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d´Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. Les Parties contractantes sont l´Allemagne, la Belgique, le Danemark, l´Espagne, la Finlande, la France, l´Irlande, l´Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume- Uni de Grande Bretagne et d´Irlande du Nord, la Suède, la Suisse et l´Union européenne

Contributors

Lead authors: Abigail McQuatters-Gollop, Matthew Holland, Arnaud Louchart, Luis Felipe Artigas

Supporting authors: Shannon White, Federico Cornacchia, Julien Favier, Eric Goberville, Emily Corcoran, Birgit Heyden, Janos Hennicke, Daniel Wood, Angus Atkinson, Eileen Bresnan, Isabelle Rombouts, Margarita Machairopoulou, Rita Pires, Paulo Oliveira, Marie Johansen, Gavin Tilstone, Jos Schilder, Rafael González-Quirós, Jeanette Göebel, Rowena Stern, Lena Avellan, Michelle Devlin, Eva Verkevisser, Gro van der Meeren, Dorothee Vincent

Supported by: Biodiversity Committee (BDC), Intersessional Correspondance Group on the Quality Status Report (ICG-QSR), Intersessional Correspondance Group on Ecosystem Assessment Outlook (ICG-EcoC), Intersessional Correspondance Group on Economic and Social Analysis (ICG-ESA), Climate Change Expert Group (CCEG), and OSPAR Commission Secretariat.

Delivered by

This work was co-funded by the European Maritime and Fisheries Fund through the project: "North-east Atlantic project on biodiversity and eutrophication assessment integration and creation of effective measures (NEA PANACEA)", financed by the European Union's DG ENV/MSFD 2020, under agreement No. 110661/2020/839628/SUB/ENV.C.2.

NEA PANACEA
North East Atlantic project on biodiversity and eutrophication assessment integration and creation of effective measures

Co-funded by the European Union

Citation

OSPAR, 2023. *Pelagic Habitats Thematic Assessmen*t. In: OSPAR, 2023: Quality Status Report 2023. OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/thematic-assessments/pelagic-habitats/impact/

Contents

Contributors	1
Delivered by	1
Citation	1
Executive Summary	3
Q1. Identify the problems? Are they the same in all OSPAR regions?	4
Q2. What has been done?	6
Q3. Did it work?	7
Q4. How does this field affect the overall quality status?	7
Q5. What do we do next?	8
D - Drivers	9
A - Activities	10
P – Pressures	12
S – State	13
I - Impacts	46
R - Response	53
Cumulative Effects	62
Climate Change	68
Thematic Metadata	75

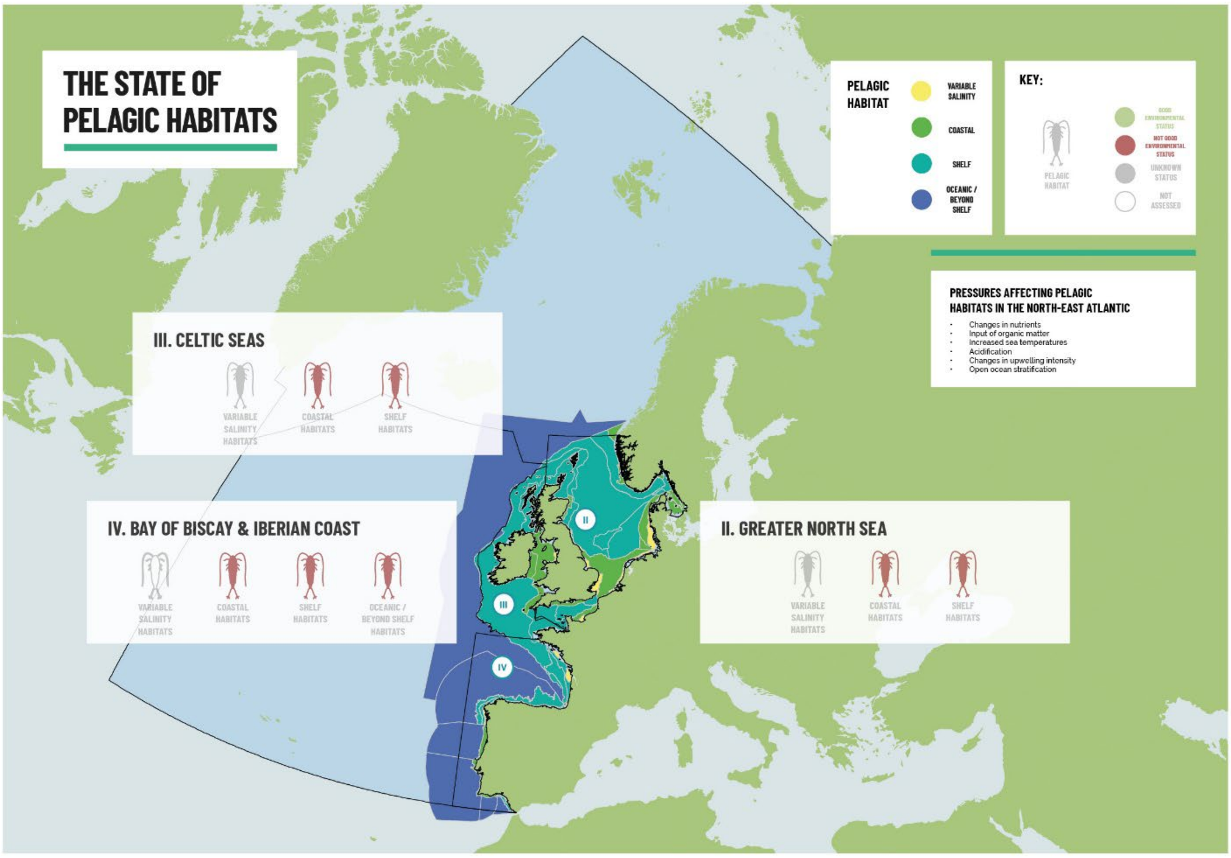
Executive Summary

Pelagic habitats are open-water environments occupied by floating and suspended organisms, or simply plankton, which occupy the lower tiers of the food web and are the main source of marine production. Short generational times, small size and, for phytoplankton, direct dependence on dissolved nutrients, make plankton particularly sensitive to environmental change. Changes in plankton communities can also affect higher food web levels, such as shellfish, fish, and seabirds, which they support either directly or indirectly.

The growing global population has generated increasing demand for food production, waste disposal, coastal development and energy systems, all of which contribute to human-induced climate change. Climate change (both from natural variability and human-induced) is probably the greatest pressure currently impacting plankton communities across the OSPAR Maritime Area as a whole. These activities also influence the supply of nutrients entering coastal environments, which can generate eutrophication and impact the productivity of pelagic habitats.

Pelagic habitats in the OSPAR Maritime Area have experienced widespread changes over the past 60 years, with indicator assessments revealing a general pattern of decreasing phytoplankton and zooplankton abundance and/or biomass across the Greater North Sea, Celtic Seas, and Bay of Biscay and Iberian Coast. Long-term trends have largely continued into the current assessment period, and are expected to continue into the future, eventually impacting higher food web levels. Due to widespread changes linked to pressures generated by human activities, the Greater North Sea, Celtic Seas, and Bay of Biscay and Iberian Coast had not good status, under the current definition and categorisation of quality status.

Global efforts to slow climate change are probably the best mechanism to counter widespread changes in plankton communities, although effective measures for reducing or preventing climate change mostly lie outside the remit of OSPAR. Regionally targeted management measures (e.g., controlling inputs of nutrients and organic matter) in coastal areas may affect pelagic habitats at the shelf scale. While these mitigation efforts are only likely to generate noticeable impact in coastal areas, they may also have some effect in areas where plankton communities are affected by the cumulative impacts of multiple pressures (i.e., both warming and eutrophication).



Q1. Identify the problems? Are they the same in all OSPAR regions?

Pelagic habitats are open-water environments occupied by floating and suspended organisms, or simply plankton, which occupy the lower tiers of the food web and are the main source of marine production. These organisms include phytoplankton (e.g., green algae and diatoms) and zooplankton (e.g., copepods and the larvae of fish and benthic invertebrates), but not larger organisms such as pelagic fish.

Compared with more complex organisms, plankton typically have fewer mechanisms to buffer themselves against environmental change, and less mobility to evade adverse conditions. Moreover, they tend to be fast-growing due to short generation times. For these reasons, plankton communities are considered excellent sentinels of environmental change, most notably changes in climate variables and nutrient availability.

The most important human activities affecting pelagic habitats are therefore those that affect the nutrient status of marine waters (such as agriculture, aquaculture, and waste-water treatment) and those leading to climate change (any process involving burning of fossil fuels, agriculture, or deforestation) or that attempt to reduce climate change (including investment in renewable energy). Pelagic habitats were not specifically assessed in the Quality Status Report 2010 (QSR 2010), although climate change was flagged as a threat to marine habitats in general.

Plankton communities that form pelagic habitats are also not currently considered within Marine Protected Area (MPA) status assessment or the Environmental Impact Assessment (EIA) guidance. There is recent evidence that offshore wind infrastructure can impact the productivity of pelagic habitats; however, this is not currently a consideration for new offshore wind projects.

The Intermediate Assessment 2017 introduced for the first time a set of pelagic habitat indicators, which revealed trends in pelagic community composition and productivity and were primarily linked to climate change. In the 2017 assessment there were no threshold values or conditions to define the ecological status of pelagic habitats, and that situation has not changed. For the current assessment, detected trend linked to human activity (not good) status was assigned when the following conditions were met: change in an indicator was detected, the indicator demonstrated high correlation with pressures linked to human activities (e.g. warming, nutrients), and when there was high spatial and temporal confidence among the evaluated time-series.

It is expected that pressures from climate change (and also from ocean acidification) will intensify in the near future and persist for the longer term. Changes in the physicochemical conditions of the water column as a result of these pressures are likely to disturb plankton communities, impacting the relative abundance of plankton functional groups (e.g., diatoms vs dinoflagellates, holoplankton vs meroplankton) as well as the occurrence of planktonic species (groups). This may in turn have an impact on the ecosystem's carrying capacity and create knock-on effects for organisms higher up the marine food web.

Agricultural run-off and Blue-green algae © Shutterstock

Q2. What has been done?

There are no OSPAR measures which directly address problems in pelagic habitats. Climate change is the most important factor currently affecting plankton communities in the OSPAR Maritime Area. Effective measures for reducing or preventing climate change lie outside the remit of OSPAR, except for North-East Atlantic Environment Strategy 2030 strategic objective 12, which addresses the safeguarding of natural carbon stores.

Nutrient input is, however, an area for which OSPAR measures have been put in place. Starting in 1988, OSPAR has implemented programmes to reduce nutrient inputs (see: Eutrophication Thematic Assessment for details) and this area of work has been taken up in EU legislation. The ambition to manage nutrient pressure remains high. NEAES 2030 includes the strategic objective to "tackle eutrophication through limiting inputs of nutrients and organic matter".

Other relevant human activities are regulated through the competent organisations that manage shipping and fisheries.

Land run-off. © Forest and Kim Starr

Q3. Did it work?

No responses specifically address pelagic habitat quality, but some measures aimed at eutrophication impact pelagic habitats. With the increasing success of OSPAR's ability to assess this ecosystem component comes the need to further develop scientific understanding of the ecological consequences which can result from variation in the physical drivers of plankton production.

Since their introduction in the late 1980s, OSPAR's long-term programmes and measures to limit nutrient inputs have been those with the greatest impact in improving pelagic habitat quality. While these nutrient reductions have had the positive effect of reducing the prevalence of eutrophication, there has been little change in the number of assessment units and surface area with elevated chlorophyll concentrations since the Intermediate Assessment 2017.

The pelagic habitats indicator assessments also concluded that it is likely that some measures put in place to control nutrient inputs in the Greater North Sea and Celtic Seas may have the consequence of limiting ecosystem productivity in shelf areas.

Q4. How does this field affect the overall quality status?

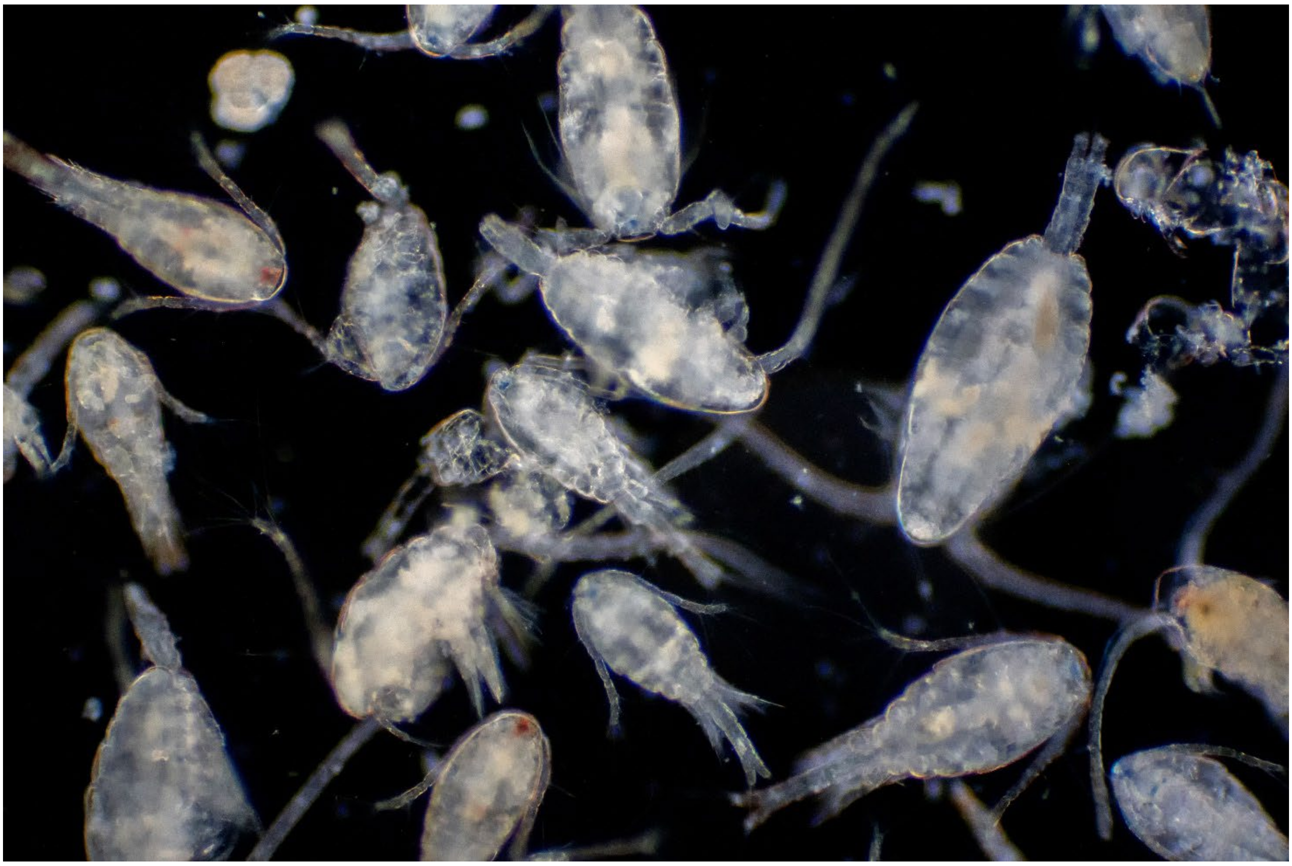
Pelagic habitats, and the planktonic organisms they support, provide most of the energy responsible for sustaining marine food webs. Therefore, large-scale shifts in plankton have the potential to impact entire ecosystems. Trends in plankton detected with pelagic habitat indicators can reveal important changes in the quality status of marine ecosystems. The assessments presented in the current edition of the QSR report on changes in the abundance of important plankton functional groups, the abundance of copepods and biomass of phytoplankton, and finally changes in phytoplankton and zooplankton community composition through species turnover and changes in dominance.

The Indicator Assessments revealed that pelagic habitats in the OSPAR Maritime Area have experienced widespread changes over the past 60 years. There was a general pattern of decreasing phytoplankton and zooplankton abundance and/or biomass across the Greater North Sea, Celtic Seas, and Bay of Biscay and Iberian Coast. Many of the observed changes were statistically linked to climate change (both from natural variability and human-induced), probably the greatest pressure currently impacting pelagic habitats. Additionally, measures put in place to control eutrophication in the Greater North Sea and Celtic Seas are intended to reduce productivity.

Despite the recent advancements in assessment methods, it is important to note that there were few suitable datasets available for assessing changes in gelatinous zooplankton, and in zooplankton in variable salinity habitats, due in both cases to insufficient monitoring.

While pelagic habitats were not formally assessed in 2010 and were not assessed with the same level of sophistication in 2017, long-term trends have for the most part continued into the current assessment period.

Due to widespread changes linked to pressures generated by human activities, the Greater North Sea, Celtic Seas, and Bay of Biscay and Iberian Coast were assigned not good environmental status, under the current definition and categorisation of quality status.



Copepod under the microscope. © Shutterstock

Q5. What do we do next?

In NEAES strategic objective 1, OSPAR has committed to “tackle eutrophication, through limiting inputs of nutrients and organic matter to levels that do not give rise to adverse effects on the marine environment”. This presents an opportunity to address a key pressure affecting the status of pelagic habitats. Future assessments must consider how to include plankton community indicators directly as part of the eutrophication assessment. The assessment needs to build the evidence of how nitrate and phosphate ratios lead to changes in phytoplankton communities (which negatively impact the efficiency of the ecosystem services those communities provide).

Furthermore, there may be opportunities to explore how to consider plankton communities that form pelagic habitats within the MPA status assessment, and to consider including plankton community dynamics in the EIA guidance. Given the current scaling-up of offshore renewable energy infrastructure, it is also important to consider the effects this will have on plankton dynamics.

In the future, OSPAR’s ongoing work to improve understanding of linkages across trophic levels (top-down and bottom-up) should incorporate the concept of trophic cascades, with particular focus on links to plankton health, food web function and derived ecosystem services.

Finally, future assessments should aim to quantify the effects of plankton change on ecosystem services and the effects of pressures on plankton as natural capital. Both should be integrated into policy development (OSPAR Science Agenda / Knowledge gap).

Agricultural run-off and Blue-green algae © Shutterstock

D - Drivers

Social and economic drivers for activities affecting pelagic habitats

All social and economic drivers have the potential to influence the quality status of pelagic habitats. In particular, the growing global population and the demand this generates for food production, waste disposal, coastal development and energy systems are probably the most important drivers. Policy responses for managing human activities need to consider all relevant driving forces so as to meet society's needs while reducing the risks to pelagic habitats and facilitating societal change.

All social and economic drivers have the potential to influence the quality status of pelagic habitats. Growing global populations increase the demand for food. Agriculture and aquaculture help to address this need, but agricultural run-off and waste products from aquaculture can introduce nutrients, organic matter and pathogens to the marine environment, which can alter plankton communities via bottom-up effects. Fisheries also help address this need; however, the extraction of wild species can impact the stability of pelagic food webs (e.g., "top-down" or "wasp waist" effects) and the plankton community supporting them.

The growing global population is increasing the demand for coastal development, housing, utilities, other urban uses, and associated waste water treatment and disposal. This also increases the demand for materials and their processing. The manufacturing, processing and production of goods can introduce pollutants to the marine environment, including nutrient pollution. The trading of goods by sea requires maintaining the navigability of waterways, and therefore dredging of the seabed, which can release nutrients and other pollutants into the water column. Shipping can also introduce non-indigenous species through ballast water discharge and input sound and other forms of energy. The introduction of infrastructure to the marine and coastal environments to meet society's need for economic development and energy (e.g., ports, housing, tourism and leisure, energy generation facilities) can alter hydrological and hydrodynamic conditions and thereby influence plankton distributions (directly or indirectly via effects on nutrients, primary productivity or food webs).

Policy responses for managing human activities need to consider all these driving forces so as to meet society's needs while reducing the risks to pelagic habitats and facilitating societal change.

A - Activities

Human activities exert pressures which can affect pelagic habitats

Human activities with the potential to affect pelagic habitats include human-induced climate change, agriculture, waste treatment, dredging, shipping, fisheries, aquaculture, renewable energy generation, and offshore extraction of oil and gas. Among these activities, those associated with the most significant pressures impacting the state of pelagic habitats include human-induced climate change, agriculture, and waste treatment.

Trends for each OSPAR Region taken from the Human Activities Thematic Assessment:

Table A.1: Characteristics of the main anthropogenic activities affecting benthic habitats in the OSPAR Maritime Area as adapted from the Human Activities Thematic Assessment. H = High, M = Medium and L = Low intensity. The arrow is used to show either increasing (↑) or decreasing (↓) trends. The symbol ↔ is used where there has been little change in intensity since QSR 2010; the symbol? is used where future trends are uncertain

Main activities	Arctic Waters	Greater North Sea	Celtic Seas	Bay of Biscay and Iberian Coast	Wider Atlantic
Agriculture					
Intensity	L	H	M	M	L
Trend since QSR2010	↔	↔	↔	↔	↔
Trend to 2030	↔	↔	↔	↔	↔
Aquaculture					
Intensity	H	H	M	M	L
Trend since QSR2010	↑	↑	↔	↑	↑
Trend to 2030	↑	↑	↑	↑	↑
Fisheries					
Intensity	H	H	H	M	L
Trend since QSR2010	↓	↑	↑	↔	↔
Trend to 2030	?	?	?	?	?
Oil/gas production					
Intensity	M	H	M	L	L
Trend since QSR2010	↔	↔	↔	↔	↔
Trend to 2030	↔	↔	↔	↔	↔
Renewable energy					
Intensity	L	H	M	L	L

Trend since QSR2010 Trend to 2030	↑ ↑	↑ ↑	↑ ↑	↑ ↑	↔ ↔
Shipping *Intensity* *Trend since QSR2010* *Trend to 2030*	M ↔ ?	H ↔ ?	H ↔ ?	H ↔ ?	L ↔ ?
Tourism *Intensity* *Trend since QSR2010* *Trend to 2030*	L ↑ ↑	H ↑ ↑	M ↔ ↔	H ↑ ↑	L ↑ ↑

The key human activities affecting pelagic systems are:

Human-induced climate change:
Human activities have caused changes in the atmospheric concentrations of greenhouse gases, for example from the burning of fossil fuels (for energy and transport), industrialised farming practices and deforestation. This human-induced climate change has affected pelagic systems through pressures in the physical and chemical ocean climate at multiple scales. See: Climate Change Thematic Assessment, Ocean Acidification.

Agriculture [Cultivation of living resources]: Agricultural run-off can lead to changes in turbidity and the input of substances to the environment, including nutrients. In addition to the direct effects of terrestrial run-off, the increasing nutrient, dissolved, particulate, and detrital (organic and inorganic) inputs to the marine environment (including microorganisms and pathogens) can affect primary productivity and the structure of pelagic habitats. See: OSPAR Feeder Report 2021 - Agriculture.

Waste treatment and disposal and Industrial uses [Urban and industrial uses]: Industrial atmospheric emissions and direct discharges can lead to turbidity changes and the input of substances and nutrients to the environment, affecting pelagic habitats. In localised areas, nutrient run-off from industry and sewage can cause significant eutrophication impacts on pelagic habitats. See: OSPAR Feeder Report 2021 – Waste water.

Restructuring of seabed morphology, including dredging and depositing of materials [Physical restructuring of rivers, coastline or seabed (water management)]: Dredging of the seabed can cause localised increases in nutrients and turbidity. See: Human Activities Thematic Assessment

Transport – shipping [Transport]: Shipping contributes to greenhouse gas emissions and can introduce non-native species through ballast water discharge. See: OSPAR Feeder Report 2021 – Shipping and Ports

Fish and shellfish harvesting (professional, recreational) [Extraction of living resources]: Removal of fish (and new fisheries for plankton, e.g., copepods) can alter balance in food webs (leading to trophic cascades), affecting plankton communities. Changes in the lower trophic levels induced by a disequilibrium in nutrients (e.g., nitrogen and phosphorus) can also alter this balance (bottom-up effects). Fishing vessels also contribute (alongside shipping) to greenhouse gas emissions. See OSPAR Feeder Report 2021 - Fisheries

Aquaculture - marine, including infrastructure [Cultivation of living resources]: Operational and production chemicals and nutrients have the potential to affect pelagic communities. Stocks will also contribute to changing balance within food webs. Moreover, parasites and diseases can propagate from highly dense structures. See: OSPAR Feeder Report 2021 - Aquaculture

Renewable energy generation (wind, wave and tidal power) including infrastructure [Production of energy], **Extraction of oil and gas including infrastructure** [Extraction of non-living resources], **Offshore**

structures (other than for oil/gas/renewables) and **Coastal defence and flood protection** [Physical restructuring of rivers, coastline or seabed (water management)]: Coastal development and the introduction of infrastructure to the marine environment can cause hydrological and hydrodynamic changes and thereby influence nutrient and plankton distributions. They also provide new substrate which meroplankton could potentially colonise. See: OSPAR Feeder Report 2021 – Offshore Renewable Energy Generation, OSPAR Feeder Report 2021 – Assessment of the impacts of the offshore oil and gas industry on the marine environment

Extraction of oil and gas, including infrastructure [Extraction of non-living resources]: and the consequent burning of fossil fuels contributes to greenhouse gas emissions. See: Human Activities Thematic Assessment, Offshore Industry Thematic Assessment

P – Pressures

Pressures affecting pelagic habitats

The main pressures affecting pelagic habitats are human-induced climate change, nutrient and organic enrichment, chemical contaminants, and non-indigenous species. While there is currently insufficient evidence to describe trends in pressures specifically in the context of MSFD pelagic habitats or OSPAR Regions, trends in the human activities exerting the above-mentioned pressures could provide a suitable proxy for trends in the pressures themselves.

NOTE: this is expanded narrative focusing on pelagic habitats - the standard descriptions of the relevant pressures are provided in the DAPI reference list.

The key direct pressures affecting pelagic systems are as follows:

Most importantly, pressures on pelagic systems are increased by **Climate change**

Human-induced climate change is likely to create the greatest pressures on pelagic systems through changes in ocean temperature, stratification/mixing regimes, potential oxygen depletion, upwellings, atmospheric and oceanographic circulation, and pH (ocean acidification). See: Climate Change, Climate Change Thematic Assessment, Ocean Acidification

Input of nutrients - diffuse sources, point sources, atmospheric deposition [Substances, litter and energy]: At local scales, inputs of nutrients from farming run-off (driven by society's need for food), aquaculture, dredging (driven by society's need for trade and movement of goods) and from industrial and sewage releases can create negative changes in plankton communities. Industrial uses are driven by society's need for industrial processes, stable economies, health and wellbeing, materials, and trade and movement of goods. Waste treatment and disposal is driven by society's need for industrial processes and urban uses. Nutrient levels are managed via the EU Water Framework Directive (2000/60/EC) and local equivalents. Effects on hydrodynamics are managed via Environmental Impact Assessments (EIAs), Habitat Regulation Assessments (HRAs) and terrestrial planning processes.

Extraction of, or mortality/injury to, wild species (by commercial and recreational fishing and other activities) [Biological]: Society's need for food is a driver of fishing. Mortality/Injury to wild species through overfishing can create imbalances across food webs. The removal of predatory fish can lead to forage fish (plankton consumers) becoming too abundant. In turn, zooplankton are consumed at unsustainable levels, leading to imbalances in plankton communities. Management measures to reduce the impacts of fishing are carried out via the Common Fisheries Policy (CFP) with fishing quotas. However, it should be noted that the drivers for the CFP mostly focus on sustainable fishing levels, rather than on protecting pelagic systems.

Changes to hydrological conditions [Physical]: Driven by society's need for economic development, coastal development and the introduction of infrastructure such as offshore wind farms and oil and gas platforms can cause hydrological changes with direct impacts on pelagic habitats at local scale. Hydrodynamic changes can, in turn, can lead to localised changes in stratification / mixing of water column, nutrients, turbidity, currents and plankton distributions.

Input or spread of non-indigenous species [Biological]: Offshore and coastal development, such as windfarms, can provide a substrate for meroplankton, including non-natives, to settle, while ballast water discharge from shipping can introduce NIS.

S – State

Assessing the state of pelagic habitats

Pelagic habitats in the OSPAR Maritime Area have experienced widespread changes over the past 60 years. Climate change (both from natural variability and human-induced) is probably the greatest pressure currently impacting pelagic habitats. Measures put in place to control nutrient inputs in the Greater North Sea and Celtic Seas may be limiting productivity. There was a general pattern of decreasing phytoplankton and zooplankton abundance and/or biomass across the three OSPAR Regions considered in the indicator assessments (i.e., Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast), which will probably have consequences for higher food web levels. Due to widespread changes linked to human pressures across multiple pelagic habitat types (**Table S.1; Figure S.1**) with medium to high confidence (**Table S.2**), the three OSPAR Regions considered in the indicator assessments were all in not good environmental status under the definition and categorisation of quality status described in McQuatters-Gollop *et al*. (2022).

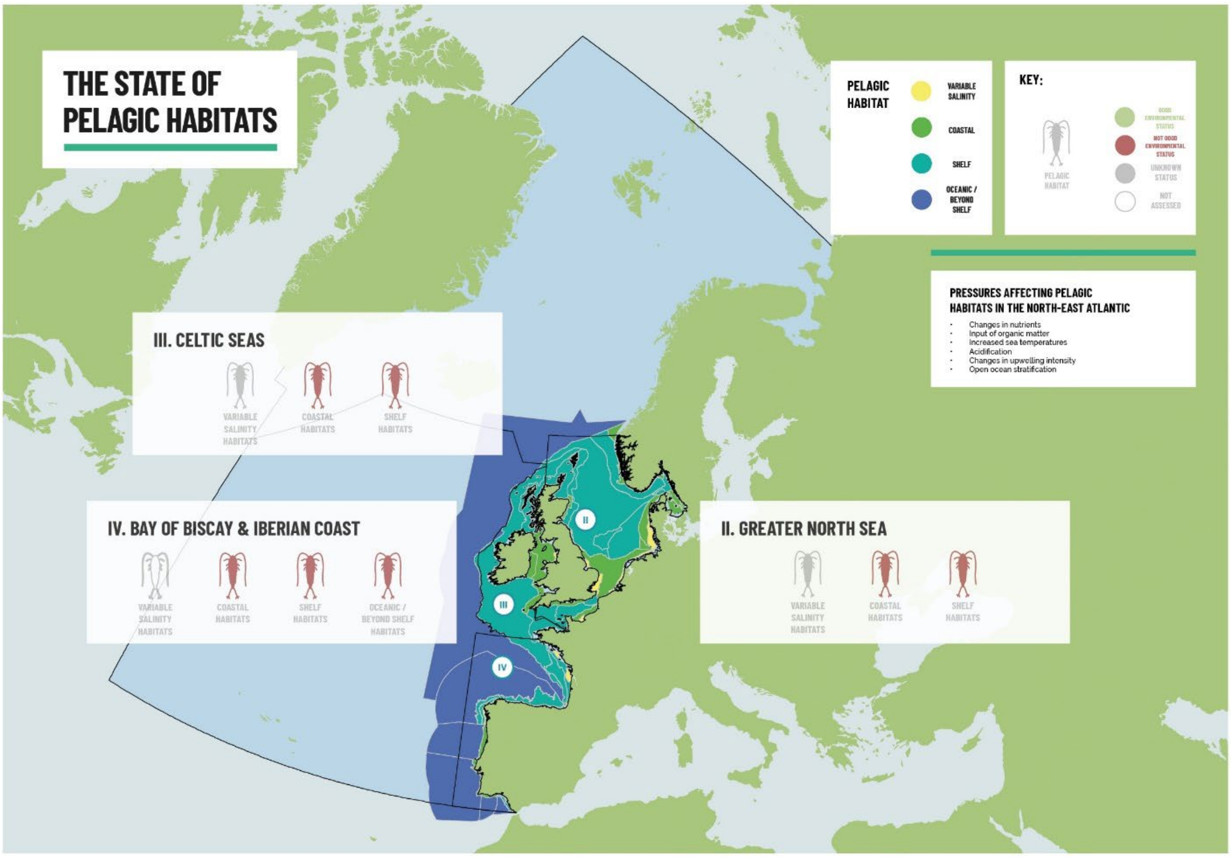


Figure S.1: Integrated status assessment schematic for pelagic habitat types (variable salinity habitats, coastal habitats, shelf habitats, oceanic/beyond shelf habitats) in the assessed OSPAR Regions

Table S.1: The biodiversity status of pelagic habitats in each OSPAR Region, derived by integrating the status of pelagic habitat types

Arctic Waters (Region I)	Greater North Sea (Region II)	Celtic Seas (Region III)	Bay of Biscay and Iberian Coast (Region IV)	Wider Atlantic (Region V)
Not assessed	Not in good environmental status	Not in good environmental status	Not in good environmental status	Not assessed

Table S.2: Confidence assessment results across the five OSPAR Regions, determined using the methodology outlined in the QSR guidance

OSPAR Region	Arctic Waters (Region I)	Greater North Sea (Region II)	Celtic Seas (Region III)	Bay of Biscay and Iberian Coast (Region IV)	Wider Atlantic (Region V)
Confidence	Not assessed	Medium	High	Medium	Not assessed

OSPAR acts as a coordination platform in the North-East Atlantic for the regional implementation of the EU Marine Strategy Framework Directive (MSFD) that aims to achieve a Good Environmental Status (GES) in European marine environments, as well as for the coordination of other national frameworks. The *characteristics of GES are determined by the individual EU member states, based on criteria elements, threshold values and methodological standards set regionally or at EU level. Norwegian, Icelandic, United Kingdom, Greenlandic and Faroese marine areas are not covered by the MSFD.*

Specific impacts on the state of pelagic systems include changes in food webs and loss of energy transfer from pelagic systems to higher trophic levels. Knock-on impacts can include changes in the strength of coupling between pelagic and benthic systems. Such changes can be detected through variation in benthic productivity and reproduction. In localised areas eutrophication impacts can lead to a dominance of problematic species, including harmful-bloom-forming phytoplankton; however, not all large phytoplankton blooms are in themselves harmful (**Figure S.2**). Eutrophication can be managed by controlling the flow of anthropogenic nutrients entering rivers, and by setting environmental targets.

Figure S.2: Copernicus Sentinel 2B Image showing a short-lived coccolithophore bloom off the south-west coast of England in June 2020. Image processed at Plymouth Marine Laboratory by the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS). Image credit: Daniel Clewley

Climate change can alter the local ecological conditions of pelagic habitats and affect the abundance of species, their life history traits and physiology and the composition of biological communities. However, unlike eutrophication, which can be managed at local or regional scale, climate change must be managed globally for any mitigation efforts to be effective.

The environmental impacts relating to an undesirable state in pelagic habitats can include:

- Changes in food available (both quantity and quality) for higher trophic levels;
- Productivity impacts across trophic levels;

- Reduction in the concentration of dissolved oxygen leading to negative change in plankton functional groups or lifeforms;
- Changes in energy flow between phytoplankton and zooplankton;
- Changes in benthic-pelagic coupling and reproductive output;
- Eutrophication leading to less desirable food webs;
- Introduction and spreading of NIS;
- Changes in phenology, or mistiming of seasonal events, due to climate change;
- Changes in carbonate chemistry and the cycling of key elements, including carbon, nitrogen, phosphorus, and silica.

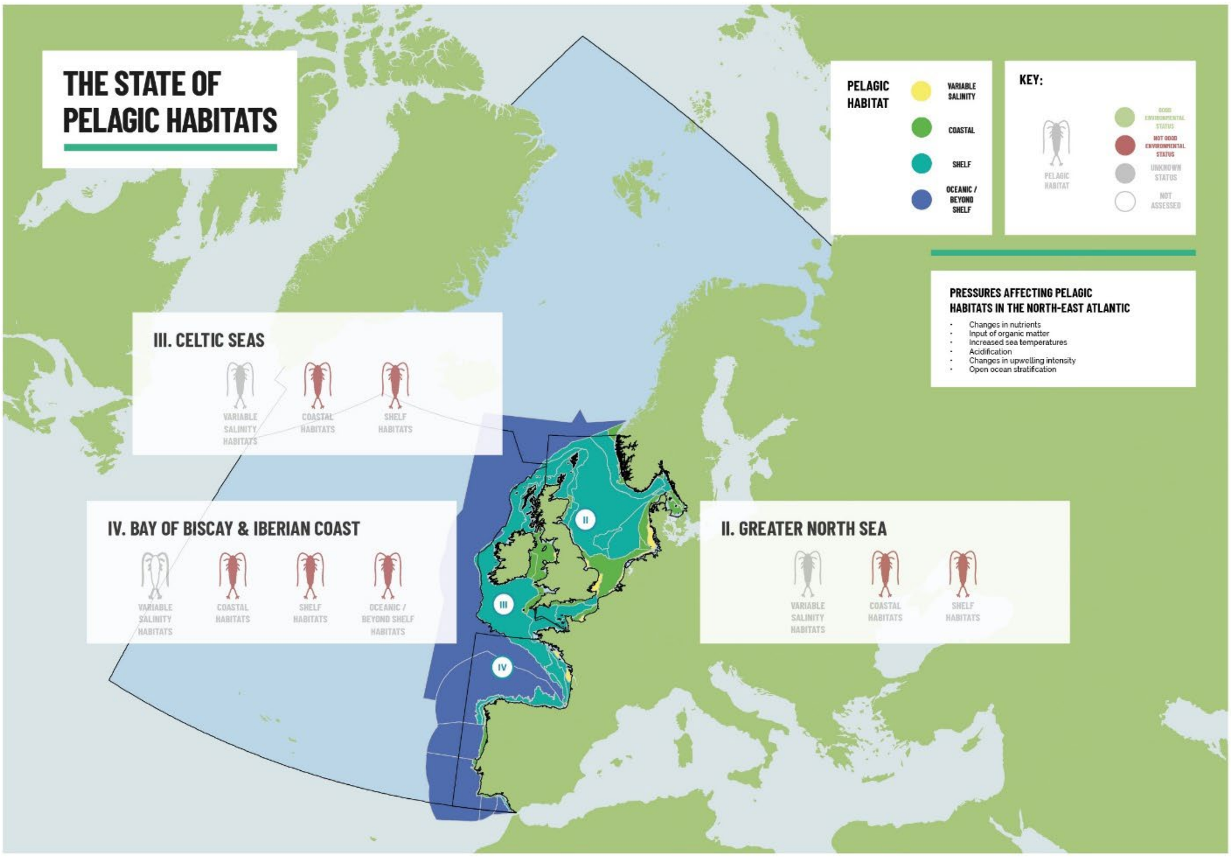


Figure S.3: Indicator results schematic for pelagic habitat types (variable salinity, coastal, shelf, and oceanic / beyond shelf habitats) within the OSPAR Regions assessed for the pelagic habitats indicator assessments. This graphic has been designed to follow the format outlined in McQuatters-Gollop et al. (2022)

For the OSPAR pelagic habitat biodiversity indicators there was variability among indicators, pelagic habitat types and OSPAR Regions. Icons have been coloured according to indicator status. Grey colour for unknown is the default colour if the indicator has been assessed. Red indicates that the assessment detected a trend and that the trend is linked to a human activity (not good). Current integration methods for pelagic habitats do not allow for the determination of good status, due to uncertainty around conditions not significantly affected by anthropogenic pressures. White identifies indicators that were not assessed in some Regions or habitat types due to lack of data. Pelagic habitat types without results displayed indicate that the particular habitat type is not present within the OSPAR Region. Grey background and "pilot" labelling indicate that an indicator has candidate status in the respective Region and that a pilot assessment has been prepared.

For the current assessment, changes in the state of pelagic habitats in Greater North Seas, Celtic Seas and Bay of Biscay and Iberian coast (OSPAR Regions II, III, and IV) were evaluated over the period between 1960 and 2019 (except for phytoplankton biomass, which was assessed between 1998 and 2019) through analysis of three common biodiversity indicators:

- Changes in Phytoplankton and Zooplankton Communities (PH1/FW5);
- Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2);
- Changes in Plankton Diversity (PH3).

Changes in Phytoplankton and Zooplankton Communities (PH1/FW5) is an indicator of ecosystem function which measures changes in the abundance of important plankton functional groups or "lifeforms".

Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2) is a bulk indicator which examines changes in the abundance of copepods (the largest contributor to total zooplankton abundance) and changes in the biomass of phytoplankton (the main marine primary producers) (**Figure S.4**).

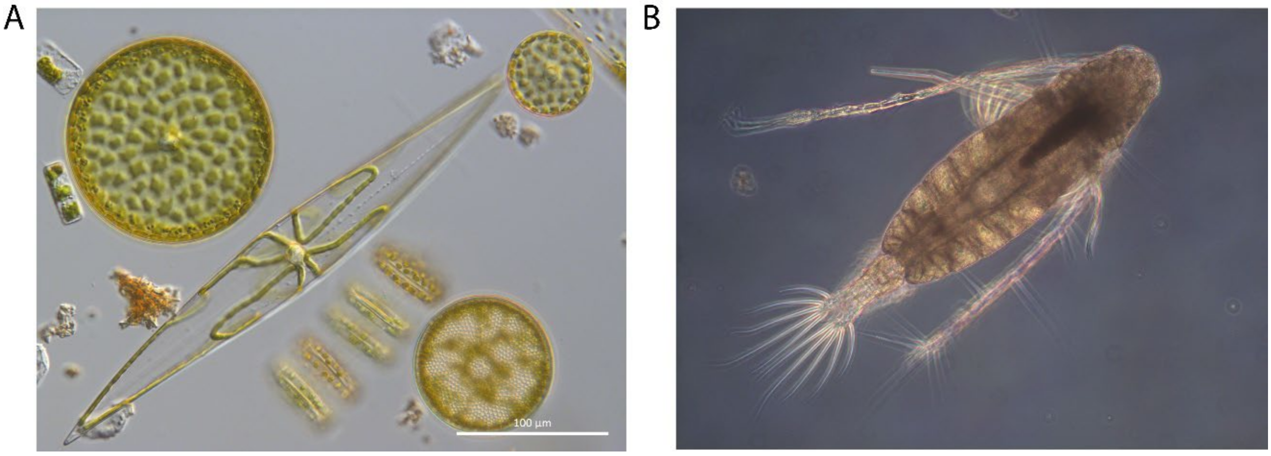


Figure S.4: The changes in plankton biomass and/or abundance (PH2) common indicator measures changes in the total biomass of phytoplankton, including pennate and centric diatoms (A). This common indicator also measures changes in the abundance of copepods such as the calanoid copepod *Acartia tonsa* (B). Image credits: Claire Widdicombe (A), Tanja Burgmer (B)

Changes in Plankton Diversity (PH3) is a biodiversity indicator which examines changes in composition, species turnover and dominance within phytoplankton and zooplankton communities. For the current assessment, PH3 was evaluated as a common indicator in the Celtic Seas (OSPAR Region III) and as a candidate indicator in the Greater North Sea and the Bay of Biscay and Iberian Coast (OSPAR Regions II and IV, respectively; **Table S.3**). While the results of the pilot assessment of PH3 were included in this Thematic Assessment, they were not considered in the region-specific summary or confidence assessment for pelagic habitats in the Greater North Sea and Bay of Biscay and Iberian Coast (OSPAR Regions II and IV), since PH3 is not currently a common indicator in those Regions.

Table S.3: The status of how each indicator was considered or evaluated across the five OSPAR Regions

	Arctic Waters (Region I)	Greater North Sea (Region II)	Celtic Seas (Region III)	Bay of Biscay and Iberian Coast (Region IV)	Wider Atlantic (Region V)
Changes in Phytoplankton and Zooplankton Communities (PH1/FW5)	Not assessed	Common	Common	Common	Not assessed
Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2)	Not assessed	Common	Common	Common	Not assessed
Changes in Plankton Diversity (PH3)	Not assessed	Pilot assessment	Common	Pilot assessment	Not assessed

These indicators were analysed to evaluate biological changes occurring across a set of assessment units and fixed-point stations within the OSPAR Maritime Area. The "OSPAR Common Procedure Assessment Units" (Common Procedure for the Identification of the Eutrophication Status of the OSPAR Maritime Area, 4th application), an OSPAR data product, were used to spatially subdivide plankton samples (**Figure S.5**). These assessment units are a geographical representation of the conditions most likely to drive plankton distribution, dynamics and community composition.

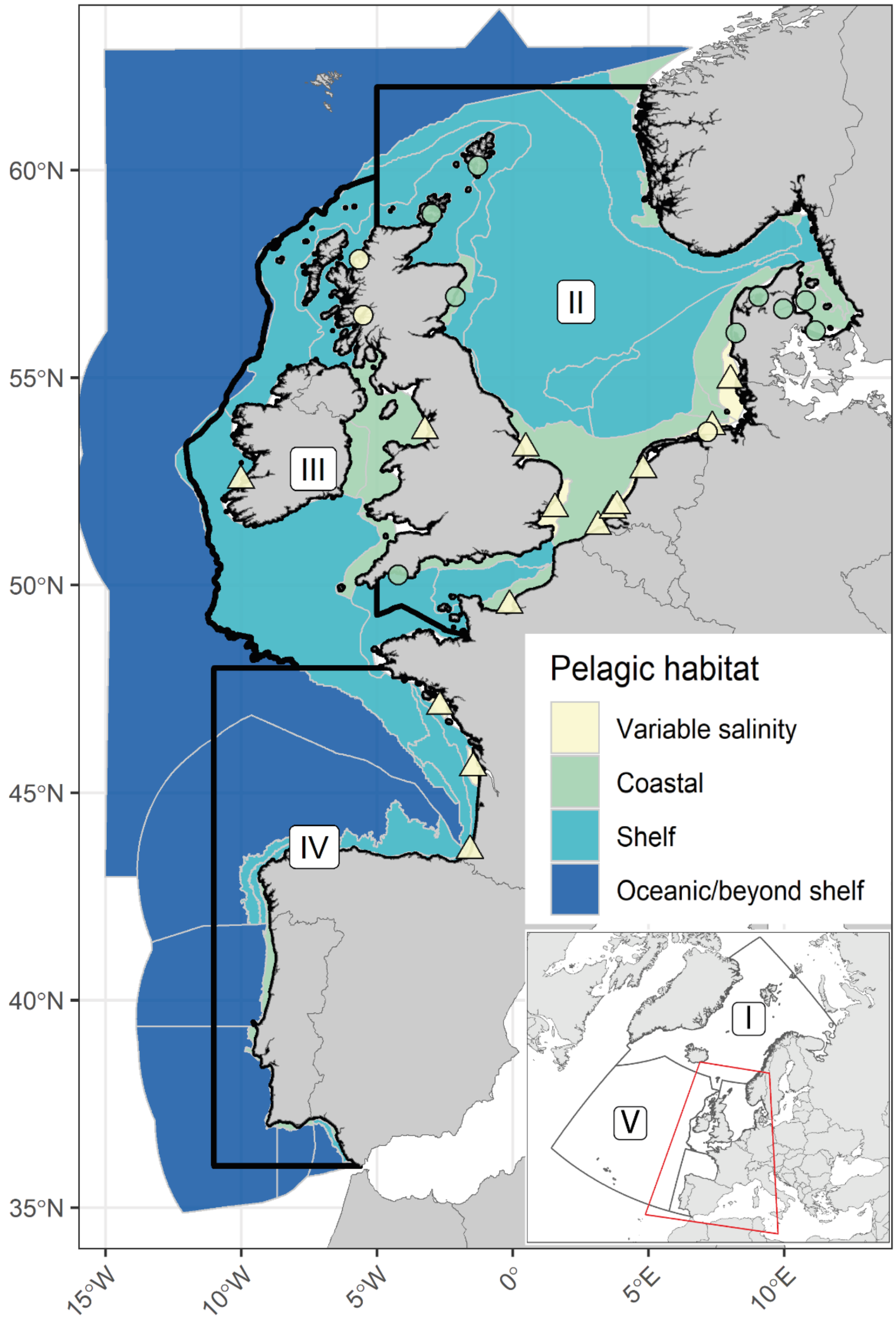


Figure S.5: The distribution of the four pelagic habitat types across the three OSPAR Regions considered in the pelagic habitat indicator assessments, and the boundaries of the five OSPAR Regions across the OSPAR Maritime Area (inset). Fixed-point stations are represented as circles and river plumes are represented as triangles. Boundaries between COMP4 assessment units used in this assessment are indicated in grey

For OSPAR Regions II, III and IV, assessment units and fixed-point stations were grouped according to four pelagic habitat types so that indicator results could be integrated by habitat (**Figure S.5**). The intention of this approach was to provide broad overarching conclusions on the state of pelagic habitats within each OSPAR Region, despite likely important differences among assessment units of the same habitat type. For a more detailed description of indicator results at the scale of the individual assessment units, consult the pelagic habitats indicator assessments: Changes in Phytoplankton and Zooplankton Communities (PH1/FW5); Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2); Changes in Plankton Diversity (PH3).

The habitat type categories were created to align assessment outputs with EU MSFD features, with a view to allowing Contracting Parties to use the information for MSFD Art. 8 reporting. The four pelagic habitat types used in the assessment were:

- Variable salinity habitats;
- Coastal habitats;
- Shelf habitats;
- Oceanic / beyond shelf habitats.

Variable salinity habitats were defined according to EU GES Decision 2017/848 for situations where estuarine plumes extend beyond waters designated as Transitional Waters under Directive 2000/60/EC.

Coastal habitats were defined according to EU GES Decision 2017/848. 'Coastal' is to 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 (WFD).

Shelf habitats were defined according to a mean salinity threshold of >34.5 as the boundary between outer coastal and offshore waters, as defined in OSPAR Agreement 13-08, and as used for nutrients in the previous Common Indicator Assessment IA 2017. For future assessment, this salinity threshold should be reassessed, as isohaline boundaries will probably be impacted by salinity changes already occurring in the wider Atlantic.

Oceanic / beyond shelf habitats were defined according to a mean depth threshold of >200 m.

Indicator assessment results were integrated across common indicators for the four pelagic habitat types (**Table S.4**) to ultimately facilitate determination of a single status for each OSPAR Region, see: CEMP Guideline for Pelagic Habitats Thematic Assessment Integration Method. The status for each pelagic habitat type was determined by majority status. However, in the case of a tie when only two indicators were common and one of the two indicators was detecting a trend linked to human activity (not good) status, the status for the habitat type was also not good. In cases where a common indicator was not assessed within a particular pelagic habitat type, the status for that habitat would only consider the indicators which were assessed.

Table S.4: The status for each pelagic habitat type within each OSPAR Region, derived by integrating the status of common indicators for pelagic habitats**.** Diagonally hatched cells indicate that an indicator has candidate status in a particular Region and a pilot assessment has been produced. As the PH3 indicator remains a candidate indicator for OSPAR Regions II and IV, the status of PH3 for these Regions is given for information purposes only and was not considered in the integration of overall habitat or Region status

Region	Habitat	PH1/FW5	PH2	PH3	Habitat Status	Region Status
Greater North Sea (Region II)	Variable salinity	Unknown	Unknown	Not good	Unknown	Not good
	Coastal	Unknown	Detected trend linked to human activity	Not good	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Not assessed	Not assessed	Not assessed	Not assessed	
Celtic Seas (Region III)	Variable salinity	Unknown	Unknown	Not assessed	Unknown	Not good
	Coastal	Detected trend linked to human activity	Detected trend linked to human activity	Detected trend linked to human activity	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Not assessed	Not assessed	Not assessed	Not assessed	
Bay of Biscay and the Iberian Coast (Region IV)	Variable salinity	Not assessed	Not assessed	Not assessed	Not assessed	Not good
	Coastal	Unknown	Detected trend linked to human activity	Not good	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	

The overall status for each OSPAR Region (**Table S.4**) was also determined by majority status among the pelagic habitats it contains. However, in the case of a tie when only two pelagic habitat types were assessed and one of the two habitat types was in not good status, the status for the habitat type was also not good. In cases where the status for a particular pelagic habitat type was not assessed, the status for that OSPAR Region only considered the habitats which were assessed.

In the following section the current state of pelagic habitats across the five OSPAR Regions has been summarised by discussing current peer-reviewed literature. This review is complemented by integrating the results of the indicator assessments, wherever they were considered a common indicator.

Confidence assessment

A confidence assessment was conducted according to the recommendations in the QSR Guidance and confidence scores were integrated according to the CEMP Guideline for the Pelagic Habitats Thematic Assessment. The overall confidence score for each OSPAR Region was determined by considering the type, amount, quality, and consistency of evidence (i.e., Robust, Medium, or Limited) as well as the degree of agreement (i.e., High, Medium, or Low) in the results among the indicator assessments.

The confidence assessment also incorporated the temporal extent of plankton monitoring time-series. While offshore areas were extensively surveyed from 1960 by the Continuous Plankton Recorder (CPR) programme, coastal areas and river plumes had shorter time-series, typically commencing between 1980 and 2000.

Each indicator assessment also included its own internal confidence assessment, which considered the spatial distribution of samples within each assessment unit as well as the temporal distribution of samples within each time-series. Evidence and agreement scores were used to determine a combined score, using the matrix method outlined in the QSR Guidance (**Table S.5**). Agreement and evidence scores for each OSPAR Region (**Table S.6**), as well as the rationale for selecting them, are described below.

Table S.5: A depiction of the evidence and agreement statement and their relationship to the confidence criteria from the QSR Guidance. An overall confidence score is determined by locating the appropriate agreement and evidence scores in the matrix and selecting a confidence score with the same fill colour in the bottom table

High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Table S.6: Confidence assessment of the type, amount, quality, and consistency of evidence (i.e., Robust, Medium, or Limited), as well as the degree of agreement in the results (i.e., High, Medium, or Low), for the three pelagic habitat indicators across the five OSPAR Regions. Colours are used for interpretation. Diagonally hatched cells indicate that an indicator has candidate status in the Region and that, while a pilot assessment has been conducted, a confidence assessment has not been produced

Region	Criteria	PH1/FW5	PH2	PH3	Criteria Status	Region Status
Greater North Sea (Region II)	Agreement	Medium	Medium	Not assessed	Medium	Medium
	Evidence	Medium	Medium	Not assessed	Medium	
Celtic Seas (Region III)	Agreement	High	High	High	High	High
	Evidence	Medium	Medium	Medium	Medium	
Bay of Biscay and the Iberian Coast (Region IV)	Agreement	High	High	Not assessed	High	Medium
	Evidence	Limited	Limited	Not assessed	Limited	

Pelagic habitats in the Greater North Sea (Region II)

PH1/FW5: Medium

Agreement: Medium

While some lifeforms demonstrated consistent trends across multiple pelagic habitats, others showed variable trends. Changes in meroplankton were strongly supported by the literature. Due to high variability in the ranking of pressures, links between trends in the indicator and pressures were only clear for shelf habitats. This may be a reflection of the higher complexity of direct and indirect pressures exerted on coastal and variable salinity pelagic habitats.

Evidence: Medium

There were multiple datasets supporting this indicator assessment, providing nearly full coverage of all assessment units within coastal and shelf habitats. The temporal scale of the assessment also spanned more than six decades for many of the offshore areas. However, zooplankton lifeforms within variable salinity habitats were poorly represented. Pressure datasets were also primarily sourced from satellite remote sensing and hydrodynamic / ecological models, rather than *in situ* sampling.

PH2: Medium

Agreement: Medium

The overall trend was consistent across the three pelagic habitats and both plankton components. However, local-scale results showed some variability, which was reduced once results were integrated within pelagic habitats. The local direction of changes, as well as the pressures responsible for the changes, were supported by current literature (e.g., Capuzzo *et al*., 2018).

Evidence: Medium

The Greater North Sea benefits from multiple datasets obtained by various observing systems (e.g. satellite sensors, fixed monitoring stations, non-station data from "ships of opportunity" or research vessels) with coverage across all assessment units. However, zooplankton lifeforms within variable salinity habitats were poorly represented. The temporal scale of the assessment spanned more than three decades, revealing robust trends as well as links to pressures.

PH3: Not assessed

A pilot assessment of the PH3 indicator was also produced for the Greater North Sea (OSPAR Region II). However, since the PH3 indicator is only a candidate indicator in this Region it did not contribute to the overall confidence scoring. For further information, please consult the PH3 indicator assessment: Changes in Plankton Diversity (PH3).

Pelagic habitats in the Celtic Seas (Region III)

PH1/FW5: High

Agreement: High

The indicator demonstrates consistent downward trends across multiple pelagic habitats. Linkage between trends in indicator and pressures show some variability among lifeforms, but mostly consistent within pelagic habitats.

Evidence: Medium

There were multiple datasets supporting this indicator assessment, with full coverage of all assessment units within coastal and shelf habitats. The temporal scale of the assessment also spanned more than six decades for many of the offshore areas. However, zooplankton lifeforms within variable salinity habitats were poorly represented. Pressure datasets were also primarily sourced from satellite remote sensing and hydrodynamic / ecological models rather than by *in situ* sampling.

PH2: High

Agreement: High

There was generally low variability in the direction and magnitude of trends among assessment units comprising each pelagic habitat type. Phytoplankton and zooplankton exhibited different linkages between indicator trends and relevant pressures, but these linkages remained consistent across pelagic habitats.

Evidence: Medium

The Celtic Seas Region benefits from multiple datasets obtained by various observing systems (e.g., satellite sensors, fixed monitoring stations, non-station data from "ships of opportunity" or research vessels) with coverage across all assessment units. However, zooplankton lifeforms within variable salinity habitats were poorly represented. The temporal scale of the assessment spanned more than three decades, revealing robust trends as well as links to pressures.

PH3: High

Agreement: High

There was generally low variability in the direction and magnitude of trends among assessment units comprising the pelagic habitat types. Phytoplankton and zooplankton exhibited different linkages between indicator trends and relevant pressures, but these linkages remained consistent across pelagic habitats.

Evidence: Medium

No data were available for phytoplankton and zooplankton in the variable salinity habitats. However, coastal and shelf habitats benefited from long-term monitoring (commencing in 1960), which provided coverage across all assessment units.

Pelagic habitats in the Bay of Biscay and Iberian coast (Region IV)

PH1/FW5: Medium

Agreement: High

The indicator demonstrated consistent downward trends for most planktonic lifeforms across multiple pelagic habitats. Linkage between trends in the indicator and pressures showed some variability among lifeforms but was mostly consistent within pelagic habitats. Downward trends in shelf and offshore areas were supported by literature (e.g., Edwards *et al*., 2022).

Evidence: Limited

The temporal scale of the assessment in shelf and oceanic / beyond shelf habitats spanned more than six decades for many of the offshore areas. However, there were no data available for zooplankton lifeforms in variable salinity or coastal habitats and phytoplankton lifeforms in coastal habitats were poorly represented. Similarly, shelf and oceanic / beyond shelf habitats were only partially represented. Pressure datasets were also primarily sourced from hydrodynamic / ecological models rather than by *in situ* sampling. Further, since the assessment units in the Bay of Biscay and Iberian Coast had to be defined with a different methodology from that used for the Greater North Sea and Celtic Seas, they may not be fully representative of the oceanography and plankton dynamics of the Region.

PH2: Medium

Agreement: High

There was generally low variability in the direction and magnitude of trends among assessment units comprising the pelagic habitat types. Phytoplankton and zooplankton exhibited different linkages between indicator trends and relevant pressures, but these linkages remained consistent, with strong evidence supporting them across pelagic habitats.

Evidence: Limited

No data were available to evaluate both phytoplankton and zooplankton within variable salinity habitats. No assessment units were represented for coastal habitats, and the only data available were from fixed-point reference stations. Shelf and oceanic habitats were also poorly represented due to limited spatiotemporal coverage of CPR samples. Further, since assessment units in the Bay of Biscay and Iberian Coast had to be defined with a different methodology from that used for the Greater North Sea and Celtic Seas, they may not be fully representative of the oceanography and plankton dynamics of the Region.

PH3: Not assessed

A pilot assessment of the PH3 indicator was also assessed for the Bay of Biscay and Iberian Coast (OSPAR Region IV). However, since the PH3 indicator is only a candidate indicator in the Bay of Biscay and Iberian Coast, it did not contribute to the overall confidence scoring. For further information, please consult the PH3 indicator assessment: Changes in Plankton Diversity (PH3).

Region-specific summary

Pelagic habitats in Arctic Waters (Region I)

The region-specific summary for Arctic Waters (OSPAR Region I) has been entirely based on the scientific literature, since no indicator assessments were conducted in this Region.

Region I consists of Atlantic and Arctic waters. In its Atlantic waters, phytoplankton are present throughout the year, with seasonal and annual fluctuations among species (Dale *et al*., 1999). Phytoplankton are eaten by herbivorous zooplankton, with *Calanus* the biomass-dominant genus, particularly *Calanus finmarchicus*, but there are also several other genera. Carnivorous zooplankton belong to a range of taxa, including pelagic amphipods, gelatinous zooplankton, chaetognaths, and omnivorous krill (Melle *et al*., 2004). *Calanus* abundance has fallen below the long-time average since the early 2000s, with few fluctuations (ICES, 2020a). Likewise, euphausiid abundance has declined substantially in the surface waters south of 65°N since the 1960s (Edwards *et al*., 2021).

In the Arctic portion of Region I, where sea surface temperatures have increased and ice cover has diminished (Dahlke *et al*., 2020), changes in phytoplankton bloom time and in zooplankton communities have been found (Dalpadado *et al*., 2020), leading to temporal mismatch between predators and their prey. There has also been a decline in Arctic copepods, particularly *Calanus glacialis,* and the amphipod *Themisto libellula*, in the warmest years (Aarflot *et al*., 2018; Stige *et al*., 2019). Arctic pelagic habitats are continuing to resemble boreal pelagic habitats, driving a doubling in the biomass of krill (Eriksen *et al*., 2016; 2017). Finally, *Calanus* *finmarchichus* has shifted its distribution further north into waters which were previously too cold for it to occupy (ICES, 2020b).

Pelagic habitats in the Greater North Sea (Region II)

The status for variable salinity habitats in Region II was unknown, since this was the status for both: PH1/FW5 Changes in Phytoplankton and Zooplankton Communities and PH2 Changes in Phytoplankton Biomass and Zooplankton Abundance indicators (**Table S.7**). The status for coastal habitats was not good, since the status for the PH2 indicator was a trend linked to a human activity (interpreted as not good), while the PH1/FW5 result was unknown. The status for shelf habitats was not good, since this was the result for both PH1/FW5 and PH2 indicators. Considering that coastal and shelf habitats had not good status while only variable salinity habitats had unknown status (**Table S.7**), the status for pelagic habitats in the Greater North Sea (Region II) was not good. The integration of confidence scores for common indicators in the Greater North Sea resulted in an overall score of Medium for this OSPAR Region (**Table S.8**).

Table S.7: The status for each Common and Candidate indicator within each pelagic habitat type for the Greater North Sea (OSPAR Region II), derived from the integration of results for each indicator. Diagonally hatched cells indicate that an indicator has candidate status in the Region and that a pilot assessment has been produced. PH3 results have been presented for information purposes only

Region	Habitat	PH1/FW5	PH2	PH3	Habitat Status	Region Status
Greater North Sea (Region II)	Variable salinity	Unknown	Unknown	Not good	Unknown	Not good
	Coastal	Unknown	Detected trend linked to human activity	Not good	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Not assessed	Not assessed	Not good	Not assessed	

A pilot assessment of the PH3 indicator was also produced for the Greater North Sea (OSPAR Region II). However, since the PH3 indicator is only a candidate indicator in the present region, the results are not described in detail below. For further information, please consult the PH3 indicator assessment, Changes in Plankton Diversity.

Table S.8: Confidence assessment of the type, amount, quality, and consistency of evidence (i.e. Robust, Medium, or Limited), as well as the degree of agreement in the results (i.e. High, Medium, or Low) for the pelagic habitat indicators assessed in the Greater North Sea (OSPAR Region II). Colours are used for interpretation. Diagonally hatched cells indicate that an indicator has candidate status in the Region and that, while a pilot assessment has been conducted, a confidence assessment has not been produced

Region	Habitat	PH1/FW5	PH2	PH3	Habitat Status	Region Status
Greater North Sea (Region II)	Agreement	Medium	Medium	Not assessed	Medium	Medium
	Evidence	Medium	Medium	Not assessed	Medium	

The Greater North Sea (Region II) experiences regular eutrophication events, particularly along shorelines in the southern part, where several large rivers input nutrients released from agricultural practices, sewage discharge and natural processes (Van der Zande *et al*., 2019). For QSR 2023, the Eutrophication Thematic Assessment has emphasised the need to further reduce eutrophication effects in the Greater North Sea, see: Condition of Benthic Habitat Communities: Assessment of some Coastal Habitats in Relation to Nutrient and/or Organic Enrichment. As a result of management measures, nutrient loads from river discharge into the Greater North Sea have been reduced considerably since 1988, when the OSPAR Contracting Parties agreed to limit inorganic nitrogen and phosphorus inputs to 50% of 1985 levels (Desmit et al., 2020). Reduction objectives have mostly been achieved for phosphorus, but nitrogen has been more difficult to mitigate (McQuatters-Gollop et al., 2007; Riemann et al., 2016). The greater success in mitigating phosphorus may, however, lead to changes in phytoplankton community structure (see: Eutrophication Thematic Assessment, Input of Nutrients to the OSPAR Maritime Area).

Surface warming and a reduction in nutrient inputs from rivers have contributed to declining primary production and phytoplankton biomass across the North Sea (Capuzzo *et al*., 2018; Desmit *et al*. 2020). These reductions have primarily occurred within variable salinity and coastal pelagic habitats and may be associated with changes in the abundance of micro-phytoplankton, including diatoms and dinoflagellates (Spilling *et al*., 2018; Xiao *et al*., 2018). Declines in the abundance of diatoms and dinoflagellates have co-occurred with increases in the proportion of biomass from the pico- and nano-phytoplankton size fractions in the western English Channel (Schmidt *et al*., 2020). A major contributor to this shift is the cyanobacterium *Synechococcus*, which flourishes under low-nutrient conditions during summer stratification (Schmidt *et al*. 2020). However, its small size and low nutrient content make it a poor primary producer unlikely to sustain shelf food webs and may lead to community changes in the upper food web levels.

Nutrient inputs to the North Sea have been reduced as a result of efforts to mitigate eutrophication. While this has been an important step towards combating eutrophication in variable salinity and coastal pelagic habitats, it is also likely to limit the productivity of the system (Skogen *et al*., 2004). The results of the indicator assessments for the Greater North Sea suggest that these reductions, more so for phosphate than for nitrate (reduction of 70% for phosphate and 50% for nitrate; van Beusekom *et al*., 2009), may have generated an imbalance between two essential nutrients for phytoplankton production by effectively increasing the ratio of nitrogen to phosphorus. This imbalance may have impacted phytoplankton communities, as indicator assessment results revealed the nitrogen to phosphorus ratio (N/P ratio) as the most important pressure associated with the reduction in phytoplankton biomass (PH2) (see: Changes in Phytoplankton Biomass and Zooplankton Abundance, Input of Nutrients to the OSPAR Maritime Area). These changes have altered the structure of phytoplankton communities, resulting in a general pattern of increase in the abundance of dinoflagellates relative to diatoms (PH1/FW5, Changes in Phytoplankton and Zooplankton Communities).

The Greater North Sea has also experienced a much faster temperature increase than the North-East Atlantic due to its shallow bathymetry (mean depth 95 m), particularly along its southern coast. In southern areas of the Greater North Sea, warming has led to nutrient limitation from increased stratification, driving a decline in diatom abundance (Edwards *et al*., 2022). In more northern areas of the North Sea which exhibit less nutrient limitation because of their origin in Atlantic waters, warming has elevated metabolic rates, leading to greater diatom biomass in the spring bloom (Edwards *et al*., 2022). Continued warming is driving poleward range shifts in copepods (Defriez *et al*., 2016) at alarmingly fast rates (Beaugrand *et al*., 2009). There is also evidence that meroplankton, the larvae of benthic organisms (**Figure S.6**), and particularly echinoderms, molluscs and arthropods, have responded positively to the increase in temperature (Kirby *et al*., 2008) despite a declining trend in primary production (Capuzzo *et al*., 2018). Elevated water temperatures may facilitate increases in meroplankton abundance by increasing the reproductive output of some benthic invertebrates, particularly the sea urchin *Echinocardium cordatum* (Kirby *et al.*, 2007). Increased temperatures may similarly improve the survival of egg and larval stages for small-bodied fish (Rijnsdorp *et al.*, 2009).

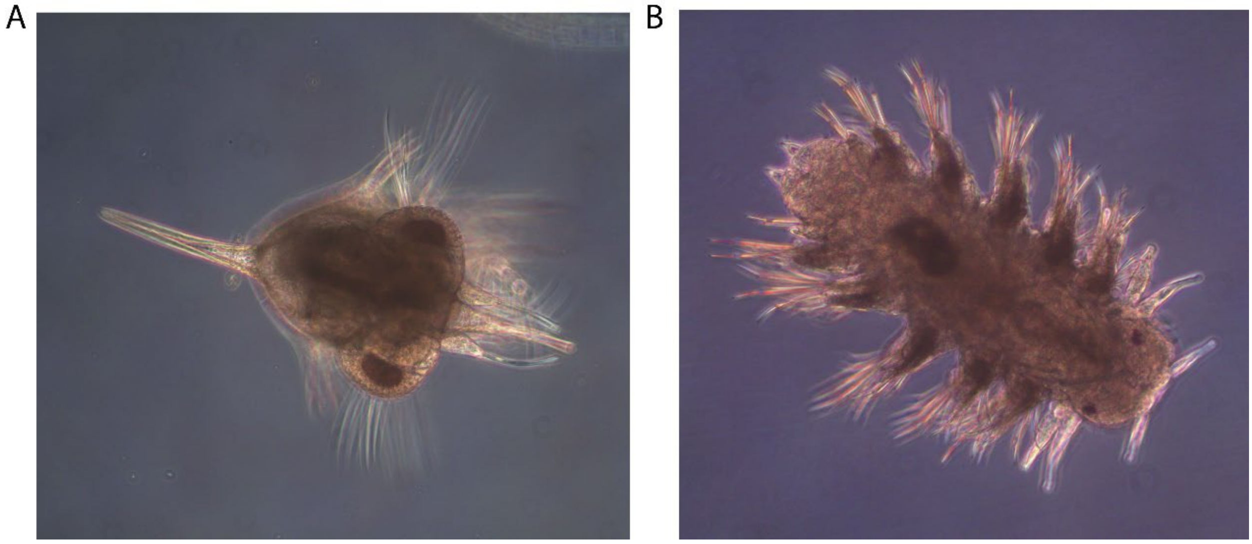


Figure S.6: Meroplankton are increasing in abundance in the Greater North Sea. Meroplankton are the planktonic larvae of benthic invertebrates, and changes in their abundance can reveal information about connectivity between the benthic and pelagic environment. Meroplankton are a taxonomically diverse group which includes decapod crustaceans, such as *Cancer pagurus* (A), polychaete worms, such as *Nereis* spp. (B), molluscs, cirripedes, echinoderms, bryozoans, among several others. Image credits: Tanja Burgmer (A, B)

The indicator assessments PH1/FW5 Changes in Phytoplankton and Zooplankton Communities, PH2 Changes in Phytoplankton Biomass and Zooplankton Abundance and PH3 Changes in Plankton Diversity also concluded that climate change has impacted benthic-pelagic coupling in coastal and shelf areas over the past 60 years, with rising sea surface temperatures concomitant with increasing trends in the abundance of meroplankton, likely by driving increased reproduction and recruitment. Conversely, holoplankton, which spend their entire lifecycle as plankton, displayed decreasing abundance trends over the same period. A shallowing mixed layer, typically driven by sustained warming and stable atmospheric conditions, also co-occurred with decreasing trends in zooplankton abundance (PH2; Changes in Phytoplankton Biomass and Zooplankton Abundance). This shallowing mixed layer concentrates productivity within a smaller water volume, thus limiting the flux of nutrients, and imposing further limitations on productivity.

Pelagic habitats in the Celtic Seas (Region III)

In Region III, the status for variable salinity habitats was unknown since this was the status for both PH1/FW5 Changes in Phytoplankton and Zooplankton Communities and PH2 Changes in Phytoplankton Biomass and Zooplankton Abundance indicators, while the PH3 Changes in Plankton Diversity indicator was not assessed (**Table S.9**). Due to all three pelagic habitat indicators detecting a trend associated with human activity in coastal habitats, the status for coastal habitats was classified as not good environmental status. The shelf habitats result identified a trend associated with human activity for both PH1/FW5 and PH2 indicators (unknown for PH3) which resulted in the status of shelf habitats being classified as not good. Considering that coastal and shelf habitats had not good environmental status while only variable salinity habitats had unknown status (**Table S.9**), the status for pelagic habitats in the Celtic Seas (Region III) is not good. The integration of confidence scores for common indicators in the Celtic Seas resulted in an overall score of High for this OSPAR Region (**Table S.10**).

Table S.9: The status for each common and candidate indicator within each pelagic habitat type for the Celtic Seas (OSPAR Region III), derived from the integration of results for each indicator

Region	Habitat	PH1/FW5	PH2	PH3	Habitat Status	Region Status
Celtic Seas (Region III)	Variable salinity	Unknown	Unknown	Not assessed	Unknown	Not good
	Coastal	Detected trend linked to human activity	Detected trend linked to human activity	Detected trend linked to human activity	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Not assessed	Not assessed	Not assessed	Not assessed	

Table S.10: Confidence assessment of the type, amount, quality, and consistency of evidence (i.e. Robust, Medium, or Limited), as well as the degree of agreement in the results (i.e. High, Medium, or Low), for the pelagic habitat indicators assessed in the Celtic Seas (OSPAR Region III). Colours are used for interpretation

Region	Criteria	PH1/FW5	PH2	PH3	Criteria Status	Region Status
Celtic Seas (Region III)	Agreement	High	High	High	High	High
	Evidence	Medium	Medium	Medium	Medium	

The Celtic Seas differ from the adjacent Greater North Sea in that they are more strongly influenced by conditions in the Atlantic Ocean, particularly along the edge of the continental shelf. This region is also characterised by more complex bathymetry, including slope, canyons, ridges, and seamounts, which generate local and regional influences on hydrography (ICES, 2021). Within shallower shelf waters, sea surface temperatures are rising, driving an increase in summer stratification and nutrient limitation (ICES, 2021).

Long-term declines in dinoflagellate abundance have been observed in offshore areas (Hinder *et al*., 2012) and show strong negative correlation with the rising trend in sea surface temperature (Bedford *et al*., 2020). Conversely, within more coastal and inshore waters, increases in dinoflagellate abundance have been detected, which may have implications for the frequency and severity of harmful algal blooms (HABs), impacting pelagic and benthic communities as well as aquaculture (Bresnan *et al*., 2021). Eutrophication in the Celtic Seas typically occurs only within inlets, estuaries and other semi-enclosed areas of freshwater influence.

The abundance of holoplankton in the Celtic Seas has declined over the past 60 years, with the net trend primarily driven by a 50% reduction in small copepod abundance during summer (Bedford et al., 2020). The decline in copepods is probably driven by the earlier occurrence of the spring phytoplankton bloom (Atkinson *et al*., 2015) and the increasing contribution of picophytoplankton to overall phytoplankton abundance (Schmidt et al., 2020), a size fraction which is too small for most microzooplankton to eat. Northward range shifts in cold-water zooplankton assemblages have also occurred over recent decades (Beaugrand *et al*., 2002; Harris *et al*., 2015), driving declining abundance trends in cold-water species throughout the Celtic Seas. Such range shifts have driven a change in the dominant *Calanus* copepod taxa, with the cold-water *C. finmarchicus* being mostly replaced by the warm-water *C. helgolandicus* (Beaugrand, 2003) (**Figure S.7**).

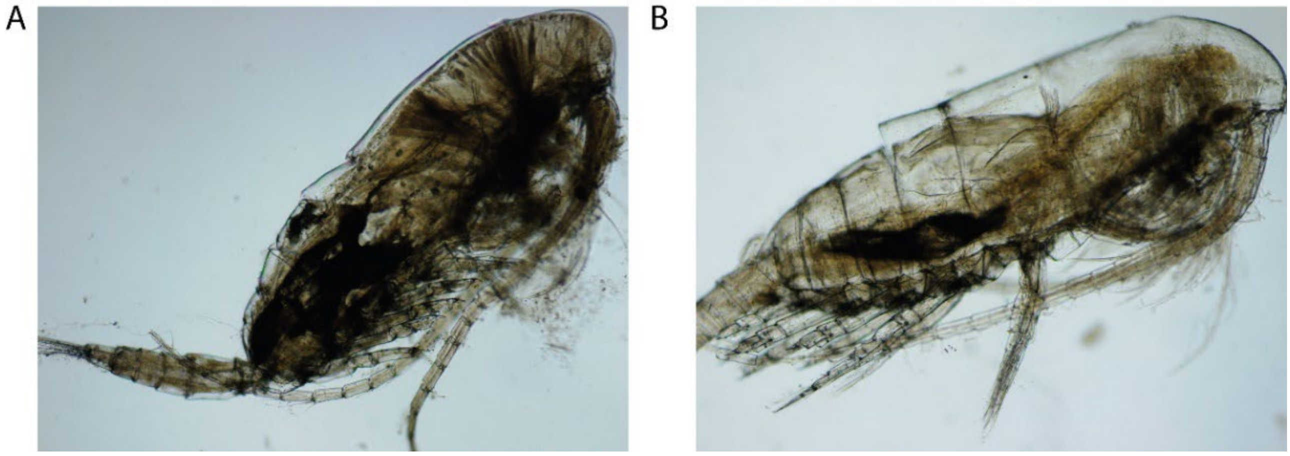


Figure S.7: In the Celtic Seas and Greater North Sea, the temperate copepod *Calanus helgolandicus* (A) is quickly becoming the dominant species, while the boreal copepod, *Calanus finmarchicus* (B) has shifted its range further north due to climate change. These two species are functionally similar, despite their differences in thermal range. Image credits: Hannah Lloyd-Hartley (A, B)

Phytoplankton biomass has declined across pelagic habitats over the last two decades, as revealed by *in situ* and satellite data (Gohin *et al*., 2019). Recent studies have linked these declines in biomass to surface warming and phosphorus limitation driven by variation in natural climatic cycles (Gohin *et al*., 2019; Romero *et al*., 2013). Over the five-year assessment period for the QSR, the PH2 indicator, Changes in Phytoplankton Biomass and Zooplankton Abundance, also detected this decline in phytoplankton biomass. Within variable salinity pelagic habitats, the decline in phytoplankton biomass has been attributed to decreasing nitrate input from rivers, due to reductions in river outflow (Gohin *et al*., 2019).

The results of the indicator assessments for Region III showed that reductions in nutrients, more so for phosphate than for nitrate (Gowen et al., 2008), along with increased stratification due to rising sea surface temperature, may also be contributing to decreasing trends in diatom abundance (Edwards *et al*., 2022) and in overall phytoplankton biomass (**Figure S.8**) Winter Nutrient Concentrations in the Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast. The PH2 assessment Changes in Phytoplankton Biomass and Zooplankton Abundance noted a decreasing trend in phytoplankton biomass between 2015 and 2019, without drawing any particular conclusions on environmental status. By contrast, the assessment of chlorophyll-*a* concentration in the Greater North Sea and Celtic Seas (from HASEC; Concentrations of Chlorophyll-a in the Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast) determined that variable salinity and coastal habitats were in moderate, poor, or bad status during this period, since chlorophyll-*a* concentrations exceeded threshold levels. Discrepancies between the chlorophyll-*a* concentration in the Greater North Sea and Celtic Seas indicator Concentrations of Chlorophyll-a in the Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast and the PH2 assessment Changes in Phytoplankton Biomass and Zooplankton Abundance are probably due to different datasets underlying the assessments [Eutrophication Thematic Assessment]. Better identification of the synergies and discrepancies between pelagic habitat and food web indicators, as well as their causes, are being further investigated under Task 1.5 of the NEA PANACEA project.

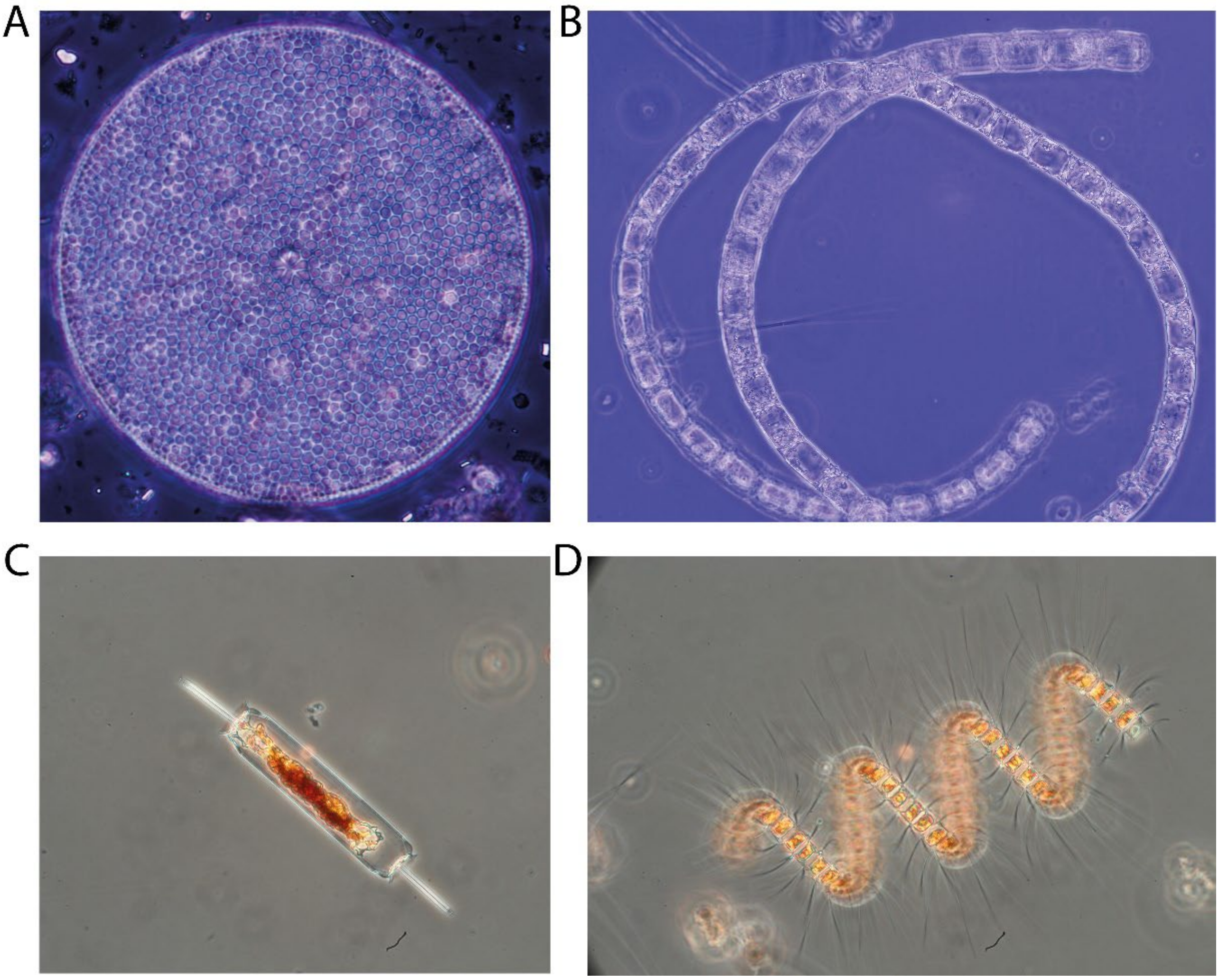


Figure S.8: Diatoms are decreasing in abundance in the Celtic Seas. Diatoms are phytoplankton with silicious cell walls. They are highly abundant and play an essential role in sustaining marine food webs. Common diatoms in the OSPAR Maritime Area include *Coscinodiscus radiatus* (A), *Bellerochea horologicalis* (B), *Ditylum brightwellii* (C) and *Chaetoceros debilis* (D), among many others. Image credits: Sandra Meier (A, B), Nils Hintz (C, D)

Coastal regions were characterised by contrasting trends, particularly for zooplankton, with decreasing trends in the abundance of several phytoplankton and zooplankton lifeforms Changes in Phytoplankton and Zooplankton Communities, while zooplankton abundance anomalies showed a net increasing trend. These contrasting trends, as well as changes in phytoplankton and zooplankton community composition from pre-2015 conditions, were statistically linked to rising sea surface temperature, accelerated by the warming phase of a natural climatic cycle (i.e., Atlantic Multidecadal Oscillation). With the current analysis method it was not possible to disentangle the separate influences of these two effects.

The contrasting increase in zooplankton abundance despite the decline in phytoplankton biomass suggests that phytoplankton are not currently exerting bottom-up control on zooplankton production, or that phytoplankton abundance is currently excessive; bottom-up control on zooplankton may become more important if phytoplankton biomass continues to decline. Larval fish can also exert top-down control on zooplankton by contributing to their mortality (Ji *et al*., 2013)., However, the PH1/FW5 indicator Changes in Phytoplankton and Zooplankton Communities detected no trend in larval fish abundance in the Celtic Seas. It is likely that larval fish are also currently at levels below those required to become a limiting influence on zooplankton abundance.

Reductions in pH may have also been a factor within coastal and shelf habitats; however, it is important to note that this inference was based solely on modelled data. This result should be interpreted with caution, as the effects of pH are often obscured by the combined effects of other climatic, chemical, and biotic drivers (Beare *et al*., 2013). Changes in pH can be linked to changes in primary production, since phytoplankton ingest Dissolved Inorganic Carbon (DIC) to fuel growth and reproduction, but also to the concentration of atmospheric carbon dioxide, the main driver of global warming. Further investigation, taking advantage of *in situ* pH measurements from long-term monitoring programmes, will help improve scientific understanding about the impacts of decreasing pH on the plankton community.

Pelagic habitats in the Bay of Biscay and Iberian coast (Region IV)

No determination could be made for variable salinity habitats in Region IV since they were not assessed by the PH1/FW5 and PH2 indicators (**Table S.11**). Due to the coastal habitats assessed as having a trend linked with human activities in PH2, while PH1/FW5 was unknown, the status for coastal habitats was also classified as not good. Both shelf and oceanic / beyond shelf habitats detected trends linked to human activities for PH1/FW5 and PH2, and therefore the status for shelf and oceanic / beyond shelf habitats was not good. Considering that coastal, shelf, and oceanic / beyond shelf habitats were all in not good environmental status (**Table S.11**), the status for pelagic habitats in the Bay of Biscay and Iberian Coast (Region IV) was also not good. The integration of confidence scores for common indicators in the Bay of Biscay and Iberian Coast resulted in an overall score of Medium for this OSPAR Region (**Table S.12**) (see: CEMP Guideline for Pelagic Habitats Thematic Assessment Integration Method).

Table S.11: The status of each Common and Candidate indicator within each pelagic habitat type for the Bay of Biscay and Iberian Coast (OSPAR Region IV), derived from the integration of results for each indicator. Diagonally hatched cells indicate that an indicator has candidate status in the region and that a pilot assessment has been produced. PH3 results have been presented for information purposes only

Region	Habitat	PH1/FW5	PH2	PH3	Habitat Status	Region Status
Bay of Biscay and Iberian Coast (Region IV)	Variable salinity	Not assessed	Not assessed	Not assessed	Not assessed	Not good
	Coastal	Unknown	Detected trend linked to human activity	Not good	Not good	
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	
	Oceanic	Detected trend linked to human activity	Detected trend linked to human activity	Unknown	Not good	

A pilot assessment of the PH3 indicator was also produced for the Bay of Biscay and Iberian Coast (OSPAR Region IV). However, since the PH3 indicator is only a candidate indicator in the present Region, the results are not described in detail below. For further information, please consult the PH3 indicator assessment.

Table S.12: Confidence assessment of the type, amount, quality, and consistency of evidence (i.e., Robust, Medium, or Limited) as well as the degree of agreement in the results (i.e. High, Medium, or Low) for the pelagic habitat indicators assessed in the Bay of Biscay and Iberian Coast (OSPAR Region IV). Colours are used for interpretation. Diagonally hatched cells indicate that an indicator has candidate status in the Region and that, while a pilot assessment has been conducted, a confidence assessment has not been produced

Region	Criteria	PH1/FW5	PH2	PH3	Criteria Status	Region Status
Bay of Biscay and Iberian Coast (Region IV)	Agreement	High	High	Not assessed	High	Medium
	Evidence	Limited	Limited	Not assessed	Limited	

The Bay of Biscay and Iberian Coast are characterised by marked seasonal mixing and stratification dynamics typical of temperate seas. Productivity in this Region is driven by wind-driven upwelling, river outflow and tidal processes, making this pelagic ecosystem particularly productive, with large variations in productivity at smaller scales (ICES, 2021). The Bay of Biscay and Iberian Coast Region has experienced several important changes in recent decades. Climate change has influenced pelagic habitats throughout this Region, with the strongest warming occurring over the past two decades, particularly within the Gulf of Cadiz (ICES, 2021). Surface warming has been responsible for driving decreasing trends in zooplankton abundance and community-wide changes, with cold-water species being replaced by warm-water species as their distributions shift northward (Bode et al., 2009). Strong surface warming has also intensified stratification in recent years, countering the influence of increasing local wind speed on upwelling intensity (Sousa et al., 2020). In contrast, estuarine sites along the Iberian coast have experienced decreasing trends in wind speed over the past 60 years, with current trends predicted to continue until at least 2100 (Álvarez Salgado et al., 2008).

Eutrophication is an important pressure in the Bay of Biscay, particularly within variable salinity and coastal pelagic habitats. However, in contrast to the decrease in inorganic nitrate and phosphorus achieved through management measures in other OSPAR Regions, nitrate concentrations have remained relatively stable in the Bay of Biscay. During the period between 2012 and 2016, both nitrogen and phosphorus remained above threshold levels, and GES was not achieved for Criterion 1 under Descriptor 5 of the EU MSFD (Nutrients in the Water Column) (Lefebvre and Devreker, 2020) (*OSPAR acts as a coordination platform in the North-East Atlantic for the regional implementation of the EU Marine Strategy Framework Directive (MSFD) that aims to achieve a Good Environmental Status (GES) in European marine environments, as well as for the coordination of other national frameworks. The characteristics of GES are determined by the individual EU member states, based on criteria elements, threshold values and methodological standards set regionally or at EU level. Norwegian, Icelandic, United Kingdom, Greenlandic and Faroese marine areas are not covered by the MSFD.*) (See: Winter Nutrient Concentrations in the Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast).

To support QSR 2023, the Bay of Biscay and Iberian Coast (OSPAR Region IV) was sub-divided into assessment units enabling the pelagic habitat indicators to be resolved at beyond the regional scale. However, because this OSPAR Region extends beyond the boundaries of the hydrological model used to define the COMP4 assessment units for the Greater North Sea and the Celtic Seas (OSPAR Regions II and III respectively; DCSMv6

FM), it was necessary to adapt a separate methodology to define assessment units within it. Although the procedure for sub-dividing the Bay of Biscay and Iberian Coast (OSPAR Region IV) has been validated by OSPAR (see: COMP4 annexes), for the purposes of this and other eutrophication and food web assessments it needs to be reviewed in order to better represent the oceanography and plankton dynamics of the Region and to ensure greater consistency and accuracy in the conclusions of subsequent OSPAR assessments.

In agreement with the results of the PH2 indicator for coastal habitats, natural climatic variability (i.e., the North Atlantic Oscillation) and surface warming have been extensively reported as factors influencing the variability of phytoplankton biomass (Bode et al., 2013). The declines in biomass detected by the PH2 indicator were supported by the PH1/FW5 indicator, which revealed a significant increase in the abundance of dinoflagellates, while diatom abundance remained stable (Edwards et al., 2022). In agreement with the increasing trend in copepod abundance detected by the PH2 indicator, Bode et al. (2013) also reported increasing trends in copepod abundance at coastal stations, except for the north-west coast of Spain, where copepod abundance has declined due to surface warming (Bode et al., 2020).

Long-term studies have explored the complex dynamics of coastal plankton communities in this region (Bode et al., 2020; Buttay et al., 2016). While the PH1/FW5 indicator revealed declining abundance trends for most planktonic lifeforms (e.g., small copepods, large copepods and holoplankton), meroplankton abundance increased (Bode et al., 2020). Similar important shifts in the plankton community have been observed over the past twenty years off the coast of Galicia. Bode et al. (2020) identified the year 1998 as marking a shift in the relative abundance of meroplankton versus holoplankton, with the former becoming more dominant during a period of wet conditions and surface warming. The year 2002 marked a second shift, with increasing microzooplankton abundance associated with changes to local oceanographic conditions (Bode et al., 2020). However, these results should be interpreted with caution, since there was high variability in long-term trends at site scale (Richirt *et al.,* 2019).

The indicator assessment results (see: PH1/FW5 Changes in Phytoplankton and Zooplankton Communities and PH2 Changes in Phytoplankton Biomass and Zooplankton Abundance) showed that rising sea surface temperature was statistically linked to decreasing trends in small and large copepods and to total zooplankton abundance within shelf and oceanic pelagic habitats. Within these offshore areas nearly all planktonic lifeforms have experienced decreasing long-term abundance trends, indicating a reduction in the energy available to sustain higher trophic levels. Unfortunately, no data were available to evaluate any indicators within variable salinity habitats. Similarly, there were no suitable data available to evaluate change in zooplankton lifeforms within coastal habitats.

Pelagic habitats in the Wider Atlantic (Region V)

The region-specific summary for the Wider Atlantic (OSPAR Region V) has been entirely based on the scientific literature, since no indicator assessments were conducted in this Region.

The bathymetry of Region V consists primarily of abyssal plain, interrupted by the dominant Mid-Atlantic Ridge. It is also characterised by the presence of seamounts, of which 143 are scattered within its boundaries (91% of all seamounts occurring within the OSPAR Maritime Area) (Harris et al., 2014). While upwelling around seamounts is often hypothesised to generate areas of high phytoplankton and zooplankton productivity, studies within Region V have not found this to be the case (Kutti et al., 2019). Seamounts do, however, act as aggregation sites for demersal and pelagic fish stocks and are thus heavily targeted by high seas fisheries (Kutti et al., 2019). This high concentration of fishing pressure around seamounts may impact pelagic food webs (Clark et al., 2010).

In the Wider Atlantic, the North Atlantic Current (NAC) is the dominant influence on pelagic habitats and generates the Subpolar Front, which sharply delineates Atlantic waters from the much colder Arctic waters to the north (Belkin and Levitus, 1996). Seasonal variations in Region V are generally of much lower magnitude than in Arctic Waters. This stability is driven by the difference in latitude coupled with strong bathymetric steering, generating spatially stable hydrodynamic regimes of high mesoscale turbulence in the central North Atlantic (Rossby, 1996). This turbulence generates high mixing, which fuels phytoplankton productivity. The phytoplankton in this region are eaten by herbivorous zooplankton, particularly Calanoid copepods, together with *Oithona* and *Oncaea* spp., which dominate zooplankton abundance (Woodd-Walker et al., 2002). The high spatial stability of productive conditions in the central North Atlantic allows the region to support high numbers of mesopelagic fish, seabirds and higher predators (Davies et al., 2021).

This is the most isolated OSPAR Region, with the Azores constituting the only major landmass within its boundaries and most of its area consisting of international waters. As a result of its isolation, there have been very few recent studies focusing specifically on changes in the state of pelagic habitats within this Region. Regular monitoring programmes are scarce and most studies within this Region rely solely on Continuous Plankton Recorder (CPR) or satellite data. Recent investigations of the phytoplankton community from long-term time-series (1958 to 2017) have demonstrated a trend, linked to climate warming, of increasing diatom abundance in northerly waters, and a decline in diatom abundance in southerly waters in the North-East Atlantic (Edwards et al., 2022). The abundance of euphausiids (i.e., krill) in this Region has also experienced a decreasing trajectory over the past 60 years coincident with latitudinal constriction of their optimal thermal range (Edwards et al., 2021).

Habitat-specific summary

In the description of habitat-specific results below, the linkage between indicators and pressures refers to the pressure which best predicts each indicator component, while other pressures may have an important but less statistically significant contribution to the observed changes in pelagic habitats. Relationships with other pressures are not reported here, although they are described in the relevant indicator assessments: PH1/FW5 Changes in Phytoplankton and Zooplankton Communities, PH2 Changes in Phytoplankton Biomass and Zooplankton Abundance, PH3 Changes in Plankton Diversity.

Pelagic habitats in the Greater North Sea (Region II)

Table S.13: The status of each Common and Candidate indicator within each pelagic habitat type for the Greater North Sea (OSPAR Region II), derived from the integration of the results for each indicator. Diagonally hatched cells indicate that an indicator has candidate status in the region and that a pilot assessment has been produced. PH3 results have been presented for information purposes only

Region	Habitat	PH1/FW5	PH2	PH3 - Pilot Assessment
Greater North Sea (Region II)	Variable salinity	Unknown	Unknown	Not good
	Coastal	Unknown	Detected trend linked to human activity	Not good
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown
	Oceanic	Not assessed	Not assessed	Not assessed

A pilot assessment of the PH3 indicator was also produced for the Greater North Sea (Region II). However, since the PH3 indicator is only a candidate indicator in the present region, the results are not described in detail below. For further information, please consult the PH3 indicator.

Variable salinity habitats

For variable salinity habitats, PH1/FW5 indicated that dinoflagellates and larval fish have been increasing in abundance, based on long-term trends. Holoplankton, large copepods and small copepods indicate significant decreasing trends. Plankton monitoring datasets were only available for a limited number of assessment units, although with significant gaps in the time-series. Therefore, lower confidence must be assigned to these results, particularly for the zooplankton lifeform time-series. No clear links between changes in lifeform abundance and anthropogenic pressures could be made.

For the PH2 indicator, a strong decreasing trend in phytoplankton biomass was observed. Modelling of the linkage between environmental pressures and phytoplankton biomass attributed this change to decreasing concentrations of dissolved inorganic phosphate. The PH2 indicator also detected a significant downward trend in zooplankton abundance which was linked statistically to the rise in sea surface temperature. It is also likely that the downward trend in phytoplankton biomass influenced the downward trend in zooplankton abundance; however, the PH2 indicator does not currently test phytoplankton biomass as a pressure on zooplankton. Further, the assessment of zooplankton abundance was based on a single assessment unit; there was very low spatial representation of assessment units and a high degree of uncertainty in establishing the status for this pelagic habitat type.

Coastal habitats

For coastal habitats, the PH1/FW5 indicator revealed significant upward trends in meroplankton and larval fish abundance, which may have been associated with the rise in sea surface temperatures and increasing salinity, respectively. The confidence assessment for the indicator revealed generally high spatial and temporal confidence among the time-series considered in the assessment, and high spatial representation of assessment units, except for gelatinous zooplankton. However, there was a high degree of variability in associating trends in lifeform abundance with environmental pressures; thus, the associations with sea surface temperature and salinity lacked confidence.

The PH2 indicator revealed a significant downward trend in phytoplankton biomass. The most important predictor in declining phytoplankton biomass was the increase in the ratio of nitrogen to phosphorus (N/P ratio). This upward trend in the N/P ratio has been a consequence of efforts to combat eutrophication, with greater reductions achieved for phosphorus loading than for nitrogen. Zooplankton abundance indicated a significant upward trend linked to a shallowing of the mixed layer. The contrasting increase in zooplankton abundance despite the decline in phytoplankton biomass suggests that phytoplankton are not currently exerting bottom-up control on zooplankton production; bottom-up control on zooplankton may become more important if phytoplankton biomass continues to decline. However, as stated previously, the PH2 indicator does not currently test phytoplankton biomass as a pressure on zooplankton and further investigation should be carried out.

Shelf habitats

For shelf habitats, the PH1/FW5 indicator revealed that diatoms, meroplankton, and larval fish have undergone significant upward long-term trends, while dinoflagellates, holoplankton, and small copepods experienced significant downward trends. For meroplankton and holoplankton, the abundance trends were associated with rising sea surface temperature with a high degree of spatial consistency. The increase in larval fish abundance was statistically linked to changes in light attenuation. It is likely that larval fish abundance also correlated with spawning stock biomass and reproductive output; however, the PH1/FW5 indicator does not test for this. While no data were available to assess trends for gelatinous zooplankton, the confidence assessment for the indicator revealed generally high spatial and temporal confidence among the time-series considered in the assessment, and high spatial representation of assessment units.

Similar to the patterns observed in coastal habitats, the PH2 indicator also revealed a significant downward trend in phytoplankton biomass, linked to an increase in the ratio of nitrogen to phosphorus (N/P ratio) due to a more successful effort to mitigate phosphorus versus nitrogen. Zooplankton abundance exhibited a significant downward trend linked to the shallowing mixed layer depth. It is also likely that the downward trend in phytoplankton biomass influenced the downward trend in zooplankton abundance; however, the PH2 indicator does not currently test phytoplankton biomass as a pressure on zooplankton.

Oceanic / beyond shelf habitats

While the Greater North Sea (Region II) intersects a small portion of an oceanic / beyond shelf assessment unit (**Figure S.3**), this habitat type was not assessed, since it shares far greater overlap with the Bay of Biscay and Iberian Coast (Region IV).

Pelagic habitats in the Celtic Seas (Region III)

Table S.14: The status of each Common and Candidate indicator within each pelagic habitat type for the Celtic Seas (OSPAR Region III), derived from the integration of results for each indicator

Region	Habitat	PH1/FW5	PH2	PH3
Celtic Seas (Region III)	Variable salinity	Unknown	Unknown	Not assessed
	Coastal	Detected trend linked to human activity	Detected trend linked to human activity	Detected trend linked to human activity
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown
	Oceanic	Not assessed	Not assessed	Not assessed

Variable salinity habitats

For variable salinity habitats, the PH1/FW5 indicator revealed that dinoflagellates have experienced significant upward long-term trends, while all other planktonic lifeforms have undergone significant downward trends. However, there was very low representation of assessment units for all zooplankton lifeforms. For diatoms, trends indicating decreasing abundance were linked to an increase in the ratio of nitrogen to phosphorus. While silicate may have also been an important factor, there were no suitable data available to test this. For large copepods, which were only assessed at a single fixed-point monitoring station, the decreasing trend was linked to a rise in sea surface temperature.

The PH2 indicator detected a significant decline in zooplankton abundance, linked to a decrease in surface current velocity. However, it is probable that changes in water current dynamics were also linked to the rise in water temperature (van der Molen and Pätsch, 2022). PH2 also detected a significantly decreasing trend in phytoplankton biomass, which was linked to a decrease in the concentration of both nitrogen and phosphorus.

Due to a combination of limited data availability within variable salinity habitats and the methodological limitations associated with spatial and temporal interpolation of diversity, the PH3 indicator was not assessed in this habitat.

Coastal habitats

For coastal habitats, the PH1/FW5 indicator showed that dinoflagellates, holoplankton, large copepods, and small copepods all underwent significant downward trends linked to rising sea surface temperature, and, for holoplankton, to pH. No data were available for gelatinous zooplankton. There was high confidence for all time-series assessed and high spatial representation of assessment units.

The pH level of seawater is controlled by the concentration of dissolved inorganic carbon (DIC). Changes in pH can be linked to changes in phytoplankton activity, since phytoplankton ingest DIC to fuel growth and reproduction, but also to the concentration of atmospheric carbon dioxide, the main driver of global warming. The OSPAR Ocean Acidification Other Assessment measured a significant decrease in pH at a rate of -0,0019 yr^{-1} within OSPAR Region III. This decreasing trend in pH was strongly linked with the decreasing trend in phytoplankton biomass detected by the PH2 indicator. However, for reasons described above, the relationship between pH and phytoplankton biomass should be evaluated cautiously and further analysis is necessary to quantify phytoplankton's contribution to pH variability. This general statement also applies to the other OSPAR Regions. The second plankton component of the PH2 indicator, zooplankton abundance, demonstrated a significant upward trend linked to an increase in the Atlantic Multidecadal Oscillation (AMO), which corresponds with the warming phase of natural climate variability in the North Atlantic. The contrasting increase in zooplankton abundance despite the decline in phytoplankton biomass suggests that phytoplankton are not currently exerting bottom-up control on zooplankton production; bottom-up control on zooplankton may become more important if phytoplankton biomass continues to decline.

While trends in holoplankton abundance detected by the PH1/FW5 indicator and trends in phytoplankton biomass revealed by PH2 were statistically significant, long-term trends in plankton community diversity (PH3) were not. Despite this lack of statistical significance, PH3 results trended towards atypical biodiversity composition, indicating greater instability in the plankton community due to high species turnover and increasing relative abundance of dominant taxa. Zooplankton have also shifted towards an atypical community composition, which may have been linked to changes in salinity. However, these long-term trends in zooplankton community diversity (PH3) were also not statistically significant, leading to the conclusion that there were no long-term changes in phytoplankton and zooplankton community composition.

Shelf habitats

For shelf habitats, the PH1/FW5 indicator revealed significant upward trends for meroplankton and significant downward trends for dinoflagellates and holoplankton. For dinoflagellates, the trend showing decreasing abundance demonstrated the strongest correlation with increase in N/P ratio driven by the reduction in anthropogenic nutrient inputs, more so for phosphate than for nitrate. For meroplankton and holoplankton, changes were linked to increasing sea surface temperature and reductions in pH, respectively. Rising temperatures may increase the reproductive output of benthic invertebrates (Kirby et al., 2007; Kirby et al., 2008) and reductions in pH can affect reproduction in copepods (Vehmaa et al., 2016) and can make them more vulnerable to food limitation (Mayor et al., 2015; Pedersen et al., 2014). The confidence assessment for the PH1/FW5 indicator revealed generally high spatial and temporal confidence among the time-series considered in the assessment, and high spatial representation of assessment units. No data were available to assess gelatinous zooplankton.

Reductions in pH were also associated with the decreasing trajectories detected for both phytoplankton and zooplankton components of the PH2 indicator. It is important to note that pH is not an independent variable. Dissolved Inorganic Carbon (DIC) levels from both natural and anthropogenic sources influence pH levels in sea water. Autotrophic phytoplankton take up DIC during the process of photosynthesis, and the increased primary productivity reduces DIC concentrations and potentially increases pH. From the analysis performed here it is not possible to determine if the net change in phytoplankton biomass is the result of changes in pH. This merits further investigation.

No significant long-term changes in phytoplankton or zooplankton community composition were detected with the PH3 indicator. Despite this lack of statistical significance, PH3 results trended towards lower stability in phytoplankton and greater stability in zooplankton community composition. The decrease in stability was most closely linked with the decrease in the concentration of dissolved inorganic phosphate. By contrast, the increasing stability of the zooplankton community was most closely linked with a decrease in light attenuation. Decreasing dinoflagellate abundance, detected with the PH1/FW5 indicator, and decreasing phytoplankton biomass, detected with PH2, probably contributed to the increasing trend in light penetration, as there have been no recent changes in suspended particulate matter (SPM) within shelf habitats in Region III (see: https://moat.cefas.co.uk/ocean-processes-and-climate/turbidity/ for information on SPM). Before it is possible to generate such conclusions it will be necessary to develop an improved methodology for identifying common themes among the results of the three pelagic habitat indicators.

Oceanic / beyond shelf habitats

While the Celtic Seas (Region III) intersects a small portion of an Oceanic / beyond shelf assessment unit (**Figure S.3**), this habitat type was not assessed, since it shares far greater overlap with the Bay of Biscay and Iberian Coast (Region IV).

Pelagic habitats in the Bay of Biscay and Iberian coast (Region IV)

Table S.15: The status of each Common and Candidate Indicator within each pelagic habitat type for the Bay of Biscay and Iberian Coast (OSPAR Region IV), derived from the integration of results for each indicator. Diagonally hatched cells indicate that an indicator has candidate status in the region and that a pilot assessment has been produced. PH3 results have been presented for information purposes only

Region	Habitat	PH1/FW5	PH2	PH3 - Pilot Assessment
Bay of Biscay and the Iberian Coast (Region IV)	Variable salinity	Not assessed	Not assessed	Not assessed
	Coastal	Unknown	Detected trend linked to human activity	Not good
	Shelf	Detected trend linked to human activity	Detected trend linked to human activity	Unknown
	Oceanic	Detected trend linked to human activity	Detected trend linked to human activity	Unknown

A pilot assessment of the PH3 indicator was also produced for the Bay of Biscay and Iberian Coast (OSPAR Region IV). However, since the PH3 indicator is only a candidate indicator in the present region, the results are not described in detail below. For further information, please consult the PH3 indicator assessment.

Variable salinity habitats

For variable salinity habitats, there were no suitable plankton monitoring data available to evaluate the pelagic habitat indicators.

Coastal habitats

For coastal habitats, only phytoplankton data were available to inform the PH1/FW5 indicator. Further, trends in diatoms and dinoflagellates in this case had to be represented by a dataset which records only specimens from the genera *Pseudo-nitzschia* and *Dinophysis*, and thus is not representative of the microphytoplankton community as a whole. While the assessed time-series had moderate confidence, there was poor spatial representation of assessment units, and no clear links could be drawn between changes in lifeform abundance and environmental pressures.

The PH2 indicator revealed a decreasing trend in phytoplankton biomass, associated with the North Atlantic Oscillation (NAO). The NAO is a natural climatic cycle which describes the latitudinal gradient in atmospheric pressure across the North Atlantic. On examining the current literature, it was surprising to observe a significant NAO effect within coastal habitats in the Bay of Biscay, since the effects of the NAO are typically stronger within shelf habitats (e.g., Ferreira et al., 2019). However, pelagic habitat experts who study OSPAR Region IV have stated concerns that the COMP4 assessment units may not fully capture the hydrological and ecological conditions of the Region. For future assessments it will be important to further refine these assessment units to better fit the features and dynamics of distinct pelagic habitats within Region IV. PH2 also revealed an increasing trend in zooplankton abundance, linked to rising sea surface temperature. However, results for zooplankton were obtained from a single fixed-point monitoring station, making spatial confidence limited.

Shelf habitats

For shelf habitats, PH1/FW5 revealed that diatoms, holoplankton, meroplankton, large copepods, and small copepods all showed significant downward trends. No data were available to assess gelatinous zooplankton; however, there was generally high confidence across the assessed time-series and moderate spatial representation of assessment units. Downward trends in holoplankton, large copepods, and small copepods were all linked to rising sea surface temperature.

The PH2 indicator also revealed a significant upwards trend in phytoplankton biomass linked to reduced wind velocity, which generates a more stable surface layer with reduced vertical mixing. This observation is currently supported by several studies in the Region. Off the coast of Galicia and Portugal, phytoplankton biomass tends to increase (Ferreira et al., 2019) as upwelling intensity decreases (Santos et al., 2011). In shelf habitats, patterns of increasing phytoplankton biomass were better explained by variation in climatic conditions and mixed layer depth than by changes in nutrient concentration (Ferreira et al., 2019). In agreement with trends observed in small and large copepods (PH1/FW5 indicator), zooplankton abundance (PH2 indicator) showed a significant downward trend linked to variation in mixed layer depth.

Oceanic / beyond shelf habitats

For oceanic / beyond shelf habitats, the PH1/FW5 indicator demonstrated that meroplankton underwent significant upward trends. All other lifeforms underwent significant downward trends except for gelatinous zooplankton, which were not assessed due to the lack of data. Downward trends in holoplankton, large copepods, and small copepods were all linked to rising sea surface temperature. Despite the low spatial representation of assessment units for informing PH1/FW5, the assessment units considered for this pelagic habitat were spatially extensive and incorporated a very large quantity of samples with wide spatial distribution. This contributed to the high confidence in the time-series used to assess PH1/FW5.

The PH2 indicator revealed a significant downward trend in phytoplankton biomass, correlated with a downward trend in light attenuation (increasing water clarity). However, it is likely that the downward trend in light attenuation was the direct result of the change in phytoplankton biomass. In agreement with PH1/FW5, PH2 also revealed a significant downward trend in zooplankton abundance, linked to increasing sea surface temperature. It is likely that the downward trend in zooplankton abundance was also influenced by the decline in phytoplankton biomass; however, the three indicator assessments currently only consider links to abiotic environmental variables.

References

Aarflot, J.M., Skjoldal, H.R., Dalpadado, P. and Skern-Mauritzen, M. (2018.) Contribution of Calanus species to the mesozooplankton biomass in the Barents Sea. ICES J. Mar. Sci. 75, 2342–2354.https://doi.org/10.1093/icesjms/fsx221

Álvarez-Salgado, X. A., Labarta, U., Fernández-Reiriz, M. J., Figueiras, F. G., Rosón, G., Piedracoba, S. and Cabanas, J. M. (2008). Renewal time and the impact of harmful algal blooms on the extensive mussel raft culture of the Iberian coastal upwelling system (SW Europe). Harmful Algae, 7(6), 849-855.

Atkinson, A., Harmer, R. A., Widdicombe, C. E., McEvoy, A. J., Smyth, T. J., Cummings, D. G. and McConville, K. (2015). Questioning the role of phenology shifts and trophic mismatching in a planktonic food web. Progress in Oceanography, 137, 498-512.

Beaugrand, G. (2003). Long-term changes in copepod abundance and diversity in the north-east Atlantic in relation to fluctuations in the hydroclimatic environment. Fisheries Oceanography, 12(4-5), 270-283.

Beaugrand, G., Luczak, C. and Edwards, M. (2009). Rapid biogeographical plankton shifts in the North Atlantic Ocean. Global Change Biology 15: 1790-1803.

Beaugrand, G., Reid, P. C., Ibanez, F., Lindley, J. A. and Edwards, M. (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. Science, 296(5573), 1692-1694.

Bedford, J., Ostle, C., Johns, D. G., Atkinson, A., Best, M., Bresnan, E. and McQuatters-Gollop, A. (2020). Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. Global Change Biology, 26(6), 3482-3497.

Belkin, I. M. and Levitus, S. (1996). Temporal variability of the subarctic front near the Charlie-Gibbs Fracture Zone. Journal of Geophysical Research: Oceans 101: 28317-28324.

Bode, A., Álvarez, M., García García, L. M., Louro, M. Á., Nieto-Cid, M., Ruíz-Villarreal, M. and Varela, M. M. (2020). Climate and local hydrography underlie recent regime shifts in plankton communities off Galicia (NW Spain). Oceans, 1(4), 181-197.

Bode, A., Alvarez-Ossorio, M. T., Miranda, A. and Ruiz-Villarreal, M. (2013). Shifts between gelatinous and crustacean plankton in a coastal upwelling region. ICES Journal of Marine Science, 70(5), 934-942.

Bode, A., Álvarez-Ossorio, M., Cabanas, J., Miranda, A. and Varela, M. (2009). Recent trends in plankton and upwelling intensity off Galicia (NW Spain). Progress in Oceanography, 83: 342–350.

Bresnan, E., Arévalo, F., Belin, C., Branco, M. A., Cembella, A. D., Clarke, D. and Enevoldsen, H. (2021). Diversity and regional distribution of harmful algal events along the Atlantic margin of Europe. Harmful Algae, 102, 101976.

Buttay, L., Miranda, A., Casas, G., Gonzalez-Quiros, R. and Nogueira, E. (2016). Long-term and seasonal zooplankton dynamics in the northwest Iberian shelf and its relationship with meteo-climatic and hydrographic variability. Journal of Plankton Research, 38(1), 106-121.

Capuzzo, E., C. P. Lynam, J. Barry, D. Stephens, R. M. Forster, N. Greenwood, A. McQuatters-Gollop, T. Silva, S. M. van Leeuwen and G. H. Engelhard. (2018). A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment. Global change biology 24: e352-e364.

Clark, M. R., A. A. Rowden, T. Schlacher, A. Williams, M. Consalvey, K. I. Stocks, A. D. Rogers, T. D. O'Hara, M. White and T. M. Shank. (2010). The ecology of seamounts: structure, function, and human impacts. Ann Rev 2.

Dahlke, S., Hughes, NE., Wagner, PM., Garland, S., Wawrzyniak, T., Ivanov, B. and Maturilli, M. 2020. The observed recent surface air temperature development across Svalbard and concurring footprints on local sea ice cover. Int. J.Climatol. 2020: 1-20.

Dale, T., Bagøien, E., Melle, W. and Kaartvedt, S. (1999). Can predator avoidance explain varying overwintering depth of Calanus in different oceanic water masses? Mar Ecol Prog Ser 179,113- 121.

Dalpadado, P. Arrigo, KR., van Dijken, G.L., Skjoldal, HR., Bagøien, E., Dolgov, AV., Prokopchuk, IP. and Sperfeld, E. (2020). Climate effects on temporal and spatial dynamics of phytoplankton and zooplankton in the Barents Sea. Prog. Oceanofr. 185,1-20.

Davies, T. E., Carneiro, A. P., Tarzia, M., Wakefield, E., Hennicke J. C., Frederiksen, M., Hansen, E. S., Campos, B., Hazin, C. and Lascelles, B. (2021). Multispecies tracking reveals a major seabird hotspot in the North Atlantic. Conservation Letters 14: e12824.

Defriez, E. J., Sheppard, L. W., Reid, P. C. and Reuman, D. C.

(2016). Climate change-related regime shifts have altered spatial synchrony of plankton dynamics in the North Sea. Global Change Biology 22: 2069-2080.

Desmit, X., Nohe, A. =, Borges, A. V., Prins, T., De Cauwer, K., Lagring, R., Van der Zande, D. and Sabbe, K. (2020). Changes in chlorophyll concentration and phenology in the North Sea in relation to de-eutrophication and sea surface warming. Limnology and Oceanography 65: 828-847.

Edwards, M., Beaugrand, G., Kléparski, L., Hélaouët, P. and Reid, P. C. (2022). Climate variability and multi-decadal diatom abundance in the Northeast Atlantic. Communications Earth & Environment, 3(1), 1-8.

Edwards, M., Hélaouët, P., Goberville, E., Lindley, A., Tarling, G. A., Burrows, M. T. and Atkinson, A.. (2021). North Atlantic warming over six decades drives decreases in krill abundance with no associated range shift. Communications biology 4:644.

Eriksen, E., Skjoldal, H.R., Dolgov, A.V., Dalpadado, P., Orlova, EL. and Prozorkevich, D.V. (2016). The Barents Sea euphausiids: methodological aspects of monitoring and estimation of abundance and biomass. ICES Journal of Marine Science, 73:1533–1544.

Eriksen, E., Skjoldal, HR., Gjøsæter, H. and Primicerio, R. (2017). Spatial and temporal changes in the Barents Sea pelagic compartment during the recent warming. Progress in Oceanography 151, 206-226.

Ferreira, A., Garrido-Amador, P. and Brito, A. C. (2019). Disentangling environmental drivers of phytoplankton biomass off western Iberia. Frontiers in Marine Science, 6, 44.

Gohin, F., Van der Zande, D., Tilstone, G., Eleveld, M. A., Lefebvre, A., Andrieux-Loyer, F. and Saulquin, B. (2019). Twenty years of satellite and *in situ* observations of surface chlorophyll-a from the northern Bay of Biscay to the eastern English Channel. Is the water quality improving? Remote Sensing of Environment, 233, 111343.

Gowen, R. J., Tett, P., Kennington, K., Mills, D. K., Shammon, T. M., Stewart, B. M. and Wither, A. (2008). The Irish Sea: is it eutrophic? Estuarine, Coastal and Shelf Science, 76(2), 239-254.

Harris, P., M. Macmillan-Lawler, J. Rupp and E. Baker. (2014). Geomorphology of the oceans. Marine Geology 352: 4-24.

Harris, V., Olhede, S. C. and Edwards, M. (2015). Multidecadal spatial reorganisation of plankton communities in the North East Atlantic. Journal of Marine Systems, 142, 16-24.

Hinder, S. L., Hays, G. C., Edwards, M., Roberts, E. C., Walne, A. W. and Gravenor, M. B. (2012). Changes in marine dinoflagellate and diatom abundance under climate change. Nature Climate Change, 2(4), 271-275.

ICES 2021. Celtic Seas ecoregion – Ecosystem Overview. ICES Advice: Ecosystem Overviews. Report.

ICES 2020 a. Working Group on the Integrated Assessments of the Norwegian Sea (WGINOR; outputs from 2019meeting). ICES Scientific Reports. 2:29. 46 s. http://doi.org/10.17895/ices.pub. 5996

ICES 2020 b. Report of the Working Group on Integrated Assessments of the Barents Sea (WGIBAR).

ICES. 2021. Bay of Biscay and the Iberian Coast ecoregion – Ecosystem overview. In Report of the ICES Advisory Committee, 2021. ICES Advice 2021.

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner,D.C. Kvingedal, B. (2005). Sea-Ice Extent and Variability in the Nordic Seas, 1967-2002. I: Drange, H., Dokken,T., Furevik, T., Gerdes, R. and Berger, W. (Red.) b. 158 The Nordic Seas: An Integrated Perspective, Oceanography, Climatology, Biogeochemistry, and Modelling, s. 39-50, American Geophysical Union, Washington DC, USA.

Ji, R., Stegert, C. and Davis, C. S. (2013). Sensitivity of copepod populations to bottom-up and top-down forcing: a modelling study in the Gulf of Maine region. Journal of Plankton Research, 35(1), 66-79.

Kirby, R. R., Beaugrand, G. and Lindley, J. A. (2008). Climate-induced effects on the meroplankton and the benthic-pelagic ecology of the North Sea. Limnology and Oceanography 53: 1805-1815.

Kirby, R. R., Beaugrand, G., Lindley, J. A., Richardson, A. J., Edwards, M. and Reid, P. C. (2007). Climate effects and benthic–pelagic coupling in the North Sea. Marine Ecology Progress Series 330: 31-38.

Kutti, T., Windsland ,K., Broms, C., Falkenhaug, T., Biuw, M., Thangstad, T. H. and Bergstad, O. A. (2019). Seamounts in the OSPAR maritime area-from species to ecosystems. Rapport fra havforskningen.

Lefebvre, A. and Devreker, D. (2020). First Comprehensive Quantitative Multi-Parameter Assessment of the Eutrophication Status from Coastal to Marine French Waters in the English Channel, the Celtic Sea, the Bay of Biscay, and the Mediterranean Sea. Journal of Marine Science and Engineering, 8(8), 561.

Mayor, D. J., Sommer, U., Cook, K. B. and Viant M. R. (2015). The metabolic response of marine copepods to environmental warming and ocean acidification in the absence of food. Scientific Reports, 5(1), 1-12.

McQuatters-Gollop, A., Guerin, L., Arroyo, N. L., Aubert, A., Artigas, L. F., Bedford, J. and Vina-Herbon, C. (2022). Assessing the state of marine biodiversity in the Northeast Atlantic. Ecological Indicators, 141, 109148.

McQuatters-Gollop, A., D. E. Raitsos, M. Edwards and M. J. Attrill. (2007). Spatial patterns of diatom and dinoflagellate seasonal cycles in the NE Atlantic Ocean. Marine Ecology Progress Series 339: 301-306.

Melle W., Ellertsen B. and Skjoldal HR. (2004). In: The Norwegian Sea Ecosystem, H. R. Skjoldal (ed.). Tapir academic press. Trondheim.

Pedersen, S. A., Håkedal, O. J., Salaberria, I., Tagliati, A., Gustavson, L. M., Jenssen, B. M. and Altin, D. (2014). Multigenerational exposure to ocean acidification during food limitation reveals consequences for copepod scope for growth and vital rates. Environmental Science & Technology, 48(20), 12275-12284.

Richirt, J., Goberville, E., Ruiz-Gonzalez, V. and Sautour, B. (2019). Local changes in copepod composition and diversity in two coastal systems of Western Europe. Estuarine, Coastal and Shelf Science, 227, 106304.

Riemann, B., J. Carstensen, K. Dahl, H. Fossing, J. W. Hansen, H. H. Jakobsen, A. B. Josefson, D. Krause-Jensen, S. Markager and P. A. Stæhr. (2016). Recovery of Danish coastal ecosystems after reductions in nutrient loading: a holistic ecosystem approach. Estuaries and Coasts 39: 82-97.

Rijnsdorp, A. D., Peck, M. A., Engelhard, G. H., Möllmann, C and Pinnegar, J. K. (2009). Resolving the effect of climate change on fish populations. ICES journal of marine science 66: 1570-1583.

Romero, E., Garnier, J., Lassaletta, L., Billien, G., Le Gendre, R. and Riou, P. (2013). Largescale patterns of river inputs in southwestern Europe: seasonal and interannual variations and potential eutrophication effects at the coastal zone. Biogeochemistry 113, 481.

Rossby, T. 1996. The North Atlantic Current and surrounding waters: At the crossroads. Reviews of Geophysics 34: 463-481.

Santos, F., Gómez-Gesteira, M., DeCastro, M. and Álvarez, I. (2011). Upwelling along the western coast of the Iberian Peninsula: dependence of trends on fitting strategy. Climate Research, 48(2-3), 213-218.

Schmidt, K., Birchill, A. J., Atkinson, A., Brewin, R. J., Clark, J. R., Hickman, A. E., Johns, D. G., Lohan, M. C., Milne, A. and Pardo, S. (2020). Increasing picocyanobacteria success in shelf waters contributes to long-term food web degradation. Global Change Biology 26: 5574-5587.

Skogen, M. D., Søiland, H. and Svendsen, E. (2004). Effects of changing nutrient loads to the North Sea. Journal of Marine Systems, 46(1-4), 23-38.

Sousa, M. C., Ribeiro, A., Des, M., Gomez-Gesteira, M., deCastro, M. and Dias, J. M. (2020). NW Iberian Peninsula coastal upwelling future weakening: Competition between wind intensification and surface heating. Science of the Total Environment, 703, 134808.

Spilling, K., Olli, K., Lehtoranta, J., Kremp. A., Tedesco, L., Tamelander,T., Klais, R., Peltonen, H. and Tamminen, T. (2018). Shifting diatom—dinoflagellate dominance during spring bloom in the Baltic Sea and its potential effects on biogeochemical cycling. Frontiers in Marine Science 5: 327.

Stige, LC., Eriksen, E., Dalpadado P. and Kotaro O. (2019). Direct and indirect effects of sea ice cover on major zooplankton groups and planktivorous fishes in the Barents Sea. ICES Journal of Marine Science, in press. https://doi.org/10.1093/icesjms/fsz063

van Beusekom, J. E., Loebl, M. and Martens, P. (2009). Distant riverine nutrient supply and local temperature drive the long-term phytoplankton development in a temperate coastal basin. Journal of Sea Research, 61(1-2), 26-33.

van der Molen, J. and Pätsch, J. (2022). An overview of Atlantic forcing of the North Sea with focus on oceanography and biogeochemistry. Journal of Sea Research, 102281.

Van der Zande, D., Eleveld, M., Lavigne, H., Gohin, F., Pardo, S., Tilstone, G., Blauw, A., Markager, S. and Enserink, L.. (2019). Joint Monitoring Programme of the EUtrophication of the NOrthSea with SATellite data user case. Journal Of Operational Oceanography 12.

Vehmaa, A., Almén, A. K., Brutemark, A., Paul, A., Riebesell, U., Furuhagen, S. and Engström-Öst, J. (2016). Ocean acidification challenges copepod phenotypic plasticity. Biogeosciences, 13(22), 6171-6182.

Woodd-Walker, R. S., Ward, P. and Ward, A. (2002). Large-scale patterns in diversity and community structure of surface water copepods from the Atlantic Ocean. Marine Ecology Progress Series 236: 189-203.

Xiao, W., Liu, X., Irwin, A. J., Laws, E. A., Wang, L., Chen, B., Zeng, Y. and Huang, B.. (2018). Warming and eutrophication combine to restructure diatoms and dinoflagellates. Water research 128: 206-216.

I - Impacts

Impacts on the provision of ecosystem services by pelagic habitats

Given the current changes occurring in pelagic habitats, in no case is a positive outcome observed or expected for the ecosystem services they provide. Climate change represents the most important pressure on pelagic habitats, but pressures related to nutrient inputs, eutrophication, fishing, introduction of non-indigenous species and other human activities can also impact pelagic habitats. The provision of marine ecosystem services is intrinsically linked to the dynamics of pelagic habitats. The holistic nature of the interactions between physical and biological systems that characterise pelagic habitats means that adverse changes in pelagic characteristics can affect the provision of ecosystem services to the entire marine ecosystem.

This section evaluates the impact that changes in the environmental state of pelagic habitats, as described in the State section, have on the ecosystem services that the North-East Atlantic provides. The section was developed through a literature review combined with expert judgement, using the same methodology across all Thematic Assessments. Several workshops involving ecosystem service experts and pelagic habitat experts were held to discuss and agree the presented results. A detailed description of the anthropogenic pressures that impact pelagic habitat state, and thus the provision of ecosystem services, are provided in the Pressure section. The following provides further details on the role that pelagic habitats (and their state) have in relation to the provision of ecosystem services outlined in **Figure I.1.**

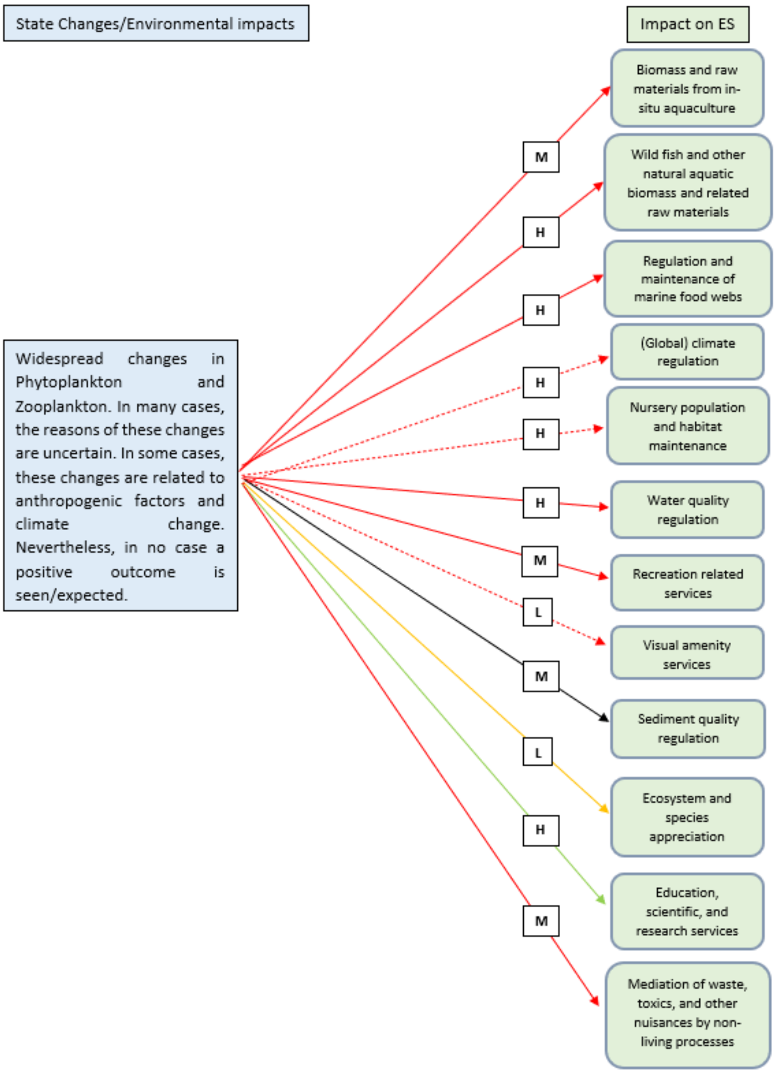


Figure I.1: Schematic depicting the 'State (changes)' - 'Impact on ES' linkages for the Pelagic Habitats thematic assessment. The ecosystem services shown are those considered most relevant in relation to the Pelagic Habitats thematic assessment. Each arrow also denotes an expert judgement estimate of the nature and magnitude of the impact (black arrow = recognition of the existence of the impact but no clear negative or positive impact (uncertain nature); yellow arrow = neutral impact; red arrow = negative impact; red dashed arrow = potential negative impact; green arrow = positive impact; H = high impact; M = medium impact; L = low impact)

Detailed rationale for the role of pelagic habitats (and their state) in relation to the provision of ecosystem services

To assess pelagic habitat status for OSPAR QSR 2023, three indicators based on species (PH3 indicator 'Changes in Plankton Diversity'), functional groups (PH1/FW5 indicator 'Changes in Phytoplankton and Zooplankton Communities'), and community abundance/biomass (PH2 indicator 'Changes in Phytoplankton Biomass and Zooplankton Abundance') were identified. These indicators provide complementary information on the status and functioning of plankton communities, and for a solid overall assessment of pelagic habitat they should be considered simultaneously (OSPAR CEMP, 2018).

In the previous schematic, the message presented within the “State change” box was formulated by the Pelagic Habitats experts. This key message, obtained from an integrated consideration of the results obtained from the different indicators employed in QSR 2023 for the State assessment of Pelagic Habitats, concisely conveys the overall observed state (change) of the pelagic habitats in the OSPAR Maritime Area as a whole.

In the context of OSPAR IA 2017, the assessments demonstrated that for the most recent period (post-2000) zooplankton abundance tended to decrease while phytoplankton biomass tended to increase (OSPAR, 2017i). Additionally, OSPAR assessments of planktonic lifeforms (functional groups) showed that plankton communities (phytoplankton and zooplankton) had experienced significant changes, indicating possible alterations in pelagic habitats and marine ecosystem functioning (OSPAR, 2017i). However, although these assessments demonstrated that important changes had occurred, they were only preliminary assessments, and it is difficult to draw conclusions about direction, implications for the overall marine ecosystem dynamics, and consequently the provision of ecosystem services by pelagic habitats for the OSPAR Maritime Area (OSPAR, 2017i). In the context of the latest OSPAR QSR 2023 assessments, widespread changes in phytoplankton and zooplankton were observed. In some cases, the drivers of these changes are uncertain. In some cases, these changes are related to direct anthropogenic factors as well as climate change. Nevertheless, in no case is a positive outcome observed or expected.

By presenting and describing the ecosystem services underpinned by phytoplankton and zooplankton, and in general by pelagic habitats and their components, it is possible to develop informed assumptions as to which ecosystem services may be impacted (and how) because of major changes in phytoplankton and zooplankton abundance, community functioning, and the overall state of pelagic habitats which may result from environmental impacts related to human-induced pressures (Bedford et al., 2020). The following provides an elaboration on the contribution by plankton, and more generally by pelagic habitats, to the provision of the ecosystem services illustrated in the previous section. In the case of this thematic assessment, it should be noted that climate change represents the most important pressure on pelagic habitats, but pressures related to nutrient inputs, eutrophication, fishing, introduction of non-indigenous species and other human activities can also impact pelagic habitats (see: Trends in New Records of Non-indigenous Species Introduced by Human Activities and the other pressure-related thematic assessments for more details).

The dynamics of the interaction between physical and biological systems underpin the functioning of pelagic habitats. The physical system refers to the entire water column and its gradients of temperature, salinity, density, light, particles, and nutrients. The physical system significantly influences the distribution of pelagic biological communities. Pelagic habitats support biodiversity ranging in size from sub-millimetres (i.e., plankton) to metres (i.e., marine mammals) that involves primary production (e.g., phytoplankton), covers all trophic levels and regulates the physical and chemical conditions of the water (e.g., carbon sequestration) (Magliozzi et al., 2021). Key examples of interactions between pelagic physical and biological systems include the fluxes of matter and energy that sustain food webs, the interactions between different habitats (e.g., benthic-pelagic coupling), climate regulation through atmospheric oxygen production, and carbon sequestration. Many oceanic ecosystem services are mediated by plankton (both phytoplankton and zooplankton) and thus plankton are also used to track changes in upper trophic levels and top-down and bottom-up pressures. The holistic nature of the interactions between physical and biological systems that characterise pelagic habitats means that adverse changes in pelagic characteristics can affect the provision of ecosystem services to the entire marine ecosystem (Magliozzi et al., 2021). Indeed, as argued by Santora et al. (2021), the provision of marine ecosystem services is intrinsically linked to the dynamics of pelagic habitats. Consequently, given the multitude of interacting communities and the innumerable dynamics at play, the task of describing all ecosystem functioning and the resulting ecosystem services relating to the pelagic realm remains challenging (Dickey-Collas et al., 2017). Also, given the complexity of ecological dynamics within pelagic habitats and between habitats (e.g., benthic-pelagic coupling), all the ecosystem services considered in this work could potentially be considered as provided directly or indirectly by pelagic habitats, their ecological components and their interactions with the surrounding marine environment. Nevertheless, as stated by Dickey-Collas et al., (2017), key ecosystem services provided by pelagic habitats can be identified.

Life-cycle maintenance service, which in the most recent CICES v.5.1 classification (Haines-Young and Potschin, 2018) and in the ecosystem services considered in this report is represented by the regulation service nursery population and habitat maintenance (including the protection of natural gene pools), is considered one of the essential ecosystem services in relation to pelagic habitats. Indeed, pelagic habitats act as breeding (including spawning and mating), nursery and feeding grounds, as well as migration and advection routes, thus contributing to the maintenance of habitats and their biodiversity, both for species that live constantly in the water column and species that live in it only for specific stages of their life cycle (Dickey-Collas et al., 2017).

Pelagic habitats are crucial for nourishing the oceans through nutrient cycling, thus contributing directly and indirectly to supporting the growth of biomass in the various trophic levels that make up food webs ('regulation and maintenance of marine food webs'). Also, one of the most tangible ecosystem services from pelagic habitats is represented by fish stocks (wild fish and other natural aquatic biomass and related raw materials) (Hays et al., 2005). In addition, through processes of ocean-atmosphere gas exchange regulation, the ocean is a net sink of atmospheric carbon dioxide ((global) climate regulation). Ocean warming due to climate change pressures is expected to reduce the provision of this ecosystem service by pelagic habitats (Dickey-Collas et al., 2017).

Other ecosystem services that are underpinned by the physical and biological processes taking place in the water column are water quality regulation and the mediation of waste, toxins and other nuisances by abiotic processes. Under natural conditions, organic waste entering the water undergoes degradation processes that include remineralisation by pelagic communities of microbes and accumulation in biomass. As for more persistent contaminants, their toxicity can be reduced through abiotic processes occurring at the ocean-atmosphere interface, such as photochemical and hydrolytic degeneration reactions. Phytoplankton, zooplankton and fish also contribute, albeit to a lesser extent, to further waste degradation in the water column. In addition, abiotic processes such as dispersion and advection help to provide export pathways for wastes that thus avoid being concentrated in hot spots (Watson et al., 2016). The provision of these services, in similar fashion to the other mentioned ecosystem services, may be reduced and/or compromised as a result of major alterations in physical-biological dynamics following environmental impacts related to pressures such as eutrophication, climate change and excessive input of pollutants etc (see pressure-related thematic assessments for more details).

The pelagic realm provides all cultural ecosystem services ranging from the scientific knowledge that can be obtained from the different pelagic environments, educational value, exploration and related technological developments, to services including literature, entertainment, ethical considerations, tourism and spiritual health and wellbeing (Thurber et al., 2014).

Half of the primary production that supports food webs is provided by photosynthetic processes carried out by microbial and phytoplankton communities in the water column. Changes in these communities can in turn affect the survival of organisms at higher levels of the food web. This is one of the main reasons why the ecological processes provided by pelagic habitats contribute directly to the provision of various ecosystem services and indirectly support the provision of ecosystem services also provided by organisms at other levels of the food web (EEA, 2015).

Marine phytoplankton are a well-known provider of ecosystem services, crucially contributing to the climate cycle and functions of the marine ecosystem and beyond. Phytoplankton are one of the main marine ecosystem components that contribute most to providing the ecosystem service of (global) climate regulation. Some phytoplankton species produce dimethylsulphoniopropionate (DMSP), a precursor to dimethyl sulphide (DMS), important for the process of cloud formation. Phytoplankton are also a major contributor to the carbon fixation process and its sequestration in sediments and ocean depths, capturing carbon dioxide from the atmosphere (Tweddle et al., 2018). At the same time, as a food source for pelagic herbivores (including larval stages), phytoplankton also form the basis of marine food webs ('regulation and maintenance of marine food webs'), supporting the production and supply of biomass from the upper trophic levels, including biomass produced in marine aquaculture or mariculture contexts (wild fish and other natural aquatic biomass and related raw materials and biomass and raw materials from in situ aquaculture). Spatial variability in primary productivity and phytoplankton abundance can influence the distributions of upper trophic levels, including fish, birds and marine mammals and, indirectly, the local provision of ecosystem services by these organisms (see: Marine Birds Thematic Assessment, Marine Mammals Thematic Assessment, Fish Thematic Assessment for more details about the range of ecosystem services provided by marine birds, marine mammals, and fish; Tweddle et al., 2018).

It should also be noted that shelf areas support most oceanic primary production but are, at the same time, the areas most directly affected by human activities and related pressures (e.g., offshore oil and gas, wind energy, wave and tidal renewable energy, aquaculture, aggregate dredging and waste dumping; see these sections in the pressure-related OSPAR thematic assessments and Tweddle et al., 2018). The role played by anthropogenic pressures and their impacts in relation to food webs and components such as phytoplankton must be kept in mind. Given the importance of pelagic environments in supporting the entire marine ecosystem, cumulative impacts resulting from human-induced pressures (addressed in the pressure-related thematic assessments) can alter the physical and biological dynamics governing the water column and in turn have a negative cascading effect on the provision of ecosystem services by other habitats that depend on them. Phytoplankton are essential in benthic-pelagic coupling. Benthic-pelagic coupling is crucial for the functioning and balance of food webs as it involves functions from nutrient cycling to energy transfer between habitats (Griffiths et al., 2017). A climate change-related increase in water temperature may cause changes in the timing and decrease in the magnitude of phytoplankton blooms, which in turn may lead to a decrease in the transport of organic matter to the benthos and reduce the release of inorganic nutrients from the marine sediment. Changes in coupling between pelagic and benthic systems can in turn lead to a decrease in benthic productivity and reproduction.

Regarding OSPAR pelagic habitat indicators (Changes in Phytoplankton and Zooplankton Communities, Changes in Phytoplankton Biomass and Zooplankton Abundance), changes in the balance of 'planktonic lifeforms' (phytoplankton and zooplankton), namely the changes in functional group abundance, are analysed to assess the state of the lower trophic levels in the North-East Atlantic. This can be used to detect changes in community functioning, which in turn can inform changes in ecosystem services (Bedford et al., 2020; McQuatters-Gollop et al., 2019). In addition, zooplankton are directly linked to the higher trophic levels representing primary consumers. The presence and abundance of zooplankton, and their predator-prey relationship with other trophic levels, influence fish recruitment and the production of wild biomass in higher trophic levels (wild fish and other natural aquatic biomass and related raw materials) and the biomass produced in mariculture contexts (biomass and raw materials from in situ aquaculture). Zooplankton's contribution to sustaining the balance of food webs ('regulation and maintenance of marine food webs') is also detectable in their role as a grazer for phytoplankton and bacteria and as a provider of nitrogen and phosphorus (nutrient cycling), which has positive effects on the primary productivity of phytoplankton. In addition, zooplankton, through processes such as the export of particles by grazing, the fractioning of sinking particles, and the transport of particulate organic carbon at depth through their diel vertical migration, play a crucial role in the functioning of the oceanic biological carbon pump that contributes to regulating atmospheric carbon dioxide levels ((Global) climate regulation) (Lomartire et al., 2021). Regarding plankton diversity, species composition and abundance are influenced by changes in physical and chemical environmental conditions. Human-induced disturbances can lead to changes in plankton diversity because only some species are able to tolerate altered habitat conditions. Consequently, plankton diversity, as well as plankton lifeform biomass and abundance, will differ between disturbed and undisturbed communities (OSPAR, 2017i).

Examples of the impacts that may result from human-induced pressure are the negative changes in plankton communities due to local-scale inputs of nutrients (e.g., from farming run-off, sewage, dredging). Changes in plankton lifeforms can result from inputs and increases in nutrients. The onset of eutrophication leads to an increase in phytoplankton biomass. However, the composition of the phytoplankton community becomes more uneven, with the disappearance of some species and the predominance of opportunistic species. This leads to a decrease in species diversity due to competitive exclusion. However, this depends on the level of eutrophication: whereas, with a slight increase in eutrophication, the competition loosens, resulting in greater diversity, when there is a further increase in eutrophication, the diversity decreases again due to stress (McQuatters-Gollop et al., 2009; Spatharis et al., 2007). Either way, eutrophication, by impacting plankton and primary productivity, can lead to less desirable food web conditions. Localised changes in nutrients and plankton distribution can also result from changes to hydrological conditions following coastal development and the introduction of infrastructures.

Changes in the balance of food webs can occur because of injury, mortality and/or extraction associated with overfishing (commercial and recreational). The removal of predatory fish can lead to forage fish (plankton consumers) becoming too abundant. In turn, zooplankton are over-consumed, leading to imbalances in plankton communities (changes in plankton biomass and/or abundance). This may then result in changes (reductions) in the energy available for supporting higher trophic levels.

References

Bedford, J., Ostle, C., Johns, D. G., Atkinson, A., Best, M., Bresnan, E. and McQuatters-Gollop, A. (2020). Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. Global Change Biology, 26(6), 3482-3497.

Dickey-Collas, M., Link, J. S., Snelgrove, P., Roberts, J. M., Anderson, M. R., Kenchington, E. and Johannesen, E. (2022). Exploring ecosystem-based management in the North Atlantic. Journal of Fish Biology, 101(2), 342-350.

EEA (2015). State of Europe's seas. EEA Report No 2/2015, European Environment Agency. Retrieved September 23, 2021, from http://www.eea.europa.eu/publications/state-of-europes-seas

Griffiths, J. R., Kadin, M., Nascimento, F. J., Tamelander, T., Törnroos, A., Bonaglia, S. and Winder, M. (2017). The importance of benthic–pelagic coupling for marine ecosystem functioning in a changing world. Global change biology, 23(6), 2179-2196.

Haines-Young, R. and Potschin ,M.B.(2018). Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure. Retrieved from https://cices.eu/content/uploads/sites/8/2018/01/Guidance-V51-01012018.pdf

Hays, G. C., Richardson, A. J. and Robinson, C. (2005). Climate change and marine plankton. Trends in ecology & evolution, 20(6), 337-344.

Lomartire, S., Marques, J. C. and Gonçalves, A. M. M. (2021). The key role of zooplankton in ecosystem services: A perspective of interaction between zooplankton and fish recruitment. Ecological Indicators, 129, 107867. doi: https://doi.org/10.1016/j.ecolind.2021.107867

Magliozzi, C., Druon, J. N., Palialexis, A., Aguzzi, L., Alexande, B., Antoniadis, K. and Zervoudaki, S. (2021). Pelagic habitats under the MSFD D1: scientific advice of policy relevance. European Commission, Luxembourg.

McQuatters-Gollop, A., Atkinson, A., Aubert, A., Bedford, J., Best, M., Bresnan, E. and Tett, P. (2019). Plankton lifeforms as a biodiversity indicator for regional-scale assessment of pelagic habitats for policy. Ecological Indicators, 101, 913-925.

McQuatters-Gollop, A., Gilbert, A. J., Mee, L. D., Vermaat, J. E., Artioli, Y., Humborg, C. and Wulff, F. (2009). How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? Estuarine, Coastal and Shelf Science, 82(4), 583-596. doi: https://doi.org/10.1016/j.ecss.2009.02.017

OSPAR (2017i). OSPAR Intermediate Assessment 2017: Habitats. Retrieved from https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/habitats/

OSPAR CEMP (2018). OSPAR CEMP Guideline. Common indicator: PH1/FW5 Plankton lifeforms (OSPAR Agreement 2018-07). Retrieved from https://www.ospar.org/documents?v=39001

Santora, J. A., Schroeder, I. D., Bograd, S. J., Chavez, F. P., Cimino, M. A., Fiechter, J. and Field, J. C. (2021). PELAGIC BIODIVERSITY, ECOSYSTEM FUNCTION, AND SERVICES. Oceanography, 34(2), 16-37.

Spatharis, S., Danielidis, D. B. and Tsirtsis, G. (2007). Recurrent Pseudo-nitzschia calliantha (Bacillariophyceae) and Alexandrium insuetum (Dinophyceae) winter blooms induced by agricultural runoff. Harmful Algae, 6(6), 811-822.

Thurber, A. R., Sweetman, A. K., Narayanaswamy, B. E., Jones, D. O., Ingels, J. and Hansman, R. L. (2014). Ecosystem function and services provided by the deep sea. Biogeosciences, 11(14), 3941-3963.

Tweddle, J. F., Gubbins, M. and Scott, B. E. (2018). Should phytoplankton be a key consideration for marine management? Marine Policy, 97, 1-9.

Watson, S. C. L., Paterson, D. M., Queirós, A. M., Rees, A. P., Stephens, N., Widdicombe, S. and Beaumont, N. J. (2016). A conceptual framework for assessing the ecosystem service of waste remediation: In the marine environment. Ecosystem Services, 20, 69-81. doi: https://doi.org/10.1016/j.ecoser.2016.06.011

R - Response

Measures to address the status of pelagic habitats

There are no OSPAR measures that directly address pelagic habitats.

Climate change remains the most significant factor affecting the health of the plankton communities that form the pelagic habitat at the scale of the OSPAR Maritime Area, but the responses required to address the source of this issue lie outside of OSPAR's competence. Other significant human activities and pressures include nutrient inputs and living resource extraction (fisheries). Addressing some of these activities and pressures is within the remit of OSPAR, the most significant being the input of nutrients at a more local scale. Improving the state of pelagic habitats will require OSPAR to continue to strengthen cooperation with relevant competent organisations in order to strengthen ecosystem resilience to climate change and to safeguard the marine environment in line with the ambition set out in S11.O1 of NEAES 2030.

Pelagic Habitat R-section ANNEX: The section development has been supported by the collation of relevant measures: measures of relevance to pelagic habitats included in this section.

Overview

This section describes the responses to minimise the effect of human activities and their resulting pressures or impacts on ecosystem services, and which aim to improve the state of pelagic habitats in the North-East Atlantic. These responses can include the development of policy, legislation, measures to manage or regulate specific human activities, or to mitigate impacts on ecosystem services.

Plankton provide an important range of provisioning and regulation for ecosystem services, see: Impact section. They act as a CO_2 sink, form the basis of most marine food webs, and support production of higher trophic levels such as shellfish, fish, seabirds, and marine mammals (Tweddle et al., 2018). Understanding the health, dynamics and spatial distribution of plankton is important for informing (a) how pelagic habitat is used by higher trophic levels, including highly mobile species, (b) climate-related changes in prey availability (Nedstrom et al., 2020), (c) how pelagic habitats support exploited or potentially exploitable living resources, and (d) how the potential impacts of human activities might affect the natural dynamics and patchiness of plankton communities. This improved understanding of the health and function of pelagic habitats provides an opportunity to make better use of information about primary productivity and phytoplankton stock and composition so as to inform ecosystem-based management responses (Tweddle et al., 2018) and is linked to the consideration of eutrophication, harmful algal blooms, change in hydrographic conditions as well as food webs and trophic guilds, including commercial species.

The primary focus of this section is the responses that have been adopted by the OSPAR Commission for implementing the Contracting Parties' commitments under the OSPAR Convention and the strategic objectives of the NEAES. There are no OSPAR measures that directly target the plankton community. However, this section considers management measures relevant to the pelagic habitats created by plankton communities and which target specific human activities and pressures impacting their status, such as eutrophication. This section aims to describe the progress made in the implementation of these measures and whether they are working in terms of achieving the ambitions set out in the North-East Atlantic Environment Strategy 2030 (NEAES). Efforts are made to set OSPAR's responses in the wider policy context and to look at responses by other competent organisations, where these are pertinent to improving the status of pelagic habitats in the North-East Atlantic.

NEAES 2030 includes objectives for conservation and management actions that will ensure ecosystem function and resilience, taking account of changing climatic conditions. The pelagic habitat is fundamental to achieving such ambitions and is specifically referred to in the following operational objectives:

> **S5.O4**: By 2025 at the latest OSPAR will take appropriate actions to prevent or reduce pressures to enable the recovery of marine species and benthic and **pelagic habitats** in order to reach and maintain good environmental status as reflected in relevant OSPAR status assessments, with action by 2023 to halt the decline of marine birds.
>
> **S11.O1**: By 2025 OSPAR will develop a coordinated management approach to strengthening ecosystem resilience, including to the consequences of climate change and ocean acidification.

There are several linkages to other thematic assessments, including Food webs, Fish, Benthic habitats, Climate Change, Eutrophication.

The reader is referred to the following feeder reports for additional information on some of the key human activities affecting pelagic habitats: Agriculture, Extraction of non-living resources, Fisheries, Offshore Renewable Energy Generation

Measures adopted by OSPAR

As noted, OSPAR has not adopted any measures specifically aimed at improving the status of the pelagic habitat, beyond measures to combat eutrophication. This section focuses on measures adopted by OSPAR which have consequences for pelagic systems.

The implementation status of all OSPAR measures was reported on in 2021.

The OSPAR network of Marine Protected Areas (MPAs) and their role in supporting pelagic habitats

Within OSPAR, MPAs are understood as areas for which protective, conservation, restorative, or precautionary measures have been instituted for the purpose of protecting and conserving species, habitats, ecosystems or ecological processes of the marine environment (as defined in Recommendation 2003/3 implementing Annex V of the OSPAR Convention). In 2003, OSPAR adopted a Recommendation to establish an ecologically coherent and well managed network of MPAs; this was then amended in 2010. By 1 October 2021, the OSPAR network comprised 583 MPAs, eight of which were collectively designated in ABNJs. The network of MPAs has a total surface area of 1 468 053 km^2, covering 10,8% of the OSPAR Maritime Area and achieving the spatial coverage component of Aichi Biodiversity target 11 of the United Nations Convention on Biological Diversity (CBD) and Sustainable Development Goal 14, target 14.5, “to conserve at least 10 per cent of coastal and marine areas by 2020.” (See: Report and assessment of the status of the OSPAR network of Marine Protected Areas in 2021)

MPAs as a response for pelagic habitats:
The use of MPAs as a management tool is considered relevant for plankton communities (Tweddle et al., 2018). There is evidence of co-location of primary productivity patchiness and the presence of highly

mobile species, including top predators (Tweddle et al., 2018), and of intermediate trophic levels which include species of commercial interest (living resources). It is essential that effective marine management take account of where and how patchiness occurs by identifying areas of high primary productivity or where there are particular physical features, such as bathymetry, which drive increased productivity. This could inform the development of management measures, including MPAs, to protect target species as well as the intermediate trophic levels and plankton they rely on (Tweddle et al., 2018).

There are challenges associated with using MPAs as a response for pelagic habitats owing to the dynamic nature of plankton across time and space (Maxwell et al., 2014) and the fact that pelagic ecosystems spread across multiple governance scales and jurisdictional boundaries (Game et al., 2009). Nevertheless, MPAs often include pelagic habitats, such as frontal zones, which are known to be highly productive and provide important feeding areas for a wide variety of species, thereby enhancing biodiversity (Mousing et al., 2016).

Is the measure working?:
Pelagic habitats are not explicitly addressed within the OSPAR MPA Status Assessment. However, the evidence supporting the designation of OSPAR MPAs in areas beyond national jurisdiction includes reference to the importance of plankton communities, especially in relation to key pelagic features such as fronts, high energy eddies and seamounts, which aggregate primary productivity and zooplankton, providing a temporally and spatially reliable foraging zone for higher trophic level predators including marine birds and mammals, fish, and turtles. Examples include the meandering subpolar front associated with the Charlie-Gibbs Fracture Zone (OSPAR, 2010) within the designations of the Charlie-Gibbs South MPA and the Charlie-Gibbs North High Seas MPA.

Other OSPAR measures responding to relevant human activities and pressures

Human-induced climate change
There is a strong climate coupling with changes in pelagic habitats, bringing wide-scale impacts. The principal response to address human-induced climate change is being implemented by other competent bodies. See: Climate Change Thematic Assessment, Climate Change section.

Eutrophication from nutrient input
Input of nutrients - diffuse sources, point sources, atmospheric deposition [Substances, litter and energy]: The input of nutrients leading to eutrophication can originate from a number of human activities: agriculture [cultivation of living resources]; industrial uses [urban and industrial uses] and waste treatment and disposal [urban and industrial uses].

The OSPAR response to eutrophication and subsequent implementation of measures adopted by the EU, the European Economic Area and other international forums, including the Urban Waste Water Treatment Directive (91/271/EEC), the Nitrates Directive (91/676/EEC), the Water Framework Directive (2000/60/EC) and the Marine Strategy Framework Directive (2008/56/EC), have had some effect in improving the eutrophication status of the OSPAR Maritime Area. However, there remain regional variations and local problem areas, particularly in areas sensitive to nutrient inputs, such as estuaries, fjords, and bights, and in areas affected by river plumes. The work to “Tackle eutrophication, through limiting inputs of nutrients and organic matter to levels that do not give rise to adverse effects on the marine environment” remains a strategic objective for OSPAR within NEAES 2030 (Strategic Objective 1). The operational objectives S1.O2 and S1.O3 on “determining maximum nutrient inputs” and “agreeing on nutrient reduction needs for each Contracting Party” are the most relevant. Another operational objective of the NEAES focuses on the application of nature-based solutions to safeguard the natural capacity of the ecosystem to sequester nutrients through the conservation and restoration of estuarine, coastal, and marine habitats (S1.O6).

Restructuring of seabed morphology, including dredging and depositing of materials [Physical restructuring of rivers, coastline or seabed (water management)]:
Activities which involve dredging and dumping at sea are regulated by the OSPAR Convention. OSPAR Agreement 2014-06 establishes guidelines for the management of dredged material at sea and refers specifically to the need to include the water column and pelagic species in the consideration of potential deposit areas, as well as potential impacts on the water column, such as turbidity and sediment suspension. These impacts could affect plankton communities in shallow waters and / or species living at the bottom of the water column. A 2020 report showed that the 2014 Guidelines are fully implemented by most Contracting Parties and considered to be well regulated.

Extraction of minerals (rock, metal ores, gravel, sand, shell) [Extraction of non-living resources]:

This activity is likely to have a very localised effect on plankton communities. OSPAR Agreement 2003-15 on sand and gravel extraction requires Contracting Parties which are coastal states of the Maritime Area to take the ICES Guidelines for the Management of Marine Sediment Extraction into account within their procedures for licensing the extraction of marine sediments (including sand and gravel). The agreement does not specifically reference pelagic habitats, but clearly encourages an ecosystem-based approach to management of human activities. The agreement also recommends that necessary steps should be taken to avoid adverse impacts on ecosystem functioning. This could include subjecting plans for extraction of sediments to strategic environmental assessment, and placing controls on the extraction of sediments from any ecologically sensitive site. The ICES Guidelines are subject to a forthcoming review. (See: OSPAR Feeder Report 2021 – Extraction of non-living resources).

Fish and shellfish harvesting (professional, recreational) [Extraction of living resources]:
Article 4, Annex V of the OSPAR Convention sets out that no programme or measure concerning a question relating to the management of fisheries must be adopted under that Annex. However, where the Commission considers that action is desirable in relation to such a question, it must draw that question to the attention of the competent authority or international body. Where action within the competence of the Commission is desirable so as to complement or support action by those authorities or bodies, the Commission must endeavour to cooperate with them.

Please refer to ‘Other important measures’ for more information about measures implemented to address fisheries.

Renewables
Significant upscaling of offshore renewable infrastructure is expected by 2050 and is likely to have fundamental impacts on the physical functioning of the North Sea, including local wind patterns, wave generation, tidal amplitudes, stratification of the water column, the dynamics of suspended particles and bedload transport of sediment. These changes may have far-reaching consequences for the ecosystem, including primary production, food availability across trophic levels, and habitat suitability (Deltares, 2018). Modelling has shown that phytoplankton concentrations may be affected by the presence of offshore wind farms, but how, or if, these changes are significant in terms of CO_2 fluxes or animal populations is currently

unknown (Van der Molen, 2014). A recent study has also demonstrated the positive effect of offshore wind farms on the abundance of meroplankton (Floeter et al., 2017), while effects on holoplankton (including copepods) have not yet been reported.

OSPAR published Guidance on Environmental Considerations for Offshore Wind Farm Development in 2008. The guidance provides that the erection, operation, and removal of wind turbines should not be a hazard to the marine environment, including water quality or by disturbing hydrodynamic processes. However, it does not specifically address the potential impacts on primary production or disruption of plankton communities. Similarly, within the EU context, the European Commission Guidance document on wind energy developments and EU nature legislation, document (C/2020/7730), does not make specific reference to plankton or pelagic habitats but again refers to the need to be aware of changes to water quality arising from suspended sediment, hydrodynamic changes or the introduction of contaminants through the construction of offshore developments, which will be locally important for pelagic habitats. (See: OSPAR Feeder Report 2021 - Offshore Renewable Energy Generation)

Other relevant activities

Aquaculture has been identified as a human activity that could have relevance to pelagic habitats, but on which OSPAR has not taken any specific measures.

Other important measures

Climate change measures

There is a strong climate coupling with changes in pelagic habitats. The significance for society lies in the potential negative impacts on ecosystem services provided by plankton, such as support for higher trophic levels including top predators and commercial species. The principal response is the Paris Agreement, adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in Paris on 12 December 2015. This is a legally binding international treaty on climate change adopted by 196 Parties with the goal to limit global warming to well below 2˚C, and preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate-neutral world by mid-century. The outputs of the IPCC sixth climate assessment cycle indicate that at the current rate of progress, the world is not on track to meet the Paris Agreement targets and climate change action needs to be massively increased if we are to do so. (See: Climate Change Thematic Assessment, Climate Change section).

Conservation measures

The Marine Strategy Framework Directive 2008/56/EC aims to "achieve or maintain good environmental status in the marine environment". It does not explicitly acknowledge the role of plankton in the provision of many ecosystem services such as regulating carbon and nutrient cycles and other biogeochemical cycles. However, plankton community composition is used as an indicator of biological diversity in relation to MSFD Descriptor 1: "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" (Tweddle et al., 2018). Pelagic habitats are specifically addressed as a dedicated theme by criterion D1C6 of the Good Environment Status (GES) Decision under the MSFD: "The condition of the habitat type, including its biotic and abiotic structure and its functions (for example, 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". Criterion D1C6 must be assessed as the "extent of habitat adversely affected in square kilometres (km^2) and as a proportion (percentage) of the total extent of the habitat type". There are also links to Descriptor 4 (Food webs) "All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity". It has not been possible to determine whether any measures have been undertaken specifically to address the status of pelagic habitats under the MSFD.

Directive 2014/89/EU, which establishes a framework for maritime spatial planning, includes a general reference to "healthy marine ecosystems and their multiple services, if integrated in planning decisions, can deliver substantial benefits in terms of food production, recreation and tourism, climate change mitigation and adaptation, shoreline dynamics control and disaster prevention." Action under this directive is considered to be important to the regulation of nutrient inputs. Information on plankton community dynamics (spatial and temporal) would be a very useful input to the Marine Spatial Planning (MSP) process (Tweddle et al., 2018).

Eutrophication from nutrient input

The Water Framework Directive 2000/60/EC (WFD) is currently the principal document covering the management of inland, transitional, and coastal waters in the EU. It requires Member States to take measures to prevent deterioration of the ecological and chemical status of waters, restore polluted waters, reduce pollution and cease or phase out inputs of hazardous substances. Its scope includes coastal waters one nautical mile out to sea and, for chemical status, out to twelve nautical miles. It also contains requirements for the monitoring and management of shellfish protected areas. The WFD is the key legislative instrument for tackling phosphorus pollution from agriculture (along with all causes of poor water quality). The Directive establishes a framework for sustainable water management through the development of River Basin Management Plans and Programmes of Measures, with the objective of preventing deterioration of the aquatic environment and achieving good status of all water bodies by 2015. The WFD considers phytoplankton parameters such as abundance and community composition in assessing Good Ecological Status (Tweddle et al., 2018), with indicators to measure these parameters still under development by Member States.

Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment (Phosphates Directive) and Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive) are also both important for the regulation of diffused land-based pollution into the marine environment. The Nitrates Directive (91/676/EEC) and the Urban Waste Water Treatment Directive (91/271/EEC) are credited with having reduced the nitrate and phosphate input into rivers, and consequently the coastal North Sea (McQuatters-Gollop et al., 2007). (See: Eutrophication Thematic Assessment).

Fisheries

The removal of fish from the ecosystem through fishery activities can alter the balance of food webs, leading to a trophic cascade. For example, if fisheries target higher trophic levels, thereby reducing predation on intermediate trophic levels, this can result in an increase in abundance of these species, which in turn can overgraze zooplankton and increase the grazing pressure on phytoplankton, whose stocks then decrease. A trophic cascade can also be observed from the bottom-up, where changes in lower trophic levels, often induced by a disequilibrium in nutrients, including cases of eutrophication, can impact fish populations.

A response to the management of fishery activities is outside the mandate of OSPAR, as set out in section 2.2. Within the OSPAR Maritime Area, the principal response is made through the Common Fisheries Policy for those Contracting Parties that are EU Member States. For non-EU Member States this is achieved through the relevant national fisheries management legislation as well as measures taken at a regional scale by the regional fisheries management organisations. These include the North-East Atlantic Fisheries Commission, which is the mechanism for fisheries management in areas beyond national jurisdiction within the North-East Atlantic. The principal objective of such measures is the sustainable management of stocks and not the preservation of ecosystem health, despite the introduction of amendments to apply an ecosystem approach.

Regional differences

As noted previously in this section, there is no policy specifically focused on the management of plankton communities. However, there are some important responses which address the main pressures and drivers of change, such as the management of carbon emissions, nutrient inputs (including through the WFD, MSFD, UWWTD and Nitrates Directive) as well as fisheries management measures at the regional and national scales which can have a top-down impact on plankton. Many of the policies are applicable to EU waters, although some such as the WFD are limited to the coastal zone. Fisheries management in non-EU Member States that are OSPAR Contracting Parties is also applied at the national level.

The biggest driver of change for plankton communities at the OSPAR Maritime Area scale is climate. The actions to address these impacts are being taken at a global scale and will have wide-ranging impacts, including in the open ocean.

So far, the assessment of pelagic habitats within the OSPAR Maritime Area has focused on the Greater North Sea (Region II), Celtic Seas (Region III), and the Bay of Biscay and Iberian Coast (Region IV).

Gaps and opportunities

Are we doing enough?

The ability to assess the state of pelagic habitats and support decision making is advancing rapidly. There is a greater understanding of what a healthy, functioning or "good" pelagic system looks like (Dickey-Collas et al., 2017). Responses to achieve the climate change goal, reduce nutrient inputs and increase measures to achieve sustainable fisheries remain the most significant in terms of ensuring the health and dynamics of plankton communities. Other activities may only result in localised effects.

Very few responses specifically address pelagic habitats. With the increasing success in being able to assess this ecosystem component there comes a need to better connect the loop between the ecological consequences and physical drivers of plankton production (Tweddle et al.,2018) as a part of the information being used to inform management responses.

Many of the physical processes affecting the patterns of primary production are able to produce predictable patches of plankton concentration. However, climate change is affecting this predictability and such changes, often occurring across multiple temporal and spatial scales, are important to take into account in the development and adaptation of marine management processes, so as to effectively and adaptably plan towards, and manage for, future conditions (Tweddle et al., 2018). Technological improvements in remote sensing and automated *in situ* data acquisition, at higher frequency than the classical monthly or fortnightly monitoring, will facilitate an improved understanding of important changes and impacts on the state of pelagic habitats.

The movement of highly mobile species often takes place between predictable locations that are important for key life histories, such as feeding or breeding. There is, however, an increasing level of variability in the areas being used by these species, due to the impacts of climate change (Nedstrom et al., 2020). Predators will aggregate and spend more time in areas of high prey density and so, if there are changes in the composition, abundance or distribution of pelagic prey species, this will affect the important aggregation sites for highly mobile species and therefore the management of these areas. Climate-driven changes to organisms low in the food chain can propagate to higher levels. If these higher species have different reliance on the range of prey species available in the system, changes in relative abundance may occur. This is relevant to MPA designation and effective management.

Case study: Why managing plankton communities is critical for the conservation of mobile species

The North Atlantic right whale is a marine mammal on the OSPAR List of threatened and/ or declining species and habitats. This case study is taken from the western Atlantic, where the right whale has recently experienced shifts in feeding habitat, thought to be a result of rapid warming effects on copepods in the Gulf of Maine. Before this shift in habitat occurred, the National Oceanic and Atmospheric Administration (USA) and the Department of Fisheries and Oceans (Canada) had designated a critical habitat located in their traditional feeding habitat, including the Gulf of Maine and southern Scotian Shelf. Right whale sightings in traditional feeding habitats began declining in 2012, and in 2015 an aggregation of right whales was discovered in the southern Gulf of St. Lawrence – an area outside the earlier-defined critical habitat. This resulted in large additional right whale mortality due to their vulnerability to marine traffic and entanglement threats in the new foraging habitat. The case of the North Atlantic right whale exemplifies how ecosystems and the species interactions within them are not static, and how anticipating change in these dynamic systems under climate change is needed (Source: Nedstrom *et al.*, 2020).

Are there other types of responses that could be undertaken by OSPAR to improve the status of pelagic habitats?

For OSPAR the biggest opportunity is offered by the NEAES strategic objective to "tackle eutrophication, through limiting inputs of nutrients and organic matter to levels that do not give rise to adverse effects on the marine environment" (SO1).

There may also be opportunities to:

- Explore how to consider plankton communities that form pelagic habitats within the MPA status assessment;
- Include consideration of plankton community dynamics in EIA guidance;
- Include consideration of plankton dynamics in the scaling-up of offshore renewable infrastructure;

- Include the trophic cascade concept within OSPAR's work so as to be able to continue developing linkages across trophic levels (top-down and bottom-up), including between plankton health, food web function and derived ecosystem services;
- Quantify the effects of plankton change on ecosystem services and integrate into policy development (OSPAR Science Agenda/ OSA / Knowledge gap);
- Quantify the effects of pressures on plankton as natural capital and integrate into policy development (OSPAR Science Agenda/ OSA / Knowledge gap);
- Improve the frequency and spatial coverage of plankton observations by integrating both remote sensing products, but also automated *in vivo/in situ* approaches at high spatial and temporal resolution.

References

Deltares (2018). *Assessment of system effects of large-scale implementation of offshore wind in the southern North Sea*. Available at: https://www.noordzeeloket.nl/publicaties/

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. and Trenkel, V.M. (2017). Pelagic habitat: exploring the concept of good environmental status. ICES Journal of Marine Science, 74: 2333-2341. 10.1093/icesjms/fsx158

Floeter, J., van Beusekom, J. E., Auch, D., Callies, U., Carpenter, J., Dudeck, T. and Möllmann, C. (2017). Pelagic effects of offshore wind farm foundations in the stratified North Sea. Progress in Oceanography, 156, 154-173.

Frederiksen, M., Edwards, M., Richardson, A.J., Halliday, N.C. and Wanless, S. (2006). From plankton to top predators bottom-up control of a marine food web across four trophic levels. Journal of Animal Ecology 75, 1259-1268. 10.1111/j.1365-2656.2006.01148.x

Maxwell, S.A., Ban, N.C. and Morgan, L.E. (2014). Pragmatic approaches for effective management of pelagic marine protected areas. Endangered Speceis Research, Vol.26: 59-74. 10.3354/esr00617.

McQuatters-Gollop, A., Raitsos D.E., Edwards, M., Pradhan Y., Mee, L.D., Lavender S.J. and Attrill, M.J. (2007). A long-term chlorophyll data set reveals regime shift in North Sea phytoplankton biomass unconnected to nutrient trends. Limnol. Oceanogr., 52(2), 2007, 635–648. 10.4319/lo.2007.52.2.0635

Magurran, A. E., Deacon, A. E., Moyes, F., Shimadzu, H., Dornelas, M., Phillip, D. A. and Ramnarine, I. W. (2018). Divergent biodiversity change within ecosystems. Proceedings of the National Academy of Sciences, 115(8), 1843-1847. 10.1073/pnas.1712594115

Mousing, E.A., Richardson, K., Bendtsen, J., Cetinić, I. and Perry, M.J. (2016), Evidence of small-scale spatial structuring of phytoplankton alpha- and beta-diversity in the open ocean. J Ecol, 104: 1682-1695. 10.1111/1365-2745.12634

Nordstrom, B., James, M.C., and Worm, B. (2020). Jellyfish distribution in space and time predicts leatherback sea turtle hot spots in the Northwest Atlantic. PLoS ONE 15(5): e0232628. 10.1371/journal.pone.0232628 https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0232628

OSPAR (2010) Background document on the Charlie-Gibbs Fracture Zone. https://www.ospar.org/documents?v=7251

Tweddle, J.F., Gubbins, M. and Scott, B.E. (2018) Should phytoplankton be a key consideration for marine management? Marine Policy 97: 1-9 10.1016/j.marpol.2018.08.026.

van der Molen, J., H.C.M. Smith, P. Lepper, S.Limpenny and J. Rees. Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem Cont. Shelf Res., 85 (2014), pp. 60-72, https://doi.org/10.1016/j.csr.2014.05.018

Cumulative Effects

Cumulative effects assessment for pelagic habitats

It should be noted that the Sankey plots and associated narratives in this thematic assessment are an illustrative representation of a complex set of interactions between DAPSIR components at the coarse North-East Atlantic scale and should be considered and interpreted alongside the supporting full thematic assessment narrative. The Sankey plots should thus be applied with caution and not considered or used as the sole basis for management decisions.

A range of human activities contribute pressures which cumulatively have the potential to affect the state of pelagic habitats and associated ecosystem services (with consequences for societal drivers, e.g., food, energy, space, health, biodiversity). Climate change and ocean acidification, the input of nutrients and organic matter, and changes to hydrological conditions are the predominant pressures. Following a Driver-Activity-Pressure-State-Impact-Response (DAPSIR) framework and a weighting exercise, an indicative assessment of cumulative effects was undertaken (see: CEMP Guideline for details) as a first step to describing potential pathways of cumulative causes and consequences of change in the ecosystem linking these to impacts on ecosystem services.

The Pelagic Habitats thematic assessment describes the connectivity between the relevant DAPSIR components. Sankey diagrams provide a schematic of potential impact pathways which describes the cumulative causes and consequences of change in the ecosystem, demonstrating that multiple human activities are contributing to multiple pressures, which can lead to multiple impacts on the state of pelagic habitats and associated ecosystem services (see: CEMP Guideline for details). A better understanding of this complexity in the causes and consequences of the cumulative effects from human activities on ecosystem state and ecosystem services is critical in order to explicitly apply the appropriate ecosystem approach to target management measures.

The evidence underpinning the analyses described in this section are drawn from the Driver, Activity, Pressure, State, Impact and Response sections of this thematic assessment and it should therefore be read and interpreted alongside the extended narratives provided therein. The Human activities and Pressures sections of this thematic assessment provide details of the threats that the left-hand side of the Sankey plot **(Figure CE.1)** poses to pelagic habitats. The State section of this thematic assessment provides details of ecosystem state, shown in the centre of the Sankey plot (**Figure CE.1**) for pelagic habitats. The right-hand side of **Figure CE.1** incorporates the impact on ecosystem service scores in order to present the APSI components of the pelagic habitat 'ecosystem' in a single plot. This is consistent with NEAES operational objective S7.O3 on ecosystem services and natural capital, namely to recognise, assess and consistently account for human activities and their consequences in the implementation of ecosystem-based management.

Figure CE.1 shows the complex combinations of human activities and pressures affecting state changes (left-hand side) and the state changes affecting ecosystem services (right-hand side). However, there is currently insufficient understanding and evidence to be able to directly track from left to right, hence the single bar in the centre. This should be a focus of study to inform future assessments.

Overall, confidence in the evidence for the weighted Bow-tie analysis outputs presented in this Pelagic Habitats thematic assessment is described as **medium for evidence** and **medium for degree of agreement**. Additionally, separate confidence assessments have been applied to each module.

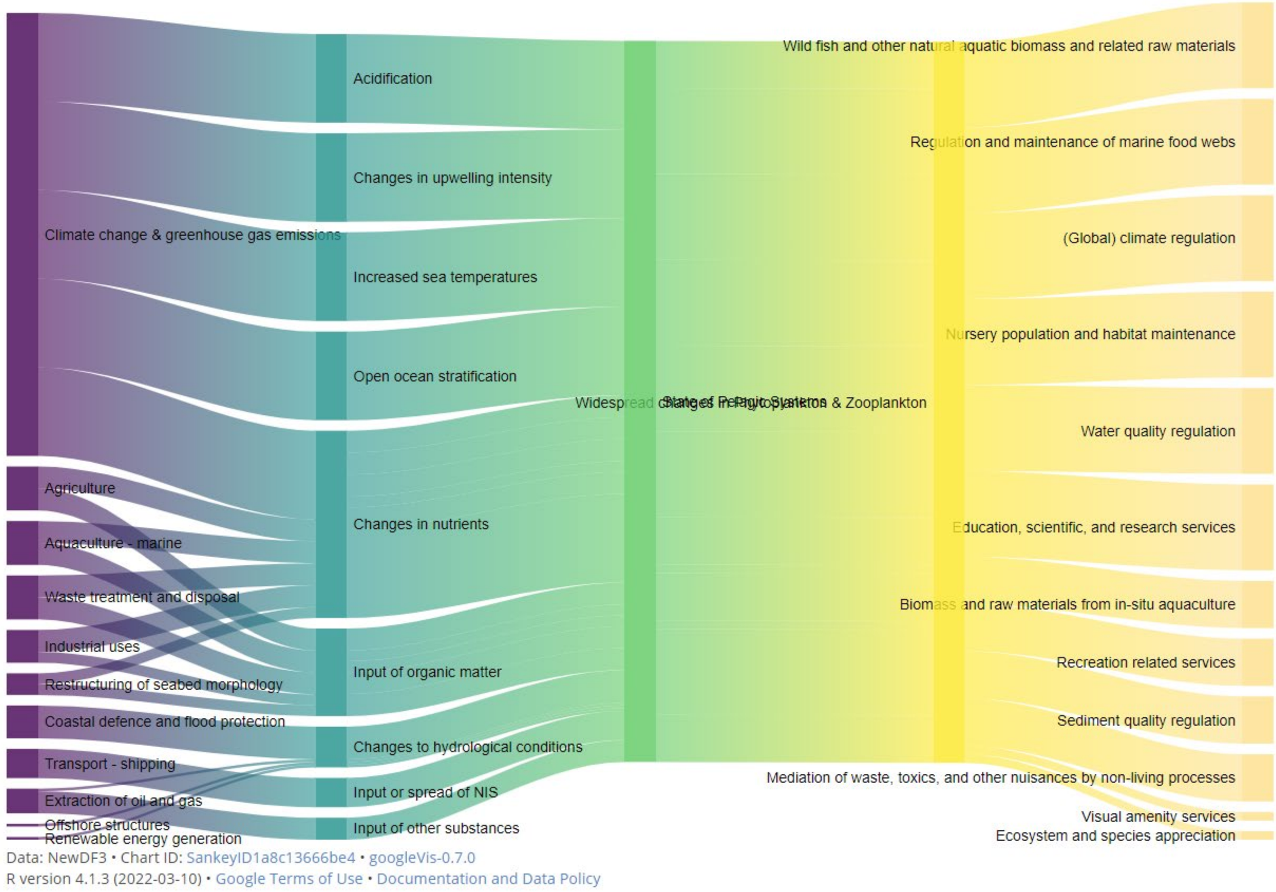


Figure CE.1: Impact Potential of Pelagic Habitats under exposure to pressures from human activities in the North-East Atlantic <hyperlink to Impact Potential section>. Columns left to right: Activity, Pressure, State, Environmental Impact, Ecosystem Service. Derived from Exposure score (Extent x Frequency of pressure) x Degree of Impact score (in terms of whether impact is Acute or Chronic). Pressures with a low Degree of Impact score have been removed for clarity. 'Impact' in this context does not consider the persistence of the pressure or the resilience of the ecosystem associated with that pressure. If these parameters were included, the relative contribution for some pressures would most likely increase and score higher in the relative ranking. Links are weighted to indicate relative contribution to impact. A wider link = greater potential for impact

It should be noted that the Sankey plots and associated narratives in this thematic assessment are an illustrative representation of a complex set of interactions between DAPSIR components at the coarse North-East Atlantic scale and should be considered and interpreted alongside the supporting full thematic *assessment narrative. The Sankey plots should thus be applied with caution and not considered or used as the sole basis for management decisions.*

Figure CE.1 demonstrates the complex relationships which the collective pressures from human activities have on the quality status of pelagic habitats. This complexity suggests that while single-issue responses may be effective, in order to fully apply ecosystem-based management OSPAR needs to consider the causes and consequences of changes in ecosystem state more holistically, and thus:

- recognise that any measures to reduce impacts, while critical to ecosystem health, could have potential consequences for our ability to maintain ecosystem services to meet society's needs, which in turn has consequences for the viability of human activities in the North-East Atlantic;
- recognise that pressures may have additive, multiplicative, synergistic or antagonistic interactions when combined, which has implications for the nature of the threats posed to pelagic habitats and how best to manage those threats.

Methodology

(See: CEMP Guideline: Cumulative effects assessment for the QSR 2023 (Bow Tie Analysis))

A modified Bow-tie Analysis (Cormier et al*.,* 2018; Cormier et al*.,* 2019) was developed to identify and connect all the DAPSIR components, integrating these into either a pressure (e.g., underwater sound, litter, hazardous substances, eutrophication) or a biodiversity receptor- focused analysis of the causes and consequences of change (e.g., pelagic habitats, benthic habitats, fish, marine birds, marine mammals). For the biodiversity assessments, the APS connections are weighted to determine which are the most important, using an adaptation of the ODEMM pressure assessment (Robinson et al., 2013; Knights et al., 2015) focusing on:

1. **Exposure module:** spatial extent and frequency for all activity pressure combinations on state, to generate exposure weightings;
2. **Impact potential module:** spatial extent, frequency of occurrence and impact potential for all activity pressure combinations on state, to generate impact potential weightings;
3. **Risk module:** spatial extent, frequency of occurrence, impact potential for all activity pressure combinations on state, combined with pressure persistence and ecosystem resilience, to generate risk weightings.

The SI (ecosystem services) connections are weighted to determine the most important (Cornaccia, 2022).

The impact potential and ecosystem services outputs are combined and presented in Sankey diagrams (**Figure CE.1**).

Confidence in this weightings exercise for pelagic habitats was assessed according to the QSR 2023 Guidance. Confidence is based on two criteria to communicate the degree of uncertainty in the key findings: (i) level of evidence (determined by considering the type, amount, quality, and consistency of evidence (i.e., Robust, Medium, or Limited)), and (ii) degree of agreement (i.e., High, Medium, or Low).

Exposure module

Confidence Assessment: Evidence – Medium; Consensus – Medium

The assessments for this QSR have demonstrated that pressures from human activities are widely distributed in the OSPAR Maritime Area. The presence of pressures does not automatically lead to adverse impacts. However, in the first instance, consideration of the spatial and temporal extents of pressures provides a useful basis for our consideration of cumulative effects within a risk-based approach (in line with the NEAES principle and strategic approach).

The exposure module describes the extent of the pressure from human activities in the North-East Atlantic. It considers the spatial extent and frequency of human activity / pressure combinations which have been identified as important for pelagic habitats (derived from spatial extent score multiplied by frequency score). Exposure only relates to the pressure cell in the DAPSIR schema. Consideration of exposure in isolation provides a coarse cross-cutting assessment to provide early identification, which allows OSPAR to develop management strategies for pressures to prevent or minimise impacts.

The thematic assessments for Eutrophication and Climate Change and the Ocean Acidification Other Assessment describe the pressures on pelagic habitats. The Radioactive Substances Thematic Assessment identifies inputs of radionuclides from a range of human activities but has concluded that their current levels do not exert significant radiological impacts on biodiversity.

Climate Change and ocean acidification pressures, inputs of nutrients and organic matter, input of radionuclides and changes to hydrological conditions have some of the highest exposure scores, demonstrating the ubiquitous nature of some of these pressures in the North-East Atlantic. Changes to hydrological conditions also rank highly.

The exposure scores support the importance that OSPAR places on these pressures in the North-East Atlantic Environment Strategy:

- Strategic Objective 1 to tackle eutrophication through limiting inputs of nutrients and organic matter, and the work of the Hazardous Substances and Eutrophication Committee (Eutrophication Thematic Assessment).
- Strategic Objective 3 to prevent pollution by radioactive substances, and the work of the Radioactive Substances Committee (Radioactive Substances Committee Thematic Assessment).
- Strategic Objective 9 to safeguard the structure and functions of the seabed/marine ecosystems by preventing significant habitat loss.
- Strategic Objectives 10 to raise awareness of climate change and ocean acidification; 11 to facilitate adaptation to the impacts of climate change and ocean acidification; and 12 to mitigate climate change and ocean acidification (Climate Change Thematic Assessment, Ocean Acidification – Other Assessment).

Multiple human activities have been identified as exerting these pressures in the North-East Atlantic. Any actions to manage these pressures so as to prevent or reduce impacts on state, either individually or cumulatively (collectively), will need to consider if and how these human activities might best be targeted (and the consequences for the associated drivers and ecosystem services) within an Ecosystem Approach.

Impact potential module

Confidence Assessment: Evidence – Medium; Consensus – High

The impact potential is incorporated with the exposure module (spatial extent and frequency) of pressures from specified human activities (derived from the aggregated exposure score multiplied by the degree of impact score). Impact potential here relates to the generic interaction in terms of the likely effects of a pressure on the ecological component, in the following categories: low potential for significant impact, chronic impact or acute impact (Robinson et al., 2013). **Figure CE.1** shows the combined weighted scores for exposure and impact potential.

Following discussions with the expert groups, activity-pressure combinations with a low potential impact score based on the current available evidence were filtered out. Thus, the input of radionuclides has been filtered out based on the conclusions in the Radioactive Substances Committee Thematic Assessment, as these have been demonstrated to have low potential for significant impact. Other pressures filtered out as having low potential for significant impact are extraction of, or mortality/injury to, wild species from fishing activities.

The relative ranking of pressures changes when impact is considered. Climate change and ocean acidification pressures rank highly (see the Climate Change Thematic Assessment for detail on contributing human activities). Input of nutrients, input of organic matter and changes to hydrological conditions also rank highly.

Risk module

Confidence Assessment: Evidence – Low; Consensus – Low

Given their low confidence scoring, the outputs from the risk analyses have not been included in this thematic assessment for QSR 2023. Details of the criteria applied in the risk module are described in the CEMP Guideline.

Regional Summary of likely cumulative effects

Confidence Assessment: Evidence – High; Consensus – Medium

While the weighted Bow-tie analyses displayed in the Sankey diagrams have been produced at the North-East Atlantic scale, consideration can also be given to where regional differences may arise, by cross-referencing other assessments in the QSR 2023.

The Pelagic Habitats thematic assessment identifies the cumulative pressures for pelagic habitats (but no regional breakdown of pressures is attempted there) in terms of both exposure and impact:

The list below summarises the main pressures impacting pelagic habitats, with information on associated activities. Please note that activity-pressure combinations scored as having a low degree of impact based on the current available evidence were filtered out from the relevant Sankey diagram; the activity-pressure links listed below relate to the unfiltered outputs used in the Exposure assessment. The climate change pressures are increased sea temperatures, open ocean stratification, acidification, changes in nutrients and changes in upwelling intensity.

- Input of nutrients from agriculture; aquaculture; restructuring of seabed morphology; waste water treatment and disposal; and industrial uses;

- Changes in hydrological conditions from coastal defence and flood protection; offshore structures; extraction of oil and gas; renewable energy generation;
- Input of other substances (including chemical contaminants and radionuclides) from industrial uses; extraction of oil and gas; military operations; non-renewable energy generation (Nuclear); research, survey and educational activities; and urban uses.
- Extraction of, or mortality/injury to wild species from fish and shellfish harvesting;
- Input of NIS from transport – shipping.

While OSPAR does not have evidence for all human activities, the regional breakdown of relative intensities of activities, namely agriculture; aquaculture; oil and gas; nuclear; renewable energy; fisheries and shipping, has been extracted from the supporting evidence for the QSR 2023 and is summarised below. The direct influence of the cumulative pressures from these activities on pelagic habitats is likely to follow similar trends in intensity within these regions. Although pressures spread beyond the spatial extents of the human activities, insufficient evidence is currently available, and so trends in indirect cumulative pressures have not been considered.

The Human Activities Thematic Assessment describes:

- low relative intensity of agriculture sector activity in Arctic Waters (Region I) and Wider Atlantic (Region V);
- moderate relative intensity of agriculture sector activity in Celtic Seas (Region III) and Bay of Biscay and Iberian Coast (Region IV);
- high relative intensity of agriculture sector activity in Greater North Sea (Region II);
- moderate relative intensity of aquaculture sector activity in Celtic Seas (Region III) and Bay of Biscay and Iberian Coast (Region IV);
- high relative intensity of aquaculture sector activity in Arctic Waters (Region I) and Greater North Sea (Region II);
- low relative intensity of fisheries sector activity in Wider Atlantic (Region V);
- moderate relative intensity of fisheries sector activity in Bay of Biscay and Iberian Coast (Region IV);
- high relative intensity of fisheries sector activity in Arctic Waters (Region I), Greater North Sea (Region II) and Celtic Seas (Region III);
- low relative intensity of offshore renewable energy sector activity in Bay of Biscay and Iberian Coast (Region IV);
- moderate relative intensity of offshore renewable energy sector activity in Celtic Seas (Region III);
- high relative intensity of offshore renewable energy sector activity in Greater North Sea (Region II);
- low relative intensity of transport and shipping sector activity in Wider Atlantic (Region V);
- moderate relative intensity of transport and shipping sector activity in Arctic Waters (Region I); and
- high relative intensity of transport and shipping sector activity in Greater North Sea (Region II), Celtic Seas (Region III) and Bay of Biscay and Iberian Coast (Region IV).

The Offshore Industry Thematic Assessment describes:

- low relative intensity of oil and gas sector activity in the Bay of Biscay and Iberian Coast (Region IV) and Wider Atlantic (Region V);
- moderate relative intensity of oil and gas sector of activity in Arctic Waters (Region I) and Celtic Seas (Region III); and

- high relative intensity of oil and gas sector activity in Greater North Sea (Region II).

The Radioactive Substances Committee Thematic Assessment describes:

- no nuclear sector activity in Wider Atlantic (Region V);
- low relative intensity of nuclear sector activity in Arctic Waters (Region I);
- moderate relative intensity of nuclear sector activity in Bay of Biscay and Iberian Coast (Region IV); and
- high relative intensity of nuclear sector activity in Greater North Sea (Region II) and Celtic Seas (Region III).

Regional evidence for trends in the intensity of other human activities and climate change and ocean acidification was not available in sufficient detail to be utilised in this assessment.

References

Cormier, R., Elliott, M. and Rice, J. (2019). Putting on a Bow-tie to sort out who does what and why in the complex arena of marine policy and management. *Science of the Total Environment*, 648: 293-305. https://doi.org/10.1016/j.scitotenv.2018.08.168.

Cormier, R., Elliott, M. and Kannen, A. (2018). IEC/ISO Bow-tie analysis of marine legislation: A case study of the Marine Strategy Framework Directive. ICES Cooperative Research Report No. 342. 70 pp. https://doi.org/10.17895/ices.pub.4504 http://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/CRR342/CRR342.pdf

Cornacchia, F. (2022) Impacts on Ecosystem Services due to changes in the state of the environment in the North-East Atlantic Ocean. https://open.rws.nl/open-overheid/onderzoeksrapporten/@142922/impacts-on-ecosystem-services-due-to/

Knights, A. M., Piet, G. J., Jongbloed, R. H., Tamis, J. E., White, L., Akoglu, E., Boicenco, L., et al. (2015). An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES Journal of Marine Science, 72: 1105–1115. http://academic.oup.com/icesjms/article/72/3/1105/703182/An-exposureeffect-approach-for-evaluating.

Robinson, L.A., White, L.J., Culhane, F.E. and Knights, A.M. (2013). ODEMM Pressure Assessment Userguide V.2. ODEMM Guidance Document Series No.4. EC FP7 project (244273) 'Options for Delivering Ecosystem-based Marine Management'. University of Liverpool. ISBN: 978-0-906370-86-5: 14 pp

Climate Change

Climate change and ocean acidification in pelagic habitats

All OSPAR Regions are currently experiencing an increase in sea surface temperature due to climate change and a decrease in pH due to ocean acidification. Elevated sea surface temperature has impacted seasonal stratification patterns, causing greater nutrient depletion in the growing season and shifting the base of pelagic food webs towards a less desirable state. Biodiversity indicators have revealed changes in sea surface temperature from 1960 to 2019 linked to widespread declines in the biomass and abundance of phytoplankton and zooplankton, particularly for shelf and oceanic / beyond shelf areas. Rising temperatures were linked to increasing trends in meroplankton abundance and decreasing trends in copepods throughout the Greater North Sea. Global efforts to slow climate change will probably be the best mechanism to counter widespread changes in plankton communities. Regionally targeted management measures are likely to generate noticeable impact only in coastal areas, but may have some effect in areas where plankton communities are affected by the cumulative impacts of multiple pressures (i.e., warming and eutrophication).

In the North-East Atlantic Ocean, sea surface temperature warming (e.g., Harris et al., 2014; Costoya et al., 2015) is an important climate change-related stressor impacting plankton communities. The increase in atmospheric carbon dioxide, which is primarily responsible for driving this warming, is also generating ocean acidification by increasing the flux of carbon dioxide across the ocean surface; however, there is still much uncertainty around the effects of ocean acidification on plankton communities (e.g., Beare et al., 2013; Beaugrand et al., 2013). Climate change is also altering local climate conditions such as wind speed (e.g., Rusu, 2022) and precipitation regimes (e.g. Rodríguez-Puebla and Nieto 2010; Tsanis and Tapoglou, 2019), which also potentially impact light attenuation (Cappuzzo et al., 2015) and sea surface salinity (Holt et al., 2010).

Air and water temperatures in the Arctic waters of OSPAR Region I have been increasing since the late 1980s, with record high temperatures recorded in 2016 (IPCC; Lind et al., 2018). This prolonged warming trend is primarily due to a reduction in heat exchange from the ocean to the atmosphere (Skagseth et al., 2020). Boreal zooplankton (e.g., *Calanus finmarchicus*) has been increasing in abundance throughout eastern and northern areas of the Barents Sea (ICES WGIBAR, 2020). Future changes in temperature, ice cover, precipitation, freshwater run-off and wind are expected to affect both primary and secondary production as surface salinity and seasonal dynamics continue to change (von Quillfeldt et al., 2018). If summer stratification between deeper water and the surface layer continues to intensify, the surface layer may become increasingly nutrient-limited during the growing season, causing reductions in phytoplankton production and biomass and further reducing the energy available to support the rest of the food web (Li et al., 2004). Such changes, occurring at different spatial and temporal scales, will benefit smaller planktonic lifeforms such as flagellates and picocyanobacteria, which are of poor availability and lack the nutritional quality to support higher trophic levels (Schmidt et al., 2020). By contrast, any increase in mixing would provide more favourable conditions for supporting diatom production (Sakshaug, 2004). Stronger mixing can occur when strong winds and storms increase exchange between the surface layer and deeper water. This mixing replenishes nutrient concentrations in surface waters, facilitating productive conditions for microphytoplankton growth.

In the current assessment, sea surface warming has been statistically linked to changes in plankton communities, primarily within shelf and oceanic pelagic habitats, between 1960 and 2019. Indicator results for PH1/FW5 (**Figure CC.1**) reveal that increasing sea surface temperature is linked to declining abundances of planktonic lifeforms, particularly small and large copepods, across the North-East Atlantic. This trend was also reflected by the patterns in zooplankton abundance detected with the PH2 indicator over the same period. Decreasing trends in zooplankton abundance were probably also influenced by the decreasing trends in phytoplankton biomass and abundance; however, links between phytoplankton and zooplankton have not been explicitly tested in the current assessment.

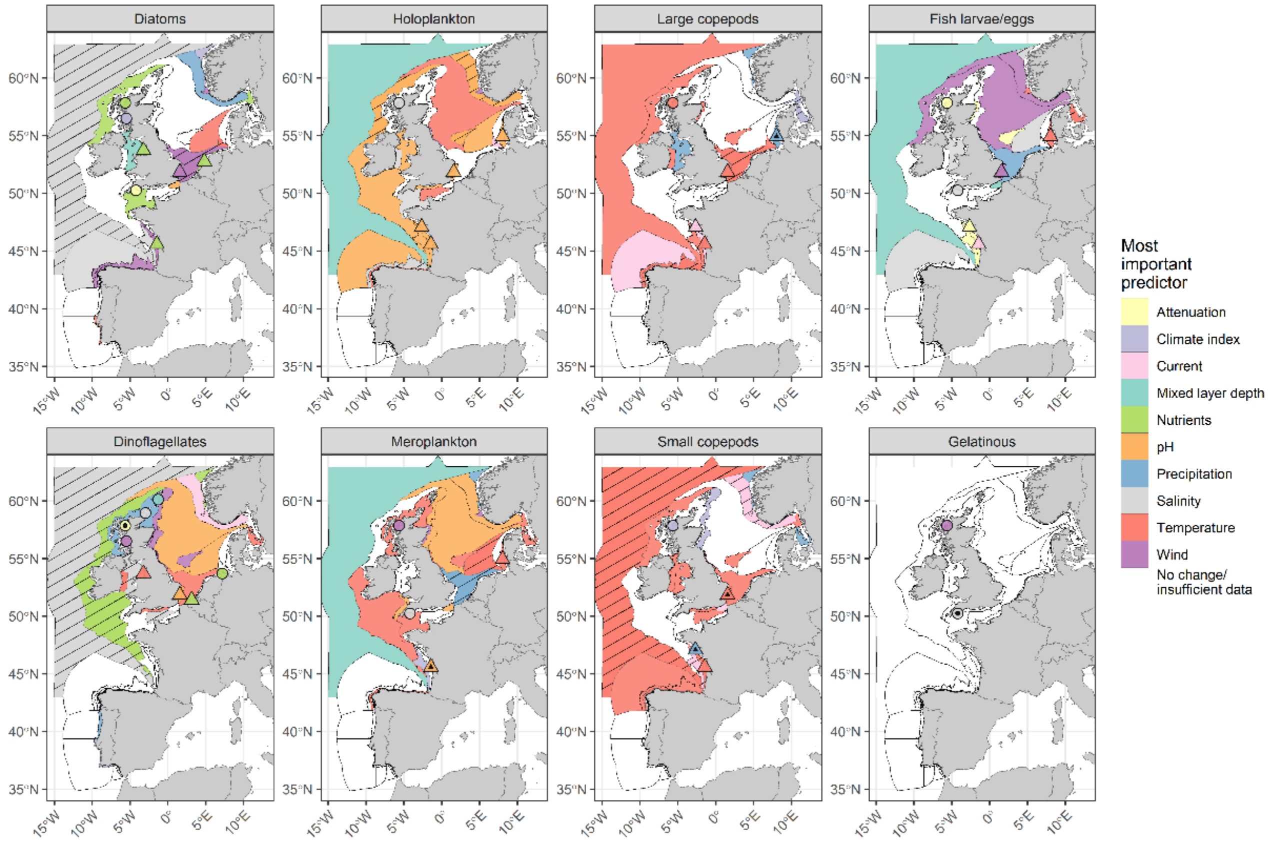


Figure CC1: PH1/FW5 indicator results displaying the most important environmental variable linked to abundance trends for eight planktonic lifeforms. For a detailed description of methods, please refer to the PH1/FW5 indicator assessment

Rising temperatures were also strongly linked to increasing meroplankton abundance and decreasing copepod abundance throughout the Greater North Sea between 1960 and 2019. The increase in meroplankton abundance, particularly that of the sea urchin *Echinocardium cordatum*, over holoplankton (primarily copepods) has been well studied since the early 2000s (Kirby et al., 2007; Kirby et al., 2008). The current assessment has identified changes in plankton community composition which are strongly linked with the increasing trend in sea surface temperature. The results from the pilot assessment of the PH3 candidate indicator in the Greater North Sea also support this conclusion. The increasing dominance of meroplankton identified by the PH1/FW5 indicator was also supported by the output from the pilot assessment of the PH3 candidate indicator, which detected a trend towards atypical zooplankton community composition in the current OSPAR assessment period (2015-2019) due to the high relative abundance of echinoderm larvae and post-larval stages.

At the scale of the four pelagic habitat types (i.e., variable salinity, coastal, shelf, oceanic / beyond shelf) the PH1/FW5 indicator has revealed that meroplankton increased in abundance primarily within coastal and shelf areas of the Greater North Sea, with the increasing trends closely linked to rising sea surface temperatures between 1960 and 2019. Simultaneous declines in the abundance of holoplankton in shelf regions have also been linked to the rise in temperature. In OSPAR Region III (Celtic Seas), declining abundances of dinoflagellates, and of large and small copepods in coastal areas, have been observed and are similarly linked to the rise in temperature. In shelf areas of this Region there has also been a strong increase in meroplankton abundance in response to temperature. Finally, zooplankton abundance (**Figure CC.2B**) and, more specifically, large and small copepod abundance (**Figure CC.1**), have declined in oceanic / beyond shelf habitats of Region IV (Bay of Biscay and Iberian Coast), concurrently with the rise in sea surface temperature.

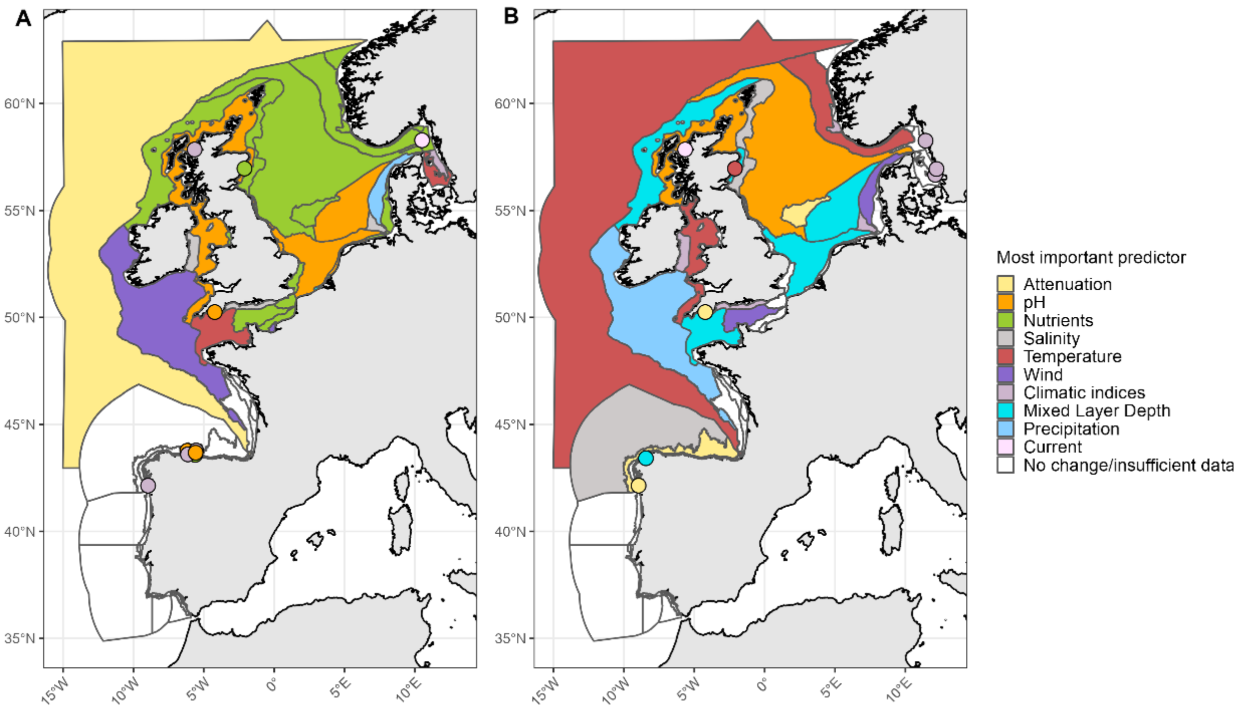


Figure CC2: PH2 indicator results displaying the most important environmental variable linked to trends in phytoplankton biomass (A) and zooplankton abundance (B). For a detailed description of methods, please refer to the PH2 indicator assessment

The pelagic habitats indicator assessments have collectively identified modelled pH as another factor which probably relates to the changes occurring in plankton communities, particularly within shelf and oceanic habitats. The pH level of seawater is controlled by the concentration of dissolved inorganic carbon (DIC). Changes in pH can be linked to changes in phytoplankton activity, since phytoplankton ingest DIC to fuel growth and reproduction, but also to the concentration of atmospheric carbon dioxide, the main driver of global warming. The Ocean Acidification Other Assessment found a pattern of widespread decline in pH across all OSPAR Regions. Open ocean areas are experiencing rates of pH decline between -0,001 to -0,002 yr^{-1}, and up to -0,03 yr^{-1} along the near-shore coastline of the English Channel and Bay of Biscay. The rate of change also varies with depth, with the fastest decline occurring at the surface, due primarily to the influence of atmospheric carbon dioxide. At a more localised scale, trends in pH can show greater variation, and increasing pH trends still persist. Due to the high complexity of ocean acidification dynamics, it is important for future assessments to focus on untangling the primary drivers responsible for the net decline in pH, and to determine how their influence varies across OSPAR Regions and pelagic habitat types.

Indicator assessment results suggest that in the Celtic Seas, declining abundance of holoplankton in coastal and shelf areas between 1960 and 2019 may also be linked to effects of decreasing pH, while phytoplankton diversity is not affected (**Figure CC.3A**). The decrease in pH also co-occurred with a decline in phytoplankton biomass (**Figure CC.2A**) and zooplankton abundance (**Figure CC.2B**) within shelf habitats of the Celtic Seas. A reduction in phytoplankton biomass would also cause a reduction in the uptake of DIC from the water column (to be confirmed by the primary productivity food web indicator FW2), which could contribute to the observed decline in pH.

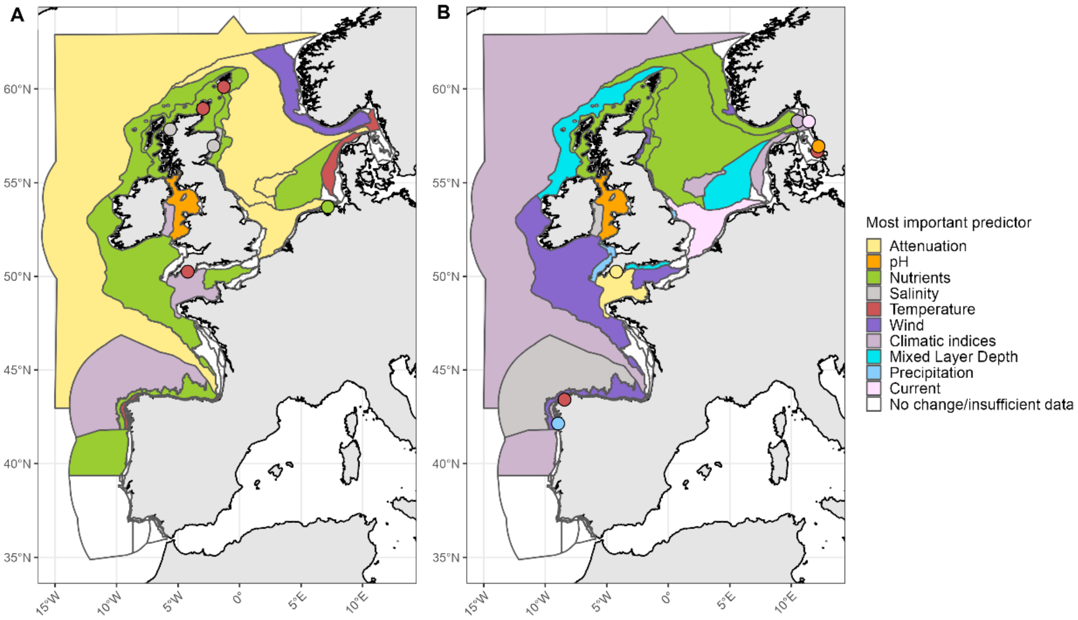


Figure CC.3: PH3 indicator results displaying the most important environmental variable linked to trends in phytoplankton diversity (A) and zooplankton diversity (B). For a detailed description of methods, please refer to the PH3 indicator assessment. Note that the PH3 is currently only considered a common indicator in the Celtic Seas (OSPAR Region III). However, a pilot assessment was also conducted for the Greater North Sea and the Bay of Biscay and Iberian Coast (OSPAR Regions II and IV, respectively). This is a hybrid figure showing results from the common indicator assessment for the Celtic Seas and for the pilot assessment for the Greater North Sea and the Bay of Biscay and Iberian Coast.

In the Bay of Biscay and Iberian Coast Region, shelf areas exhibited declining holoplankton abundance from 1960 to 2019, also linked to the decrease in modelled pH. Across the OSPAR Maritime Area the holoplankton lifeform is primarily composed of copepods. While negative changes in pH can inhibit shell formation in pelagic gastropods and other calcareous zooplankton (Beare et al., 2013), these organisms do not contribute a large proportion of holoplankton abundance and are therefore unlikely to be responsible for driving net decreasing trends. It is likely that this apparent relationship between pH and holoplankton abundance is driven by the decline in phytoplankton biomass and the resulting decrease in the uptake of DIC by phytoplankton, or by the combined effects of other climatic, chemical, and biotic drivers (Beare et al., 2013).

In addition to driving ocean warming, climate change can lead to changes in sea surface salinity and light attenuation. However, climate change is not always responsible for driving changes in these variables. The [PH3](PH3) indicator assessment suggested a decrease in zooplankton diversity associated with decreasing sea surface salinity in the Celtic Seas (**Figure CC.3B**). Similar observations were made for oceanic habitats of the Bay of Biscay and Iberian Coasts, where declining phytoplankton biomass in oceanic habitats was linked to changes in light attenuation (**Figure CC.2A**).

Changes in plankton communities (including lifeforms, biomass, abundance, and diversity) due to other anthropogenic influences (e.g., nutrient input from rivers) were less definitive, since there was high variability in the relative ranking of pressures according to their degree of influence on the pelagic habitat indicators.

Indicator assessment results reveal that climate change is probably the most important pressure currently impacting plankton communities, with the strongest effects detected in shelf and oceanic habitats. Considering the influence of climate change on nutrient availability in stratified waters and the co-occurring declines in phytoplankton detected throughout much of the OSPAR Maritime Area, it is increasingly important for future assessments to consider the links between trends in phytoplankton and zooplankton in the context of climate change. Global efforts to slow climate change will probably be the best mechanism to counter widespread changes in plankton communities occurring across these offshore pelagic habitats. Regionally targeted management measures, which include improved control over nutrient input from anthropogenic sources, are likely to generate noticeable impact only within variable salinity and coastal habitats, but may have some effect in areas where pelagic habitats are affected by the cumulative impacts of multiple pressures (i.e., warming and eutrophication).

References

Beare, D., McQuatters-Gollop, A., van der Hammen, T., Machiels, M., Teoh, S. J. and Hall-Spencer, J. M. (2013). Long-term trends in calcifying plankton and pH in the North Sea. PLoS One, 8(5), e61175.

Beaugrand, G., McQuatters-Gollop, A., Edwards, M. and Goberville, E. (2013). Long-term responses of North Atlantic calcifying plankton to climate change. Nature Climate Change, 3(3), 263-267.

Capuzzo, E., Stephens, D., Silva, T., Barry, J. and Forster, R. M. (2015). Decrease in water clarity of the southern and central North Sea during the 20th century. Global change biology, 21(6), 2206-2214.

Costoya, X., Decastro, M., Gómez-Gesteira, M. and Santos, F. (2015). Changes in sea surface temperature seasonality in the Bay of Biscay over the last decades (1982–2014). Journal of Marine Systems, 150, 91-101.

Hallegraeff, G. M., Anderson, D. M., Belin, C., Bottein, M. Y. D., Bresnan, E., Chinain, M. and Zingone, A. (2021). Perceived global increase in algal blooms is attributable to intensified monitoring and emerging bloom impacts. Communications Earth & Environment, 2(1), 1-10.

Harris, V., Edwards, M. and Olhede, S. C. (2014). Multidecadal Atlantic climate variability and its impact on marine pelagic communities. Journal of Marine Systems, 133, 55-69.

Holt, J., Wakelin, S., Lowe, J. and Tinker, J. (2010). The potential impacts of climate change on the hydrography of the northwest European continental shelf. Progress in Oceanography, 86(3-4), 361-379.

ICES 2020. Working Group on the Integrated Assessments of the Norwegian Sea (WGINOR; outputs from 2019 meeting). 52s. ICES Scientific Reports. 2:29. 46 s. http://doi.org/10.17895/ices.pub.5996

IPCC 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H-O. Pörtner, DC.

Kirby, R. R., Beaugrand, G. and Lindley, J. A. (2008). Climate-induced effects on the meroplankton and the benthic-pelagic ecology of the North Sea. Limnology and Oceanography, 53(5), 1805-1815.

Kirby, R. R., Beaugrand, G., Lindley, J. A., Richardson, A. J., Edwards, M. and Reid, P. C. (2007). Climate effects and benthic–pelagic coupling in the North Sea. Marine Ecology Progress Series, 330, 31-38.

Li, W.K.W., McLaughlin, F.A., Lovejoy, C. and Carmack, E.C. (2009). Smallest algae thrive as the Arctic Ocean freshens. Science 326, 539-539.

Lind, S., Ingvaldsen, R.B. and Furevik, T. (2018). Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. Nature climate change, 8 (7), 634-639.

Rodríguez-Puebla, C. and Nieto, S. (2010). Trends of precipitation over the Iberian Peninsula and the North Atlantic Oscillation under climate change conditions. International Journal of Climatology, 30(12), 1807-1815.

Rusu, E. (2022). Assessment of the wind power dynamics in the North Sea under climate change conditions. Renewable Energy, 195, 466-475.

Sakshaug E. (2004). Primary and secondary production in the Arctic Sea, in Stein, R. and Macdonald, R.W. (eds): The organic carbon cycle in the Arctic Ocean. Springer, Berlin, pp. 57-81.

Schmidt, K., Birchill, A. J., Atkinson, A., Brewin, R. J., Clark, J. R., Hickman, A. E. and Ussher, S. J. (2020). Increasing picocyanobacteria success in shelf waters contributes to long-term food web degradation. Global Change Biology, 26(10), 5574-5587.

Skagseth, Ø., Eldevik, T., Årthun, M., Asbjørnsen, H., Lien, V. S. and Smedsrud, L. H. (2020). Reduced efficiency of the Barents Sea cooling machine. Nature Climate Change, 10(7), 661-666.

Tsanis, I. and Tapoglou, E. (2019). Winter North Atlantic Oscillation impact on European precipitation and drought under climate change. Theoretical and Applied Climatology, 135(1), 323-330.

von Quillfeldt, C. H. (2018). Miljøverdier og sårbarhet i iskantsonen.

Thematic Metadata

Field	Explanation
Linkage	Bedford, J., Johns, D. G.a nd McQuatters-Gollop, A. (2020). Implications of taxon-level variation in climate change response for interpreting plankton lifeform biodiversity indicators. ICES Journal of Marine Science, 77(7-8), 3006-3015. https://doi.org/10.1093/icesjms/fsaa183 Bedford, J., Ostle, C., Johns, D. G., Atkinson, A., Best, M., Bresnan, E. and McQuatters-Gollop, A. (2020). Lifeform indicators reveal large-scale shifts in plankton across the North-West European shelf. Global Change Biology, 26(6), 3482-3497. https://doi.org/10.1111/gcb.15066 Bedford, J., Ostle, C., Johns, D. G., Budria, A. and McQuatters-Gollop, A. (2020). The influence of temporal scale selection on pelagic habitat biodiversity indicators. Ecological Indicators, 114, 106311. https://doi.org/10.1016/j.ecolind.2020.106311 McQuatters-Gollop, A., Atkinson, A., Aubert, A., Bedford, J., Best, M., Bresnan, E. and Tett, P. (2019). Plankton lifeforms as a biodiversity indicator for regional-scale assessment of pelagic habitats for policy. Ecological Indicators, 101, 913-925. https://doi.org/10.1016/j.ecolind.2019.02.010 McQuatters-Gollop, A., Guérin, L., Arroyo, N. L., Aubert, A., Artigas, L. F., Bedford, J. and Vina-Herbon, C. (2022). Assessing the state of marine biodiversity in the Northeast Atlantic. Ecological Indicators, 141, 109148. https://doi.org/10.1016/j.ecolind.2022.109148 Ostle, C., Paxman, K., Graves, C. A., Arnold, M., Artigas, L. F., Atkinson, A. and McQuatters-Gollop, A. (2021). The Plankton Lifeform Extraction Tool: a digital tool to increase the discoverability and usability of plankton time-series data. Earth System Science Data, 13(12), 5617-5642. https://doi.org/10.5194/essd-13-5617-2021 Rombouts, I., Simon, N., Aubert, A., Cariou, T., Feunteun, E., Guérin, L. and Artigas, L. F. (2019). Changes in marine phytoplankton diversity: Assessment under the Marine Strategy Framework Directive. Ecological Indicators, 102, 265-277. https://doi.org/10.1016/j.ecolind.2019.02.009
Relevant OSPAR Documentation	OSPAR Agreement 2022 18-07e CEMP Guideline: Common Indicator – Changes in Phytoplankton and Zooplankton Communities (PH1/FW5) OSPAR Agreement 2022 19-06e CEMP Guideline: Common Indicator – Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2)

	OSPAR Agreement 2022 19-07e CEMP Guideline: Common Indicator – Changes in Plankton Diversity (PH3) OSPAR Agreement 2023-07 CEMP Guideline for Pelagic Habitats Thematic Assessment Integration Method

OSPAR's Quality Status Report 2023

OSPAR Secretariat
The Aspect
12 Finsbury Square
London
EC2A 1AS
United Kingdom

t: +44 (0)20 7430 5200
f: +44 (0)20 7242 3737
e: secretariat@ospar.org
www.ospar.org

Our vision is a clean, healthy and biologically diverse North-East Atlantic Ocean, which is productive, used sustainably and resilient to climate change and ocean acidification.

Publication Number: 958/2023