

Original Articles

Integrating plankton indicators to assess the state of pelagic habitats in the Northeast Atlantic

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A B S T R A C T

Pelagic habitats in the Northeast Atlantic (NEA) have undergone substantial ecological change over the past six decades due to pressures such as climate change, overfishing, and nutrient pollution. To assess Good Environmental Status (GES; under the EU Marine Strategy Framework Directive) we present an integrated assessment of NEA pelagic habitat status using two plankton biodiversity indicators, representing community composition and plankton biomass/abundance, alongside an informative assessment of plankton diversity. We applied a stepwise approach, first combining component-level results across assessment units and fixed-point stations for four pelagic habitat types, then integrating status across indicators and habitat types to derive regional environmental status. Because operational thresholds are lacking, 'Uncertain' was the default status, while 'Not Good' required consistent, spatially representative biological change plausibly linked to anthropogenic pressures.

Across the assessed indicators, we found regional and habitat-specific changes in plankton lifeform abundance, and general declines in phytoplankton biomass and zooplankton abundance. Six habitat-region combinations were assessed as 'Not Good', three as 'Uncertain', and one was 'Unassessed' due to lack of data. No pelagic habitats or regions were found to be in GES. It was only possible to designate 'Not Good' or 'Uncertain' status due to lack of suitable baseline data and uncertainty around what constitutes 'Good' status in the context of NEA pelagic habitats. Sea surface temperature and nutrients were the most important pressures associated with change. These results highlight the need to reduce nutrient pollution and meet international climate targets to conserve pelagic habitats and their ecosystem services.

1. Introduction

Planktonic communities, which form the ecological foundation of

pelagic marine ecosystems in the Northeast Atlantic, are both highly productive and biodiverse. However, these communities are undergoing profound changes in response to increasing anthropogenic pressures

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such as climate warming, ocean acidification, and continued nutrient enrichment (Deschamps et al., 2024; Devlin et al., 2023; Henson et al., 2021; Holland et al., 2023b; McQuatters-Gollop et al., 2007; Semmouri et al., 2023). These pressures are associated with shifts in plankton composition (Bedford et al., 2020a; Bedford et al., 2020b; Edwards et al., 2022; Graves et al., 2023; Holland et al., 2023b; Kléparski et al., 2024; McQuatters-Gollop et al., 2019), distribution (Beaugrand et al., 2002; Kléparski et al., 2024; Montero et al., 2021), productivity (Atkinson et al., 2024; Capuzzo et al., 2018; Tittensor et al., 2021), diversity (Di Pane et al., 2023; Henson et al., 2021; Rombouts et al., 2019), and phenology (Edwards and Richardson, 2004; Kléparski et al., 2023; Silva et al., 2021). These changes may, in turn, impact critical ecosystem services, including oxygen production, food provisioning, carbon sequestration, and anthropogenic nutrient cycling (Cornacchia et al., n.d; Faith et al., preprint; Faith et al., 2025; Naselli-Flores and Padisák, 2023; OSPAR, 2023d; Wanek et al., 2025).

This accelerating ecological change has prompted coordinated policy response at both global and regional levels. The EU Marine Strategy Framework Directive (MSFD) represents one of the most comprehensive marine ecosystem-based management frameworks globally. It mandates the assessment and achievement of Good Environmental Status (GES) across multiple ecosystem components, including pelagic and benthic habitats, fish, birds, mammals, and turtles (European Commission, 2008, 2010, 2017). Crucially, “pelagic habitats” (i.e. plankton) are explicitly recognised as a standalone ecosystem component. Descriptor 1 (biological diversity) and Descriptor 4 (food webs) explicitly address primary and secondary producers (which are predominantly planktonic), highlighting their significance in marine biodiversity assessments. In the Northeast Atlantic, the OSPAR Regional Seas Convention coordinates regional biodiversity indicator development and GES assessment under this framework.

Within the OSPAR assessment framework, three plankton indicators have been developed to evaluate biodiversity in pelagic habitats:

1. *Changes in Phytoplankton and Zooplankton Communities*: An operational indicator, assessing community composition via functional groups (“lifeforms”), capturing structural and functional changes in the ecosystem (McQuatters-Gollop et al., 2019; Tett et al., 2008).
2. *Changes in Phytoplankton Biomass and Zooplankton Abundance*: An operational indicator, reflecting ecosystem size structure, overall biomass, and trophic interactions (e.g., top-down regulation of phyto- and zooplankton).
3. *Changes in Plankton Diversity*: A candidate indicator still in development, evaluating structural biodiversity using metrics such as species evenness, dominance, and richness (Rombouts et al., 2019).

Together, these indicators capture different dimensions of plankton biodiversity and ecosystem functioning. In this assessment, the two operational indicators form the scientific basis for assessing progress towards GES, while the candidate diversity indicator is used as supporting evidence.

In 2017, OSPAR conducted a biodiversity assessment of the Northeast Atlantic, including the three plankton indicators (OSPAR, 2017). However, several methodological challenges precluded the establishment of quantitative thresholds/targets for most indicators. These included limited data availability, uncertainties in linking pressures to observed ecological changes, and the novelty of applying biodiversity indicators across ecosystems using multiple datasets. As a result, biodiversity changes were described, but formal status assessments, including for pelagic habitats, were not completed (OSPAR, 2017).

To address this gap, McQuatters-Gollop et al. (2022) proposed a semi-quantitative approach to assess individual plankton indicators. However, a quantitative method was still needed to integrate multiple elements within plankton indicators and to integrate results across plankton indicators, first at habitat and then at regional scale, in order to determine whether pelagic habitats in the Northeast Atlantic are in GES.

The aim of this work is, therefore, to 1) quantitatively assess changes and integrate assessment results within plankton indicators, considering assessment units and habitat types; 2) quantitatively integrate assessment results between the operational plankton indicators, using the candidate indicator as supporting evidence; and 3) assess the environmental status of pelagic habitats in the Northeast Atlantic.

2. Methods

2.1. Regions, assessment units and habitat types

OSPAR, the Regional Seas Convention for the Northeast Atlantic, is responsible for coordinating the development and assessment of MSFD biodiversity indicators, including those used to evaluate GES. OSPAR's latest ecosystem assessment, the *Quality Status Report 2023* (hereafter, QSR2023), provides a holistic evaluation of the Northeast Atlantic marine ecosystem, linking changes in biodiversity components, including pelagic habitats, to the benefits (ecosystem services) they provide to anthropogenic pressures and societal drivers (OSPAR, 2023e). Approximately 40 plankton experts from the 16 OSPAR Contracting Parties contributed to the pelagic habitats assessment (OSPAR, 2023d).

For pelagic habitats, this assessment focused on three OSPAR Regions: the Greater North Sea, the Celtic Seas, and the Bay of Biscay and Iberian Coast (Fig. 1). Spatial subdivision was based on the OSPAR Common Procedure (COMP4) assessment units, which represent biogeographic areas that reflect the environmental conditions most likely to structure plankton communities (Fig. 1) (OSPAR, 2023a). Originally developed for eutrophication assessments, the COMP4 assessment units are now also used for pelagic habitats assessments to enhance coherence between state and pressure evaluations across MSFD descriptors. This approach was intended to enable trend detection in areas with similar ecosystem characteristics at a scale that is relevant for the definition of mitigating management measures. For the Greater North Sea, Celtic Seas, and the northern portion of the Bay of Biscay and Iberian Coast, COMP4 assessment units were derived from a combination of physical parameters such as depth, salinity, and stratification regime, and biological features like phytoplankton biomass and primary productivity (Devlin et al., 2023; OSPAR, 2023a). A different approach was applied to define some assessment units for the Bay of Biscay and Iberian Coast region, due to the region's extension beyond the geographic coverage of the hydrodynamic model used to define COMP4 assessment units (Dutch Continental Shelf Model), which extends only to the northern coast of Spain (43°N). The COMP4 approach was therefore applied to all French waters, but assessment units around the Spanish and Portuguese coasts south of 43°N were delineated using phytoplankton dynamics (for Spanish waters) and salinity patterns (for Portuguese waters), based on national datasets. This alternative methodology was reviewed and validated by OSPAR experts (OSPAR, 2023a).

Assessment unit results were aggregated per region and habitat type to provide broad overarching conclusions on the state of pelagic habitats within each OSPAR Region.

Within each OSPAR Region, assessment units and fixed-point stations were grouped into four pelagic habitat types to enable the integration and comparison of indicator results across spatial and habitat-specific scales (Fig. 1), consistent with European Commission guidance (European Commission, 2017). In most cases, assignment to habitat type was clear and straightforward, but in some instances decisions around categorisation were supported by expert judgement. Fixed-point stations were usually assigned to a pelagic habitat type based on the assessment unit they intersected or were adjacent to. These habitat types are defined as follows (see also Table S1):

- **Variable salinity habitats**: Estuarine-influenced waters where freshwater plumes extend beyond areas designated as Transitional Waters under the EU Water Framework Directive (WFD; Directive 2000/60/EC);

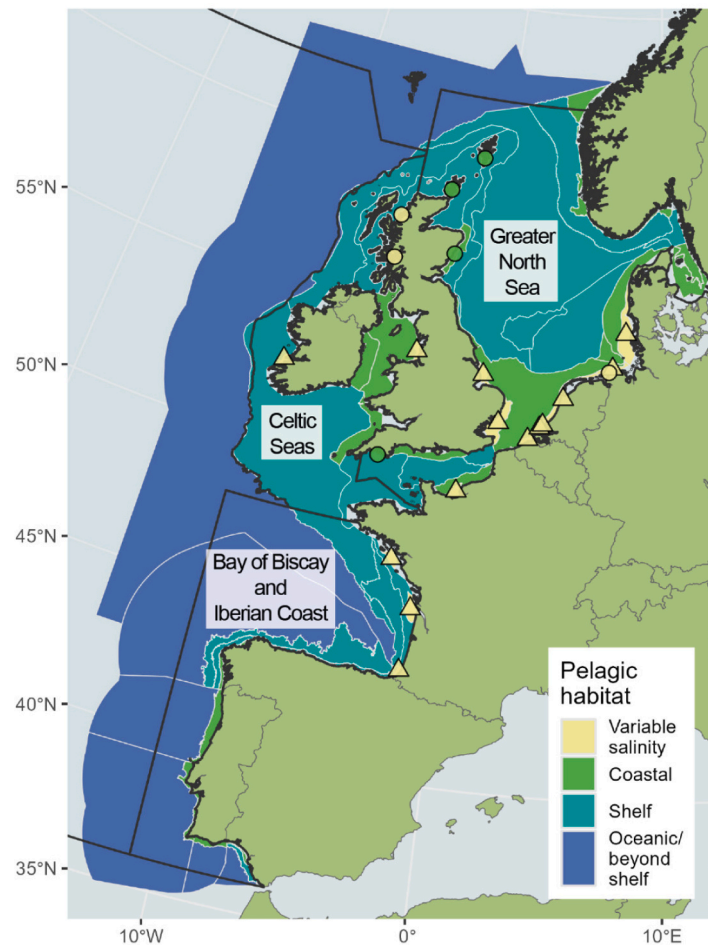


Fig. 1. The distribution of the four pelagic habitat types across the three OSPAR Regions (Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast) considered in the pelagic habitat indicator assessments, and their boundaries across the OSPAR Maritime Area. Four habitat types (variable salinity, coastal, shelf, and oceanic/beyond shelf) were considered, in line with the MSFD. Oceanic/beyond shelf habitats were not assessed for the Greater North Sea or Celtic Seas regions, as that habitat type makes up only a small spatial area of each region. River plumes (categorised as variable salinity habitats) are highlighted with triangles since they often represent very small polygons, and sampling stations are represented as circles. Boundaries between polygon assessment units used in this assessment are indicated in grey.

- Coastal habitats: Defined using physical, hydrological and ecological characteristics, rather than administrative boundaries or the WFD definition of “coastal waters” (European Commission, 2017);
- Shelf habitats: Offshore areas on the continental shelf, characterised by a mean salinity >34.5 , serving as the boundary between coastal and offshore waters (OSPAR, 2022);
- Oceanic / beyond shelf habitats: Deep oceanic areas defined by a mean water depth >200 m.

2.2. Pelagic habitats indicators

Changes in Phytoplankton and Zooplankton Communities is a functional indicator that tracks changes in the abundance of ecologically relevant plankton groups, referred to as ‘lifeforms’, which serve as proxies for ecosystem functioning (Bedford et al., 2020b; Holland et al., 2023b; McQuatters-Gollop et al., 2019). Eight lifeforms were selected based on trait confidence and ecological relevance, representing a range of trophic roles and life strategies: diatoms, dinoflagellates, small copepods, large copepods, holoplankton, meroplankton, gelatinous zooplankton, and fish eggs and larvae (McQuatters-Gollop et al., 2019). Further details on the classification of lifeforms and analytical approaches are provided in McQuatters-Gollop et al. (2019) and Ostle et al. (2021).

Changes in Phytoplankton Biomass and Zooplankton Abundance is a

bulk indicator which measures plankton stocks available for energy transfer through higher trophic levels. Phytoplankton biomass is represented by chlorophyll-a concentration (see Sections 2.4 and S2.2). Zooplankton abundance is based on total copepod counts, as copepods are a dominant and ecologically important group of marine zooplankton. This indicator provides insights into the base of the marine food web and potential bottom-up effects across the pelagic ecosystem. Further methodological details are available in Louchart et al. (2023a, 2023c).

The compositional indicator *Changes in Plankton Diversity* addresses the diversity dimension of pelagic ecosystems. It assesses: (i) taxonomic richness, (ii) species turnover, and (iii) dominance patterns, in both phytoplankton and zooplankton communities, thereby capturing shifts in biodiversity and community stability (Rombouts et al., 2019). The Local Contribution to Beta Diversity (LCBD) was calculated for both phytoplankton and zooplankton to capture changes in community variance over time (Bedford et al., 2020a; Rombouts et al., 2019). When significant deviations in β -diversity were detected, α -diversity indices were computed to identify the drivers of change (richness and/or dominance). Species richness was estimated using the Menhinick Index (Whittaker, 1977), selected for its sensitivity to environmental changes (Budria et al., 2017; Rombouts et al., 2019). Dominance in phytoplankton was evaluated via the Hulbert (1963) while dominance in

zooplankton was assessed using the Gini (1912) and Patten (1962) indices (e.g. Duflos et al., 2017).

In the context of OSPAR's QSR2023, the *Changes in Plankton Diversity* indicator was formally assessed as an operational indicator in the Celtic Seas and as a candidate indicator in the Greater North Sea and the Bay of Biscay and Iberian Coast. The latter distinction reflects differences in methodological standardisation among OSPAR Contracting Parties rather than limitations in data quality or scientific validity. The science and data informing the *Changes in Plankton Diversity* indicator in the Greater North Sea and Bay of Biscay and Iberian Coast regions are robust. However, the indicator remains under development within the three regions. Therefore, it was excluded from the formal Indicator-to-habitat integration. Instead, it is presented here to supplement the two common indicators while acknowledging its relevance. For full methodological detail, see Louchart et al. (2023b, 2023d).

2.3. Phytoplankton and zooplankton abundance data

The assessment was based on 23 phytoplankton and zooplankton abundance datasets from 13 contributing institutes (Table S2, Fig. 2). Due to consisting of individual isolated sampling stations or multiple sampling stations in close proximity, seven submitted datasets (Denmark: Aarhus University (AU); Germany: Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten und Naturschutz (NLWKN); Spain: Instituto Espanol de Oceanografia (IEO); Sweden: Swedish Meteorological and Hydrological Institute (SMHI); UK: Marine Directorate of the Scottish Government (MD); UK: Plymouth Marine Laboratory (PML); and UK: Scottish Association for Marine Science (SAMS) (Table S2, Fig. 2) were treated, upon consultation with the data holders, as independent fixed-point time-series. Although some stations (i.e. AU, SAMS, MD) are located in transitional waters rather than MSFD-defined

variable salinity habitats, they were included to improve data coverage. The SAMS dataset, while collected across a small estuarine area, was aggregated and treated as a single fixed-point time-series due to its limited spatial extent.

The remaining datasets consisted of spatially distributed observations, including transects, clustered station arrays, or widely scattered samples in coastal regions (**complete dataset list in Table S2**). Among these, the Continuous Plankton Recorder (CPR) survey, collected by the Marine Biological Association (MBA, United Kingdom), provided extensive spatial and temporal coverage across the region via ships of opportunity (Table S2, Fig. 2).

Due to differences in sampling methodologies, taxonomic resolution, and enumeration methods, the datasets were not pooled. Instead, each dataset was analysed separately, following internal QA/QC procedures to ensure consistency and accuracy. Many data providers also participate in the **NE Atlantic Marine Biological Analytical Quality Control (NMBAQC) Scheme (2025)**, ensuring external verification and intercomparability.

Additional datasets were submitted but excluded due to insufficient temporal coverage (e.g. time-series that were too short to conduct robust trend analysis (i.e., < 10 years), ended before, or began during the assessment period). All included datasets were based on phytoplankton and/or zooplankton counts identified and enumerated using light microscopy and are accessible via the Plankton Lifeform Extraction Tool (<https://www.dassh.ac.uk/lifeforms/>; (Ostle et al., 2021)). These datasets informed the three MSFD biodiversity indicators: *Changes in Phytoplankton and Zooplankton Communities*, *Changes in Phytoplankton Biomass and Zooplankton Abundance*, and *Changes in Plankton Diversity*.

For *Changes in Phytoplankton and Zooplankton Communities*, the following standardisation steps were applied:

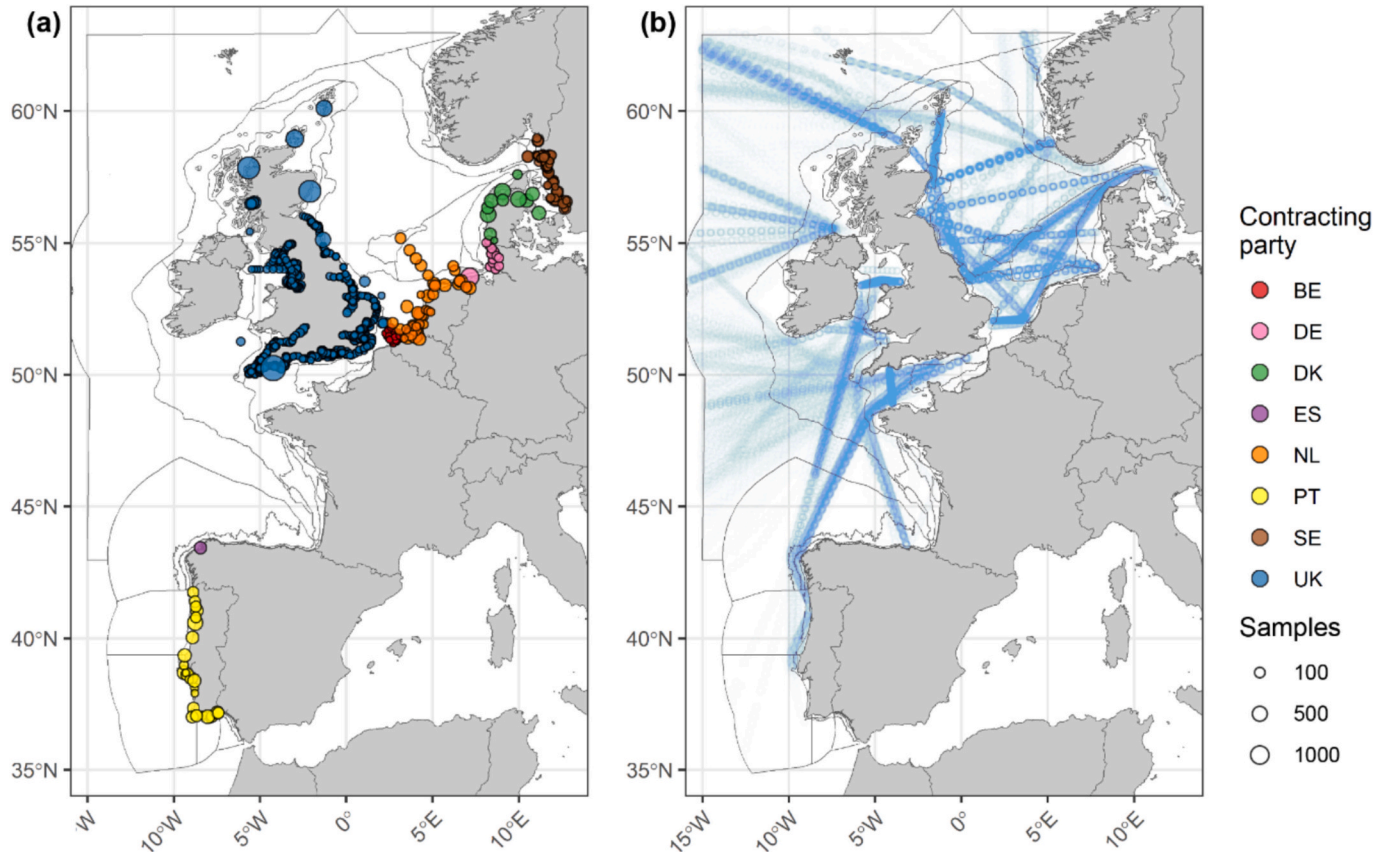


Fig. 2. Sample locations from all datasets except Continuous Plankton Recorder (CPR) (a) and CPR sampling routes (b) used in the assessment. For (a), point size is proportional to the number of samples taken at each location. Points are coloured according to OSPAR Contracting Party. See Table S2 for further dataset detail.

- For individual plankton samples, the total abundance of each relevant lifeform was calculated.
- For fixed-point station datasets, monthly averages were computed from individual samples.
- For spatially-distributed datasets, monthly averages were computed for each assessment unit.
- A nominal abundance value (half of the minimum non-zero lifeform abundance observed per assessment unit) was added to all abundance values to allow log transformation of time-series containing zeroes.
- Data were $\log_{10}$ transformed.
- For spatially-distributed datasets, missing months were gap-filled using inverse distance weighting (IDW) interpolation from nearby samples (< 250 nautical miles) from the same dataset onto a 1° latitude x 1° longitude grid.
- For both fixed-point station and spatially-distributed datasets, remaining short gaps (≤ 3 months) were interpolated linearly, acknowledging that this approach may not fully capture seasonal dynamics but provides a conservative gap filling method (with minimal assumption about underlying ecological processes).
- Years from continuous time-series with fewer than eight valid (observed or interpolated) monthly values were discarded.

Copepod abundance data from the CPR survey were used to inform the zooplankton component of the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator. These data were used due to their high spatial, temporal, and taxonomic resolution. Data processing included:

- Summation of all copepods per sample.
- Spatial aggregation onto a 1° latitude x 1° longitude grid.
- Monthly averaging within grid cells (averaged if multiple samples were available).
- Time-series interpolation, with years excluded if a grid cell had more than 3 consecutive or more than 4 total months missing.

For *Changes in Plankton Diversity*, the same general procedure was applied as for *Changes in Phytoplankton Biomass and Zooplankton Abundance*, but with a finer spatial resolution to enhance sensitivity to spatial changes.

- Data were processed on a 0.25° latitude x 0.5° longitude grid.
- The diversity indicator was applied to both phytoplankton and zooplankton taxa.

2.4. Phytoplankton biomass data

To assess phytoplankton biomass as part of the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator, two main data sources were used:

1. Satellite-derived chlorophyll-*a* (Chl-*a*) data for regional-scale, synoptic coverage (1997–2019)
2. In situ biomass data from fixed-point coastal monitoring stations (1986–2020)

Satellite Chl-*a* data covering the period 1997–2019 were used to characterise spatial and temporal patterns of phytoplankton biomass in the Northeast Atlantic (Table S3). These data provided high-resolution, region-wide coverage and were particularly useful for areas lacking consistent in situ sampling:

- European Space Agency Ocean Colour Climate Change Initiative (ESA OC-CCI) data were provided by Plymouth Marine Laboratory (PML), derived using the OC5CI algorithm, suitable for both open ocean and coastal waters (Tilstone et al., 2023).

- Additional satellite data from the Royal Belgian Institute of Natural Sciences (RBINS) were sourced from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), using the CHL-Gons algorithm applied to Sentinel3/OLCI observations (Lavigne et al., 2021).

To harmonize the satellite dataset and achieve as long a time-series as possible, chlorophyll-*a* data from PML (monthly; from Sept. 97 to Dec. 2016) and the Royal Belgian Institute of Natural Sciences (RBINS; daily; from Jan. 2009 to Dec 2020) were first aligned in space (1° longitude and 1° latitude) and time (Jan. 2009 through Dec. 2016). Linear regression models were then applied within each assessment unit to harmonize the PML dataset with the RBINS data. Satellite-derived Chl-*a* concentrations were aggregated onto a 1° latitude x 1° longitude grid to be consistent with the gridding method used for CPR zooplankton abundance data (Section 2.3). Temporal interpolation was applied to supplement missing values, especially for winter months (November–February) in the North Sea, where short days, low solar angles, and increased cloud cover limit data availability. Details of the interpolation procedures are described in Louchart et al. (2023a, 2023c).

Local-scale biomass data were also obtained from fixed-point monitoring stations in coastal waters. Measurements included Chl-*a* determined using a variety of methods, e.g. fluorometry, spectrophotometry, and high-performance liquid chromatography (HPLC), as well as carbon biomass converted from phytoplankton biovolume, which is dependent on cell counts, cell size, and cell shape. Each dataset was processed independently, as sampling methods, frequency, and analytical protocols varied across contributing institutes. The processing steps were as follows:

- Temporal regularisation: Irregularly sampled time-series were aligned to monthly intervals.
- Gap-filling: Within each time-series, missing data were interpolated using cubic interpolation, provided:
 - o No more than three consecutive months, or
 - o No more than four non-consecutive months, were missing within a calendar year.
- Data exclusion: Time-series exceeding these thresholds were excluded from further analysis.
- Anomaly calculation: Monthly anomalies were computed to remove seasonal cycles and facilitate comparison across stations. For each month *i*, the anomaly was calculated as:

$$z_i = Z_i - \mu_{m(i)} = Z_i - \frac{1}{n_m} \sum_{j=1}^{n_m} Z_{j,m}$$

where, the monthly chlorophyll-*a* anomalies (z_i) were computed by subtracting the climatological mean μ for the corresponding calendar month *m*, from each monthly chlorophyll-*a* value Z_i , where μ_m represents the mean annual cycle.

2.5. Overview of the assessment workflow

The pelagic habitats assessment followed a stepwise workflow from indicator-specific trend detection to regional status integration. First, trends were identified for each indicator component within each assessment unit or fixed-point station. Second, the confidence and spatial representativeness of these trends were evaluated. Third, environmental variables associated with significant trends were identified using random forest models. Fourth, indicator components were assigned status based on trend direction, confidence, spatial representativeness, and links to anthropogenic pressures. Finally, component-level results were integrated across the two operational indicators, pelagic habitat types, and OSPAR Regions to determine regional

environmental status. The *Changes in Plankton Diversity* indicator was retained as supporting evidence.

In this workflow, ‘indicator components’ refers to the individual elements assessed within each plankton indicator. For the *Changes in Phytoplankton and Zooplankton Communities* indicator, these were the plankton lifeforms. For the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator, these were phytoplankton biomass and zooplankton abundance. For the *Changes in Plankton Diversity* indicator, these were the phytoplankton and zooplankton diversity metrics.

2.6. Identifying trends in pelagic habitats indicators

OSPAR assessments typically involve investigating differences between two periods in time, with one period comprising samples used to determine a reference state, referred to as a ‘reference period’, and the other comprising samples compared to this reference state, referred to as a ‘comparison period’. The reference period usually contains historic samples used to establish reference, or baseline, conditions, while comparison data usually represent the most recent samples.

For the *Changes in Phytoplankton Biomass and Zooplankton Abundance* and *Changes in Plankton Diversity* indicators, this comparison was reversed. The most recent years in all sampling time-series, i.e. 2015–2019, were used as a common assessment-period benchmark, while all samples occurring prior to 2015 were used for comparison. This approach was adopted because the individual plankton time-series varied substantially in length. A common historical reference period containing samples across all datasets would therefore have been constrained by the shortest time-series, limiting the ability to detect meaningful change or requiring the exclusion of valuable historic data from multi-decadal time-series. Using a common recent period as the benchmark therefore allowed time-series of varying length to be examined alongside one another, while maintaining a consistent basis for assessing the current assessment period.

However, this methodological choice has implications for interpretation. The 2015–2019 period should not be interpreted as representing historical, pre-impact, or Good Environmental Status conditions. Rather, it provides a recent assessment-period benchmark against which earlier samples were compared. This means that the assessment identifies how earlier plankton conditions differed from the recent period, rather than measuring the degree of departure from an unimpacted baseline. As a result, the approach improves comparability across datasets with different temporal coverage, but may limit the ability to detect the full magnitude of long-term ecological change where historical baselines were already affected by anthropogenic pressures.

The benchmark period 2015–2019, was therefore the period of assessment and is hereafter referred to as the “assessment period”.

In contrast, the *Changes in Phytoplankton and Zooplankton Communities* assessment considered trends across the entire length of available time-series. Further detail about trend identification for each indicator is included in **Section S2.3**.

2.7. Assessing confidence and spatial representativeness

A confidence scoring methodology was applied to evaluate the robustness of observed trends for each plankton dataset across assessment units (see **Section S3** for summary statistics). Confidence was evaluated separately for temporal and, where applicable, spatial dimensions. Two metrics were calculated for each dimension: one specific to annual sampling (specific confidence) and one general to the full time-series (general confidence). Each metric was calculated for each indicator for each assessment unit. Further detail about confidence assessment is included in **Section S2.4**.

Spatial representativeness was assessed separately by calculating the proportion of possible polygon assessment units for each habitat type that were included in the analysis. For example, if the analysis for a habitat type was based on 6 polygon assessment units out of 12 possible

coastal assessment units in the Greater North Sea, the spatial representativeness score was 0.5. Fixed-point station datasets were not included in this calculation because they do not represent polygon assessment-unit coverage.

In the QSR2023, confidence assessment was only applied to the *Changes in Phytoplankton and Zooplankton Communities* indicator. Here, we extended this approach to the *Changes in Phytoplankton Biomass and Zooplankton Abundance* and *Changes in Plankton Diversity* indicators, providing a consistent confidence evaluation across all three pelagic habitat indicators. Consequently, the introduction of confidence evaluation for these two indicators might lead to some slight discrepancies between the results reported in the QSR2023 and this work. Because the *Changes in Plankton Diversity* indicator was used as supporting evidence only, any effect on final habitat and regional status was limited to the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator.

Confidence and spatial representativeness were later used as criteria for assigning ‘Not Good’ status to indicator components.

2.8. Identifying environmental pressure links

To identify environmental drivers that may be linked to or associated with variation in plankton indicators, a random forest regression approach was conducted using the R package ‘ranger’, a computationally efficient implementation of the random forest algorithm (Wright and Ziegler, 2015).

For each instance in which a significant trend in indicator values was detected (i.e., for each unique combination of dataset, assessment unit, and indicator), a separate random forest model was fitted. Each model included the indicator value as the response variable and a common set of 16 environmental predictors (see **Table S4** for variable descriptions).

Variable importance was quantified using mean decrease in impurity, which measures how much each predictor contributes to reducing prediction error across decision trees (Holland et al., 2024). Because variable importance values are not directly comparable across models, predictors were ranked within each model. Across all locations showing the net trend direction for a given indicator component, the mean rank of each environmental variable was then calculated. These rankings were used to identify environmental pressures most closely associated with observed biological trends.

This approach identifies statistical associations between indicator change and environmental variables, rather than direct causal relationships.

Further details on pressure data analysis are included in **Section S2.5**.

2.9. Determining status of indicator components and indicators

Before indicator results were integrated across habitat types and regions, each indicator component was first assigned a status within each pelagic habitat type and OSPAR Region. Component-level status decisions were based on five criteria: net trend direction, mean confidence, spatial representativeness, relevance of the associated environmental pressure, and strength of the environmental linkage. These criteria are shown in **Fig. 3**. Full component-level status results are provided in **Section S3**.

2.9.1. Component-level trend integration

Each of the three pelagic habitats indicators encompassed multiple biodiversity components. The *Changes in Phytoplankton and Zooplankton Communities* indicator assesses eight distinct plankton lifeforms, while the *Changes in Phytoplankton Biomass and Zooplankton Abundance* and *Changes in Plankton Diversity* indicators include both phytoplankton and zooplankton components.

For each indicator component, trends were integrated across all relevant polygon assessment units and fixed-point stations belonging to each pelagic habitat type and OSPAR Region. The net direction of

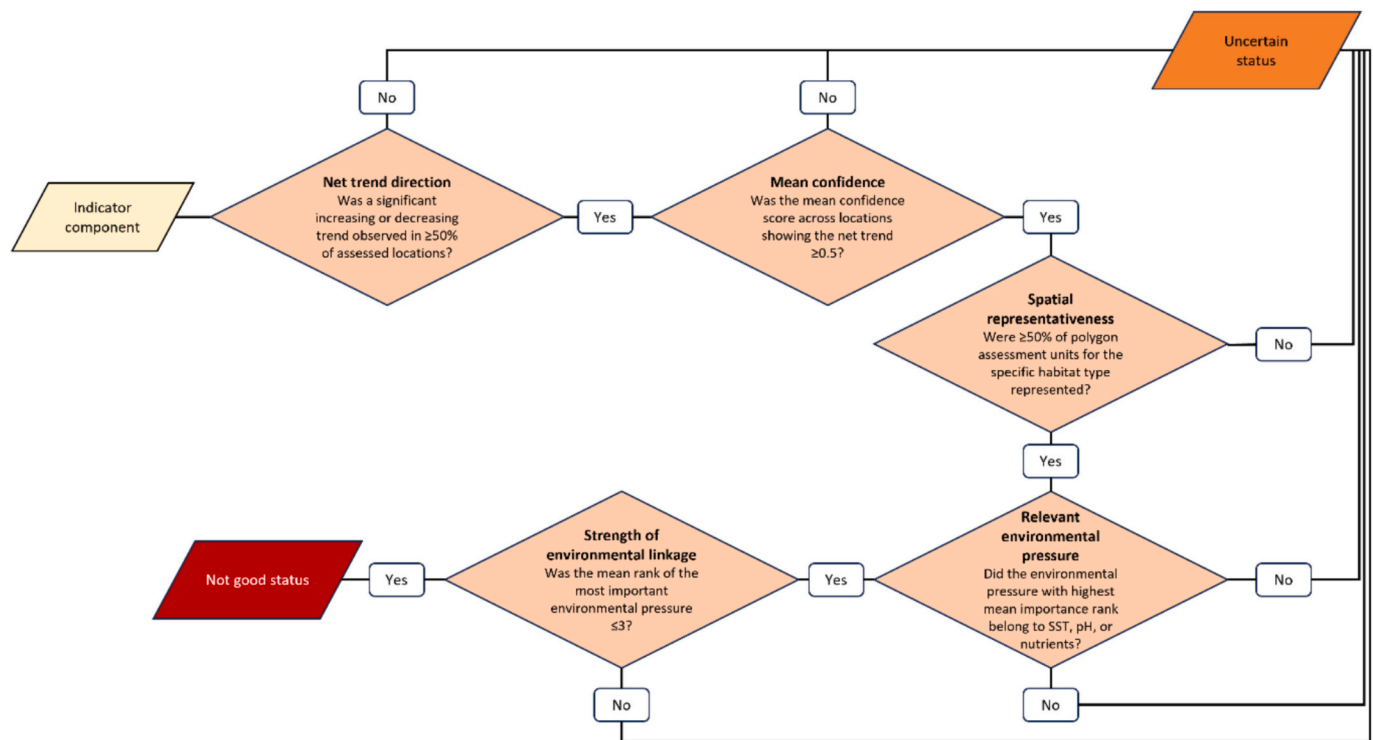


Fig. 3. Decision flow chart describing the rules applied to each indicator component (e.g., small copepods within coastal habitats of the Greater North Sea for the Changes in Phytoplankton and Zooplankton Communities indicator) to determine status of each indicator component.

change was determined using the indicator-specific outputs described in **Section S2.3**: Kendall trend test results for *Changes in Phytoplankton and Zooplankton Communities*; cumulative sums for *Changes in Phytoplankton Biomass and Zooplankton Abundance*; and Kendall trend test on the EQR values of the β -diversity for *Changes in Plankton Diversity*. Since each assessment unit or fixed-point station provides an independent test result, the trend at the indicator component level was summarised based on the majority direction (i.e., decreasing, no change, or increasing) of significant trends across assessment units.

For example, for the *Changes in Phytoplankton and Zooplankton Communities* indicator in the Greater North Sea, the abundance of the meroplankton lifeform was assessed at 12 locations (10 polygon assessment units and 2 fixed-point stations) within coastal habitats. Of these, 0 locations showed a significant decreasing trend ($p \leq 0.05$), 8

showed significant increasing trends ($p \leq 0.05$), and 4 showed no significant trend ($p > 0.05$). This yielded a net increasing trend, as most trends (8 out of 12) were positive. The proportion of increasing trends was 0.67.

2.9.2. Component-level status assignment

To assign an environmental status to indicator components within each pelagic habitat type, we applied a semi-quantitative methodology adapted from McQuatters-Gollop et al. (2022). Each component was classified into one of four status categories: 'Good', 'Uncertain', 'Not Good', or 'Unassessed' (Table 1).

Currently, no operational assessment thresholds exist for pelagic habitat indicators. This reflects the inherent difficulty in defining absolute 'desirable' or 'undesirable' states for plankton communities,

Table 1

Environmental status categories used to assess indicator state (adapted from McQuatters-Gollop et al., 2022).

Not Good	Indicator value is below assessment threshold, or change in indicator represents a declining state, or indicator change is linked to increasing impact of anthropogenic pressures (including climate change), or indicator shows no change but state is considered unsatisfactory
Uncertain	No assessment threshold and/or unclear if change represents declining or improving state, or indicator shows no change but uncertain if state represented is satisfactory
Good	Indicator value is above assessment threshold, or indicator represents improving state, or indicator shows no change, but state is satisfactory
Unassessed	Indicator was not assessed in a region due to lack of data, lack of expert resource, or lack of policy support.

except in specific contexts such as eutrophication. As a result, 'Uncertain' is considered the default status for pelagic habitats in the absence of strong supporting evidence. If a change in an indicator component was observed and could be confidently linked to the influence of anthropogenic pressures, the status was changed from 'Uncertain' to 'Not Good'. At this stage, the methodology does not support transitions from 'Uncertain' to 'Good', due to the lack of ecological thresholds and baseline knowledge. Plankton monitoring in the North-East Atlantic and western European shelf region commenced long after industrialisation and pelagic habitats were already in a disturbed state when most monitoring programmes started, so it is currently challenging to establish baselines and thresholds for GES.

The method presented here and in [McQuatters-Gollop et al. \(2022\)](#) was also broadly applied to other ecosystem components in the [OSPAR 2023 QSR](#), including marine birds, fish, mammals, and food webs ([OSPAR, 2023e](#)).

2.9.3. Criteria for assigning 'not good' status to indicator components

An indicator component was only assigned a 'Not Good' status if all five of the following criteria were met within a habitat type-region combination ([Fig. 3](#)):

- Net trend direction: A significant increasing or decreasing trend was observed in at least 50% of the assessed locations for the component.
- Mean confidence: The mean confidence score ([Section 2.7](#)) for locations showing the net trend was at least 0.5.
- Spatial representativeness: The locations with valid assessments covered at least 50% of the total number of assessment units associated with the habitat type in that region.
- Relevant environmental pressure: The environmental variables with the highest mean importance rank (from random forest models; [Section 2.8](#)) had to be one of the variables most closely linked to anthropogenic pressures: sea surface temperature, pH, or nutrient concentrations.

- Strength of environmental linkage: The mean rank of the most important environmental pressure had to be ≤ 3 , indicating that it consistently ranked among the top three predictors of indicator trends across locations expressing the net trend.

2.9.4. Expert judgement

If all five above conditions were satisfied, the indicator component was then assigned 'Not Good' status for that habitat type in a particular region. In one exceptional case for oceanic/beyond shelf habitats in the Bay of Biscay and Iberian Coast region, the spatial representativeness criterion was not met; however, in this case the spatial representativeness criterion was set aside based on expert judgement. This decision was due to the extensive data coverage for the assessment units considered, particularly for the large Atlantic assessment unit, which incorporated substantial CPR Survey sampling.

2.10. Indicator integration and regional status assessment

While disaggregated indicator results at the level of the four distinct pelagic habitat types are valuable for technical interpretation, further integration was necessary to derive a single region-wide determination of GES. After status had been assigned to individual indicator components, results were integrated through a hierarchical workflow ([Fig. 4](#)). Integration proceeded from component-level status to indicator status, from indicator status to habitat type status, and from habitat type status to regional pelagic habitat status.

2.10.1. Component-to-indicator integration

For each indicator, component-level statuses were integrated to assign one indicator status within each habitat type and OSPAR Region. Because the pelagic habitat indicators differed in the number of components assessed, different integration rules were applied to *Changes in Phytoplankton and Zooplankton Communities* than to the *Changes in Phytoplankton Biomass and Zooplankton Abundance* and *Changes in Plankton Diversity* indicator.

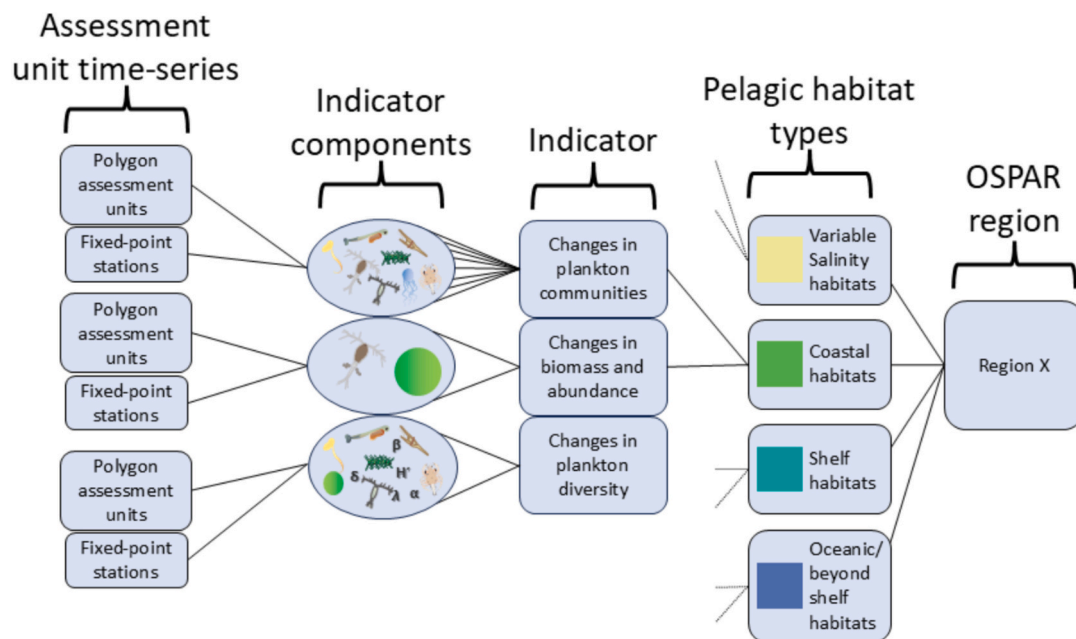


Fig. 4. Conceptual diagram showing the hierarchical integration process used to determine pelagic habitat status. Here, the coastal habitats habitat type was used as an example, but the same process was applied to all pelagic habitat types. Results were integrated from plankton monitoring time-series for each spatial assessment unit/fixed-point station for each indicator component (e.g., lifeform, biomass, index, etc.), to a combined status for each indicator component, to a combined status for each indicator, and finally to a combined status for each pelagic habitat type. Lastly, results for each pelagic habitat type were integrated to generate an overall status for each OSPAR Region. Note – The Changes in Plankton Diversity indicator was assigned indicator-level status and shown as supporting evidence, but was not included in habitat-type or regional status integration due to its developmental stage.

For *Changes in Phytoplankton and Zooplankton Communities*, the indicator status was based on the eight lifeform components. If $\geq 25\%$ of assessed lifeform components within a habitat type-region combination were classified as 'Not Good', then *Changes in Phytoplankton and Zooplankton Communities* indicator was assigned 'Not Good' status for that habitat type and region.

For the *Changes in Phytoplankton Biomass and Zooplankton Abundance* and *Changes in Plankton Diversity* indicators, indicator status was based on two components, phytoplankton and zooplankton. Where both components had the same status, that status was assigned to the indicator. Where one component was 'Not Good' and the other was 'Uncertain', the indicator was assigned 'Not Good' status, following the precautionary principle. Where only one component was assessed, the status of that component determined the indicator status. Where neither component was assessed, the indicator was classified as 'Unassessed'.

These rules ensured that an indicator was only assigned a 'Not Good' status within a habitat type when all of the following were true:

- There was consistent evidence of long-term biological change.
- The assessment was supported by sufficient temporal and spatial coverage.
- The observed trends were strongly and plausibly linked to anthropogenic pressures.

This approach provides a precautionary, evidence-based framework for status designation in the absence of formal thresholds, while also identifying clear cases of biodiversity degradation.

2.10.2. Indicator-to-habitat integration

From this stage onwards, the *Changes in Plankton Diversity* indicator was not included in the integration process (see [Section 2.2](#) for more details).

To determine habitat status, the statuses of the *Changes in Phytoplankton and Zooplankton Communities* and the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicators were integrated within each habitat type and OSPAR Region ([Table 3](#)).

At the habitat type level, the status was assigned using a majority rule:

If three indicators were assessed for a given habitat type, the status most frequently assigned among them was adopted as the overall status for that habitat type. There were no cases where this rule was applied, because the *Changes in Plankton Diversity* indicator was used here as supplementary evidence and not integrated due to its developmental stage.

If only one indicator was available for a habitat type in a region, its status determined the habitat status. There were no cases where this rule was applied.

If two indicators were assessed and had the same status, the habitat type was assigned that status for that region.

If two indicators were assessed and their statuses differed, the habitat type was assigned the more negative status. For example, if one indicator was 'Uncertain' and one was 'Not Good', the habitat type was classified as 'Not Good'.

Habitat types with no assessed indicators were classified as 'Unassessed'.

2.10.3. Habitat-to-region integration

At the regional level, the overall environmental status of each OSPAR Region was determined using a majority rule applied across the assessed pelagic habitat types:

- Where one status was assigned to the majority of assessed habitat types, that status was adopted as the regional status.
- Where there was a tie between 'Not Good' and 'Uncertain', the region was assigned 'Not Good' status, following the precautionary principle.

- If fewer than four habitat types were present in the region or had sufficient data to support assessment, only the available habitats were considered in determining the regional status.

2.11. Confidence in indicator assessments and final integrated regional status

To evaluate the confidence in each indicator assessment ([Table 4](#)), we followed the approach set out in the OSPAR QSR production guidelines ([OSPAR, 2019](#)), using two key criteria:

1. Degree of agreement

The level of consistency in assessment results across indicator components and pelagic habitat types within the region. This was scored as:

- High: Trends and pressure links were consistent across indicators and habitats;
- Medium: Moderate consistency, with some divergence in trends or causes;
- Low: Substantial inconsistency across indicators or habitats.

2. Type, amount, quality, and consistency of evidence

The robustness of the data underlying the assessments, including:

- Type of evidence (OSPAR indicators, other scientific assessments, etc.);
- Spatial and temporal coverage of monitoring ([Section 2.7](#));
- Internal confidence from individual indicators ([Section 2.7](#)), which evaluated sampling coverage and duration.

Evidence strength was scored as:

- Robust: multiple lines of evidence with broad spatial-temporal coverage;
- Medium: limited or uneven coverage, or reliance on fewer sources;
- Limited: scarce data, short time-series, or highly localised evidence.

For each indicator, confidence assessment scores were integrated within the OSPAR Regions, following the same majority integration rules as those used to integrate regional status. Subsequently, for each OSPAR Region a confidence matrix ([Table 2](#)) was used to integrate the integrated agreement and evidence scores into a final confidence level for each region. The final confidence level had one of five possible results: Very high (consisting of High agreement and Robust evidence), High (consisting of High agreement and Medium evidence, or Medium agreement and Robust evidence), Medium (consisting of High agreement and Limited evidence, Medium agreement and Medium evidence, or Low agreement and Robust evidence), Low (consisting of Medium agreement and Limited evidence or Low agreement and Medium evidence), or Very low (consisting of Low agreement and Limited evidence).

Temporal coverage was explicitly considered. For example, offshore waters benefited from long-term CPR data starting in the 1960s; coastal areas and estuarine plumes were typically only monitored from the 1980s–2000s onward.

Regions where trends were detected in long, continuous time-series (especially offshore) were assigned higher confidence than regions where only recent or spatially limited data were available.

3. Results

This work evaluates the environmental status of pelagic habitats at the regional scale across the Northeast Atlantic. For detailed results at the level of individual assessment units, readers are referred to the

Table 2

A depiction of the evidence and agreement statement and their relationship to the confidence criteria. 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.

Agreement ↑	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
Evidence →			
Very Low Low Medium High Very High			

corresponding OSPAR Pelagic Habitats indicator assessments: *Changes in Phytoplankton and Zooplankton Communities* (Holland et al., 2023a), *Changes in Phytoplankton Biomass and Zooplankton Abundance* (Louchart

et al., 2023c), and *Changes in Plankton Diversity* (Louchart et al., 2023d).

Biodiversity indicator outcomes varied substantially depending on the indicator, the pelagic habitat type, and the OSPAR Region

Table 3

The status for each pelagic habitat type within each OSPAR Region over the period 1960–2019, derived by integrating the status of indicators for pelagic habitats. Indicators are assessed as ‘Not Good’ when indicator change is statistically linked to a human pressure. 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. Changes in Plankton Diversity is shown for information only and was not included in habitat-type or regional status integration due to its developmental stage.

Region	Habitat	Changes in Phytoplankton and Zooplankton Communities	Changes in Phytoplankton Biomass and Zooplankton Abundance	Changes in Plankton Diversity	Habitat status	Region status
Greater North Sea	Variable salinity	Uncertain	Uncertain	Uncertain	Uncertain	Uncertain
	Coastal	Uncertain	Uncertain	Uncertain	Uncertain	
	Shelf	Not Good	Not Good	Uncertain	Not Good	
Celtic Seas	Variable salinity	Uncertain	Not Good	Not assessed due to data limitations	Not Good	Not Good
	Coastal	Not Good	Not Good	Uncertain	Not Good	
	Shelf	Not Good	Uncertain	Uncertain	Not Good	
Bay of Biscay and Iberian Coast	Variable salinity	Not assessed due to data limitations	Not assessed due to data limitations	Not assessed due to data limitations	Not assessed due to data limitations	Not Good
	Coastal	Uncertain	Uncertain	Uncertain	Uncertain	
	Shelf	Not Good	Not Good	Uncertain	Not Good	
	Oceanic	Not Good	Not Good	Uncertain	Not Good	

considered (Table 3, Fig. 5). Of the ten region-habitat combinations considered, six were assessed as 'Not Good' Environmental Status, three were assessed as 'Uncertain', and one remained 'Unassessed'. At the region level, the Celtic Seas and the Bay of Biscay and Iberian Coast regions were assessed as 'Not Good', while the Greater North Sea was assessed as 'Uncertain' status. Confidence was highest in the Celtic Seas and moderate in both the Greater North Sea and the Bay of Biscay and Iberian Coast (Table 4; Section S4). Indicator trends were detected in plankton lifeforms (*Changes in Phytoplankton and Zooplankton Communities*) and in phytoplankton biomass and zooplankton abundance (*Changes in Phytoplankton Biomass and Zooplankton Abundance*), but none in the diversity indices (*Changes in Plankton Diversity*). Trends were also detected most clearly in coastal and shelf waters, but variable salinity habitat status was almost always 'Uncertain'.

3.1. Pelagic habitats in the greater North Sea

Greater North Sea variable salinity habitats and coastal habitats were assessed as having 'Uncertain' status, while shelf habitats were assessed as having 'Not Good' status. Confidence was medium for both the *Changes in Phytoplankton and Zooplankton Communities* and *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator assessments, reflecting generally consistent trends and broad spatial and temporal data coverage, but with limitations arising from variable local-scale responses, weaker representation of zooplankton in variable salinity habitats, and reliance on modelled or remotely-sensed pressure datasets (Section S4.1.1 and S4.1.2). Confidence in the *Changes in Plankton Diversity* indicator assessment was high, driven by strong agreement in the absence of diversity change across the Greater North Sea, although evidence was somewhat limited due to data availability

(Section S4.1.3).

3.1.1. Variable salinity habitats in the greater North Sea

Contrasting temporal trends among plankton communities were observed for variable salinity habitats. The *Changes in Phytoplankton and Zooplankton Communities* indicator revealed significant long-term increases in dinoflagellate and larval fish abundance for a limited number of assessment units, whereas holoplankton, large copepods, and small copepods exhibited significant decreasing trends (Table S5). Random forest modelling did not establish clear links between changes in life-form abundance and anthropogenic pressures, resulting in 'Uncertain' status.

For the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator, a decreasing trend was observed in phytoplankton biomass (Table S8). Model analyses associated this decline with decreasing dissolved inorganic phosphate concentrations and changes in the nitrogen-to-phosphorus ratio. The indicator also revealed downward trends in zooplankton abundance across most assessment units, though this result should be interpreted with caution as the assessment lacks spatial coverage. Downward trends in phytoplankton biomass may have influenced the decline in zooplankton abundance; however, the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator does not currently evaluate phytoplankton biomass as a pressure on zooplankton. Additionally, the zooplankton abundance assessment relied on a single assessment unit, resulting in very limited spatial representation and elevated uncertainty for this pelagic habitat type (Table 2, Section S4). The indicator status was assessed as 'Uncertain'.

The *Changes in Plankton Diversity* indicator showed no significant trends overall (Table S9).

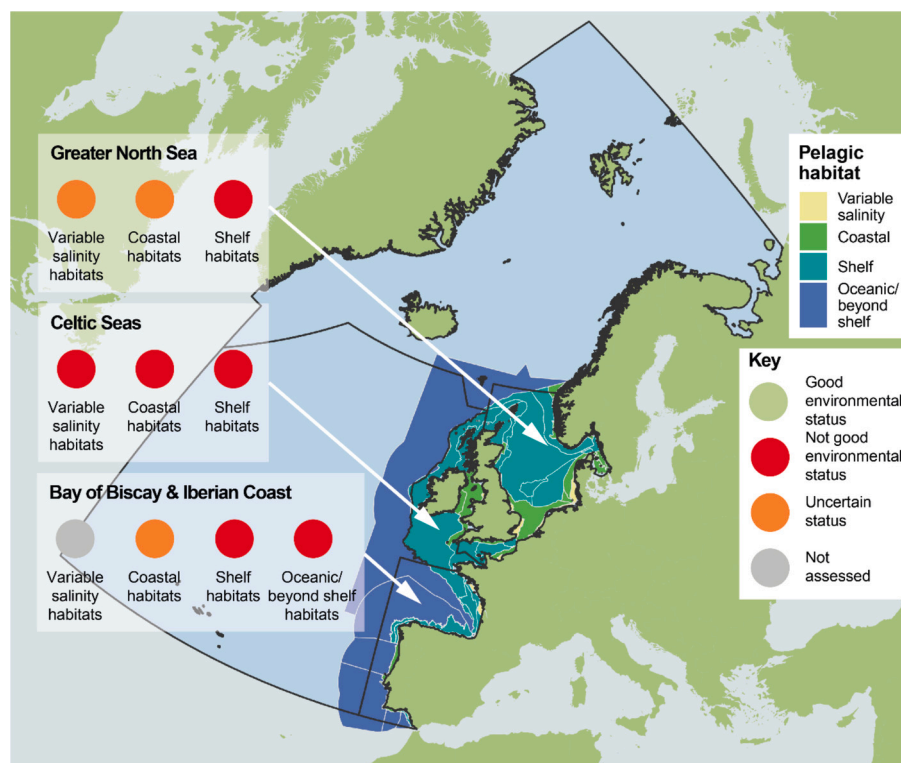


Fig. 5. Status of Northeast Atlantic pelagic habitats in four main habitat types (variable salinity, coastal, shelf, and oceanic/beyond shelf) of the Greater North Sea, the Celtic Seas, and the Bay of Biscay and Iberian Coast. Icons have been coloured according to indicator status. Orange indicates 'Uncertain' status and is the default colour if the indicator has been assessed. Red indicates that the assessment detected a trend linked to human activity ('Not Good' status). 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. Grey identifies indicators that were not assessed in some regions or habitat types due to lack of data. *Changes in Plankton Diversity* was not included in habitat-type or regional status integration. Pelagic habitat types without results displayed indicate that the particular habitat type is not present within the OSPAR Region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4

Between-indicator integration confidence assessment of the type, amount, quality, and consistency of two criteria: 1. evidence (i.e., Robust, Medium, or Limited) and 2. degree of agreement in the results (i.e., High, Medium, or Low), for the three pelagic habitat indicators across the three regions. Colours are used for interpretation, as in Table 2. Changes in Plankton Diversity is shown as supporting evidence and was not included in final habitat or regional status confidence integration.

Region	Criteria	Changes in Phytoplankton and Zooplankton Communities	Changes in Phytoplankton Biomass and Zooplankton Abundance	Changes in Plankton Diversity	Criteria status	Region status
Greater North Sea	Evidence	Medium	Medium	Medium	Medium	Medium
	Agreement	Medium	Medium	High	Medium	
Celtic Seas	Evidence	Medium	Medium	Medium	Medium	High
	Agreement	High	High	High	High	
Bay of Biscay and Iberian Coast	Evidence	Limited	Limited	Limited	Limited	Medium
	Agreement	High	High	High	High	

3.1.2. Coastal habitats in the greater North Sea

The coastal habitats assessment revealed distinct community responses to environmental pressures. The *Changes in Phytoplankton and Zooplankton Communities* indicator revealed significant upward trends in meroplankton and larval fish abundance for the majority of assessment units, associated with rising sea surface temperatures and increasing salinity, respectively (Table S5). However, the association with environmental drivers was too variable across assessment units (i.e., mean rank >3) to make a formal conclusion on habitat status, resulting in Uncertain status.

For phytoplankton biomass, a significant decline ($p < 0.05$) was observed in most assessment units. However, the association with an increased nitrogen-to-phosphorus ratio (N/P), identified as the primary predictor of this decline, was too variable (mean rank >3.0) to support a formal conclusion (Table S8). Conversely, zooplankton abundance followed an upward trend ($p < 0.05$) for most assessment units linked to mixed layer shoaling. However, the model failed to reach the required confidence, resulting in Uncertain status.

The *Changes in Plankton Diversity* indicator did not show any significant trends overall (Table S9).

3.1.3. Shelf habitats in the greater North Sea

For shelf habitats, complex abundance patterns across taxonomic groups were recorded. The *Changes in Phytoplankton and Zooplankton Communities* indicator revealed significant long-term increases in diatoms, meroplankton, and larval fish, while dinoflagellates, holoplankton, and small copepods experienced significant downward trends ($p < 0.05$) for most assessment units (Table S5). Meroplankton and holoplankton abundance trends were consistently associated with rising sea surface temperature across spatial scales. Larval fish abundance increase was statistically linked to a decrease in light attenuation.

Consistent with coastal habitats patterns, a downward trend was revealed in phytoplankton biomass ($p < 0.05$) across most assessment units, associated with increased nitrogen-to-phosphorus ratio (Table S8). Zooplankton abundance exhibited a significant downward trend ($p < 0.05$) in the majority of assessment units, linked to mixed layer shoaling.

The *Changes in Plankton Diversity* indicator showed no overall significant trends (Table S9).

3.2. Pelagic habitats in the Celtic Seas

Celtic Seas variable salinity, coastal, and shelf habitats were assessed as having 'Not Good' status. Confidence was high for all three Celtic Seas indicator assessments, reflecting strong agreement across assessment units, consistent trends in the two status-determining indicators, and consistent absence of clear change in the Diversity indicator (Section S4.2). Evidence was medium, because the assessments were supported by multiple long-term datasets with strong coverage in coastal and shelf habitats, but were limited by poor or absent representation of variable salinity habitats, particularly for zooplankton lifeforms and plankton diversity, and by reliance on remotely-sensed or modelled pressure datasets rather than in situ pressure observations.

3.2.1. Variable salinity habitats in the Celtic Seas

Pronounced shifts were recorded within plankton communities in variable salinity habitats. The *Changes in Phytoplankton and Zooplankton Communities* indicator revealed significant upward long-term trends in dinoflagellate abundance ($p < 0.05$) in most assessment units, while all other plankton lifeforms showed significant declines ($p < 0.05$) (Table S6). However, zooplankton lifeforms had very low spatial representation. Decreasing trends in diatom abundance were linked to an increase in the N/P ratio. A large copepod decline in abundance, assessed at a single fixed-point monitoring station, was linked to a rise in sea surface temperature.

The *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator detected declining trends in both zooplankton abundance and phytoplankton biomass ($p < 0.05$) across all assessment units (Table S8). Zooplankton declines were attributed to a decrease in surface current velocity, while phytoplankton biomass reduction ($p < 0.05$) was related to a decrease in nitrate concentrations. The association between phytoplankton biomass and nitrate concentration (mean rank <3.0) led to a 'Not Good' status.

The *Changes in Plankton Diversity* indicator showed no overall

significant trends (Table S9).

3.2.2. Coastal habitats in the Celtic Seas

Coastal habitats exhibited declining trends across multiple taxonomic groups included in the *Changes in Phytoplankton and Zooplankton Communities* indicator. Dinoflagellates, holoplankton, large copepods, and small copepods underwent significant downward trends ($p < 0.05$) for most assessment units linked to rising sea surface temperature, and, for holoplankton, to pH (Table S6). No data were available for assessment of gelatinous zooplankton.

The *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator revealed a decreasing trend in phytoplankton biomass associated with decreasing pH (mean rank < 3.0 ; Table S8). Decreasing pH is likely associated with climate change, resulting in 'Not Good' status. Conversely, zooplankton abundance showed a significant upward trend ($p < 0.05$) for most assessment units linked to an Atlantic Multidecadal Oscillation (AMO) increase, which corresponds with the warming phase of natural climate variability in the North Atlantic.

The *Changes in Plankton Diversity* indicator showed no overall significant trends (Table S9).

3.2.3. Shelf habitats in the Celtic Seas

The *Changes in Phytoplankton and Zooplankton Communities* indicator revealed significant upward abundance trends for meroplankton and significant downward trends for dinoflagellates and holoplankton ($p < 0.05$) for most assessment units (Table S6). Dinoflagellate abundance declines were primarily linked to increased N/P ratios, likely driven by a reduction of anthropogenic nutrient inputs affecting phosphate more than nitrates. For meroplankton and holoplankton, changes were linked to increasing sea surface temperature and reductions in pH, respectively. No data were available to assess gelatinous zooplankton.

pH reductions were also associated with statistically significant ($p < 0.05$) declining trajectories in both phytoplankton and zooplankton components of the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator for most assessment units (Table S8). However, the model failed to support a formal status conclusion for both phytoplankton biomass (mean rank pressure > 3.0) and zooplankton abundance (confidence $< 50\%$ threshold), resulting in 'Uncertain' status.

The *Changes in Plankton Diversity* indicator did not detect any significant long-term changes in community composition for either zooplankton or phytoplankton (Table S9).

3.3. Pelagic habitats in the Bay of Biscay and Iberian Coast

Coastal habitats were assessed as 'Uncertain', while shelf habitats and oceanic/beyond shelf habitats were assessed as 'Not Good' for the Bay of Biscay and Iberian Coast. Variable salinity habitats were not assessed due to lack of data. Confidence was medium for all three Bay of Biscay and Iberian Coast indicators, despite high agreement in the direction and magnitude of trends across assessed units (Section S4.3). Confidence was constrained by limited evidence, including absent or poor data coverage for variable salinity and coastal habitats, partial representation of shelf and oceanic habitats, limited spatiotemporal coverage of CPR samples, reliance on modelled rather than in situ pressure datasets, and the use of assessment units defined differently from those in the Greater North Sea and Celtic Seas, which may reduce representativeness of regional oceanography and plankton dynamics.

3.3.1. Coastal habitats in the Bay of Biscay and Iberian Coast

The coastal habitats assessment in the Bay of Biscay and Iberian Coast was constrained by limited data availability for the *Changes in Phytoplankton and Zooplankton Communities* indicator (Table S7). Only phytoplankton data were available to inform this indicator. Further, diatom and dinoflagellate trends were based solely on *Pseudo-nitzschia* and *Dinophysis* genera counts, providing limited representation of the broader microphytoplankton community.

The *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator revealed a significant decreasing trend ($p < 0.05$) in phytoplankton biomass for most coastal assessment units, associated with the North Atlantic Oscillation (NAO) (Table S8). Conversely, zooplankton abundance significantly increased ($p < 0.05$) in most assessment units, linked to rising sea surface temperature. However, both component assessments were based on single-station data with strong local evidence but no spatial coverage. These results should therefore be interpreted with considerable caution for this habitat, resulting in 'Uncertain' status.

The *Changes in Plankton Diversity* indicator did not reveal any significant trends (Table S9).

3.3.2. Shelf habitats in the Bay of Biscay and Iberian Coast

For shelf habitats in the Bay of Biscay and Iberian Coast, *Changes in Phytoplankton and Zooplankton Communities* revealed significant downward trends in diatoms, holoplankton, meroplankton, large copepods, and small copepods (Table S7). For holoplankton, large copepod, and small copepod abundances, these declines were observed in most assessment units and were linked to rising sea surface temperature.

In contrast, the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator revealed a significant upward trend in phytoplankton biomass ($p < 0.05$) for most assessment units, linked to reduced wind velocity, which may promote surface layer stability through reduced vertical mixing (Table S8). This trend should be interpreted cautiously as less than half of the assessment units were covered. Consistent with small and large copepods trends (*Changes in Phytoplankton and Zooplankton Communities* indicator), zooplankton abundance (*Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator) showed a significant downward trend ($p < 0.05$) for most assessment units linked to mixed layer depth variations. Although this met the threshold criterion (mean rank = 3), the association was at the threshold limit and should be interpreted cautiously (Table S8).

The *Changes in Plankton Diversity* indicator revealed no significant trends (Table S9).

3.3.3. Oceanic / beyond shelf habitats in the Bay of Biscay and Iberian Coast

For oceanic/beyond shelf habitats, the assessment revealed complex community dynamics despite limited spatial representation. The *Changes in Phytoplankton and Zooplankton Communities* indicator demonstrated significant upward trends for meroplankton, while all the other assessed lifeforms underwent significant downward abundance trends (Table S7). Downward trends in holoplankton, large copepods, and small copepods ($p < 0.05$) for most assessment units were consistently linked to rising sea surface temperature. Despite the low spatial representation of assessment units for informing *Changes in Phytoplankton and Zooplankton Communities*, the assessment units considered for this pelagic habitat were spatially extensive and incorporated a large number of samples with wide spatial distribution. Because of the high number of samples, expert judgement was used in this case to designate 'Not Good' status for large copepods and small copepods, despite not exceeding the 50% threshold for spatial representativeness.

The *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator revealed significant downward trends in phytoplankton biomass ($p < 0.05$) for most assessment units, associated with declining light attenuation (increasing water clarity) (Table S8). However, the reduced light attenuation likely resulted directly from a decrease in phytoplankton biomass rather than representing an independent driver. Consistent with community indicator results, zooplankton abundance (*Changes in Phytoplankton Biomass and Zooplankton Abundance*) also revealed significant downward trends ($p < 0.05$) for most assessment units, linked to increasing sea surface temperature, although spatial representation remained limited for both components in this habitat.

The *Changes in Plankton Diversity* indicator revealed no significant trends (Table S9).

4. Discussion

4.1. Widespread 'Not Good' Environmental Status needs action, widespread 'Uncertain' status needs attention

The environmental status of pelagic habitats across all OSPAR Regions was assessed as either 'Not Good' or 'Uncertain'. This assessment reflects a persistent, large-scale alteration of plankton biodiversity and signals a systemic ecological imbalance in pelagic ecosystem functioning. It constitutes a strong environmental warning and calls for a strengthened policy and management response. The drivers of this degradation, particularly increasing sea surface temperatures and shifts in nutrient regimes, are consistent with the broader suite of anthropogenic pressures identified globally.

The *Changes in Phytoplankton and Zooplankton Communities* indicator showed inconsistent trends in plankton lifeform abundance across all habitats and regions. The *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator showed widespread but regionally variable change across the Northeast Atlantic, while the *Changes in Plankton Diversity* indicator did not show clear changes at either regional or habitat scales.

The poorest pelagic habitat status was found in the Celtic Seas and the Bay of Biscay and Iberian Coast, where four out of six status-determining habitat-indicator combinations were assessed as 'Not Good' in each region. In contrast, the Greater North Sea was assessed as having 'Uncertain' regional status, with four out of six status-determining habitat-indicator combinations classified as 'Uncertain'. This differed from the QSR2023 assessment and reflected the implementation of confidence scoring for the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator (OSPAR, 2023a). The condition of pelagic habitats across different regions was largely driven by the 'Not Good' state of shelf habitats, while variable salinity and coastal habitats were assessed as either 'Not Good' or 'Uncertain'. This uncertainty may be attributed to eutrophication effects and naturally high environmental variability which complicate interpretation and make status assessment difficult (OSPAR, 2023b).

Other regional seas face similar challenges around multiple pressures, uneven monitoring coverage, and limited agreement on assessment thresholds and baseline conditions when assessing pelagic habitats. Except for a few coastal areas, Baltic Sea pelagic habitats have been assessed by HELCOM as having 'Not Good' status, which is largely driven by eutrophication and climate change (HELCOM, 2023). In the Mediterranean Sea, pelagic habitat assessment under the MSFD has been constrained by inconsistent approaches to defining GES, limited baseline knowledge, and a lack of agreed thresholds for biodiversity indicators (Francé et al., 2021; Varkitzi et al., 2018). For Black Sea pelagic habitats, comparable challenges exist around cumulative pressures, uneven monitoring coverage, and scale mismatches (Bisinicu and Harcota, 2025; Serpetti et al., 2025; Tan et al., 2025). These examples are consistent with our findings and reinforce the challenges in assessing the environmental status of pelagic habitats. Furthermore, HELCOM's assessment of Baltic Sea pelagic habitats indicates widespread failure to achieve 'Good' status, suggesting the restructuring of pelagic habitats in response to cumulative anthropogenic pressures and climate-driven environmental change is not unique to the Northeast Atlantic.

4.2. Linking pressures to ecological response

Rising sea surface temperature (SST), altered nutrient ratios, and declining pH consistently emerged as the dominant pressures associated with changes in Northeast Atlantic plankton communities. These patterns align with global scientific evidence of planktonic shifts driven by climate change, reinforcing conclusions drawn by the IPCC and earlier OSPAR assessments (IPCC, 2023; OSPAR, 2017). However, the current work offers regional specificity and operationalises integrated, indicator-based methodologies, as well as formally incorporating

environmental pressure ranking into status assessment.

SST increases, particularly in the shallow Greater North Sea, are associated with enhanced summer stratification and shoaling of the mixed layer, processes that restrict nutrient replenishment to surface waters. This limitation is likely contributing to reduced productivity of microphytoplankton that contribute to pelagic food webs (Capuzzo et al., 2018; Edwards et al., 2022; Schmidt et al., 2020) and the observed declines in copepod and holoplankton abundance in variable salinity and shelf habitats (Changes in Phytoplankton and Zooplankton Communities indicator; Atkinson et al., 2024; Defriez et al., 2016; Sandø et al., 2024). Such changes are consistent with expected trophic effects, where weakened primary production diminishes energy transfer to higher trophic levels (Capuzzo et al., 2018).

Temperature-linked physiological effects may also be enhancing meroplankton reproductive output and larval survival (Kirby et al., 2008; Kirby et al., 2007; Marques et al., 2023), despite overall declining phytoplankton biomass from the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator. In the North Sea, warming temperature has been linked to a decline in copepod abundance (Semmouri et al., 2023). For phytoplankton of the Greater North Sea Region, a decrease in chlorophyll of up to 25% has been observed in the English Channel (Huguet et al., 2024), although total phytoplankton abundance has increased, with a shift towards increased numbers of picoplankton (Hubert et al., 2025). In the Celtic Seas, similar warming and stratification patterns coincide with declines in diatoms and offshore dinoflagellates, as well as poleward shifts in copepod distributions towards warmer-water taxa (Beaugrand et al., 2002; Harris et al., 2015). In this region, climatic cycles and reduced river outflow further exacerbate nutrient limitation (Gohin et al., 2019), likely contributing to the observed reductions in phytoplankton biomass.

In the Celtic Seas, pH has declined at a rate of -0.0019 yr^{-1} (OSPAR, 2023c), coinciding with the decreasing trend in phytoplankton biomass (*Changes in Phytoplankton Biomass and Zooplankton Abundance*). While acidification can alter phytoplankton physiology by modifying dissolved inorganic carbon (DIC) availability, phytoplankton uptake of DIC also influences pH, necessitating caution in evaluating the relationship between phytoplankton and pH. DIC levels from both natural and anthropogenic sources can influence pH levels in seawater (Beare et al., 2013). Correlation does not necessarily mean causation, and the observed co-occurrence should be interpreted as a potential contributing factor rather than a confirmed causal link. Where variation in zooplankton diversity was observed, it was mostly closely associated with shifts in light attenuation (Capuzzo et al., 2018).

Natural climate variability (i.e. the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO)) influences some environmental pressures. In the Bay of Biscay and Iberian Coast, variability in NAO/AMO, surface warming, and wind speeds were associated with decreased phytoplankton biomass, diatom declines, and spatially variable copepod trends (as in Bode et al., 2013; Bode et al., 2020; Edwards et al., 2022). Coastal waters in this region show stable dinoflagellate abundance but SST-associated declines in zooplankton diversity, contrasting with offshore patterns.

Management measures to reduce nutrient inputs from riverine and direct discharges into the sea, as well as atmospheric deposition, effectively combated eutrophication, notably excess phytoplankton biomass, in the 1970's to 1990's. However, a number of variable salinity and coastal assessment units in the OSPAR area are not yet in 'Good' status, i.e. phytoplankton biomass (chlorophyll *a*) is still higher than 50% above (modelled) reference concentrations around 1900, which was before widespread application of fertilizers in agriculture. Reduction measures have been most effective for phosphorus and less for nitrogen (OSPAR, 2023a). Resulting shifts in nitrogen-to-phosphorus ratios have produced conditions consistent with phosphorus limitation (Devlin et al., 2023). This imbalance is likely influencing phytoplankton biomass and community composition. In the Greater North Sea, coastal and variable salinity habitats show increased dinoflagellate abundance,

while shelf waters exhibit the opposite trend. In the Celtic Seas, phosphate depletion may also be contributing to decreasing trends in diatom abundance and overall phytoplankton biomass shown by the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator, aligning with experimental and observational studies in other temperate shelf systems where phosphorus limitation favours less diverse assemblages (Burson et al., 2016; Groß et al., 2022). In general, it should be noted that in some mixed salinity and coastal assessment areas affected by human-induced nutrient inputs, the decline in phytoplankton biomass is considered the intentional result of a successful reduction of phosphorus alongside a less successful reduction of diffuse nitrogen. The resulting change in N/P ratio reflects difficulties in the implementation of the various reduction measures, and assessment areas where the status remained 'Not Good' can also suggest that current reduction efforts are not yet sufficient or fully perceptible.

The differing responses between the Greater North Sea, Celtic Seas, and Bay of Biscay likely reflect regional contrasts in circulation patterns, nutrient sources, and historical anthropogenic pressures—for example, legacy eutrophication in the Southern North Sea from 20th-century agricultural runoff (Axe et al., 2017; Vermaat et al., 2008), sediment resuspension from bottom trawling in shelf areas (Bradshaw et al., 2021), and reduced nutrient loads following management measures (Devlin et al., 2023). Interactions among pressures, such as warming combined with nutrient imbalance, have been shown in mesocosm experiments in NE Atlantic waters to produce non-linear, amplified impacts on productivity and community structure, favouring smaller phytoplankton, benefiting microzooplankton, and decreasing mesozooplankton (Moreno et al., 2022), underlining the need to consider both nutrients and climate effects when interpreting regional plankton trends.

4.3. Methodological advances in environmental status assessment

This work constitutes a significant methodological progression from OSPAR Intermediate Assessment 2017 (OSPAR, 2017) and its extension by McQuatters-Gollop et al. (2022). The 2017 assessment (OSPAR, 2017) was primarily descriptive, with most biodiversity indicators presented at pilot-stage or lacking defined thresholds. In particular, pelagic habitats assessments in 2017 identified and described temporal trends in indicator values, but did not evaluate biodiversity status due to the lack of thresholds for all three indicators (OSPAR, 2017). McQuatters-Gollop et al. (2022) enabled a semi-quantitative assessment of pelagic habitats, but all three indicators were found to be of 'Uncertain' status in each OSPAR Region due to data gaps, early stage indicator development, and undefined state-pressure relationships. The robustness and usefulness of the pelagic habitats assessment have here been improved through both an expanded evidence base and refined assessment methodology through several key advances:

- 1) The incorporation of 20 additional plankton abundance datasets unavailable in 2017, including satellite chlorophyll, answering the call of McQuatters-Gollop et al. (2022) for improved data harmonisation.

- 2) The statistical modelling of environmental data to establish state-pressure relationships for the three indicators at habitat scales; this modelling step, through random forest regression, captures 57% to 80% of the variability in plankton lifetimes abundance and provides relative variable importance rankings (Holland et al., 2024). This enhances our understanding of environmental drivers – particularly temperature, mixed layer depth, nutrients and derived N/P ratios. Moreover, it enables the identification of the geographic focus and type of management measures needed to achieve GES, particularly given the contrasting response of plankton components to driver influence.

- 3) The development of quantitative integration rules for status determination across component, indicator, habitat, and regional scales represents a substantial methodological advancement that addresses a critical gap in pelagic habitat assessment. Previously, the absence of defined integration methods meant that within-indicator components

remained fragmented, limiting cross-indicator synthesis at the habitat scale and preventing transparent upscaling to regional status. The approach developed here provides reproducible and transparent rules for integrating plankton assessment results and identifying which habitat type, indicator, or plankton component is driving status. Furthermore, this method enables direct comparability between regions through a standardized integration method and supports adaptive management by clearly identifying which scale (habitat or regional) and which plankton component is driving status.

- 4) The definition of habitat types from environmentally-derived assessment units improves the ecological coherence of assessments by aligning evaluation units with hydrological, physical, and biological criteria rather than administrative boundaries.

- 5) The implementation of confidence assessment frameworks ensures assessment transparency.

- 6) Finally, the environmental status determination method used here was also applied to other ecosystem components, such as marine birds, seals and small toothed cetaceans, and marine food webs (OSPAR, 2023f) allowing for a holistic view of environmental status across the ecosystem for each OSPAR Region.

The integration framework developed here also aligns with broader efforts by regional and international assessment bodies to move from individual indicators towards ecosystem-level status assessments. HELCOM's holistic assessment approach for the Baltic Sea (HELCOM, 2023), MSFD assessments in the Mediterranean (Francé et al., 2021; Varkitzi et al., 2018), and ecosystem-based assessment approaches developed through ICES and NOAA (Clay et al., 2023; Harvey et al., 2017) all face similar methodological challenges: how to combine indicators across ecosystem components, account for cumulative pressures, and determine status where quantitative thresholds or historical baselines are incomplete. The approach presented here contributes to this wider methodological development by providing transparent rules for integrating results from indicator component-level assessments to indicator, habitat, and regional status. However, as in other regional assessment frameworks, the lack of agreed thresholds and reference conditions remains a major constraint on assigning Good Environmental Status with confidence.

4.4. Limitations and sources of uncertainty

Pelagic habitat assessment could be further improved by incorporating more plankton datasets, including those from non-traditional sources such as imaging and eDNA, and filling monitoring gaps to expand the geographic spread of supporting data. Spatial coverage of plankton data remains uneven. Offshore regions generally have better long-term spatial and temporal monitoring (e.g., the CPR survey). In contrast, coastal and estuarine zones are typically monitored with a higher temporal resolution—for example, through weekly, full-depth sampling at fixed-point observatories. These fixed-point stations sample small plankton and gelatinous organisms, but offer poorer spatial coverage. Although the CPR samples both phytoplankton and zooplankton in offshore waters, data gaps exist for coastal habitats, particularly around the Spanish, Irish, Norwegian, and French coasts (Fig. 2). Coastal phytoplankton communities are much better represented here than coastal zooplankton, with only the UK and Sweden submitting zooplankton data for assessment. This contrasts with good networking of European zooplankton time-series within the ICES Working Group on Zooplankton Ecology (O'Brien et al., 2013). More effort to work with national teams to ensure all existing data are used in for assessment will strengthen assessment results, but further plankton monitoring is needed to fill data gaps, and continued financial support for existing plankton time-series is critical for understanding and assessing pelagic habitat status. While the confidence scoring framework developed in this assessment is methodologically robust, further improvement could be achieved through longer, more harmonised, and spatially representative time-series.

All pressure datasets supporting the indicator assessments have a degree of uncertainty. The Atlantic–European North West Shelf Ocean Physics Reanalysis (NWSHELF_MULTIYEAR_PHY_004_009) dataset contains uncertainties in modelled physical oceanographic data due to model limitations and observational constraints, with known seasonal and depth-dependent biases in temperature and salinity, especially in the Norwegian, Irish, and Celtic Seas (Copernicus, 2022b). The Atlantic–European North West Shelf Ocean Biogeochemistry Reanalysis (NWSHELF_MULTIYEAR_BGC_004_011) dataset contains uncertainties in modelled biogeochemical data due to unevenly distributed observational inputs, especially for variables beyond satellite-derived chlorophyll, with notable biases including overestimated nitrate and underestimated phosphate and oxygen concentrations (Copernicus, 2022a). Finally, the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) aggregates surface marine observations from multiple platforms, with quality-control procedures varying across sources and time periods; despite these uncertainties, it remains a critical, long-established resource for understanding long-term ocean–atmosphere interactions and for bias correction and uncertainty estimation in climate models.

The pelagic indicators, particularly *Changes in Phytoplankton and Zooplankton Communities* and *Changes in Plankton Diversity*, are still under development or in the process of operationalisation within the MSFD framework at the scale of OSPAR Contracting Parties. In the *OSPAR Quality Status Report 2023*, the *Changes in Plankton Diversity* indicator was evaluated as a candidate indicator for the Greater North Sea and Bay of Biscay and Iberian Coast regions. Due to a lack of consensus around methodological robustness, the *Changes in Plankton Diversity* indicator outputs were only used indicatively for those regions in the QSR2023 and did not contribute to the assessment of environmental status at the region-habitat scale (Louchart et al., 2023d).

Here we retained consistency with the OSPAR QSR2023 approach by using the *Changes in Plankton Diversity* indicator as informative across all three regions. Because the indicator remains methodologically immature we did not include it in final habitat or regional status integration. This avoided allowing a consistently ‘Uncertain’ candidate indicator to shift habitat-level outcomes towards ‘Uncertain’ in cases where the *Changes in Phytoplankton and Zooplankton Communities* and *Changes in Phytoplankton Biomass and Zooplankton Abundance* gave divergent outcomes. Should resources become available, the *Changes in Plankton Diversity* indicator should be reviewed across all three regions to optimise dataset inclusion, improve sensitivity, and strengthen interpretation of taxonomic diversity change across the OSPAR assessment area.

The relatively young state of the indicators and their evolving maturity hamper consistent application across regions and constrain the ability to assign a definitive Good Environmental Status, especially in the absence of well-established assessment thresholds. A key limitation of the assessment methodology presented here is that it does not yet support transitions from ‘Uncertain’ to ‘Good’ status. Where change has been detected and can be confidently linked to the impact of an anthropogenic pressure, the status of a habitat is ‘Not Good’. This is consistent with a precautionary approach, as pressure-linked ecological change is not assumed to be compatible with ‘Good’ status (Kriebel et al., 2001; OSPAR, 2026).

However, because the methodology does not currently allow a transition from ‘Uncertain’ to ‘Good’ status, there is a possibility that the picture for pelagic habitats in the Greater North Sea, Celtic Seas, and Bay of Biscay and Iberian Coast is more optimistic than the results presented here. Integration rules applied to this assessment also favoured the more negative status in cases of uncertainty or ties. This precautionary sensitivity was included intentionally to ensure that negative status associated with indicator components filtered through to the overall status designation for a particular habitat type or region, rather than being masked in the higher level results.

Future work must develop a technique to enable the transition from an assessment of ‘Uncertain’ status to one of ‘Good’ status. This will

require establishment of realistic reference or baseline conditions, which are challenging to determine due to most monitoring programmes commencing after pelagic habitats were already significantly impacted by anthropogenic pressures, such as eutrophication and climate change. Paleoecology may have some applications in reconstructing pre-disturbance baselines, but only for habitats like embayments and deep ocean basins where the seafloor is not exposed to bottom trawling, dredging, or oceanographic disturbances, and may be biased towards the preservation of some lifeforms, e.g. cyst forming dinoflagellates, in sediment. It may also be a logical option to consider reductions in the intensity of anthropogenic pressures correlated with slowing or reversing rates of change in plankton indicators as evidence of pelagic habitats moving towards ‘Good’ status. Finally, further modelling work may facilitate establishment of reference or baseline reconstruction based on size spectrum slopes or range of natural variability, but this would likely still be data dependent (McKellar et al., 2026; McKellar et al., 2025).

A further challenge exists in determining status in cases where indicators show ecological change attributed to an anthropogenic pressure, but some pressure trends do suggest some improvement. For example, although nutrient ratios have become imbalanced in some habitats (i.e., variable salinity habitats in Greater North Sea and Celtic Seas) and have been linked with indicator change, overall nutrient levels have also decreased in these same habitats as an intended result of management measures to combat eutrophication. However, even if nutrients are decreasing at the habitat scale, these reductions appear insufficient to counteract the observed widespread changes in plankton dynamics across the Northeast Atlantic, which are driven primarily by climate.

Finally, more work is also needed to further develop the *Changes in Plankton Diversity* indicator, particularly around sensitivity and interpretation. This indicator is less mature than the other two operational indicators, but it captures critical aspects of plankton community structure. Here, we applied confidence assessment to trends in the indicator (Section 2.7) and to the degree of agreement and consistency of evidence informing it (Section 2.11). Although the evidence base and agreement were assessed with high confidence in some regions, the *Changes in Plankton Diversity* indicator did not show clear trends or strong links to pressures. This may indicate limited sensitivity to change in its current form, making the results difficult to interpret for status assessment.

Despite these limitations, the convergence of results across indicators, habitat types, and regions provides a coherent and compelling signal of widespread change, thereby reinforcing the overall conclusions of the assessment.

4.5. A call for enhanced action and adaptive governance in a policy context

The assessment's findings carry direct implications for marine policy. The predominance of ‘Not Good’ status emphasizes the insufficiency of current management measures to safeguard pelagic biodiversity. Currently, several plankton time-series in the OSPAR assessment area are paused or at risk due to reducing resources. Maintaining a data flow that facilitates proper assessment is critical for achieving sustainable use of the oceans.

A stronger commitment to nutrient reduction, particularly of nitrogen, and to the integration of climate adaptation into marine spatial planning is clearly needed. Robust pelagic habitats assessment supported by adequate data, quantitative integration methods, and considering state-pressure relationships is fundamental for enabling confident ecosystem-based management, as required under the MSFD. The indicators applied here are effective tools for tracking ecosystem health under changing conditions, and their adoption in adaptive, ecosystem-based management frameworks should be prioritised across relevant policy instruments, including OSPAR and the MSFD.

The pressure modelling work indicated that improved nutrient management is likely necessary for moving pelagic habitats towards GES for the *Changes in Phytoplankton and Zooplankton Communities* indicator in variable salinity habitats of the Greater North Sea and Celtic Seas and for the *Changes in Phytoplankton Biomass and Zooplankton Abundance* indicator in shelf habitats of the Greater North Sea. Better alignment between the complementary aspects of pelagic habitats and eutrophication assessments (OSPAR, 2023b) would help increase the holistic understanding of pelagic habitat indicator dynamics, further solidifying the evidence base around nutrient effects on plankton dynamics. Collaboration on plankton biomass and nutrient data extraction and analysis, and results interpretation between the OSPAR Pelagic Habitats Expert Group and the OSPAR Intersessional Correspondence Group on Eutrophication is an essential first step.

The most important action to protect the functioning of pelagic habitats is to mitigate ongoing climate change through supporting global reductions in carbon emissions. Climate variables were the primary drivers of plankton indicator change in shelf habitats of the Greater North Sea and Celtic Seas and for shelf and oceanic habitats of the Bay of Biscay and Iberian Coast region. While nutrient management is a regional issue, climate change, of course, is a global and complex challenge, requiring intergovernmental collaboration. Climate change must also be incorporated more strongly into existing and future management measures targeting nutrients and other pressures at the regional level to make regional measures more efficient in a globally changing climate. Long-term trends in pelagic indicators of state are expected to translate into losses of valuable ecosystem services such as the removal of anthropogenic carbon emissions and food provision from capture fisheries (Cornacchia et al., n.d.; OSPAR, 2023d). Further work is needed to quantify the extent to which plankton state indicator changes influence the availability of specific ecosystem services (Faith et al., 2025). However, we can be confident that some indicator changes will translate into adverse societal impacts. Observed widespread declines in phytoplankton and zooplankton biomass, for example, are likely to reduce the carrying capacity of fish in the NEA (Atkinson et al., 2024; Faith et al., preprint) and result in direct socioeconomic losses (Boyce et al., 2020; Cinner et al., 2022; Faith et al., preprint). These results therefore demonstrate the urgent need to address local, regional and global pressures on pelagic habitats in the NEA, to protect ecosystem functioning and ultimately safeguard society from harm.

The indicators assessed here focus primarily on microplankton (>20 µm in size); there are currently no *Changes in Phytoplankton and Zooplankton Communities* or *Changes in Plankton Diversity* indicator components that explicitly consider the tiny (<20 µm) pico- or nanoplankton. Picoplankton and small nanoplankton are key components of marine ecosystems that may be favoured under increasing warming and summer stratification (Schmidt et al., 2020). These tiny plankton organisms, that are better quantified using flow cytometry, comprise up to 99.98% of plankton abundance and 71% of plankton biomass in some regions (McQuatters-Gollop et al., 2024), and omission of picoplankton means that a significant portion of the plankton community is not being assessed, and therefore not augmenting the evidence base required for decision making. Development of lifeforms and testing of diversity indices on these tiny plankton datasets are key steps in incorporating this important pelagic habitat biodiversity component in future assessments. Novel automated observation methods, such as imaging flow-cytometry from Ships of Opportunity, should be further explored to fill this data and knowledge gap.

4.6. Research and governance for resilient pelagic ecosystems

This assessment emphasizes the need for a long-term vision that strengthens both the scientific foundations and governance mechanisms required to sustain resilient pelagic ecosystems. Future work should address emerging pressures—such as microplastic contamination, underwater noise, and the spread of non-native species—that are not yet

fully captured by existing indicators but may increasingly shape pelagic food webs. Beyond tracking pressures, it is critical to understand how shifts in plankton biodiversity and community structure influence ecosystem functioning and the delivery of societal benefits, including fisheries productivity and carbon cycling. For example, widespread declines in phytoplankton and zooplankton amplify into more substantial declines in the carrying capacity of fish, and these declines are projected to increase with warming, based on both food web modelling (Tittensor et al., 2021) and on more empirical size spectrum approaches (Atkinson et al., 2024). This reduction in the ability of ecosystems to support fish needs to be incorporated into precautionary approaches to fisheries management. Likewise, increased temperatures, reduced nutrients, and the consequent steepening of size spectrum slopes (with small particle domination), are projected to decrease the efficiency of carbon sequestration (Serra-Pompei et al., 2022). Spatial management and conservation plans need to incorporate the varying magnitude and resilience of these key losses of ecosystem services. Progress will rely on interdisciplinary approaches that integrate in situ plankton monitoring, satellite and model-based ocean observation, climate scenario projections, and social-ecological modelling. Crucially, these efforts must sit within adaptive, science-informed governance frameworks able to respond to shifting ecological baselines and uncertainty. Sustained investment in harmonised, high-resolution time-series across all regions—including coastal and estuarine zones—is essential to track ecological change, anticipate tipping points, and enable timely, proportionate policy responses.

This work represents a significant effort in assessing pelagic habitat status for policy. It would not have been possible without the international science-policy collaboration facilitated by OSPAR. Continued investment in indicator development, stronger integration across ecosystem component assessments, and genuine science-policy co-production will be vital to achieving the ambitions of the OSPAR Strategic Objectives (2021) and the MSFD's revised biodiversity targets for sustainable management of Northeast Atlantic marine biodiversity.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used Chat GPT in order to check grammar and consistency of wording, proofread, eliminate repetition, check section number referencing, and merge responses from multiple co-author in the response to reviewers. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Abigail McQuatters-Gollop: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Matthew M. Holland:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luis Felipe Artigas:** Investigation, Conceptualization. **Arnaud P. Louchart:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Angus Atkinson:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Anais Aubert:** Writing – review & editing, Investigation, Conceptualization. **Mike Best:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Anouk Blauw:** Writing – review & editing, Conceptualization. **Eileen Bresnan:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Michelle Devlin:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Lisette Enserink:** Writing – review & editing, Investigation. **Matthew P. Faith:** Writing – review & editing, Writing – original draft, Investigation. **Eric Goberville:** Writing – review &

editing, Writing – original draft, Investigation, Conceptualization. **Birgit Heyden:** Writing – review & editing, Investigation, Conceptualization. **Hans Jakobsen:** Writing – review & editing, Investigation, Conceptualization. **Marie Johansen:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **David G. Johns:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Clare Ostle:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Isabelle Rombouts:** Investigation, Conceptualization. **Jos Schilder:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Paul Tett:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Dorothee Vincent:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2026.115005>.

Data availability

Research Link Provided
OSPAR 2023 QSR (Original data) (PLET)

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