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# 1 Plankton lifeforms as a biodiversity indicator for regional-scale assessment of pelagic habitats for policy

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## 19 20 **Abstract**

21 Plankton are sensitive indicators of change and, at the base of marine food webs, they underpin important  
22 ecosystem services such as carbon sequestration and fisheries production. In the UK and the Northeast Atlantic  
23 region, change in plankton functional groups, or 'lifeforms', constructed based on biological traits, is the formally  
24 accepted policy indicator used to assess Good Environmental Status (GES) for pelagic habitats under the Marine  
25 Strategy Framework Directive (MSFD: 2008/56/EC). To identify changes in UK pelagic habitats, plankton lifeforms,  
26 were used from diverse UK data sets collected by different methods, including plankton sampling by nets, water  
27 bottles, integrating tube samplers, and the Continuous Plankton Recorder. A Plankton Index approach was used to  
28 identify change in plankton lifeforms. This is the first time that the pelagic plankton community has been assessed  
29 on a UK-wide scale and forms the foundation of the UK's 2020 MSFD Assessment for pelagic habitat biodiversity and  
30 food webs. This approach revealed that some of the plankton lifeforms used in the assessment displayed spatially-  
31 variable changes during the past decade. Assessing plankton community change using a common indicator at the UK  
32 scale for the first time is a significant step towards evaluating GES for European seas. Determining GES for pelagic  
33 habitats, however, is a challenging process, with additional work required to interpret the assessment results and to  
34 identify causation of the changes observed.

## 35 **Key words**

36 Functional groups, ecosystem approach, Marine Strategy Framework Directive, Good Environmental Status, plankton  
37 traits

## 38 **1.1 Introduction**

39 The Ecosystem Approach (EA; Secretariat of the Convention on Biological Diversity, 2004) and Ecosystem-Based  
40 Management (EBM; Katsanevakis et al., 2011) are high-level strategies that are increasingly influencing management  
41 of marine systems for sustainability and social equity. The European Union's Marine Strategy Framework Directive  
42 (MSFD; 2008/56/EC) is a large-scale example of this holistic style of management. The MSFD requires European seas  
43 to achieve Good Environmental Status (GES). An integral part of assessing GES and ensuring that it is maintained is

44 the establishment of environmental targets and indicators of ecosystem state (Claussen et al., 2011). The Directive is  
45 a complex, adaptive, and ambitious policy, whose scientific and operational implementation will evolve and adapt  
46 throughout its lifetime. Like all Member States, the United Kingdom (UK) is required to assess the state of pelagic  
47 habitat biodiversity in its national waters, and to contribute to the MSFD regional-scale assessment, led by the  
48 Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) in the Northeast  
49 Atlantic.

50 The MSFD requires the monitoring of community-level plankton indicators in support of environmental targets for  
51 criteria in its biodiversity and food web descriptors (Table 1; European Commission, 2010; European Commission,  
52 2017). Plankton are the foundation of most pelagic and benthic food webs, supporting a range of key ecosystem  
53 functions including carbon sequestration and energy flow to higher trophic levels, including species of commercial  
54 importance to humans, such as fish (Falkowski et al., 2004). They have also been described as “beacons of climate  
55 change” due to their short lifespans, temperature-dependent physiology, and high potential for dispersal (Hays et  
56 al., 2005; Richardson, 2008). Furthermore, because most plankton species are not heavily exploited commercially,  
57 change in plankton abundances is a direct response to environmental pressures. Because the time-series coverage of  
58 plankton in the North Atlantic and fringing shelf seas is exemplary in its spatial and temporal extent (see O'Brien et  
59 al., 2017), plankton time-series provide an opportunity to tease apart the prevailing footprint of climate change on  
60 ecosystems from other pressures, for example, nutrient loading and fishing. Accordingly, plankton time-series are  
61 increasingly used to inform marine policy and management (McQuatters-Gollop et al., 2015; McQuatters-Gollop et  
62 al., 2017), as well as for fundamental understanding of marine food webs (Beaugrand and Kirby, 2018).

63 The UK has defined its MSFD target for the pelagic habitat to achieve ‘Good Environmental Status’ as *the plankton*  
64 *community is not significantly adversely influenced by direct anthropogenic pressures* at the scale of the two MSFD  
65 sub-regions that include UK seas. These two sub-regions are the Greater North Sea (OSPAR region II) and the Celtic  
66 Seas (OSPAR region III). Detecting changes in planktonic communities, and then attributing them either to climate  
67 change or to directly manageable human pressures, such as fishing or nutrient enrichment, is not a trivial task. There  
68 are two reasons for this. The first relates to sample collection and analysis. Although multiple plankton time-series  
69 exist in Europe (O'Brien et al., 2017), differences in sampling methods, levels of taxonomic identification, and  
70 methods of taxa enumeration, even within Member States (see for example Eloire et al., 2010; Richardson et al.,  
71 2006; Whyte et al., 2017; Widdicombe et al., 2010) limit the direct comparability of the data, and utilising these  
72 different time-series to deliver assessments at the MSFD sub-region level represents a significant technical  
73 challenge.

74 The second reason concerns the dynamic nature of the plankton. Species of plankton are adapted to the  
75 ecohydrodynamic conditions of the water bodies within which they live. As a consequence, the ‘patchwork’ of  
76 different hydrodynamic regimes found in north western European waters (van Leeuwen et al., 2016), gives rise to  
77 spatial variation in the abundance and diversity of plankton and the species that contribute to the plankton at the  
78 spatial scale of MSFD reporting regions and/or sub-regional scales (Gowen et al., 1998; Pingree et al., 1978).  
79 Furthermore, the inherently variable environment experienced by the plankton, coupled with the short generation  
80 time of some taxa (e.g.  $\leq$  day) influences the abundance of individual species and hence the composition of the  
81 plankton over a range of temporal scales.

82 Plankton indicators have been developed and utilised under previous European environmental directives such as the  
83 Urban Waste Water Treatment Directive (91/271/EEC) and the Water Framework Directive (2000/60/EC). While  
84 these have explored aspects of diversity and community structure as part of indicator development, the Directives  
85 focus on nutrient enrichment and eutrophication (Devlin et al., 2009; Gowen et al., 2008) and have not been used in  
86 biodiversity assessments, and also do not consider zooplankton. Plankton biodiversity indicators can be constructed  
87 from data at varying taxonomic scales, with each option possessing benefits and compromises (McQuatters-Gollop  
88 et al., 2017). Single plankton species have long been used as indicators (Beaugrand, 2005) but tend to focus on

89 specific questions, e.g. the abundance of *Calanus finmarchicus* as an assessment of the amount of food available for  
90 cod larvae. Furthermore, single species indicators do not assess the diversity of the whole plankton community.  
91 There is also the problem that there are no individual species of plankton that can be used to represent the state of  
92 the plankton as a whole. In contrast, diversity indices, composed of abundances of all species in a region, attempt to  
93 capture the diversity of the plankton community. Diversity indices, however, were developed based on ecological  
94 principles relevant to terrestrial ecology. Such indices are difficult to construct with plankton data based on light  
95 microscopy due to difficulties of identification and cryptic speciation (species that look the same under a  
96 microscope) within the plankton community (Appeltans et al., 2012), and are highly influenced by sampling effort  
97 (Stoetaert and Heip, 1990) and the identification of rare species (Lindeque et al., 2013). Finally, Tett et al. (2013, and  
98 references cited therein) point out that most meta-studies failed to find relationships between standard species  
99 diversity measures and ecosystem functions that are consistent across ecosystems and concluded that functional-  
100 group diversity is the key component of ecosystem structure.

101 Multiple characteristics of the plankton are required to assess the status of the plankton community. One such  
102 approach (Tett et al., 2008; Tett et al., 2013) uses a more theoretically-based approach to 'package' the available  
103 information by grouping species into lifeforms, or functional groups, analogous to the guilds of species used by  
104 benthic ecologists (Bremner et al., 2004; Bremner et al., 2003). A lifeform is a group of species (not necessarily  
105 taxonomically related) that carry out the same important functional role in the marine ecosystem. For example,  
106 diatoms as a group of species have a functional role related to silicon cycling. Metrics based on functional traits are  
107 more closely linked to ecosystem structure and functioning than those based on single species or number of species  
108 (Litchman et al., 2007; Mouillot et al., 2013; Stuart-Smith et al., 2013; Villéger et al., 2008). Indicators based on a  
109 functional group approach have been shown to provide a useful means of describing plankton community structure  
110 and biodiversity (Estrada et al., 2004; Gallego et al., 2012; Garmendia et al., 2012; Mouillot et al., 2006) and have  
111 been used to assess community response to pressures such as nutrient enrichment (Gowen et al., 2015; Tett et al.,  
112 2008) and climate change (Beaugrand, 2005). Indicators based on plankton lifeforms address the above challenges  
113 and can be used to examine change in plankton communities based on multiple datasets with different taxonomic  
114 resolutions (Gowen et al., 2015; Tett et al., 2008). Plankton lifeform indicators have thus been developed to inform  
115 the biodiversity and food webs MSFD Descriptors (Table 1).  
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Table 1: MSFD Descriptors for determining GES, relevant to the pelagic habitat. *Quoted text in italics.*

Descriptor (Annex I of the MSFD)	
Relevant criteria (European Commission, 2010, part B)	Relevant criteria (European Commission, 2017, Annex)
<p><b>1. Biodiversity</b> <i>Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.</i></p>	
<p>At the habitat level, assessment includes habitat distribution and extent, plus 1.6. <i>Habitat condition</i> including condition and relative abundance of <i>the typical species and communities</i>, and 1.7. <i>Ecosystem structure – composition and relative proportions of ecosystem components (habitats and species)</i></p>	<p><i>D1C6 the condition of each broad habitat type, including its biotic and abiotic structure and its functions (e.g. its typical species condition and their relative abundance, absence of particularly sensitive or fragile species, providing a key function, size structure of species) is not adversely affected due to anthropogenic pressures.</i></p>
<p><b>4. Food webs</b> <i>All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.</i></p>	
<p><i>This descriptor concerns important functional aspects such as energy flows and the structure of food webs (size and abundance) and the criteria include:</i> <i>4.3 Abundance/distribution of key trophic groups/species – Abundance trends of functionally important selected groups/species.</i></p>	<p>The relevant ‘trophic guilds’ are phytoplankton and zooplankton (ICES, 2015); the criteria are: <i>D4C1 The diversity (species composition and their relative abundance) of the trophic guild is not adversely affected due to anthropogenic pressures.</i> <i>D4C2 The balance of total abundance between the trophic guilds is not adversely affected due to anthropogenic pressures.</i> <i>DC43 The size distribution of individuals across the trophic guild is not adversely affected due to anthropogenic pressures.</i></p>

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This paper describes a preliminary and novel assessment of changes in the plankton communities found in UK waters via the OSPAR common plankton lifeform indicator (PH1/FW5: Changes in Phytoplankton and Zooplankton Communities). This is the first time that the plankton found in UK waters have been examined at a regional scale using a consistent method applied to a diverse suite of datasets. This assessment represents an important step towards determining GES for pelagic habitats and will contribute to the UK’s formal 2020 assessment for the MSFD. We explore the initial results and some of the challenges that remain and outline the additional requirements to determine whether UK pelagic habitats are in GES.

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## 2.1 Methods

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### 2.1.1 Addressing spatial variability of UK pelagic habitats

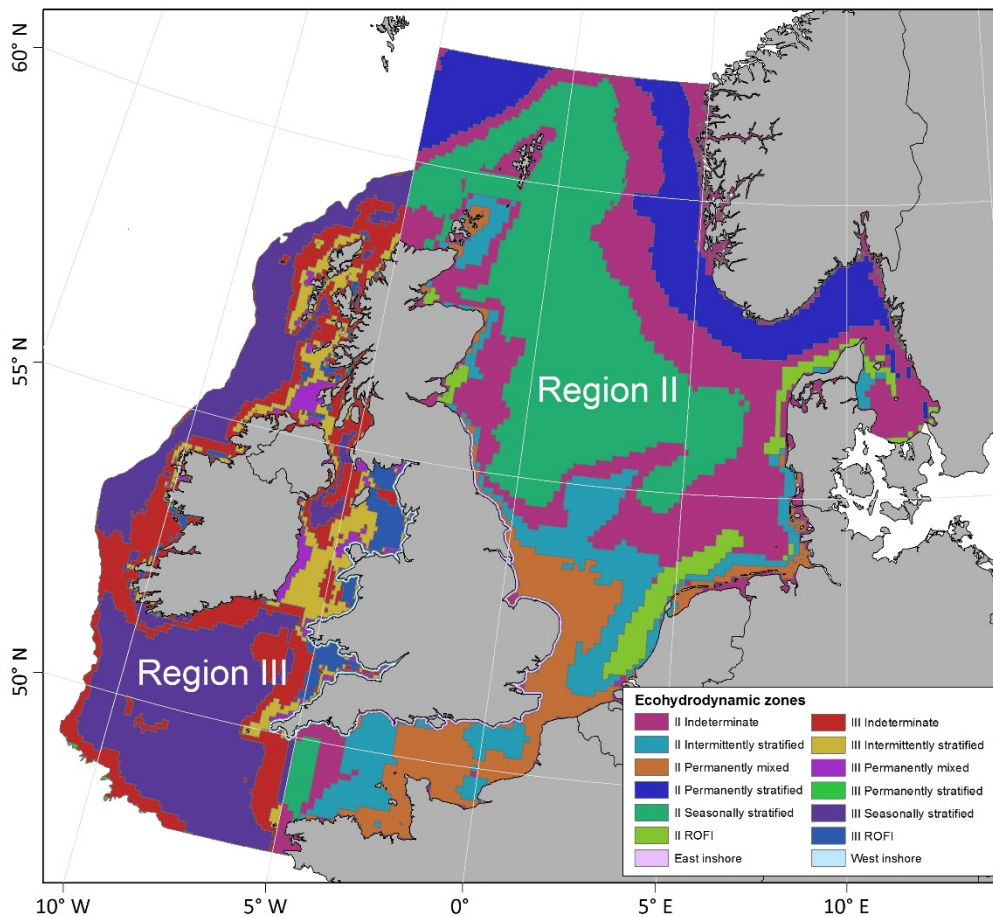
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UK waters are ecologically and physically heterogeneous and cannot be considered as one uniform system even within individual MSFD sub-regions (van Leeuwen et al., 2015; van Leeuwen et al., 2016). Furthermore, plankton taxa are adapted to live in different hydrodynamic conditions (Margalef, 1978), so that plankton community

composition, distribution, and dynamics are closely linked to environmental conditions (de Vargas et al., 2015; Jones et al., 1984; Williams et al., 1994). Using density stratification, an important large-scale physical feature in shallow shelf seas, UK waters were spatially partitioned into six “ecohydrodynamic” (EHD) regimes (Figure 1) (van Leeuwen et al., 2015). The main EHD zone types, based on a 50-year modelled hindcast of water-column structure, are:

- Permanently mixed throughout the year
- Permanently stratified throughout the year
- Regions of freshwater influence (ROFIs)
- Seasonally thermally stratified (for approximately half the year, including summer)
- Intermittently stratified
- Indeterminate regions (inconsistently alternate between the above).

UK EHD zones were divided into North Sea and Celtic Sea zones for this analysis in order to align with the OSPAR Greater North Sea (OSPAR Region II) and Celtic Seas (OSPAR Region III) sub-regions. A more highly resolved EHD model exists for the North Sea than the Celtic Seas (van Leeuwen et al., 2015; van Leeuwen et al., 2016), and therefore the zoning might be less reliable in the case of the Celtic Seas and western English Channel.



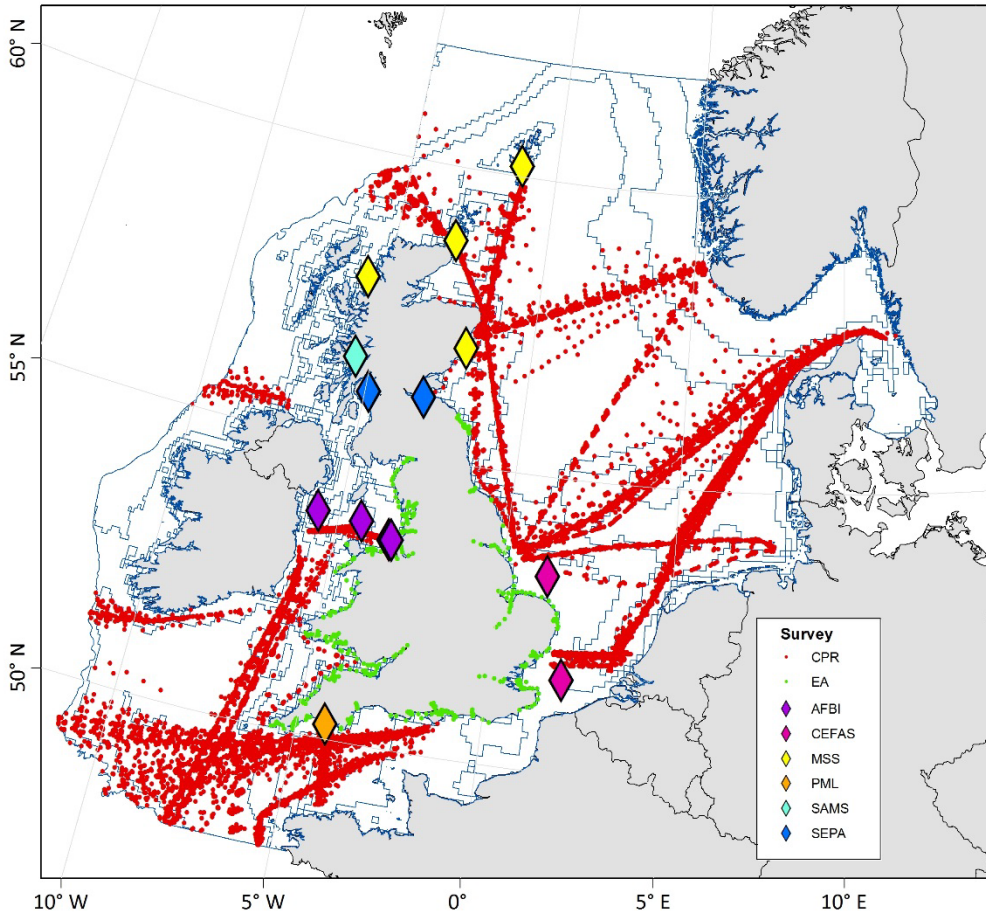
**Figure 1: Map of ecohydrodynamic (EHD) zones in the Greater North Sea (OSPAR Region II) and Celtic Seas (OSPAR Region III), coloured by EHD type and region number.** EHD zones were constructed based on key simulated water column features, which are important to plankton community structure and dynamics. The main EHD zone types, based on water-column structure, are 1) Permanently mixed throughout the year, 2) Permanently stratified throughout the year, 3) Regions of freshwater influence (ROFIs), 4) Seasonally thermally stratified (for about half the year, including summer), 5) Intermittently stratified and 6) Indeterminate regions (inconsistently alternate between the above levels of stratification). East and west inshore (>1 nm from shore) regions are also shown here, although they were not identified from simulations.

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160 As there is no coastal EHD type, the very near-coast (< 1nm from shore) regions have been divided into east and  
161 west coastal inshore EHD zones. The hydrodynamic model Figure 1 indicates an 'indeterminate' type in the inshore  
162 waters of the Scottish highlands and islands. However, observations (e.g. Inall and Gillibrand, 2010; Wood et al.,  
163 1973) show that salinity-stratification and associated density-driven circulation are common here. For this reason a  
164 fjordic system EHD type was used for sea lochs on the west coast of Scotland.

165  
166 The UK plankton monitoring programme (Figure 2) consists of coastal, fixed-point sampling stations including PML L4  
167 (Atkinson et al., 2015), CEFAS SmartBuoys (Weston et al., 2008), Environment Agency (EA) Water Framework  
168 Directive (WFD) monitoring stations (UKTAG, 2014), Scottish Environmental Protection Agency WFD monitoring  
169 stations, Agri-Food and Biosciences Institute monitoring stations (Gowen and Stewart, 2005), the Firth of Lorne  
170 Observatory (Tett, 1973; Tett and Wallis, 1978; Whyte et al., 2017), the Scottish Coastal Observatory (Bresnan et al.,  
171 2016), and the offshore Continuous Plankton Recorder (CPR) survey (Richardson, 2008) (see Figure 2). These various  
172 sources of data provide complementary information, with the CPR data illustrating regional and long-term change  
173 and the fixed-point stations providing detailed information at higher time and depth resolution at a local scale. EHD  
174 zones provide a spatial framework by which to use these two types of data together. CPR data and EA coastal  
175 sampling network were thus aggregated at the EHD zone scale, allowing comparability between CPR and fixed-point  
176 results in the same EHD zone. Because EHDs are constructed based on the dominant hydrodynamic features of the  
177 water column, this approach also enables data from one part of an EHD zone to be used for the whole of that EHD  
178 zone (Scherer et al., 2014). In other words, features of the plankton community at a fixed-point station in a particular  
179 EHD zone are assumed to be representative of the plankton community throughout that EHD zone.

### 180 181 *2.1.2 Plankton lifeform construction*

182 The UK plankton monitoring programme consists of surveys from a variety of government agencies and research  
183 organisations. They employ sampling techniques ranging from collections at fixed (buoys or moorings) time-series  
184 stations using nets, tubes integrating the top 10m of the water column, and water bottles to the Continuous  
185 Plankton Recorder survey, a large scale plankton monitoring programme which uses ships of opportunity (Figure 2)  
186 (Bean et al., 2017). All these surveys contribute towards a large quantity of UK plankton data, however, variation in  
187 sampling methods, levels of taxonomic identification, and methods of taxa enumeration provide a challenge to UK-  
188 level assessments.



**Figure 2: The UK plankton monitoring programme consists of disparate but complementary surveys.** Samples from the Continuous Plankton Recorder (CPR) are displayed as red dots along routes; samples represent 10 nautical miles of water. The other surveys operate fixed-point sampling schemes. Abbreviations: AFBI – Agri-Food and Biosciences Institute; EA – Environment Agency; PML – Plymouth Marine Laboratory; MSS – Marine Scotland Science; SAMS – Scottish Association for Marine Science; Cefas - Centre for Environment, Fisheries and Aquaculture Science; and SEPA – Scottish Environmental Protection Agency.

To address this and provide a holistic view of the UK plankton, an indicator based on plankton lifeforms was developed which allows the use of all plankton datasets, regardless of differences in sampling or analysis techniques. To construct the plankton lifeform indicator, plankton taxa were grouped into lifeforms based on traits such as size, trophic, motility, and other key biological features (Table 2, 3; Litchman et al., 2012; Litchman and Klausmeier, 2008). Taxa can be assigned multiple traits, and can be included in multiple lifeforms. In instances where the trait of a taxon was unknown, the taxon was omitted from lifeforms constructed with that particular trait. Because plankton lifeforms are constructed based on traits (Table 4) rather than on species-level information, grouping plankton taxa into lifeforms allows the use of plankton data identified at different taxonomic resolutions, which suits the UK's integrated but diverse plankton monitoring programme. Additionally, plankton lifeforms are aggregations of taxa and so are less likely to experience the extreme seasonal fluctuations of single species indicators. Finally, because lifeforms consist of multiple taxa with a similar functional role, spatial intercomparability is increased, as even though the particular taxa fulfilling a functional role may vary, the corresponding lifeform is often regionally ubiquitous. When examined in ecologically-relevant plankton lifeform pairs, plankton lifeforms can provide an indication of changes in different aspects of plankton community functioning such as energy flows, benthic-pelagic coupling, and food web structure (Table 4). The eight lifeform pairs were selected according to confidence in the traits corresponding to each lifeform and to reflect multiple features of the pelagic habitat. As the knowledge base increases or policy needs change, new plankton lifeform pairs can be developed, allowing us to address additional



215 and emerging scientific and policy questions about biodiversity, food webs, eutrophication, and responses to climate  
 216 change. Given the emerging importance of community functioning as a key characteristic of biodiversity, all of the  
 217 lifeform pairs in Table 4 contribute to the biodiversity and food web descriptors.

218 **Table 2: Plankton taxa were assigned traits based on our simple definition based on key biological features.**

Trait type	Trait categories
Plankton type	Phytoplankton: protista taxa that contribute to primary production Zooplankton: metazoan taxa of the kingdom Animalia
Zooplankton type	Fish/eggs: taxa of the subphylum Vertebrata Copepod: taxa of the subclass Copepoda Gelatinous: taxa of the phylum Cnidaria and Ctenophora Crustacean: taxa of the Subphylum Crustacea
Phytoplankton type	Diatom: taxa of the class Bacillariophyceae Dinoflagellate: taxa of the phylum Dinoflagellata
Zooplankton trophic mode	Carnivore: taxa which prey on zooplankton Herbivore: predominately suspension or filter feeders Omnivore: includes both carnivorous and herbivorous feeding Ambiguous: diet uncertain
Habitat	Holoplankton: taxa which spend their entire lifecycle in the plankton Meroplankton: taxa which spend part of their lifecycle in the plankton Tychopelagic: benthic diatoms which can become mixed into the water column
Size	Large: phytoplankton ( $\geq 20 \mu\text{m}$ diameter); zooplankton ( $\geq 2 \text{ mm}$ adult body length) Small: phytoplankton ( $< 19 \mu\text{m}$ diameter); zooplankton ( $< 1.9 \text{ mm}$ adult body length)

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220 **Table 3: Plankton lifeforms are comprised of taxa sharing the same traits.**

Lifeform	Traits
Diatoms	Plankton type = 'Diatom'
Dinoflagellates	Plankton type = 'Dinoflagellate'
Gelatinous zooplankton	Plankton type = 'Gelatinous'
Fish larvae/eggs	Zooplankton type = 'Fish' AND 'Eggs'
Non-carnivorous zooplankton	Plankton type = 'Zooplankton' AND Trophic mode = either 'Herbivore', 'Omnivore', OR 'Ambiguous'
Crustaceans	Zooplankton type = 'Crustacean'
Large phytoplankton	Plankton type = 'Phytoplankton' AND Size = 'Large'
Small phytoplankton	Plankton type = 'Phytoplankton' AND Size = 'Small'
Pelagic diatoms	Phytoplankton type = 'Diatom' AND Habitat = 'Holoplankton'
Tychopelagic diatoms	Phytoplankton type = 'Diatom' AND Habitat = 'Tychopelagic'
Holoplankton	Plankton type = 'Zooplankton' and Habitat = 'Holoplankton'
Meroplankton	Plankton type = 'Zooplankton' and Habitat = 'Meroplankton'
Large copepods	Zooplankton type = 'Copepod' AND Size = 'Large'

Lifeform	Traits
Small copepods	Zooplankton type = 'Copepod' AND Size = 'Small'
Phytoplankton	Plankton type = 'Phytoplankton'

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**Table 4: Plankton lifeform pairs consist of two contrasting and ecologically-relevant plankton lifeforms.** The rationale behind their selection is also described.

223

Lifeform pairs	Ecological rationale
Diatoms and dinoflagellates	Systems receiving high nutrient input are often dominated by dinoflagellates at the expense of diatoms (McQuatters-Gollop et al., 2009). In the North Atlantic, stratification plays a key role in structuring phytoplankton communities with dinoflagellate abundances connected to increased stratification while diatoms are better suited to mixed waters (Barton et al., 2015). Change in the relative abundance of the two plankton lifeforms can therefore indicate changes in nutrient and stratification regimes.
Pelagic diatoms and tychopelagic diatoms	Benthic disturbance, such as from development or storms, can resuspend tychopelagic (benthic) diatoms in the water column (Ubertini et al., 2012). A shift in the proportion of tychopelagic and pelagic diatoms can therefore indicate changes in the magnitude and frequency of benthic disturbance and resuspension events.
Large microphytoplankton ( $\geq 20 \mu\text{m}$ diameter) and small microphytoplankton ( $< 19 \mu\text{m}$ diameter)	Organism size is a key factor in energy transfer efficiency in pelagic habitats and may determine the system's potential to support higher trophic levels (Fox and Pitois, 2006; Thiebaut and Dickie, 1993). Changes in the relative abundance of large microphytoplankton ( $\geq 20 \mu\text{m}$ diameter) and small microphytoplankton ( $< 19 \mu\text{m}$ diameter) can therefore indicate alterations in energy flow to higher trophic levels.
Microphytoplankton and non-carnivorous zooplankton	Non-carnivorous zooplankton graze on microphytoplankton, thereby transferring energy from single-celled algae to metazoan animals. Changes in the relative abundance of the two plankton lifeforms can therefore indicate changes in energy flow through the pelagic food web.
Small copepods ( $< 1.9 \text{ mm}$ ) and large copepods ( $\geq 2 \text{ mm}$ ) adult body length	Copepods are a key food resource for higher trophic levels, including commercially important fish such as larval cod, whose survival is linked to the mean size of their prey (Beaugrand et al., 2003). A change in the proportion of large ( $\geq 2 \text{ mm}$ in length) and small ( $< 1.9 \text{ mm}$ in length) adult copepods can therefore indicate changes in food web structure (Capuzzo et al., 2018; Fox and Pitois, 2006).
Holoplankton and meroplankton	Meroplankton only spend a part of their lifecycle within the pelagic realm, and for their most part, are the larvae of benthic organisms. A change in the proportion of meroplankton and holoplankton (plankton spending their whole lifecycle within the pelagic realm) can indicate a change in the strength of benthic and/or pelagic production with consequences for pelagic-benthic coupling (Kirby et al., 2008; Lindley et al., 1995).
Crustaceans and gelatinous zooplankton	Gelatinous organisms within the plankton can have an important predatory effect on other crustacean plankton and fish larvae when abundant, thereby acting as a pressure on fish populations. A change in the relative abundance of crustaceans and gelatinous zooplankton can thus indicate a change from an ecosystem with numerous fish of commercial interest to an ecosystem dominated by gelatinous organisms of low commercial interest (Kirby et al., 2009; Purcell and Arai, 2001; Richardson et al., 2009).

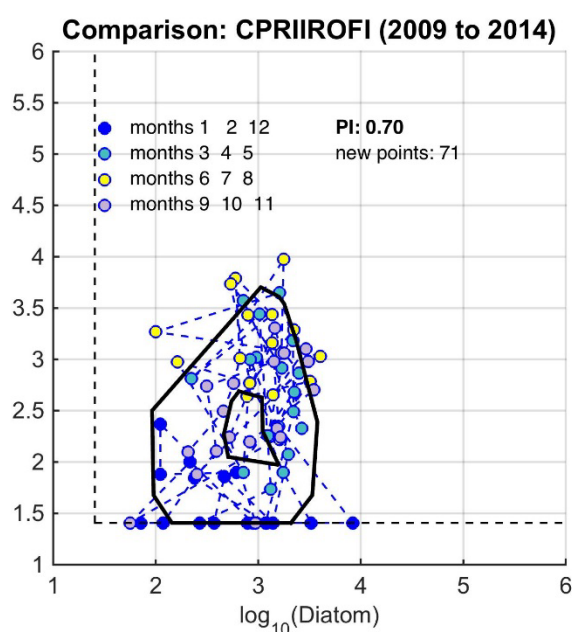
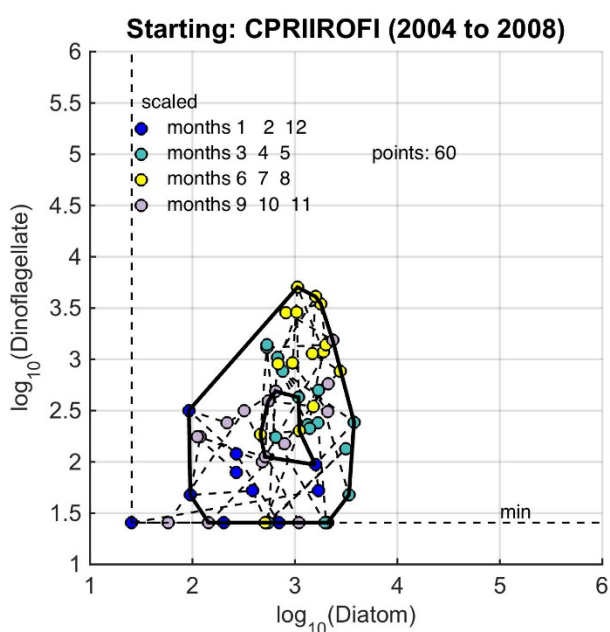
Gelatinous zooplankton and fish larvae/ eggs	Gelatinous organisms within the plankton can have an important predatory effect on other crustacean plankton and fish larvae when abundant, thereby acting as a pressure on fish populations. A change in the relative abundance of fish larvae/eggs and gelatinous zooplankton can thus indicate a change from an ecosystem with numerous fish of commercial interest to an ecosystem dominated by gelatinous organisms of low commercial interest (Kirby et al., 2009; Purcell and Arai, 2001; Richardson et al., 2009).
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225 **2.1.3 Identifying change in plankton lifeforms**

226 A 'Plankton Index' (PI) has been used to identify temporal change within plankton lifeform pairs. This approach  
 227 (Gowen et al., 2011; Scherer et al., 2014; Tett et al., 2008) identifies change plankton lifeform pairs from a starting  
 228 period, usually at the beginning of a time- series, although the PI has been used to hindcast (Gowen et al., 2015) and  
 229 compare changes in plankton in response to human pressure in different regions of the same ecohydrodynamic  
 230 regime (Scherer, 2012) . Based on general systems theory (von Bertalanffy, 1972), a sample's position at any point in  
 231 time is defined in "state space" by orthogonal axes of (log-transformed) lifeform abundance. For convenience and  
 232 ease of visualisation, the axes are plotted two at a time, so that, for example, a sample's horizontal co-ordinate is  
 233 diatom abundance and its vertical co-ordinate is dinoflagellate abundance (Figure 3).

234 To define the reference boundary, an envelope is drawn around several years of points representing monthly  
 235 samples (Figure 3); here we used a 5-year period. Monthly averaged data from subsequent periods are then plotted  
 236 in the same state space, and a Plankton Index (PI), and associated probability value, calculated as the proportion of  
 237 new points falling within the reference boundaries. A PI value approaching 1 indicates no difference in plankton  
 238 communities while a PI value approaching 0 indicates a complete change in plankton communities between the two  
 239 time periods. Low PI values across spatially disparate datasets mean that wide scale changes in the plankton  
 240 community (e.g. from climate change) can be identified. The PI approach is flexible in nature, allowing both  
 241 abundance and biomass data to be used, and furthermore it is relatively robust to periods without data collection,  
 242 making it ideal for identifying change in plankton communities when assessing environmental state by using multiple  
 243 disparate datasets. Although originally developed to track change in phytoplankton communities (Tett et al., 2008),  
 244 the PI has been adapted to also incorporate changes in zooplankton, making this a method to assess change in the  
 245 plankton community more holistically.



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247

248 **Figure 3: An example diatoms v dinoflagellate comparison between starting and contemporary conditions for Regions of**  
249 **Freshwater Influence (ROFIs) in the North Sea (OSPAR Region II).** Left: The starting conditions envelope, outlined in black, was  
250 created using sampling points from 2004-2008. Right: points from the 2009-2014 UK 2020 MSFD Assessment period (n=71) are  
251 overlain on the starting conditions envelope. The PI value of 0.70 suggests a statistically significant difference between the two  
252 time periods (binomial  $p < 0.01$ ), caused by 21 of the 71 assessment period points falling outside the bounds of the starting  
253 conditions envelope. The distribution of the points in the assessment period suggests an increase in dinoflagellates in summer  
254 months.

255 The PI value was calculated for all lifeform pairs for each fixed-point sampling station (with sufficient data) and for  
256 CPR data aggregated across each EHD zone. For the UK 2020 MSFD Assessment, the period 2004 to 2008 was  
257 selected to represent starting conditions to align with the starting condition period used in the OSPAR Intermediate  
258 Assessment 2017. This starting period selection was therefore driven by a policy rather than scientific requirement, a  
259 point we discuss later. The starting condition envelope was compared with data from the subsequent six-year MSFD  
260 Assessment period (2009 to 2014), also chosen for its alignment with the MSFD assessment and reporting cycle.  
261 From a policy perspective, this strategy facilitated comparability between the UK-level and OSPAR-level analyses and  
262 allowed the examination of change in UK plankton with respect to regional scale plankton change, as identified  
263 through the 2017 OSPAR Intermediate Assessment. Most importantly, alignment of the starting condition periods  
264 allowed the examination of plankton change on the MSFD policy timescale, a key goal of the UK 2020 MSFD  
265 Assessment to which this work will contribute. Here we have expanded the number of UK datasets beyond those  
266 used in the UK 2020 MSFD Assessment to include all UK plankton time-series with data spanning the same 2004-  
267 2014 time period. The datasets from Scottish Environmental Protection Agency (SEPA) and the Agri-Food and  
268 Biosciences Institute, Northern Ireland (AFBI), however, did not cover the full duration of the starting conditions  
269 period and were therefore excluded from this analysis.

### 270 **3.1 Results**

#### 271 *3.1.1 A first assessment of changes in UK plankton*

272 Differences in the Plankton Index between starting conditions (2004-2008) and current conditions (2009-2014) were  
273 calculated for all lifeform pairs where monthly data were available during the entire time period (Figure 4). This first  
274 analysis showed similarities and differences in PI values from different EHD zones and between lifeform pairs. Of the  
275 91 differences identified, 78 were statistically significant (Figure 4), suggesting alterations to the UK plankton  
276 community between the starting and MSFD assessment periods. Further interpretation of these results (including  
277 timing and dominance of plankton lifeforms and an investigation to the significant contributing species) were not  
278 included in the MSFD assessment and are therefore beyond the scope of this current paper.

279

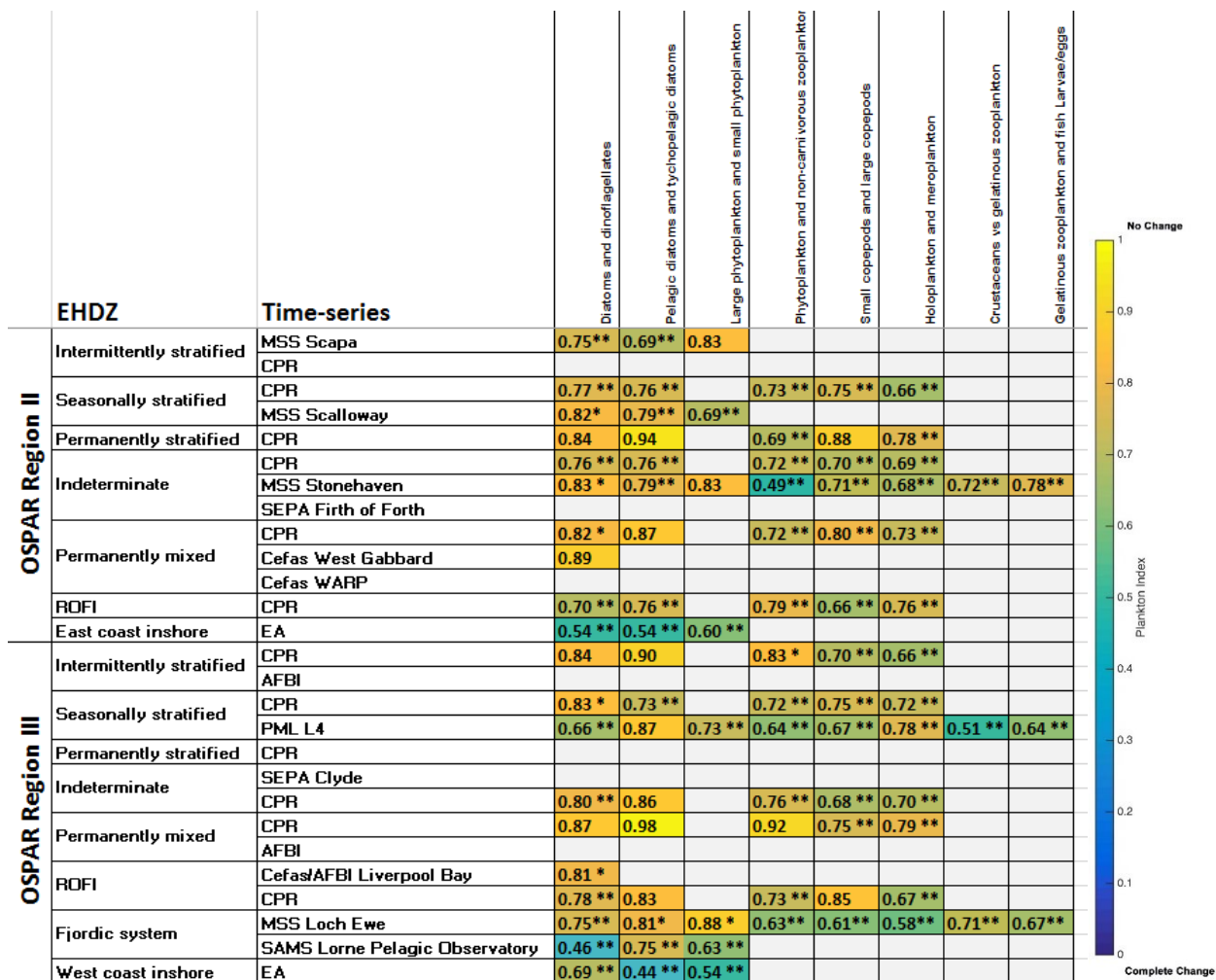
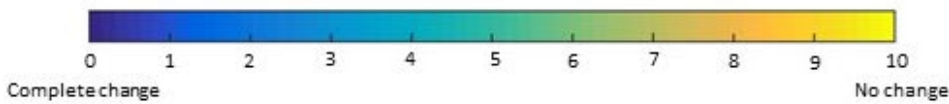
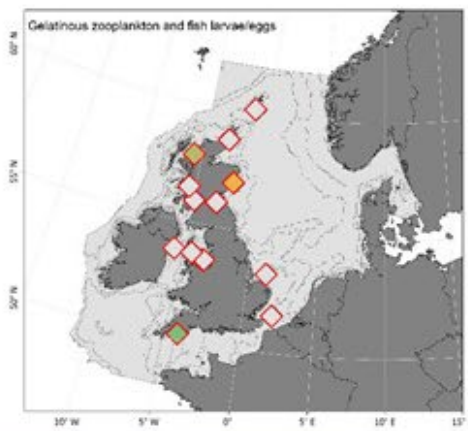
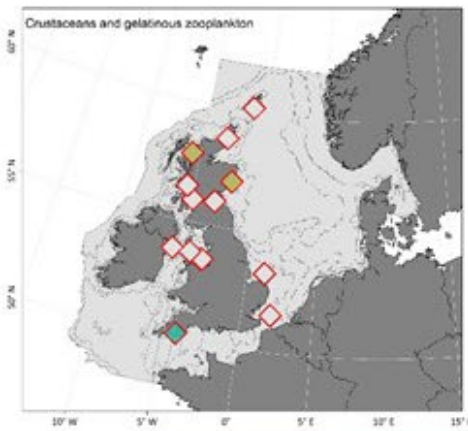
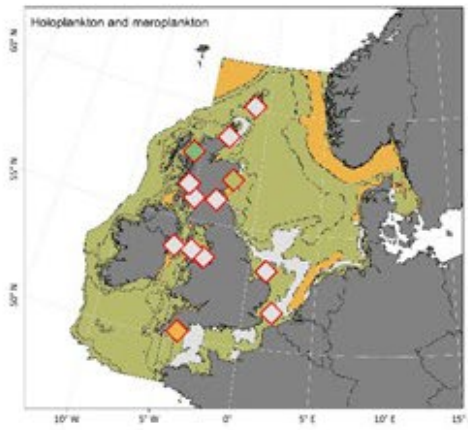
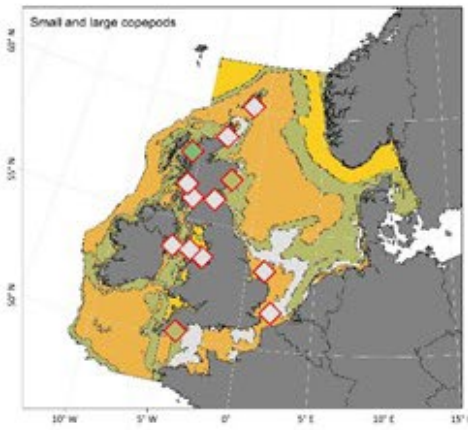
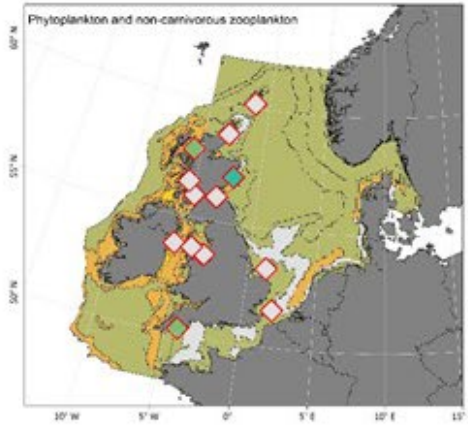
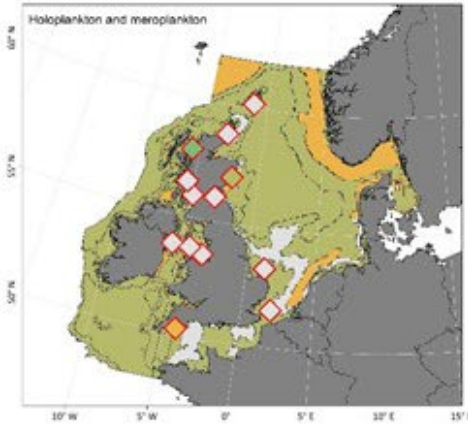
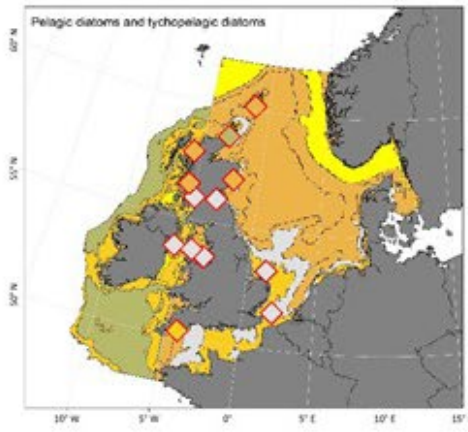
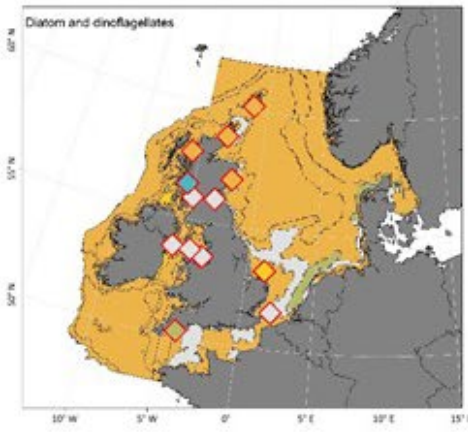


Figure 4: Plankton Indices, by OSPAR region and EHD zone, for the period 2009 - 2014 from starting conditions (2004 – 2008). Starred cells indicate theoretical significant change (\* $p < 0.05$ ; \*\* $p < 0.01$ ) from starting conditions. A Plankton Index approaching '1' (bright yellow cells) denotes no change from starting conditions while an Index approaching '0' (dark blue cells) represents complete change. White shading represents where data were insufficient to determine a Plankton Index. UK datasets with incomplete data during the starting conditions period were not used in the analysis, but all existing sampling stations are included to demonstrate the future potential of the monitoring program.

The degree of difference in PI value was spatially variable within each lifeform pair (Figure 5) although, in some cases, remarkable similarity between surveys exists. Of the lifeform pairs sampled for most datasets ( $n > 12$  datasets) holoplankton and meroplankton (range = 0.21) as well as small and large copepods (range = 0.27) had the smallest ranges in PI, indicating the highest levels of spatial harmony (Figure 4, Figure 5). The lifeform pair with the greatest variability was pelagic diatoms and tychoplagic diatoms (range = 0.54), with the greatest difference between the starting and assessment period found in the west coast inshore EHD zone (PI = 0.44,  $p < 0.01$ ). Other than the highly dynamic west and east coast inshore zones, the most extreme differences from starting conditions of any lifeform pairs were observed in Scotland and the Western Channel, with phytoplankton and non-carnivorous zooplankton at Stonehaven (PI = 0.49,  $p < 0.01$ ), and diatoms and dinoflagellates at Lorne (PI = 0.46,  $p < 0.01$ ).



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301 **Figure 5: Plankton Index for each lifeform pairs in UK waters.** Changes within EHDs are based on CPR data, with fixed-point  
302 stations overlain (red borders). Points or EHD zones in grey lack complete data during starting conditions and/or assessment  
303 period for particular lifeform pairs. Results for non-UK EHDs are also displayed as they enable regional interpretation of UK  
304 plankton dynamics.

305 Results between the near-shore fixed-point stations and CPR data in the same EHD zone were broadly consistent  
306 (Figure 4, Figure 5), suggesting spatial congruence between the two survey types. For example, the results of PML L4,  
307 located in the seasonally stratified Celtic Sea OSPAR Region III, were consistent with results from the CPR in the same  
308 EHD zone, particularly for the pairs with zooplankton lifeforms. Similarly, the results from Stonehaven, located in the  
309 indeterminate North Sea zone, matched well with CPR results from the same EHD.

## 310 **4.1 Discussion**

### 311 *4.1.1 Change in plankton lifeform indicator*

312 It has previously been established that the UK plankton community has undergone significant changes during the  
313 past six decades (Beaugrand, 2004). Changes include phenological alterations (Atkinson et al., 2015; Edwards and  
314 Richardson, 2004; Whyte et al., 2017), shifts in the balance of organisms (Beaugrand et al., 2002; Gregory et al.,  
315 2009; Whyte et al., 2017), and spatially variable changes in phytoplankton biomass and chlorophyll (McQuatters-  
316 Gollop et al., 2011; Whyte et al., 2017). Assessments of estuarine and coastal phytoplankton metrics have also been  
317 carried out under the requirements of the WFD, but focussed on changes in the total taxa counts and most  
318 numerous species (Devlin et al., 2009; Devlin et al., 2007). An integrated, region-wide view of plankton change  
319 assessed using a common indicator and all available UK datasets, however, has been lacking. The case study  
320 presented here illustrates the value of the plankton lifeform approach in connecting disparate geographic areas with  
321 diverse methods of plankton sampling and analysis, using a common and comparable indicator. This is the first  
322 application of this indicator across multiple plankton datasets throughout UK marine waters, illustrating change  
323 between two periods examined for the UK MSFD 2020 Assessment.

324 Harmony in results between fixed-point datasets and the CPR survey highlights the complementarity of the datasets  
325 comprising the UK's plankton monitoring programme (Figure 4, Figure 5). For example, results from PML L4 and the  
326 CPR survey are particularly well-matched for pairs with zooplankton lifeforms and are also in line with previous work  
327 showing that zooplankton seasonal cycles captured by the two time-series were similar, even though absolute  
328 abundances differed (John et al., 2001; Ostle et al., 2017). The similarity in PI values between CPR and fixed-point  
329 time-series suggests both are representative of EHD zones, but further validation between CPR and fixed-point data  
330 from the same EHD zones are needed. Better spatial representivity exists for EHD zones which are monitored by  
331 CPR routes compared to locations with only a fixed-point station, though some inshore fixed-point stations (PML,  
332 MSS Stonehaven, MSS Loch Ewe) are monitored weekly and so better reflect temporal variability. Some of the EHD  
333 zones are spatially large and thus averaging over such a large spatial scale may dampen or mask variability. EHD  
334 zones with both CPR data and fixed-point stations have the most comprehensive and robust information. The  
335 stations closest to shore, the east and west inshore EHDs and SAMS Lorne Pelagic Observatory, displayed some of  
336 the most extreme differences in PI values, suggesting that coastal waters are more temporally variable than waters  
337 further offshore. In the case of the east and west inshore EHDs, however, some of this variability may be caused by  
338 changes to the sampling programme as mentioned above. These preliminary results show that UK plankton lifeforms  
339 displayed spatially-variable changes during the past decade with greater depth of knowledge obtained by the  
340 merging of many UK plankton datasets.

341 This study constitutes a first step in evaluating GES for UK waters by documenting widespread change. There is work  
342 to be done in establishing the causes of change, which might include (i) the intrinsic inter-annual and decadal scale

343 cyclical variability common to many Earth systems; (ii) the longer-term effects of global change, especially that  
344 associated with climate; or (iii) the superimposed effects of manageable anthropogenic pressures such as nutrient  
345 enrichment, fisheries disturbance, pollution or seabed disturbance on food webs. The UK definition of GES for the  
346 pelagic habitat is essentially practical: if change in lifeform absolute and relative abundances (which can be signalled  
347 by the PI) is attributed to increases in manageable pressures, then the habitat is not in GES and measures need to be  
348 taken to ameliorate the pressures. Thus we have referred to the 2004-2008 period as 'starting' rather than  
349 'reference' conditions as these years were chosen to fit with the MSFD policy assessment cycle rather than any  
350 judgement of whether the condition of the pelagic habitat was in GES or not. Ideally, the envelope used to calculate  
351 a value of the PI would be drawn around a set of points from a marine ecosystem known to be in GES. Scherer et al.  
352 (2016) have proposed a method for determining pelagic GES independent of the PI tool, but in default of application  
353 of this method to all EHD types in UK waters, the PI only provides an indication of change. However, such change in  
354 PI can be used as a 'flag' to trigger further investigation into the pressures that may be causing this change in  
355 ecosystem state.

#### 356 *4.1.2 Further development of the lifeform indicator and Plankton Index approach for assessing Good Environmental* 357 *Status*

358 As an indicator of plankton functioning and structure, the lifeform approach enables the use of multiple datasets  
359 with disparate methods of sample collection and taxonomic analysis. Our results demonstrate that data collected  
360 from disparate monitoring programmes established for a variety of policy drivers (e.g., Water Framework Directive,  
361 investigative monitoring and research, Urban Waste Water Treatment Directive) can also be used for the  
362 construction of plankton lifeforms for use as a MSFD indicator. Because plankton lifeform datasets can be populated  
363 with plankton data not collected specifically for informing the MSFD indicator, the use of this single regional  
364 indicator promotes synergies between disparate UK plankton monitoring surveys. This approach, whilst innovative,  
365 does require several more steps to increase its robustness, enable the best use of all available plankton data, and to  
366 support future use of the indicator in other geographic areas. Each of these steps is a precursor to determining GES  
367 for UK pelagic habitats.

368 EHD zones provide a way to define pelagic habitats and plankton communities, but the model used to construct the  
369 EHD zones was developed for use in, and validated with data from, offshore pelagic environments and as a result  
370 may not accurately simulate conditions in near-shore areas (van Leeuwen et al., 2015; van Leeuwen et al., 2016).  
371 Observationally-informed designations of the seasonal stratification from fixed point stations in some regions such  
372 as the Western English Channel do not always agree perfectly with the EHDs defined in Figure 1. In some cases, such  
373 as the Irish Sea, it is likely that numerous EHD zones occur in a relatively small region of complex hydrography  
374 (Gowen et al., 1995; Scherer et al., 2016) and so may need revisiting. In addition, some EHDs (e.g. North Sea  
375 seasonally stratified) are large and span a latitudinal gradient of ~ 5 degrees, and thus phytoplankton may  
376 experience differing light regimes between the northern and southern regions of this EHD. Nevertheless, we have  
377 used the Figure 1 map as a single and traceable regional classification for all our analysis. Further refinement of  
378 modelling in hydrodynamically complex areas and improvements in coupled catchment and marine models would  
379 improve the delineation of EHD zones.

380 A consequence of the different methods used in the UK plankton monitoring programme is that there is some  
381 inconsistency in the elements of the plankton community sampled. As a result, the full set of lifeform pairs (Table 4)  
382 could not be derived from some data sets. Although all UK stations monitor phytoplankton, only the CPR and three  
383 fixed-point stations have historically collected and analysed zooplankton samples. Additionally, not all surveys  
384 sample all taxa equally well. The CPR, for example, inadequately captures small phytoplankton or gelatinous taxa  
385 (Richardson et al., 2006) and so did not contribute to pairs containing these plankton lifeforms. Only three 'sentinel'  
386 stations, MSS Stonehaven, MSS Loch Ewe, and PML L4, can address all lifeform pairs. Adding zooplankton sampling  
387 to the remaining fixed-point stations would increase the robustness and form a 'sentinel network' providing detailed



388 insight into coastal plankton dynamics which is complementary to the CPR's large-scale, regional sampling. It should  
389 also be noted that the smaller size portion of the pelagic assemblage, i.e. small nanoplankton, picoplankton, marine  
390 bacteria, and viruses, are poorly monitored (McQuatters-Gollop et al., 2017). Additional consideration needs to be  
391 given to taxa which are difficult to monitor or enumerate routinely, such as coccolithophores and mucilage-forming  
392 *Phaeocystis*. In general, there is a need for some further development of the trait-based theory (Litchman et al.,  
393 2012; Litchman and Klausmeier, 2008) used to define plankton lifeforms for the present work.

394 Not all UK plankton monitoring programmes collected data during the 2004 to 2008 starting conditions period for PI  
395 calculation, resulting in the exclusion of some important time-series from the UK 2020 MSFD Assessment and this  
396 analysis. While the Environment Agency (EA) dataset spanned the entire time period, the sampling and analysis  
397 methodology and frequency changed in 2008, as a result of implementation of the WFD. Special care must therefore  
398 be taken when interpreting change from this time-series. Additionally, some plankton surveys, such as the CPR,  
399 Marine Scotland Science, the SAMS Lorne Pelagic Observatory, and PML's L4, have multi-decadal databases; when  
400 data from only 2004 onward are included the historical data are not used to their full potential. It is therefore clear  
401 that further work into maximising the use of UK datasets is urgently required. Such investigations might test: using  
402 the entire time-series as the starting condition period for calculating the PI value; varying the starting condition  
403 period depending on the length of the dataset; using a more recent period for the starting conditions to include  
404 newer time-series; or shortening the starting conditions period to encompass only three years of data and therefore  
405 include more UK datasets. Each of these possibilities may have trade-offs. As suggested by Scherer et al. (Scherer et  
406 al., 2014), for example, starting condition envelopes which encompass > 5 years will incorporate a greater amount of  
407 natural variability and be less sensitive. Conversely, restricting the starting period to a single year (or two) would  
408 increase sensitivity but risk detecting inter-annual variability rather than longer-term change. Similarly, using  
409 different years for the starting conditions for different datasets will reduce comparability between surveys. Finally, if  
410 starting conditions are set too far in the past they will not reflect prevailing conditions. Exploration of these  
411 challenges will maximise the use of the UK's plankton datasets, increasing the robustness of future assessments  
412 through the inclusion of all UK data.

413 The present analysis illustrates how the PI was used to identify differences in plankton lifeforms over an 11 year  
414 (2004 - 2014) time span and applies this method to formal biodiversity assessment under the MSFD. This initial  
415 assessment used a time frame to harmonise with the OSPAR MSFD intermediate assessment. When considering the  
416 inter-annual variability that exists in the plankton community, the time period examined here is relatively short and  
417 will require the inclusion of additional years before it can confidently be established if the changes observed in Figs.  
418 4 and 5 are part of a long-term trend (Henson et al., 2009). As mentioned above, for many UK datasets this could be  
419 a matter of adjusting the starting conditions period to be further back in time, thereby making better use of multi-  
420 decadal datasets. It is therefore imperative to maintain all UK plankton time-series in their current format, as the  
421 scientific and policy value of time-series increases with dataset length (Giron-Nava, 2017).

422 Notwithstanding the shortness of the assessment period, the PI value acts successfully as a flag to trigger further  
423 investigation the changes that have taken place and the pressures causing change. For example, there have been  
424 suggestions that increases in gelatinous zooplankton signify degraded ecosystem states due to stressors including  
425 overfishing, pollution, eutrophication and anoxia (Richardson et al., 2009; Tett and Mills, 1991). The lifeform pairs  
426 involving gelatinous zooplankton are instructive in this regard with a low PI value (crustaceans and gelatinous  
427 zooplankton:  $PI = 0.51$ ,  $p < 0.01$ ) at PML's L4 station reflecting the substantial increase in gelatinous zooplankton that  
428 has recently been reported here (McConville, 2018). Several publications point to multidecadal cycles of jellyfish  
429 populations and even in heavily fished systems, climate change appears to be implicated in the fluctuations in  
430 gelatinous taxa that have been observed (Lynam et al., 2011). This is one example of the PI 'flagging' important  
431 trends that merit further analysis on causality. Particular care with interpretation, however, must be taken at the  
432 boundary of significance, where  $PI = 0.8$ , as time-series length and starting condition envelope size may influence  
433 statistical significance.

434 Another key strength of our multiple time series approach is that it allows an assessment of large-scale spatial  
435 change: are the changes observed localised or widespread? As an example, long-term declines in total copepod  
436 abundance have been reported in European shelf waters (Edwards, 2013). The fact that these trends are  
437 widespread, and observed both in oceanic and shelf waters and in geographically separate seas (e.g. Celtic and North  
438 Seas), could be argued to point more towards widespread, climate-related pressures rather than to trophic cascades  
439 induced by overfishing. Impacts from the other major anthropogenic pressure, nutrient enrichment, are more likely  
440 to be observed in coastal areas in the first instance. Comparison of PI values between coastal and offshore EHDs will  
441 flag which plankton lifeform pairs lack coherence across these broader spatial scales and require further  
442 investigation.

443 The work described here demonstrates a method to identify changes in UK plankton communities in support of the  
444 2020 UK MSFD Assessment using a diverse range of datasets. To assess GES in fulfilment of the MSFD in line with the  
445 Commission Decision on GES (2017/848/EU) (European Commission, 2017), and to use the lifeform approach to  
446 inform policy decisions about management measures, two additional, critical steps are needed. Firstly, though the  
447 present study identified change in plankton lifeforms between two time periods, identification of a trend in PI away  
448 from starting conditions can identify the trajectory of change in lifeform pairs (e.g. Gowen et al., 2015). For  
449 assessment purposes, this must be accomplished for each EHD zone and fixed-point time-series, though if time-  
450 series are short (i.e. not multi-decadal) the statistical significance of trends and relationships may be difficult to  
451 identify.

452 Secondly, change in plankton lifeforms must be interpreted with respect to environmental variation and  
453 anthropogenic pressures, to identify factors responsible for plankton community change. This information is  
454 required to support government policy decisions about enacting management measures, ensuring effort is applied  
455 to appropriate human drivers and pressures. Causal identification is critical when assessing indicator change against  
456 the agreed UK target of 'Plankton are not significantly influenced by direct anthropogenic pressure'. This target is  
457 process-based, rather than linked to a threshold, which means that as long as change in the plankton is not driven by  
458 direct anthropogenic pressures, such as fishing or nutrient loading, the pelagic habitat is deemed to be in GES. This  
459 process-based target allows the plankton community to shift and change due to environmental and/or climate  
460 change, known as 'prevailing conditions' under the Directive. The management of prevailing conditions is outside the  
461 scope of the MSFD, but failing the target will trigger management action if a directly manageable anthropogenic  
462 pressure causes change in the plankton community. Pressure identification will therefore help to recognise changes  
463 caused by prevailing environmental conditions, a state which may be different from starting conditions but which  
464 still represents GES. The pressure-state relationship in pelagic systems, however, is often unclear or non-linear and  
465 discriminating between the different pressures is challenging, requiring further research (Dickey-Collas et al., 2017).  
466 Despite challenges in understanding the pressure-state relationship for plankton communities, the use of plankton  
467 lifeforms in a surveillance role, for example in interpreting change in other ecosystem components, also requires  
468 further consideration (e.g. Bedford et al., 2018; Shephard et al., 2015).

469 The lifeform indicator is an OSPAR common indicator (PH1/FW5: Changes in Phytoplankton and Zooplankton  
470 Communities) and was used for the regional OSPAR 2017 Intermediate Assessment (OSPAR, 2017); that assessment,  
471 however, only considered data from PML, the CPR and one Swedish sampling station. There are a number of multi-  
472 decadal plankton time-series across the OSPAR area (O'Brien et al., 2017), and as these become available to support  
473 policy the lifeform indicator is flexible enough to incorporate them. This will provide an improved holistic  
474 understanding of change in plankton communities, increasing the robustness of future MSFD assessments which is  
475 also in line with the Commission Decision on GES (European Commission, 2017) which recognises the importance of  
476 practical criteria (technical feasibility, monitoring costs, adequate time-series of data). The flexibility of the lifeform  
477 approach means that the indicator can be used with data from other regional seas as long as appropriate lifeform  
478 pairs are selected (Brito et al., 2015; Gowen et al., 2015; Siddons et al., 2018), and in the future could be applied at a  
479 pan-European scale. Using the same indicator throughout Europe's seas would allow clear, easily comparable

480 assessments of plankton community change, enabling a consistent and coherent view of pelagic habitat status across  
481 Europe.

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