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At what scale should we assess the health of pelagic habitats? Trade-offs between small-scale manageable pressures and the need for regional upscaling

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A B S T R A C T

Major planktonic lifeforms such as diatoms, dinoflagellates, meroplankton and holoplankton have recently shown significant and alarming changes in abundance - mainly downwards trends - around the northwest European shelf. This has major implications for food web connections and for ecosystem services including seafood provision and carbon storage. We have quantified these changes in abundance for 2006–2019/20 using a Plankton Index (PI) and show that the scale of spatial aggregation is critical to the ability of the PI to detect change, understand causal mechanisms, and provide advice to policymakers.

We derived PI statistics in the Celtic and North Seas from data from the Continuous Plankton Recorder survey offshore and England's Environment Agency inshore using three sets of spatial units: (i) Ecohydrodynamic (EHD) units based on hydro-biogeochemical modelling, (ii) 'COMP4′ areas based on cluster analysis of satellite data for chlorophyll *a* and primary productivity, and (iii) English coastal and estuarine Water Framework Directive (WFD) waterbodies. For the largest scale areas, the EHD units (median size 87,000 km^2), we find greater change in plankton communities than previously reported, suggesting that these shifts have continued and possibly intensified in recent years. The smaller-scale COMP4 areas (median size 6,700 km^2) appear to encompass more spatially coherent changes in plankton community structure than EHD units; at this scale PI values indicate community shifts of greater magnitude. These COMP4 areas provide a reasonable compromise scale for linking offshore plankton communities to large-scale drivers of change such as climate warming. For inshore plankton communities, larger changes are detected at the smaller WFD waterbody scale (median size 11 km^2). This scale allows direct links to coastal management measures and is more suitable for linking to land-sourced pressures.

Recent integration of the UK's OSPAR and WFD plankton monitoring data management enables the exploration of changes across spatial scales to develop a holistic understanding of ecosystem health. Regional-sea scale derivation of the PI for coastal waters provides a clear indication that changes are occurring, at least in phytoplankton communities, while localised PI statistics offer an additional layer of information which can be an important tool for linking to localised drivers of change including coastal anthropogenic pressures. Broadscale inshore zooplankton monitoring is needed to evaluate the coastal plankton community holistically; zooplankton communities offshore are also changing but these changes cannot currently be linked to coastal processes. Layering information across spatial scales provides a breadth of system-level understanding beyond what any one typology can provide.

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1. Introduction

The societal importance of our oceans and marine resources is highlighted by Sustainable Development Goal 14: Life Below Water (United Nations, 2015). Accurate, evidence-based assessment of the health of the marine environment in the context of the compounding pressures on the system is fundamental to our ability to manage marine habitats sustainably. Such assessments rely on indicators to evaluate targets for the condition of the marine environment, e.g., within the Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR; e.g.: OSPAR, 2017), Marine Strategy Framework Directive (MSFD; see European Union, 2008), and the Water Framework Directive (WFD; see European Union, 2000). The indicators provide an overview of pressure, state and impact using monitoring data collected at variable spatial and temporal scales.

Pelagic habitat assessments based on the plankton community (e.g.: Bedford et al., 2018; McQuatters-Gollop et al., 2019, 2022), used in both nearshore and offshore marine assessments, make an important contribution to understanding how pressures such as climate change and eutrophication are impacting on the marine system. As the base of the marine food web, the plankton are a critical component of a healthy marine ecosystem (Tett et al., 2013), and can be a powerful indicator for the status of the marine environment. The Plankton Index (PI; Tett et al., 2007, 2008), used in OSPAR and MSFD assessments, quantifies changes in the seasonal cycles of abundance and relative abundance of pairs of plankton functional groups. Application of the PI, like most indicators, requires spatial aggregation of monitoring data which impacts its ability to identify localised plankton community changes.

While overall assessments are required at broad spatial scales (e.g., an OSPAR sea area, or a country's exclusive economic zone), the indicators they are based on must be derived at an ecologically relevant scale to be able to identify processes and changes of interest. If an indicator of change in species abundance integrates over areas of both increasing and decreasing abundance, it may report no change, whereas the localised changes may be significant and relevant to potential management measures. In pelagic habitats, there are often not clearly defined boundaries between spatial units where different processes might be acting to drive different changes in the pelagic community. Thus, efforts to define ecologically relevant pelagic spatial units for assessment are hindered by limited understanding of what constitutes a coherent area as well as a need to include political and geographical divisions in trans-boundary assessment. Plankton species distribution is sensitive to the vertical structure of the water column (Margalef, 1978), implying that hydrodynamic features define a typology for pelagic assessment (van Leeuwen et al., 2015). In such a set of assessment areas, each containing a certain community under certain pressures undergoing coherent change, data from one part of a region can inform on the status of the pelagic community of that whole region (Scherer et al., 2016). For eutrophication assessments, recent work around the UK has investigated the application of assessment typologies based on the spatial extent of river plumes in coastal waters, since riverine inputs of nutrients and turbidity are important pressures (Greenwood et al., 2019; Fronkova et al., 2022).

There is typically a transition from larger spatial assessment units offshore, where pressures are expected to be more spatially homogeneous, to smaller spatial assessment units nearshore where localised land-based pressures dominate. Even with improvements in the delineation of more ecologically relevant assessment areas, there is still a lack of continuity and integration between assessments at the finer scale of estuarine waters and the larger offshore marine seas. The WFD uses small scale areas (median size 11 km^2 in England), focusing only on estuarine and coastal waters. In contrast, past OSPAR pelagic habitat assessment at the scale of the North East Atlantic applied broadly defined ecohydrodynamic (EHD) units (median size 87,000 km^2) while the current (2023) assessment uses a combination of smaller nearshore riverine-influenced areas and larger offshore areas (median size 6,700 km^2). Both offshore and inshore, there remains an inherent trade-off between the need to consider spatial heterogeneity and detail (for example to reveal and respond to acute local stressors) and the need for a much broader-brush approach to communicate high-level messages on plankton indicator trends and to reveal the prevailing effects of climate change.

We hypothesise that smaller spatial units of assessment, so long as they are aligned with the scales of both hydrodynamic regimes and anthropogenic pressures, will provide the most clear and representative picture of changes in plankton community structure. To evaluate the importance of assessment area scale, we systematically compare PI statistics across three sets of spatial units for the Greater North Sea and Celtic Seas: (i) broad Ecohydrodynamic (EHD) units based on hydro-biogeochemical modelling (van Leeuwen et al., 2015; McQuatters-Gollop et al., 2019), (ii) smaller 'COMP4′ areas based on cluster analysis of satellite data for chlorophyll *a* and primary productivity (Blauw et al., 2019; Enserink et al., 2019), and (iii) localised English coastal and estuarine Water Framework Directive (WFD) waterbodies (Environment Agency, 2021). This is the first integrated presentation of the estuarine and coastal WFD-scale and coastal-offshore MSFD and OSPAR scale areas using the same index to quantify plankton community change. We discuss how and why different plankton community changes are suggested at the different spatial scales and make recommendations for future assessments.

2. Methods

2.1. The plankton Index

The PI was developed in the UK to measure changes in the plankton community over time and space and has been used in the MSFD and by OSPAR, where it is part of the indicator PH1/FW5 *Changes in Phytoplankton and Zooplankton Communities* (PH: Pelagic Habitats, FW: Food Webs) (McQuatters-Gollop et al., 2019, 2022). Previously referred as the Plankton Community Index, the approach has been applied in the UK (Tett et al., 2007, 2008; Whyte et al., 2017; Greenwood et al., 2019), North Sea (Bedford et al., 2020a), Hong Kong (Lei et al., 2018) and Kuwait (Devlin et al., 2019). The theoretical background is detailed in Tett et al. (2007, 2008) and in principle involves identifying changes in plankton community seasonal cycles by plotting in multidimensional state space. In practice, the index quantifies changes in the two-dimensional state space distribution of plankton abundance data for pairs of lifeforms between two intervals in time. For PH1/FW5, the PI is used alongside abundance trends in individual lifeforms (timeseries analysis) and other available evidence to establish the drivers of changes in plankton community structure and determine the implications of change for the environmental status of the pelagic habitat.

An ideal application of the PI would quantify change from a system with Good Environmental Status (GES) by using observations during GES to define the assessment envelope (Scherer et al., 2016). However, certainty that any past observed state of the system represented GES is not possible since the Northeast Atlantic has seen significant changes and anthropogenic pressures over the past decades, and thus definition of GES requires a degree of expert interpretation. Application of the PI in assessment is limited to providing a 'flag' of plankton community change relative to a chosen 'assessed period', which must then be investigated further to determine drivers of change and assess if that change is likely to be negative or positive in terms of moving towards or away from GES (McQuatters-Gollop et al., 2019).

Considered in pairs (e.g., diatoms & dinoflagellates), plankton lifeforms provide information on different aspects of the pelagic habitat and can be used to assess the impact of various pressures. We present the PI values for a subset of four key plankton lifeform pairs: diatoms & dinoflagellates, large & small phytoplankton, large & small copepods, and holoplankton & meroplankton each applied only in appropriate data sets where the data were available. The rationale for selecting these lifeform pairs is detailed in McQuatters-Gollop et al. (2019) and Bedford et al. (2020b), and references therein. Briefly, diatoms and dinoflagellates are key primary producers differentiated by their motility, silicification and nutrient requirements, preference for water column structure, seasonality of blooms, and extent of heterotrophic feeding mode. Diatom dominance can indicate enhanced energy flow to the benthos because of their more rapid sinking rates. The abundances of both lifeforms and the balance between them are expected to be sensitive to nutrient availability and ratios as well as water temperature and stratification. Phytoplankton size (here defined by large/small size threshold of 20 μm diameter) is a factor determining energy transfer efficiency and linked to the system's potential to support higher trophic levels. This phytoplankton size-based categorisation is not possible with the Continuous Plankton Recorder (CPR) data, and available data come from light microscopy of water samples. Using this method there is also a lower size detectable limit, based on what can be observed with a microscope: some larger nanophytoplankton are included but pico-plankton and smaller nano-phytoplankton are excluded. Large copepods (here defined as adult total length of greater than 2 mm) can accumulate energy rich lipids, while small copepods (which typically dominate in abundance) are a key trophic link for food webs. A shift towards small copepods may result from warming waters (Daufresne et al., 2009) and eutrophication (Uye, 1994). Holoplankton (permanent members of the plankton) and meroplankton (defined here as metazoan invertebrates with pelagic and benthic phases) are differentiated by how much of their lifecycle is spent in pelagic waters, and their relative abundance thus reflects energy partitioning between pelagic and benthic environments (Kirby et al., 2008).

2.2. Relevant assessment areas

Ecohydrodynamic units (as presented in van Leeuwen et al., 2015; Fig. 1; hereafter referred to as EHD units) were used in previous applications of the PI in OSPAR and MSFD assessments (McQuatters-Gollop et al., 2019, 2022). EHD units are based on hydro-biogeochemical modelling using the GETM-ERSEM-BFM model (GETM: General Estuarine Transport Model; ERSEM: European Regional Seas Ecosystem Model, BFM: Biogeochemical Flux Model). They provide a classification into 5 stratification regimes: region of freshwater influence (ROFI), permanently mixed, intermittently stratified, seasonally stratified, and permanently stratified) as well as unclassified 'indeterminate' areas. The stratification regimes are discontinuous across the assessed region, except for 'permanently stratified' which is limited to the Norwegian Trench.

The EHD unit stratification regimes were argued to have distinct biological characteristics, for example: diatom- based food webs in areas with prolonged stratification, and *Phaeocystis*-dominated food webs in Southern North Sea areas experiencing short-lived or no stratification (van Leeuwen et al., 2015). As such, previous application of the PI using this typology asserted that 'features of the plankton community at a fixed-point station in a particular EHD zone are assumed to be representative of the plankton community throughout that EHD zone' (McQuatters-Gollop et al., 2019). However, that assessment also noted a suite of limitations of EHD units, for example: lack of congruence of sampling stations with their designated regime; poor representation of inshore areas by the model; and spatial heterogeneity within complex (e.g., Irish Sea) or large spatial extent (e.g., North Sea) EHD units.

For the fourth application of their Common Procedure[1] (COMP4) for Eutrophication Assessment, OSPAR has adopted harmonised assessment areas for OSPAR Regions II, III and IV (Fig. 1). These were initially developed in the EU Joint Monitoring Programme of the Eutrophication of the North Sea with Satellite data (Blauw et al., 2019; Enserink et al., 2019), and further refined through expert judgement. Areas with similar phytoplankton dynamics were identified through statistical cluster analysis of satellite chlorophyll-a and primary productivity data following decomposition of these data into interannual, seasonal and residual signals. Additional factors (physical: depth, salinity, stratification; chemical: nutrient concentrations; biological: plankton biomass) were also considered. The areas spanning national boarders were separated into national sub-areas which were further subdivided into smaller areas depending on preferences and practical considerations of individual countries, for example, to produce areas allowing assessment of effects from specific river catchments. In an effort to better align the OSPAR Pelagic Habitats and Eutrophication assessments, the COMP4 areas have been used for the PH1/FW5 indicator in the the 2023 Quality Status Report (QSR) 2023.

The COMP4 areas were designed to complement the inshore Water Framework Directive (WFD; European Union, 2000); now the Water Environment Regulations 2017 in England and Wales (HM Government, 2017) waterbodies (Environment Agency, 2021; Fig. 2). Under the WFD, a phytoplankton classification (High, Good, Moderate, Poor, Bad) is derived for each of these areas based on phytoplankton abundance data (elevated cell counts, seasonal succession) and chlorophyll data (WFD-UKTAG, 2014a; 2014b; Devlin et al., 2007).

2.3. PI calculations

The workflow for PI calculations is shown in Fig. 3, with more detail provided in the Supplemental Methods.

Monthly-averaged lifeform abundances were extracted from the Plankton Lifeform Extraction tool (PLET; Ostle et al., 2021) for: (i) the Continuous Plankton Recorder (CPR) data, provided by the Marine Biological Association (available 1960–2019) which included both phytoplankton and zooplankton, and (ii) the Environment Agency (EA) phytoplankton monitoring data (available 2000–2020). The CPR sampler is towed behind ships of opportunity and collects plankton samples on a rotating 270 μm mesh silk, which is fixed in formalin until identification and counting by microscopy. The EA samples are collected in standard Niskin-style bottles and preserved with acidified Lugol's iodine and counted by the Utermöhl (1958) method. UK fixed point plankton monitoring programmes were not used in this study as the PI statistics derived from that monitoring are not dependent on the choice of spatial assessment units because plankton data are not aggregated between data providers and typically not across multiple fixed point sampling stations of the same provider (e.g., Cefas Smartbuoy sites and Marine Scotland Science stations).

The EHD unit-based PI calculation was, spatially, a replication of the 2017 OSPAR intermediate assessment (McQuatters-Gollop et al., 2019) with updated data timeseries. The COMP4 area calculation of PI values was also carried out within OSPAR regions II and III, though some COMP4 areas were excluded because they were not transited by CPR routes within the time period of interest (see Supplemental Methods for details). Most of the EA data were inshore of the COMP4 areas, with sufficient monitoring for derivation of PI statistics in only 2 areas: 'Thames Plume' and 'Liverpool Bay Plume'. PI statistics were also calculated for England's WFD waterbodies, which were sampled by the EA monitoring programme. For the period investigated here, phytoplankton monitoring data were available in 42 of 105 transitional waterbodies and 45 of 61 coastal waterbodies.

The number of samples available and aggregated into each monthly average varied significantly between assessment areas even within types of assessment unit (see Supplemental Table S2 and Supplemental Figure S2). For example, there were more CPR 'samples' (each representing 10 nautical miles of tow; Richardson et al., 2006) in the EHD units in the Greater North Sea (e.g., average of 24, range 10–39 in seasonally stratified waters), than in the Celtic Sea (greatest average of 16, range 0–39 in seasonally stratified waters, but average of less than 1 in all other Celtic Sea EHD units). Of the 24 COMP4 areas for which data were

[1] https://www.ospar.org/work-areas/hasec/eutrophication/common-procedure.

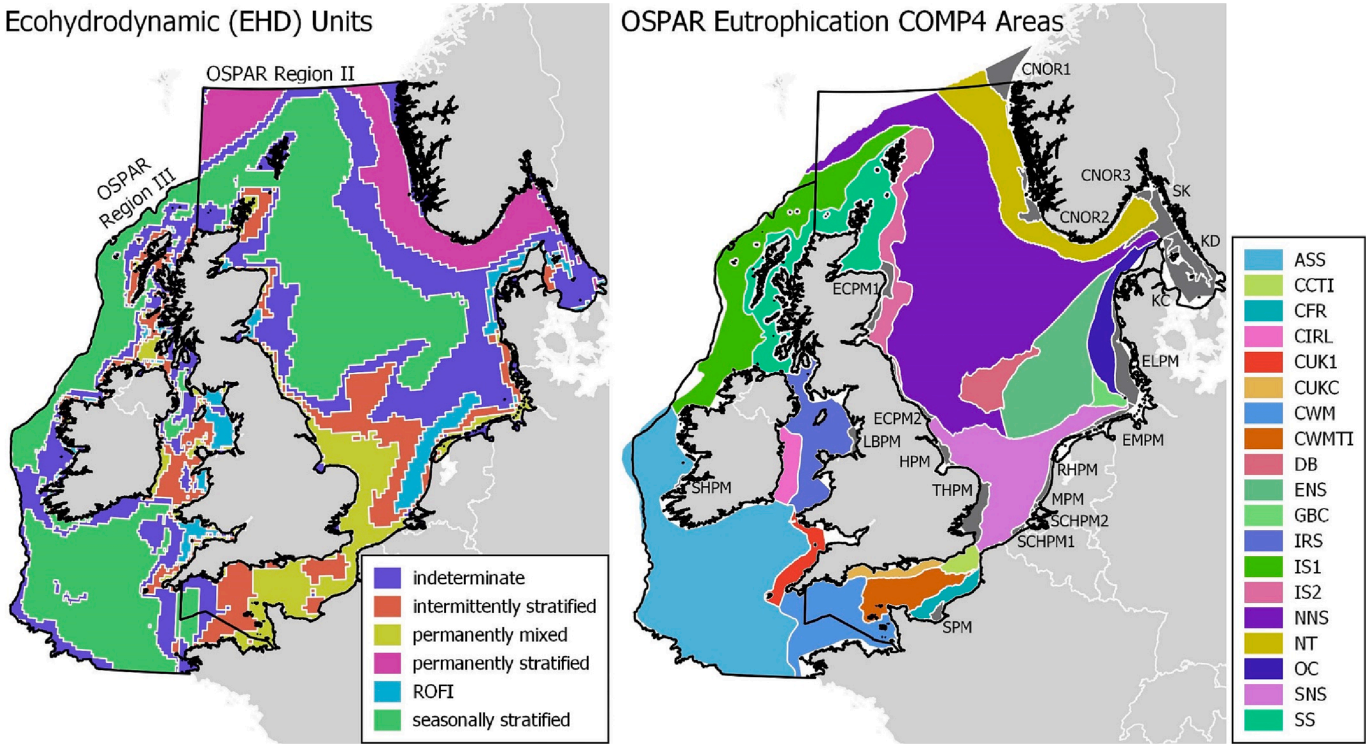

Fig. 1. Left: Ecohydrodynamic units (van Leeuwen et al., 2015), as used for pelagic habitat assessment before the 2023 OSPAR QSR (see McQuatters-Gollop et al., 2019). Right: Eutrophication COMP4 assessment areas (Blauw et al., 2019) in OSPAR Regions II and III to be used for future PI assessments. Solid black lines show the extent of OSPAR Region II (Greater North Sea) and OSPAR Region III (Celtic Seas). Larger COMP4 areas are designated by colour and listed in the legend, while smaller coastal COMP4 areas are shown in dark grey and labelled on the map. See Supplemental Table S1 for full names of COMP4 areas.

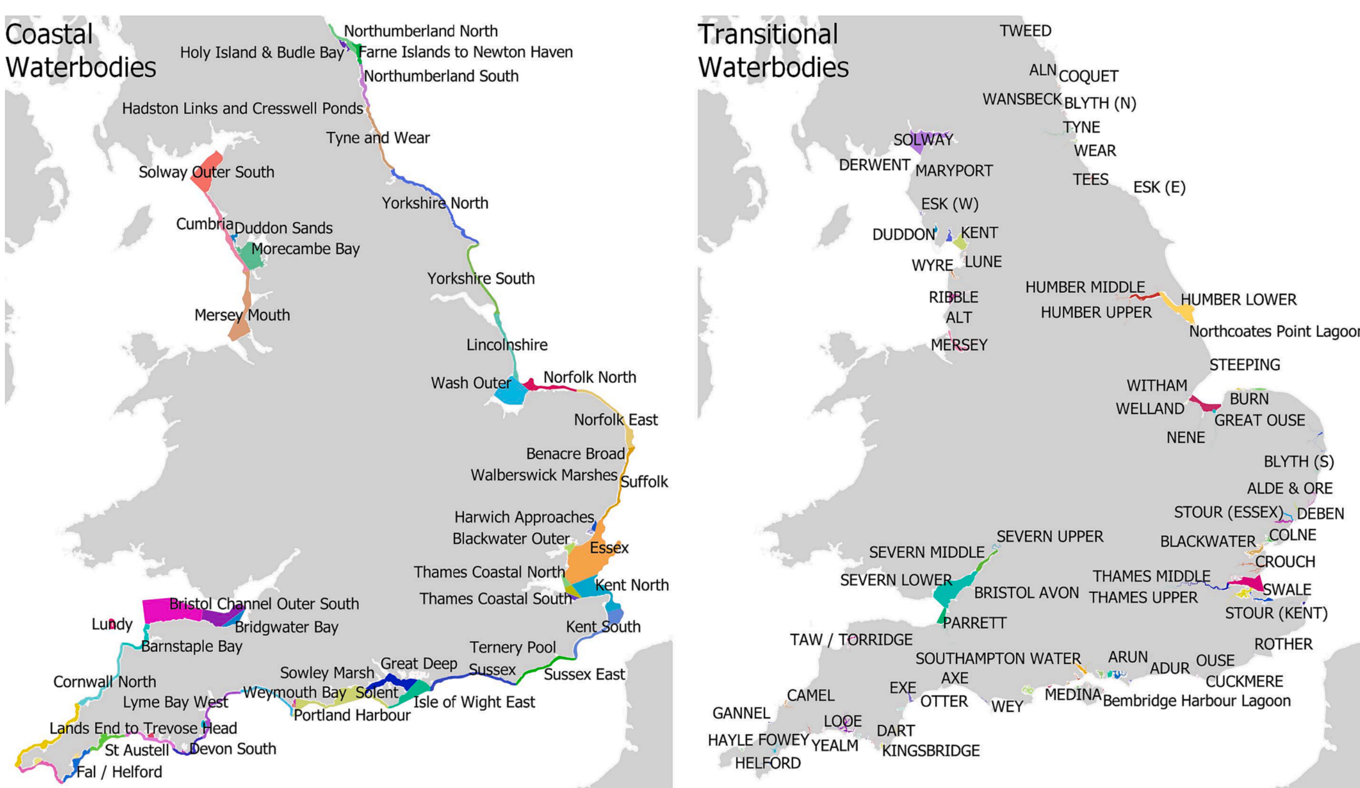

Fig. 2. Coastal (Left), and transitional (right) Water Framework Directive/Regulations (WFD/R) waterbodies in England.

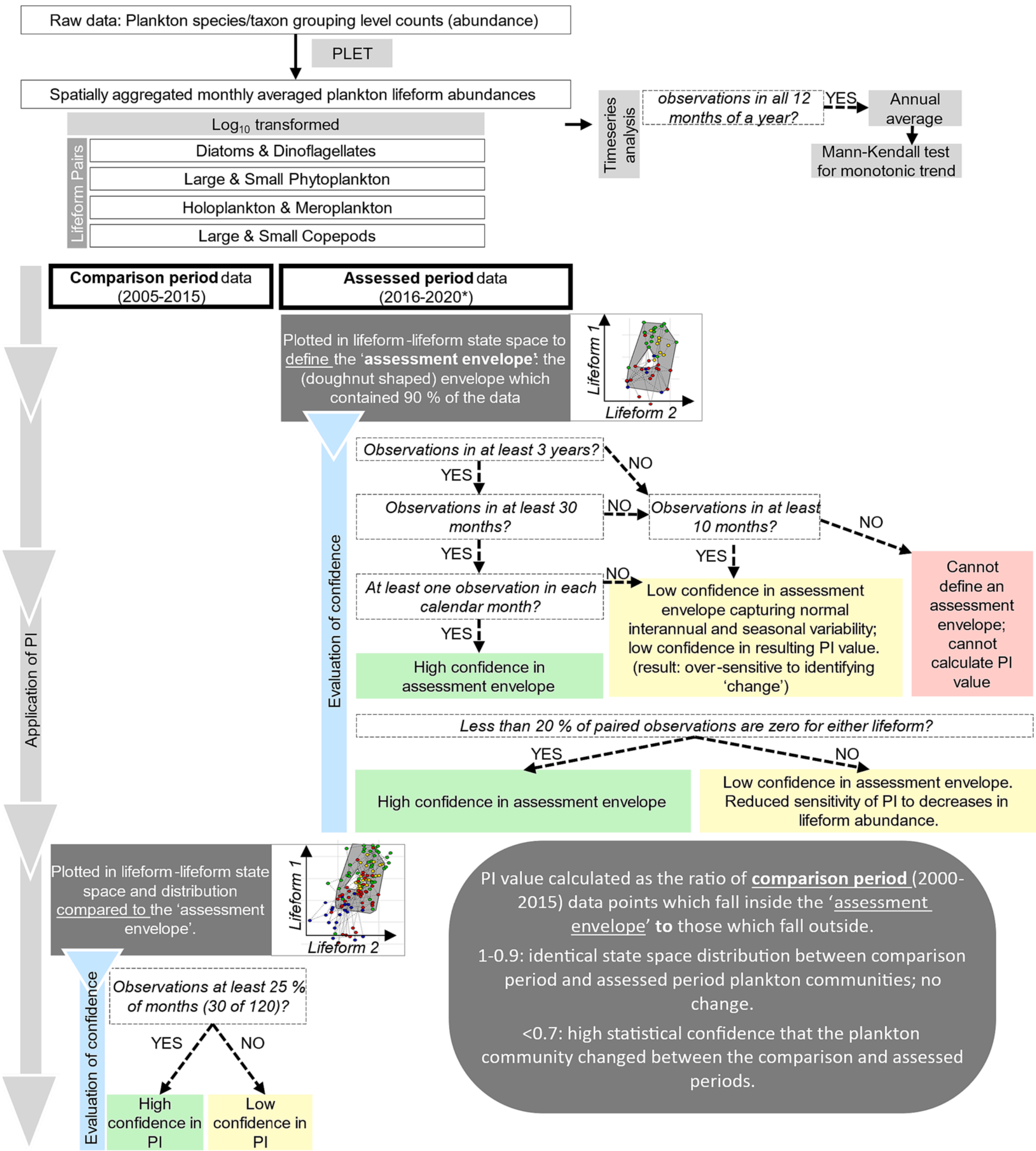

Fig. 3. Schematic representation of Plankton Index (PI) calculation workflow, including criteria for evaluating confidence in resulting PI based on availability of monthly monitoring data throughout both the comparison and assessed periods of the timeseries. PLET: the Plankton Lifeform Extraction tool (PLET; Ostle et al., 2021). See Supplemental Methods for more details.

available, only 4 areas ('East Coast (permanently mixed) 1′, 'Intermittently Stratified 2′, 'Northern North Sea' and 'Southern North Sea') had observations in all months (2006–2019) but most had an average of more than two observations per month and 5 had an average of more than 10 observations per month. In WFD areas there were fewer samples per month on average (0.01–4.7) and a much higher incidence of months without any samples.

The PI was calculated largely following the method described in (McQuatters-Gollop et al., 2019), with the addition of data availability confidence criteria (see Fig. 3 and Supplemental Methods). Here, we used the most recent 5 years of data (2016–2019/20) as the 'assessed period' which defines the PI's 'assessment envelope' and the preceding 10 years (2006–2015) as the 'comparison period' data whose distribution in lifeform-lifeform state space is compared to the assessment envelope to quantify change between the two time periods. This provided a consistent timeframe across both data sources and essentially poses the question: are plankton communities in the most recent 5 years (of available data) different from those of the preceding 10 years?

3. Results

PI values derived from CPR data are tabulated for all assessment regions in Table 1 and mapped in Fig. 4, presenting a mixed picture of change in plankton community structure between the periods 2016–2019 and 2006–2015 across the lifeform pairs and assessed spatial regions.

For diatoms and dinoflagellates, there is a statistically significant change (PI less than 0.7) in 30 % of assessed regions. However, dinoflagellates were often below the detection limit of the CPR counting method (up to 100 % zero abundances in 2016–2019) particularly in winter months, creating stretched PI assessment envelopes which limit the power of the PI as a tool to detect decreases in dinoflagellates (see

Table 1
PI values derived from CPR data in ecohydrodynamic (EHD) units and COMP4 areas, where values less than 0.7 represent a significant change in plankton community (denoted with * where derived with high confidence). No values could be calculated where less than 10 months of observations were available in the full period 2006–2019 or between 2016 and 2019 (the 'assessed period'), or where greater than 75% of abundances were below detection limit: in these cases, the number of observations is shown as n_{total} or n_{assess} or n_{zeros}. Where these minimal requirements were met, but the data availability within the assessed period was still limited, the resulting low-confidence PIs are given with superscript numbers indicating which criterion was not satisfied: [1]observations in less than three years during 'assessed period', [2]observations in less than 30 months during 'assessed period', [3] no samples in one or more calendar months during 'assessed period', [4]more than 20 % of 'assessed period' paired lifeform abundance data below detection limit (see Supplemental Table S3 for more details). PI values where data availability did not limit confidence are emphasized in bold.

OSPAR Region		EHD unit / COMP4 area		diatoms & dino-flagellates	large & small copepods	holo- & mero-plankton	Area (km²)
II	Greater North Sea	Indeterminant		**0.76**	**0.60***	**0.62***	235,474
II	Greater North Sea	Intermittently stratified		**0.78**	**0.80**	**0.77**	91,136
II	Greater North Sea	Permanently mixed		0.78[4]	**0.72**	**0.73**	82,074
II	Greater North Sea	Permanently stratified		**0.83**	**0.68**	**0.68***	97,807
II	Greater North Sea	ROFI		0.79[4]	**0.74**	**0.71**	28,403
II	Greater North Sea	Seasonally stratified		**0.53***	**0.60**	**0.68***	235,232
III	Celtic Seas	Indeterminant		n_{total}=8			111,673
III	Celtic Seas	Intermittently stratified		n_{assess}=8			40,727
III	Celtic Seas	Permanently mixed		N_{zeros}=94%	0.76[3,4]	0.45[3,4]	13,008
III	Celtic Seas	ROFI		N_{zeros}=79%	N_{zeros}=79%	0.59[2,4]	18,438
III	Celtic Seas	Seasonally stratified		0.62[4]	**0.76**	**0.64***	184,596
III	CS	ASS	Atlantic Seasonally Stratified	0.56[4]	**0.74**	**0.62***	183,286
III	CS	CIRL	Coastal (Ireland)	0.66[3,4]	0.79[3,4]	0.77[3,4]	9,591
II	GNS	CNOR2	Coastal (Norway)	0.84[4]	**0.47***	0.84[4]	2,615
III	CS	CUK1	Coastal (UK, near Bristol Channel))	0.91[2,4]	0.81[2]	0.74[2,4]	10,704
II	GNS	CUKC	Coastal (UK, channel)	N_{zeros}=94%	0.74[1,4]	0.59[1,4]	6,301
II & III	CS & GNS	CWM	Chanel well mixed	0.68[4]	**0.75**	**0.79**	41,159
II	GNS	CWMTI	Channel well mixed tidal influenced	0.97[2,4]	0.76[2,4]	0.56[2]	20,621
II	GNS	DB	Dogger Bank	0.66[4]	0.77[4]	**0.67***	14,771
II	GNS	ECPM1	East Coast (permanently mixed, UK, SE Scotland)	0.83[4]	0.72[4]	0.68[4]	3,517
II	GNS	ECPM2	East Coast (permanently mixed, UK, NE England)	n_{assess}=3			1,443
II	GNS	ENS	Eastern North Sea	**0.80**	**0.84**	**0.60***	60,911
II	GNS	GBC	German Bight Central	0.58[1,4]	0.54[1,4]	0.74[1,4]	4,590
II	GNS	HPM	Humber Plume	n_{total}=2			1,368
III	CS	IRS	Irish Sea	0.78[4]	0.70[4]	0.72[4]	32,694
II & III	CS & GNS	IS1	Intermittently Stratified (UK; NW Ireland, Scotland)	0.78[4]	0.85[4]	0.71[4]	73,643
II	GNS	IS2	Intermittently Stratified (UK; NE)	0.84[4]	**0.61***	**0.59***	26,501
II	GNS	KD	Kattegat Deep	0.65[2,4]	0.68[2,4]	0.84[2,4]	9,785
II	GNS	NNS	Northern North Sea	**0.72**	**0.78**	**0.76**	264,524
II	GNS	NT	Norwegian Trench	0.79[4]	**0.60***	**0.59***	59,340
II	GNS	OC	Coastal DEDK	**0.71**	**0.60***	**0.60***	18,694
II	GNS	SK	Skagerrak	0.75[2,4]	0.39[2,4]	0.39[2,4]	5,832
II	GNS	SNS	Southern North Sea	0.66[4]	**0.63***	**0.58***	61,902
II & III	CS & GNS	SS	Scottish Sea	0.72[4]	**0.77**	**0.66***	53,285
II	GNS	THPM	Thames Plume	n_{assess}=9			5,527

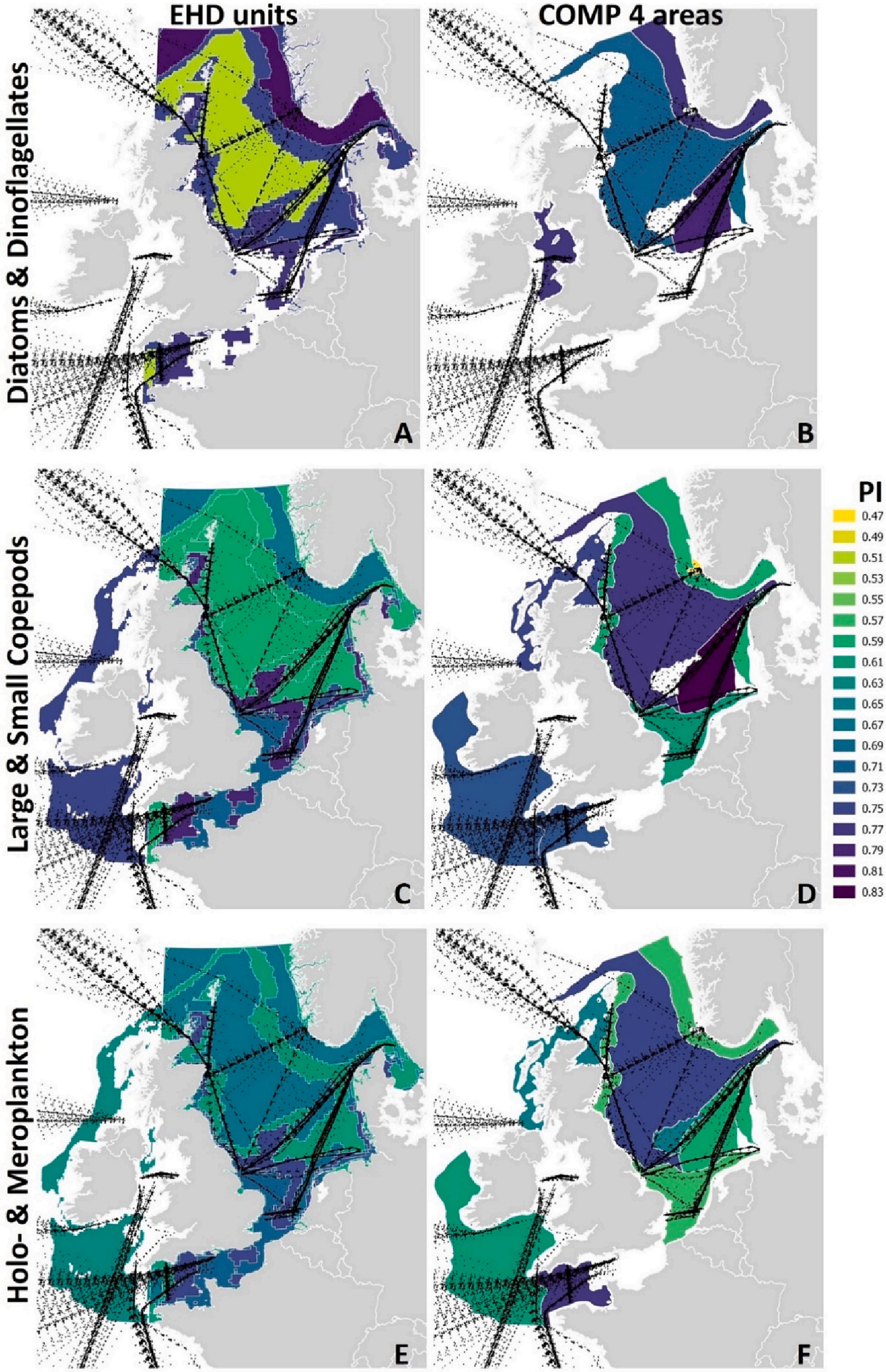

Fig. 4. PI values derived from CPR data, with darker colours indicating no or small changes in plankton community structure and lighter and brighter colours indicating larger changes. **A**,**C**,**E** for ecohydrodynamic units divided east–west into OSPAR Regions II and III, and **B**,**D**,**F** for COMP4 assessment areas. Areas within OSPAR Regions II and III with insufficient data to derive high-confidence PI values are in white. Black dashed and dotted lines show CPR survey tracks since 2000.

Supplemental Figure S3, Supplemental Table S3). The largest changes (smallest high-confidence PIs) are in seasonally stratified EHD units (PI: 0.53, 0.62), and the 'Atlantic Seasonally Stratified' COMP4 area (PI: 0.56). While the two sets of assessment areas both indicate change in the seasonally stratified waters of the Celtic Seas, indication of change is inconsistent between EHD units and COMP4 areas in the Greater North Sea. There are no statistically significant trends in annually averaged individual lifeform timeseries.

For large and small copepods, there is a statistically significant change (PI less than 0.7) in 40 % of spatial units for which the PI could be calculated. The most widespread change occurs in the holoplankton and meroplankton lifeform pair (PI less than 0.7 in 60 % of assessed regions). The COMP4 regions indicate that the largest changes are in the southern part and around the periphery of the North Sea, while the EHD units indicate a greater change in the central and northern North Sea.

Robust identification of significant change in plankton community using the PI is exemplified by holoplankton & meroplankton in the 'southern North Sea' (SNS) COMP4 area where observations were available for 80% of months in 2016–2019 (the 'assessed period') and 99% of months in 2006–2015 (the 'comparison period') (Fig. 5). Meroplankton abundance in the SNS has increased in recent years (Mann-Kendall trend of annual averages: tau = 0.64, p = 0.0009), particularly in autumn and winter months. Here, PI values differ significantly between overlapping COMP4 areas and EHD units. The SNS is overlapped by three EHD units: 'permanently mixed' in the west, 'intermittently stratified' in the centre and north-west, and 'ROFI' in the east (Fig. 6), yet the SNS PI value (0.57) indicates a stronger change than any of the overlapping EHD units (PI 0.71–0.77). While this may at first seem counterintuitive, the SNS PI value should not be expected to be an average or combination of the PI values of the three overlapping EHD units. In addition to only including a portion of the SNS data, each of the EHD units extends beyond the SNS area drawing in observations from the Channel (for 'permanently mixed' and 'intermittently stratified'), coastal western Scotland (for 'intermittently stratified'), and western coastal Denmark (for 'ROFI'). Spatially incoherent differences in plankton abundance between the SNS and in these other areas appear to be masking the shift in plankton community structure which is shown when applying the PI calculation in the SNS as a whole. Looking at individual lifeform timeseries, while meroplankton are increasing in GNS 'permanently mixed' and 'ROFI' areas, the trend is not significant (Mann-Kendall tau = 0.24, p = 0.2; tau = -0.1, p = 0.59) though it is significant in 'intermittently stratified' areas (Mann-Kendall tau = 0.41, p = 0.03). The lifeform-lifeform state space PI plots show that all four regions have lower wintertime meroplankton abundances in 2006–2015 than the 2016–2019, but the 'assessment envelopes' for the 3 EHD units are larger than that of the COMP 4 area, extending to lower meroplankton abundances (Fig. 7). More of the lower abundances from the earlier portion of the timeseries therefore fall inside the 'assessment envelopes' of the EHD units, yielding comparatively larger PI values indicating less change.

PI values for nearshore EA data (Table 2, Supplemental Figure S4) indicate a change in nearshore phytoplankton community structure (PI less than 0.7) in all but three of the spatial units for which the PI could be calculated. However, only 48 of the 108 (44%) PI values derived from EA data are high confidence. The lowest PI values, indicating the largest changes in phytoplankton community, are dominated by data-limited spatial units where a robust PI 'assessment envelope' could not be defined, and are therefore reported with low confidence. Only a quarter (4 of 17) EA PI values below 0.5 are high confidence. This result is not unexpected, since an assessment envelope derived from limited data will not capture the full natural inter-annual and seasonal variability of the system and is thus likely to be smaller in area than it would be if more observations were available. A small assessment envelope will exclude more of the comparison data, leading to a low PI value. The degree of community change indicated by these values is therefore likely to be over-estimated.

Of the high-confidence PI values from EA data, 85 % indicate a significant change in phytoplankton community (PI less than 0.7). Further confidence in the overall reporting of a spatially coherent significant phytoplankton community change is provided by the low PI values derived for the larger spatial aggregations: at the broad spatial scale of the 'Celtic Seas coastal inshore', the low PI value for diatoms & dinoflagellates (0.62) is driven by lower diatom abundances in the earlier years (particularly in the winter months) and higher dinoflagellate abundances in the earlier years (particularly in early winter) while change in the large & small phytoplankton lifeform pair (PI 0.56) is driven by an increase in small phytoplankton. The same seasonal and time series patterns appear in the 'Greater North Sea coastal inshore' region (PI 0.44 and 0.34) but are less pronounced despite the lower PI values.

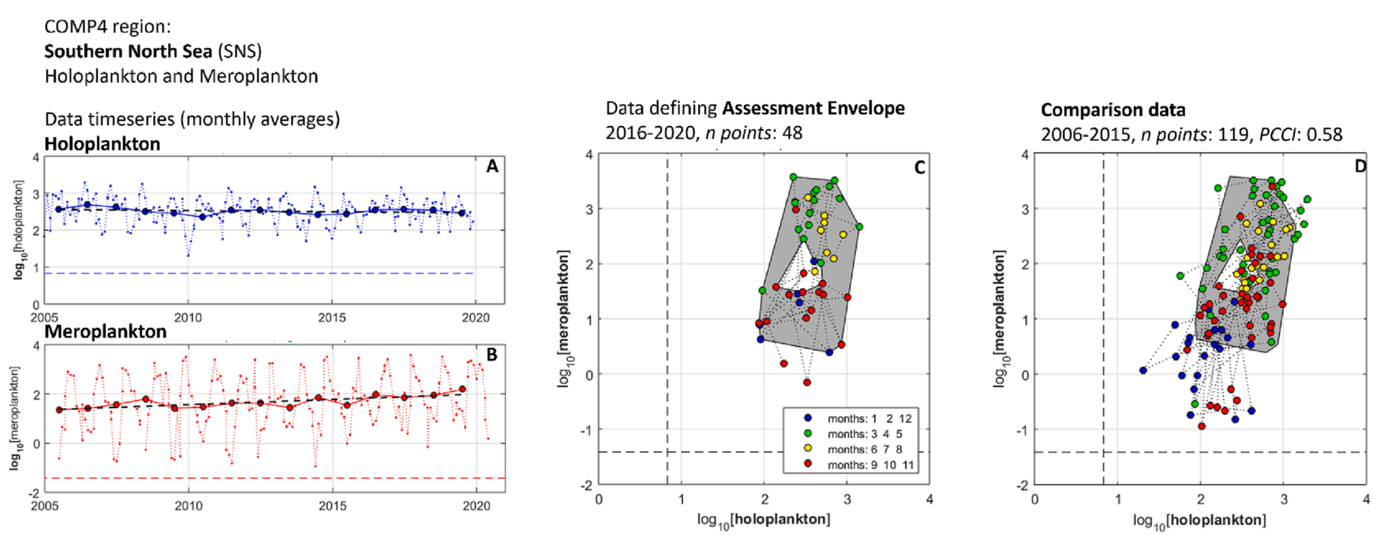

Fig. 5. CPR lifeform abundances for the holoplankton and meroplankton lifeform pair derived for the Southern North Sea (SNS) COMP4 area. **A** & **B**: timeseries of lifeform abundances showing monthly average abundances (small coloured points, where dashed coloured lines join observations from consecutive months) and annual average values (large circles with black boarders, connected by solid line) with linear fit (dashed black line) to annual averages (significant increase in meroplankton, Mann-Kendall p = 0.0004; no trend in holoplankton, Mann-Kendall p = 0.3). **C**: paired observations during the assessed period (circles, coloured by season), and resulting assessment envelope (grey doughnut shape), **D**: paired observations during the comparison period, overlain on the assessment envelope from **C**.

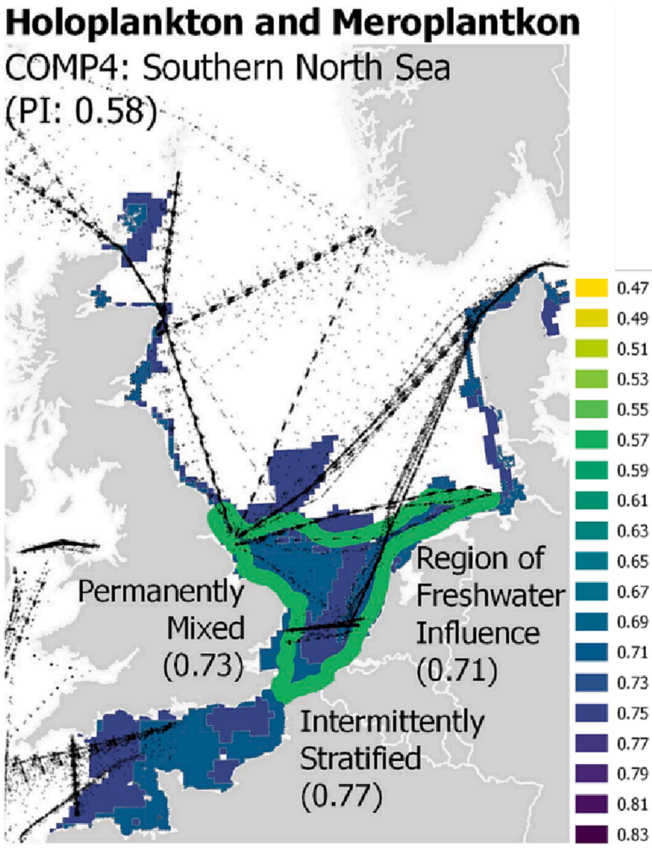

Fig. 6. PI and spatial extent comparison between the Southern North Sea COMP4 area and overlapping ecohydrodynamic units. PI values for the holoplankton & meroplankton lifeform pair are given in brackets and shown in the same colour scale as in Fig. 4. The Southern North Sea COMP4 area is designated with a thick (green) outline. EHD units are coloured by their PI values in dark blues (Permanently Mixed, dotted black outline; Region of Freshwater Influence, dashed outline) and mid-blue (Intermittently stratified). Black semi-transparent dashed and dotted lines show CPR survey tracks since 2000, with darker lines indication overlapping sampling over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Underlying these broad scale patterns, the WFD waterbody PI values reveal small scale variations in the degree of phytoplankton community change. This is illustrated in Fig. 8 for the Liverpool Bay area (see also Supplemental Figure S5). Phytoplankton communities in the Liverpool Bay Plume COMP4 area, which excludes the inner WFD transitional waterbodies, and Morecambe Bay (WFD coastal) are changing less than is suggested by the broad 'Celtic Seas coastal inshore' PI value. A similar degree of change is indicated in the outer WFD waterbodies, while nearshore waterbodies reveal more significant (for diatoms & dinoflagellates) and more spatially heterogenous (for small & large phytoplankton) changes. An example of the distribution of monitoring samples which underpins the derivation of PI values at different spatial scales is shown in Fig. 9.

4. Discussion

Changes in plankton community structure have been quantified as PI values using CPR (phytoplankton and zooplankton, offshore) and EA (phytoplankton only, inshore) monitoring data in OSPAR Regions II and III by aggregating observations into different spatial assessment units. This analysis of coastal and offshore plankton datasets at multiple spatial scales clearly demonstrates the impact of the choice of spatial aggregation on indicator outcomes, which has not been investigated by previous related studies (McQuatters-Gollop et al., 2019, 2022; Bedford et al., 2020a, 2020b). Between the most recent 5 years of observations (2016 and 2019/20) and the preceding 10 years (2006–2015) there have been widespread shifts in plankton community structure (Table 1, Table 2). PI values for offshore plankton lifeforms indicate significant changes in up to 60 % of the spatial units for which they could be calculated (though only 55% and 34% of these are high confidence based on data limitations for EHD units and COMP4 areas, respectively). PI values for inshore phytoplankton lifeforms indicate nearly ubiquitous significant change (in 92% of assessed spatial units, 35% derived with high confidence). These changes in diatoms, dinoflagellates, small and large copepods and phytoplankton, holoplankton and meroplankton abundance are an indication of pressures on the pelagic habitat such as climate change and eutrophication, and will themselves impact ecosystem functioning.

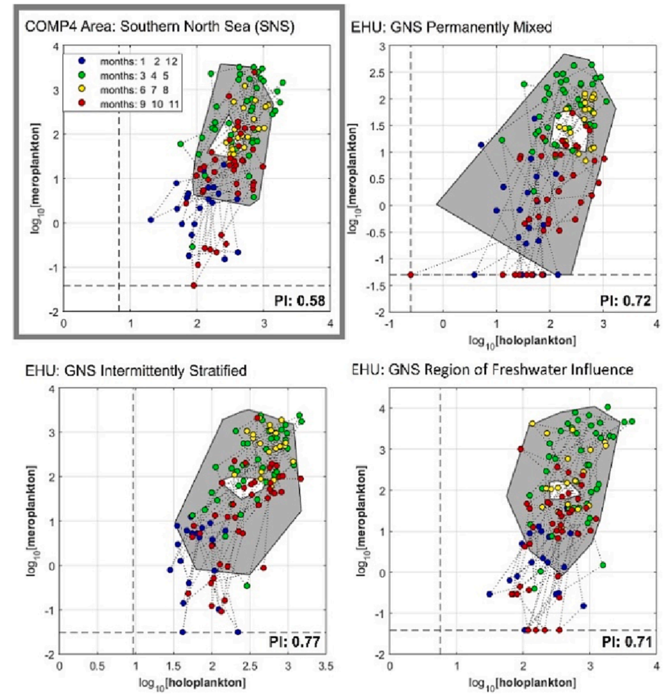

Fig. 7. Plankton Index lifeform-lifeform plots for the regions shown in Fig. 5: 'Southern North Sea' (SNS) COMP4 area (upper left, emphasised by grey box) and the three EHUs which partially overlap SNS. Circles, coloured by season, are paired holoplankton-meroplankton abundances (logarithmic scale) during the 'comparison period' (2006–2015), overlain on the 'assessment envelope' defined by each region's 'assessed period' data (grey doughnut shape, monthly data not shown). The PI values (bottom right of each plot) are the ratio of the number of points which fall inside to that which fall outside of the assessment envelopes.

PI values are in general agreement with those reported in McQuatters-Gollop et al. (2019) (Table 3). In line with the 2017 OSPAR Intermediate Assessment (OSPAR, 2017), McQuatters-Gollop et al. (2019) used the EHD units for CPR data and the east/west divide for EA data ('Greater North Sea coastal inshore' and 'Celtic Seas coastal inshore') but evaluated lifeform change over a smaller and slightly earlier time interval: 2004–2008 (5-year 'assessed period' at the begining of the timeseries defining the PI assessment envelope) and 2009–2014 (6-year 'comparison period'). Here we identify significant plankton community change in slightly more of the EHD units across the lifeform pairs considered, and a general decrease in PI values (67 % of pair-wise comparisons) with a mean difference between PI values derived for the same lifeform pair and assessment unit of 0.08. The higher instance of slightly lower PI values derived here could indicate that change is better detected by a longer (10-year) comparison period with the 'assessed period' at the end of the available timeseries, or that shifts in

Table 2
PI values derived from EA monitoring at different scales of spatial aggregation. Areas where no monitoring data were available are not shown. Also excluded are regions with observations during less than 10 months in 2016–2020 (the 'assessed period') and regions where data were available for less than a quarter of months in 2006–2015 (the 'comparison period'). Only values shown in bold were derived with high confidence based on the data availability criteria for the assessed period, for these, values less than 0.7 represent a significant change in plankton community and are denoted with *. For low-confidence values superscript numbers indicate which criterion was not satisfied: [1]observations in less than three years during 'assessed period', [2]observations in less than 30 months during 'assessed period', [3] no samples in one or more calendar months during 'assessed period', [4]more than 20 % of paired lifeform abundance data below detection limit (see Supplemental Table S3 for more details). Details on data availability for all English WFD waterbodies are available in Supplemental Table S4.

Region		Diatoms & Dinoflagellates	Large & Small Phytoplankton	% data in comparison period	Area (km^2)
Celtic Seas Coastal Inshore (East)		**0.62**	**0.56**	**93**	**7,000**
Greater North Sea Coastal Inshore (West)		**0.44**	**0.34**	**90**	**10,065**
COMP4: Thames Plume		0.43[2]	0.39[2]	78	5,527
COMP4: Liverpool Bay Plume		**0.58**	**0.53**	**87**	**1,360**
WFD Transitional Waterbodies	Adur	0.53[2]	0.68[2]	44	1.4
	Bure & Waveney & Yare & Lothing	0.55[2]	0.39[2]	62	8.9
	Camel	**0.64***	**0.47***	**78**	**11**
	Carrick Roads Inner	**0.63***	**0.54***	**78**	**13**
	Dart	0.40[2]	0.35[2]	69	8.3
	Esk East	0.5[2]	0.44[2]	62	0.28
	Exe	0.43[2]	0.22[2]	69	18
	Great Ouse	**0.72**	**0.81**	**59**	**12**
	Humber Lower	0.70[2,4]	0.50[2]	30	248
	Humber Middle	0.61[4]	**0.73**	**11**	**67**
	Lune	**0.60***	**0.63***	**63**	**3**
	Mersey	**0.32***	**0.41***	**26**	**80**
	Orwell	0.53[2,4]	0.61[2]	49	12
	Poole Harbour	**0.69***	**0.57***	**74**	**33**
	Portsmouth Harbour	0.51[2]	0.52[2]	73	16
	Ribble	**0.64***	**0.46***	**56**	**45**
	Severn Lower	0.63[4]	0.67[4]	45	466
	Solway	0.28[2]	0.40[2]	61	306
	Southampton Water	0.52[2]	0.59[2]	82	31
	Stour (Essex)	0.52[2]	0.39[2]	62	26
	Taw /Torridge	**0.51***	**0.52***	**69**	**15**
	Tees	0.44[2]	0.34[2]	79	11
	Thames Lower	**0.51***	**0.52***	**61**	**201**
	Thames Middle	0.52[2,4]	0.49[2]	25	44
	Thames Upper	0.51[2,4]	0.24[2]	27	3.2
	Tweed	0.44[2,4]	0.68[2]	51	2.4
	Wash Inner	0.58[4]	**0.88**	**49**	**134**
	Wyre	**0.56***	**0.51***	**57**	**6.4**
WFD Coastal Waterbodies	Barnstaple Bay	0.42[2]	0.65[2]	63	111
	Blackwater Outer	0.65[2,4]	0.62[2]	62	49
	Bridgwater Bay	0.41[2,4]	0.36[2]	48	92
	Bristol Channel Inner South	0.57[3,4]	0.61[3]	64	338
	Carrick Roads Outer	0.56[2]	0.39[2]	34	15
	Cornwall North	0.60[2]	0.32[2]	68	192
	Cornwall South	0.40[3]	0.30[3]	63	122
	Cumbria	**0.54***	**0.67***	**36**	**244**
	Dorset / Hampshire	0.42[2]	0.42[2]	30	513
	Fal / Helford	0.38[2]	0.21[2]	24	123
	Farne Islands to Newton Haven	0.41[2]	0.54[2]	83	70
	Holy Island & Budle Bay	0.45[2]	0.54[2]	81	30
	Kent South	0.50[2]	0.48[2]	73	248
	Lincolnshire	**0.64***	**0.69***	**85**	**170**
	Mersey Mouth	**0.59***	**0.31***	**81**	**421**
	Northumberland North	**0.59***	**0.46***	**81**	**104**
	Plymouth Sound	0.49[2]	0.62[2]	73	18
	Solent	0.43[2]	0.34[2]	79	260
	Tor Bay	**0.63***	**0.44***	**73**	**24**
	Wash Outer	**0.74**	**0.76**	**85**	**461**
	Whitstable Bay	0.78[4]	**0.72**	**73**	**26**
	Yorkshire South	0.66[2]	0.54[2]	67	158

community structure have increased in recent years (2015 to 2020 for which data were not available in the earlier work), or both.

Over the full CPR timeseries length (1958–2017), Bedford et al. (2020b) showed an increasing trend in diatom abundance alongside a decrease in dinoflagellates in the GNS, but a decreasing trend in both lifeforms in the Celtic Seas. While we do not detect statistically significant trends in annually averaged individual lifeform timeseries over the much shorter period considered here (2006–2019), changes in the seasonal cycle of the diatom & dinoflagellate lifeform pair in seasonally stratified waters of both the Greater North Sea and Celtic Seas in more recent years are indicated by their low PI values. Inshore, from annually averaged EA monitoring data (2008–2015), Bedford et al. (2020b) identified increases in both diatoms and dinoflagellates. Our PI analysis illustrates the seasonal element of these changes: decreasing autumn (September-November) dinoflagellates and increasing wintertime (December-February) diatoms.

Bedford et al. (2020b) investigated drivers of these changes and found that, for diatoms, increasing sea surface temperature was correlated with lifeform abundance but other factors including other environmental drivers (wind speed/direction, grazing pressure) were likely

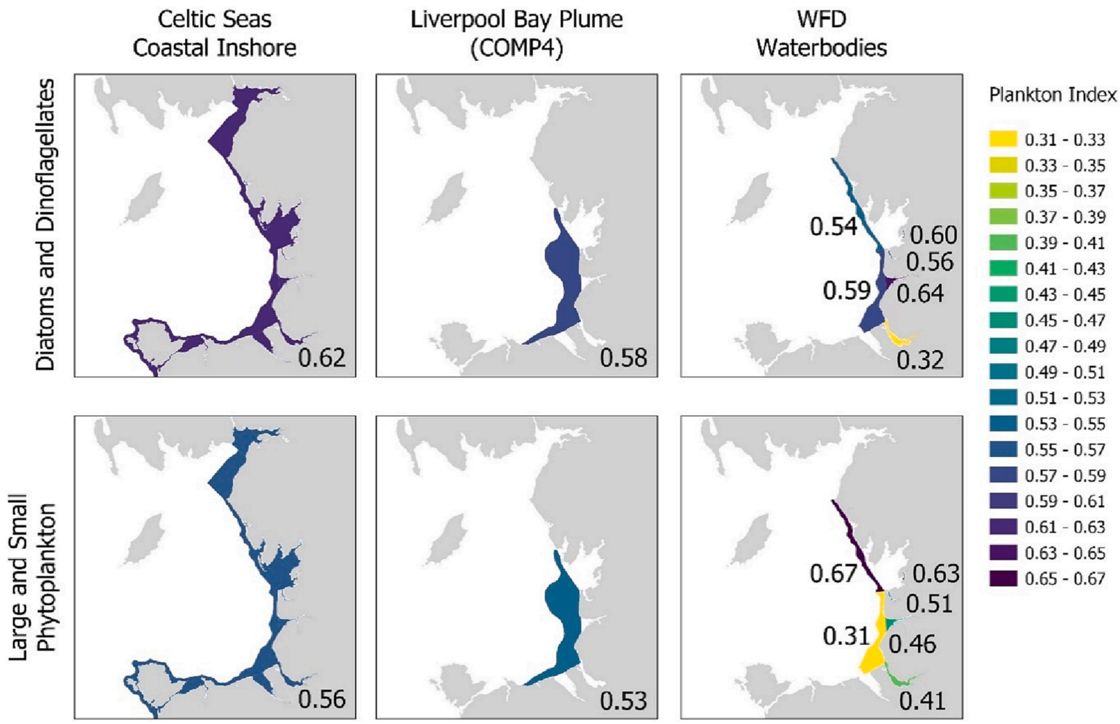

Fig. 8. PI values derived from Environment Agency monitoring data at different spatial scales. using monthly averages of: (left) all data in OSPAR Region II: Celtic Seas; (Centre) all data in in the Liverpool Bay Plume COMP4 area, and (right) all available data in each of the WFD Transitional and Coastal waterbodies. WFD waterbodies without sufficient monitoring to derive high confidence PIs for the chosen time period are not shown, though observations from these areas are included in the larger spatial aggregations. Upper row shows PI values for the diatoms & dinoflagellates lifeform pair, lower row for large & small phytoplankton.

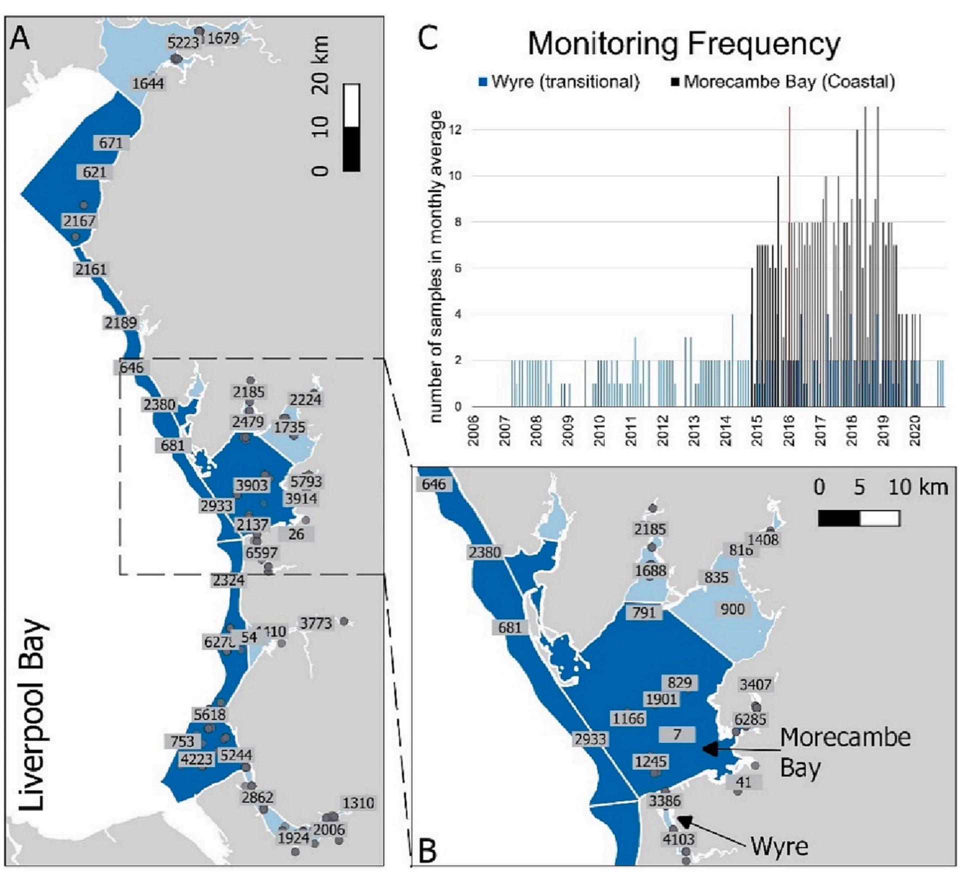

Fig. 9. Environment Agency monitoring data distribution in space and time for Liverpool Bay. **A** and **B** show coastal (dark blue) and transitional (light blue) WFD waterbodies with locations of EA plankton sampling (transparent grey circles with black outline), where return sampling at the same site is indicated by darker circles (less transparent) and total number of samples at a point (numbers in grey boxes). **B** shows a smaller area (of extent indicated by dashed box on **A**). **C** shows full information on sampling intensity over the timeseries in Morecambe Bay (coastal) and Wyre (transitional) areas, with red vertical line indicating the beginning of the assessed period used for PI calculations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Comparison between PI values derived in this study (using data from 2006 to 2019/20) and those for the same regions and datasets derived by McQuatters-Gollop et al. (2019) (using data from 2004 to 2014). The 'large & small' lifeform pair is for copepods with CPR data, and phytoplankton for EA data (coast/inshore assessment unit). The difference between PI values for the same lifeform pair and region is shown in the column 'Δ', where positive values indicate an increased change (lower PI) in this study. *Values below 0.7, indicating statistically significant change. For values derived in this study, low-confidence PIs based on limited data within the assessed period are indicated by: [1]observations in less than three years during 'assessed period', [2]observations in less than 30 months during 'assessed period', [3]fewer than 2 years' of observations in some calendar months during 'assessed period', [4]more than 20 % of 'assessed period' paired lifeform abundance data below detection limit. Missing values indicate that data limitations prevented derivation of a PI value.

OSPAR Reg.	Assessment Unit	diatoms & dinoflagellates			large & small copepods/phytoplankton			holo- & mero-plankton		
		2006–19	2004–14	Δ	2006–19	2004–14	Δ	2006–19	2004–14	Δ
II:	Indeter.	0.76	0.76	0	0.60*	0.70	0.10	0.62	0.69*	0.07
Greater North Sea	Inter. strat.	0.78			0.80			0.77		
	Perm. mixed	0.78[4]	0.82	0.04	0.72	0.80	0.08	0.73	0.73	0
	Perm. strat.	0.83	0.84	0	0.68	0.88	0.20	0.68*	0.78	0.20
	ROFI	0.79[4]	0.70	*−0.09*	0.74	0.66*	−0.08	0.71	0.76	0.05
	Season. strat.	0.53*	0.77	0.24	0.60*	0.75	0.15	0.68*	0.66*	−0.02
	Coast/inshore	0.44*	0.54*	0.10	0.34*	0.60*	0.26	–	–	–
III:	Inter. strat.								0.66*	
Celtic Seas	Perm. mixed				0.76[3,4]			0.45*[3,4]	0.79	0.34
	ROFI	0.84[2]			0.64*[2]			0.59*[2,4]	0.67*	0.08
	Season. strat.	0.62*[4]	0.66*	0.04	0.76	0.67*	−0.10	0.64*	0.78	0.12
	Coast/inshore	0.62*	0.69*	*0.07*	0.56*	0.54*	−0.02			

to have an impact, especially in inshore and coastal areas. Differences between inshore (EA) and offshore (CPR) lifeform abundance trends may be due to different drivers and pressures between the coast and the open sea, but could also result from the two monitoring programmes sampling different components of the diatom and dinoflagellate populations (Bedford et al., 2020b). The link between multi-decadal variability in climate and diatom abundance in the Northeast Atlantic, using CPR data, was recently further explored in detail by Edwards et al. (2022), who found that climate warming is causing increases in northerly but decreases in southerly diatom populations. Detailed investigation of drivers of plankton community change is not the aim of this study, but is required for a complete interpretation of changes in lifeforms across spatial scales and fully evaluating if seas are in Good Environmental Status (McQuatters-Gollop et al., 2019).

Comparing the PI values derived from the offshore CPR monitoring data between EHD units and COMP4 areas (see Fig. 4) it is clear that they are influenced by the choice of spatial unit. However, as exemplified by the holoplankton & meroplankton lifeform pair in the southern North Sea COMP4 area (Fig. 6, Fig. 7), incomplete overlap with several EHD units and inclusion of data from spatially distant areas (where EHD units are non-continuous) make it difficult to understand what drives the differences in PI values between the two sets of areas. The result suggests that more coherent plankton community change is occurring at the scale of the smaller localised COMP4 areas than that of the larger EHD units, which makes the PI more effective at identifying change at the COMP4 spatial scale in these sea areas. Integration of change over longer observational time scales could reveal patterns at a broader spatial scale: Bedford et al. (2020b) reported a relatively coherent increase in annual average meroplankton abundance alongside a decrease in holoplankton abundance in the GNS over the full CPR timeseries (from 1958) at a 2° grid square spatial scale.

Effectiveness at identifying plankton community change is significantly hindered at spatial scales which are not supported by sufficient monitoring. Plankton monitoring is resource intensive, and though the UK has an extensive plankton monitoring network (see McQuatters-Gollop et al., 2019; Bedford et al., 2020b; Ostle et al., 2021) which provides detailed information on plankton dynamics in OSPAR Regions II and III (including high temporal resolution monitoring at fixed-point stations, not presented here), some gaps in monitoring remain for the 2006–2020 time period which prevented calculation of PI values for some spatial assessment units and limited them to low confidence in others. In these cases, the PI is not an appropriate tool to screen for changes in plankton community structure. Data availability in the 'assessed period' years (here 2016–2020), which define the 'assessment envelope', is particularly critical for robust application of the PI and meaningful identification of plankton community change. Applying data-availability criteria to identify low-confidence PIs is thus vital when deriving batches of values (e.g., for a set of assessment areas). Where data limitations lead to low-confidence PI values, a more detailed look into the available data is warranted. In some regions for which we present low-confidence PI values there are more observations in earlier years, so a better confidence PI could have been derived by defining the assessment envelope with data from the beginning of the timeseries. Alternatively, timeseries analysis of annual averages (as explored in Bedford et al., 2020b) could be used to investigate plankton community change, though this approach must account for missing months of observations. In general the PI is designed to allow for robust assessment despite some observation gaps, by making a comparison to a multiple years of observations and capturing the plankton community's seasonal cycle (see Tett et al., 2007).

While the use of larger assessment units can avoid leaving regions unassessed or assessed only at low confidence because of data limitations, the resulting assessment is only valid if the sites sampled are representative of the under or un-sampled areas. This is the underlying principle behind defining spatial typologies and stratified sampling designs (e.g., Scherer et al., 2016; Cooper et al., 2019). The potential loss of information from applying a large assessment area is exemplified by the difference in PI values between the large-scale aggregation of 'Celtic Seas coastal inshore' and individual WFD waterbodies in Liverpool Bay (Fig. 8). The regional sea scale assessment unit flags statistically significant shifts in plankton community structure based on both the diatom & dinoflagellate and large & small phytoplankton lifeform pairs, but applying the PI to individual WFD waterbodies, where data availability allows, reveals that the magnitude of the phytoplankton community change varies at a much smaller scale. The phytoplankton community in the Mersey appears to be experiencing the most significant change, with greater change in transitional waterbodies than the coastal waterbodies. For diatoms and dinoflagellates in the Mersey there has been a recent decrease in summertime peak diatom abundance and an increase in winter minimum diatom abundance which is not observed in the neighbouring Mersey Mouth or Ribble waterbodies (Supplemental Figure S4). This could indicate a local (potentially anthropogenic, likely land-sourced) pressure on the plankton community, which might be manageable at the scale of River Basin Management Plans (Defra, 2021; for Liverpool Bay, see Environment Agency, 2015). In the future, localised offshore anthropogenic disturbance may increase (e.g., from offshore wind from infrastructure; Dorrell et al. 2022) which could impact the plankton community at a much smaller scale than current offshore plankton assessment areas.

In UK coastal waters and the surrounding OSPAR sea areas, centralised and standardised data management (Ostle et al., 2021) and semi-automated data processing enable relatively rapid calculation of PI statistics for many spatial aggregations, allowing different assessment areas to be chosen which are relevant to specific policy questions. In this context, assessments should include a rationale for the chosen spatial aggregation which links to the relevant policy questions. Particularly in more data-poor sea areas, this choice may be limited by availability of appropriate plankton monitoring data. In such cases, the detailed spatial aggregation comparison presented here and made possible by relatively good data availability can inform the expert analysis of more spatially limited assessment outcomes. Our results suggest significant nearshore spatial heterogeneity of phytoplankton community change as well as different relevant spatial scales of change between nearshore and coastal waters.

The proportion of the plankton community that is monitored also plays a part in dictating our understanding of change. In this study, the near-shore data do not include zooplankton while the offshore data are not appropriate for application of the large & small phytoplankton lifeform, and neither dataset include small nano and pico-plankton which play a key role in the plankton community (e.g., Atkinson *et al*, 2021). The PI provides a useful spatial indicator of change but remains only one part of a holistic assessment of the entire plankton community, and our appreciation of what is driving changes (Bedford et al., 2020b, Schmidt et al 2020, Edwards et al., 2022).

Finally, we examine the theory (Tett et al., 2007, 2008) on which the PI was founded in the context of the spatial scale comparison. The lifeform-lifeform state space 'assessment envelope' was intended to encompass the plankton community structure corresponding to a WFD type-specific reference condition. The envelope was argued to represent a bundle of annual trajectories through lifeform-lifeform state space that 'includes all those states of the ecosystem that are normal for the type-specific conditions, taking account of seasonal and interannual variation and spatial patchiness'. The 'type-specific conditions' were those of the relevant ecohydrodynamic regime, where in most cases seasonal drivers create a sequence of environmental conditions that successively favour one lifeform after another, a succession that can be viewed as a 'climatological attractor' for the system's trajectories in lifeform-lifeform state space. Variability about this 'attractor' results from weather, chaotic components in internal dynamics, and lateral boundary fluxes. Deriving the PI across large spatial units which are not defined by appropriate 'type-specific conditions' would thus be expected to broaden the assessment envelope by including more than one 'attractor' while using smaller spatial units would be expected to have only single attractor but to include more variability due to boundary effects. In practice, we find that data availability complicates these expected relationships. Moving from larger EHD units to smaller COMP4 units using CPR data increases the influence of abundances below the detection limit which stretches the PI assessment envelope to the zero axis(es) in many cases, while in others a lack of observations during some seasons or years has the opposite effect of shrinking the PI assessment envelope by not capturing the full seasonal and interannual variability. This exemplifies the need for compromise between theoretical ideal, and a robust assessment based on real monitoring data which is necessarily limited in space and time. Despite these considerations, we suggest that the lower PI values derived for COMP4 areas compared to larger EHD units imply that they better satisfy the hypothesis implicit in van Leeuwen et al. (2015) of one attractor and type-specific reference condition per area. Inshore, even smaller areas are needed to satisfy this criterion.

5. Conclusions

Regardless of the spatial scale considered, plankton community structure in the Greater North Sea and Celtic Seas is changing and further work is required to confirm the pressures, natural and anthropogenic, driving these changes. Shifts in the plankton community are expected to impact other components of the marine food web and could be deleterious to the health of the marine ecosystem as a whole and the ecosystem services it provides. The spatial scales at which these changes are investigated and described has an impact on how well they are understood. Drivers of plankton community change likely vary spatially and in their impact on individual plankton lifeforms and species.

The UK plankton monitoring network consists of fixed-point sampling stations alongside sampling programmes with broad spatial extents: the CPR survey offshore and the EA's coastal and transitional waterbody monitoring inshore. However, it is not possible to observe everywhere, and observations must be spatially aggregated to gain an understanding of the status of the system. Aggregation into large spatial units which may experience spatially heterogenous pressures (drivers of change) and thus spatially incoherent changes in plankton community structure hinders our ability to identify change, flag potential issues, and accurately represent the plankton community status. Furthermore, applying spatially limited observations to a large assessment unit extrapolates out to areas where no observations have been made, which is valid only where spatially coherent pressures and impacts can be expected across the entire assessed spatial unit. Conversely, choosing to use small assessment units can hinder our ability to derive plankton indicator values with confidence due to data limitations. Yet, where sufficient observations are available (including at fixed-point monitoring stations) localised derivation of the plankton index can provide valuable information on how observed changes link to pressures, and this mechanistic approach is crucial to scale up for a wider understanding. Multiple and adjacent fixed point time series also provide clues on spatial heterogeneity which is likely to improve our ability to link to drivers of change and pressures which act at these small scales. Including the WFD waterbody scale in investigation of changes in the marine plankton community improves the link with the scale of River Basin Management Plans, which are key to the MSFD and UK Marine Strategy Programmes of Measures. We demonstrate that application of the PI in small WFD areas is possible with existing monitoring data, providing an additional information to coastal water managers.

EHD units, used in previous pelagic habitat assessments, appear to encompass spatially incoherent shifts in plankton communities and therefore derivation of the PI at this scale indicates, in many cases, a lesser magnitude of plankton community change than is shown at finer spatial scales. Because they are based on stratification patterns, EHD units are likely to be a valuable tool for investigating the potential impacts of large scale changes in physical oceanographic conditions such as those expected from climate change (e.g., Edwards et al., 2020). However, future work should recognise or reconcile inconsistencies when comparing EHD units to observed stratification particularly in the Channel and Irish Sea. Analysis of plankton community change at regional scales using spatial gridding is also a useful approach for linking with broad-scale drivers (Bedford et al., 2020b).

The COMP4 areas, derived for eutrophication assessment based on patterns in sea surface chlorophyll *a*, appear to encompass more spatially coherent shifts in plankton communities than EHD units and thus likely provide a better spatial aggregation over which to derive the PI for the purposes of flagging changes in plankton communities for further investigation. Where sufficient plankton monitoring data are not available to derive the PI for some of the smaller COMP4 areas, it is important to critically evaluate whether extending an indicator value based on nearby observations is likely to provide an accurate representation of the status of the unmonitored area. Use of COMP4 areas in plankton assessment aligns spatial regions across MSFD/UK Marine Strategy Descriptors (i.e., between a Pelagic Habitats indicator and Eutrophication) providing an opportunity to improve application of the ecosystem approach.

Inshore plankton communities may be experiencing stronger changes, and are experiencing more intense anthropogenic pressures from land-based activities, than plankton further offshore. However, differences in sampling methodology between the CPR and EA monitoring mean that different taxa are included in the phytoplankton lifeforms sampled by each, making direct comparison of community change between inshore and offshore problematic. The EA monitoring data do not include zooplankton, which limits the scope of our nearshore analysis to phytoplankton only and prevents a holistic assessment of nearshore plankton communities. Regional-sea scale derivation of the PI for coastal phytoplankton provides a clear indication that changes are occurring while localised PI values offer an additional layer of information which can be an important tool for linking to localised drivers of change.

Layering information across different spatial scales provides a depth of system-level understanding beyond what any one typology can provide. We recommend deriving localised indicator values for inshore waters where small-scale differences in pressures and impacts are likely to dominate while applying larger spatial aggregations informed by ecologically relevant features offshore where broader scale pressures are more important. To inform management and policy, good communication of indicator results across scales is required.

CRediT authorship contribution statement

C.A. Graves: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition, Project administration. **M. Best:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition. **A. Atkinson:** Writing – review & editing. **B. Bear:** Data curation. **E. Bresnan:** Writing – review & editing. **M. Holland:** Data curation, Writing – review & editing. **D.G. Johns:** Writing – review & editing. **M. Machairopoulou:** Writing – review & editing. **A. McQuatters-Gollop:** Writing – review & editing. **A. Mellor:** . **C. Ostle:** Writing – review & editing. **K. Paxman:** Resources, Data curation. **S. Pitois:** Writing – review & editing. **P. Tett:** Software, Writing – review & editing. **M. Devlin:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

All plankton data are available from the Plantkon Lifeform Extraction Tool (Ostle et al., 2021: https://doi.org/10.5194/essd-13-5617-2021).

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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.2023.110571.

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