Healthy & Biologically Diverse Seas Evidence Group
Technical Report Series:

Evaluation and gap analysis of current and potential indicators for Plankton

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Preface

The UK Marine Monitoring and Assessment Strategy (UKMMAS) aims to provide coordinated and integrated marine monitoring programmes which support periodic assessments of the state of the UK marine environment. The strategy aims to provide vital data and information necessary to help assess progress towards achieving the UK's vision of clean, healthy, safe, productive and biologically diverse seas. The overarching strategy is supported and delivered by four evidence groups; Clean and Safe Seas Evidence Group (CSSEG); Productive Seas Evidence Group (PSEG); Healthy and Biologically Diverse Seas Evidence Group (HBDSEG) and Ocean Processes Evidence Group (OPEG). These groups are responsible for implementing monitoring and observations programmes to contribute to ecosystem-based assessments of marine environmental status.

As part of the HBDSEG programme of work, a series of reviews of environmental indicators was undertaken for the following marine ecosystem components:

1. Rock and biogenic reef habitats
2. Sediment habitats
3. Deep sea habitats
4. Seabirds and waterbirds
5. Cetaceans
6. Seals
7. Plankton
8. Microbes

The aim of the reviews was to evaluate a wide range of currently available and potential indicators for marine biodiversity monitoring and assessment. This task was undertaken particularly to inform future needs of the EU Marine Strategy Framework Directive (MSFD). The work was carried out by a group of consultants and contributors and was managed by JNCC.

Each review included a process to evaluate indicator effectiveness against a set of specified scientific and economic criteria. This process identified those indicators of activity, pressure, state change/impact and ecosystem structure and function that were considered to be scientifically robust and cost effective. The indicators which met these criteria were then assessed for inclusion within an overall indicator suite that the reviewers considered would collectively provide the best assessment of their ecosystem component's status. Within the review, authors also identified important gaps in indicator availability and suggested areas for future development in order to fill these gaps.

This report covers one of the ecosystem components listed above. It will be considered by HBDSEG, together with the other indicator reviews, in the further development of monitoring and assessment requirements under the MSFD and to meet other UK policy needs. Further steps in the process of identifying suitable indicators will be required to refine currently available indicators. Additional indicators may also need to be developed where significant gaps occur. Furthermore, as the framework within which these indicators will be used develops, there will be increasing focus and effort directed towards identifying those indicators which are able to address specific management objectives. There is no obligation for HBDSEG or UKMMAS to adopt any particular indicators at this stage, based on the content of this or any of the reports in this series.

This report has been through a scientific peer review and sign-off process by JNCC and HBDSEG. At this time it is considered to constitute a comprehensive review of a wide range of currently available and potential indicators for this marine ecosystem component.

Summary

This report identifies the most effective planktonic indicators of marine ecosystem state, pressures, structure and function to allow scientifically robust assessment of Good Environmental Status (GES) in the context of the Marine Strategy Framework Directive (MSFD) as well as fulfilment of HBDSEG monitoring programmes under UKMMAS and the UK marine biodiversity monitoring and surveillance programme objectives. The results were obtained through a process beginning with a review of existing indicators for phytoplankton and zooplankton, which included an evaluation of the scientific and economic effectiveness of these indicators. The indicators were then assessed with respect to relevant pressures and important aspects of ecosystem structure and function. This allowed the identification of gaps in indicator availability and was followed by a recommendation of an effective suite of plankton indicators.

Two classes of indicators were assessed in this work: those derived from data collected by the Continuous Plankton Recorder (CPR) survey and those collected from other, primarily coastal, in situ monitoring programmes as well as remotely-sensed satellite data. In general, the CPR indicators are based on a long time-series which is spatially extensive, are well developed with respect to policy needs and are both cost efficient and scientifically robust. For the most part, the non-CPR indicators focused on localized coastal collection sites and had shorter time-series, but may be more frequently sampled and provide critical information on plankton change in near-shore waters.

The most effective indicator suite for addressing policy and monitoring needs is comprised of both CPR indicators providing comprehensive information on a regional scale and non-CPR indicators which offer information on plankton change at some coastal sites. The combination of the two types of indicators enables effective interpretation of plankton dynamics influenced by anthropogenic pressures against regional-scale climate-driven changes in the plankton.

The most significant gap in plankton monitoring occurs in the lack of an integrated monitoring strategy which would allow a greater understanding of the changes in the plankton of UK waters and would systematically link large scale surveys such as the CPR with inshore and single station sampling programmes. An integrated monitoring strategy would enable the development of more robust ecological indicators which could be used to assess the performance of policy requirements. More effort should also be directed towards developing indicators that are able to detect change in the smallest size classes of plankton, which although are an important part of the plankton (and Harmful Algal Bloom) community, are often under-represented in monitoring programmes.

Contents

1 Introduction

1.1 Aims & objectives of report

This report identifies the most effective planktonic indicators of marine ecosystem state, pressures, structure and function to allow scientifically robust assessments of marine environmental status to be made.

1.2 Work undertaken in report

This report was developed through a five step process:

1. Review of existing indicators for phytoplankton and zooplankton
2. Evaluation of the effectiveness of the indicators against standardised scientific and economic criteria
3. Review of indicators against relevant pressures and important aspects of ecosystem structure and function
4. Identification of significant gaps and identification of any indicators that may be able to fill these gaps
5. Recommendation of a set of indicators for phytoplankton and zooplankton that are effective scientifically and economically and could be used in future within an integrated monitoring and assessment programme

1.3 Introduction to plankton

Forming the base of the food chain in the sea, the seasonal cycles of plant (phyto) and animal (zoo) plankton growth sustain all other living marine organisms up to seabirds and whales. A proportion of their production settles out of the water column or is extracted by benthic creatures, providing food for benthic animals and, in some regions, a long-term sink for carbon. Availability of light, nutrients and the depth and degree to which the water is stratified or mixed are the main agents governing the growth of phytoplankton. In turn these variables are modulated by variability in currents, climate, weather and topography in the North Atlantic and shelf seas while also highly dependent on such factors as wind strength/direction/frequency, cloudiness, water turbidity, precipitation and river runoff. The pressure of feeding by herbivorous zooplankton may at times also exert top down controls on phytoplankton productivity. Also larger predatory invertebrate plankton such as jellyfish may consume the herbivores at a rate strong enough to release this top down pressure on phytoplankton growth and allow algal blooms. There are significant variations in productivity between regions. Plankton have a wide range of ecological functions and play fundamental roles in the biological cycles of key elements. Plankton also play a crucial role in the productivity and health of the seas around the British Isles; they are sensitive indicators of environmental change and, at both regional and global levels, plankton are impacted by and contribute to climate change through ecosystem feedbacks.

Through their production and community structure, plankton largely determine the carrying capacity of ecosystems around the British Isles for those organisms which depend on this production, such as harvestable fish and shellfish. The sustainable exploitation of living marine resources is affected by variability in plankton productivity from year-to-year. Plankton and their breakdown products are intrinsic to the cycling of matter through different biogeochemical cycles. Phytoplankton may at times occur in huge concentrations (blooms) that may in part be due to increased human inputs of nutrients to the sea (eutrophication), particularly in coastal waters. However climate change is also an influencing factor. Some phytoplankton species produce toxins which pose a health risk to humans and other marine animals. Other species may cause mortalities of farmed fish or benthos due to oxygen depletion during bloom die-offs; these events are termed 'Harmful Algal Blooms' (HABs). Phytoplankton also play a key role in modulating climate change through a range of interactions, including the formation of biogenic aerosols such as dimethylsulphide (DMS). A key phytoplankton process is the photosynthetic uptake of carbon dioxide (CO_2) in the surface ocean and its export as organic and inorganic carbon to the deep ocean in what is termed the 'biological carbon pump'. Grazing and recycling of nutrients by zooplankton and bacteria, including reprocessing and packaging of planktonic detrital material as it sinks through the water column, are key processes in determining the export rate of carbon (C) fixed by primary production (Steinberg *et al* 2008). At the surface, during phytoplankton growth, concentrations of CO_2 are generally less than the equilibrium level with the atmosphere and as a consequence atmospheric CO_2 enters the ocean.

Some of the carbon incorporated through photosynthesis will be returned by in situ respiration in the water column, some will remain incorporated in plankton and dissolved organic matter, and a significant proportion sinks to the seabed. The deep bottom water of the oceans, because of their colder temperature, can hold much higher concentrations of CO_2 and retains much of the dissolved and particulate organic matter from settling plankton. Without this deep sea reservoir of stored carbon the concentrations of CO_2 in the atmosphere would be much higher.

The distribution, abundance, production and biodiversity of various plankton species and communities are very likely to be profoundly affected by projected climate-driven changes in the physical and chemical properties of the ocean; such as circulation, stratification, nutrients, light, trace metals (e.g. iron) and carbonate chemistry. Such changes are likely to be compounded by the effects of ocean acidification on the physiology and fitness of all plankton and especially those species that have calcareous body parts. The converse is also likely to occur as changes in plankton ecology and biodiversity could have large and rapid impacts through changes in important feedbacks and altered biogeochemistry that modulate climate variability. Given the role of plankton in the biological, continental shelf and carbonate carbon pumps (Reid *et al* 2009) any substantial global change in the composition or functioning of plankton ecosystems has considerable implications for climate change. Increasing evidence supports these conclusions and emphasises the need to monitor and research the plankton components of marine ecosystems.

As the primary production by phytoplankton is transferred through the zooplankton in marine food webs to fish, benthos and higher predators, it is obvious that without plankton there would be no fish in the sea. Data on plankton can be used to evaluate the causes of variability in fish stocks as plankton composition and timing of occurrence within a year regulates the success or failure of the development (recruitment) of larval fish to the adult stock (Cushing, 1975).

Phytoplankton process nutrient inputs to the sea and increased nutrient levels may promote eutrophication. Through their harmful effects, blooms of toxic jellyfish and algae can have economic and animal welfare impacts on aquaculture, both directly and by changing the buying preferences of the public through associated negative media publicity.

Eutrophication, as indicated by excessive and prolonged blooms of phytoplankton, may also have a large economic consequence through requirements to construct improved sewage systems and to reduce agricultural inputs of nutrients to the sea. Perhaps the greatest socioeconomic impact that is as yet not properly quantified is the role that plankton plays in ameliorating or increasing rates of global warming through negative and positive feedbacks to atmospheric greenhouse gases.

1.4 Policy background

1.4.1 Statutory policy drivers

Until the advent of the Water Framework Directive (WFD) there was only one statutory policy driver, the EU Shellfish Hygiene Regulations 2004/05 (EC No 854/2004) that required information or measurements on plankton. The regulations require that shellfish harvesting areas are monitored for the occurrence of toxic phytoplankton in the water column, and for the presence of their toxins in filter feeding shellfish. Sampling to assess the distribution and occurrence of potentially toxic phytoplankton has been carried out since 1992 in England and Wales, 1996 in Scotland and 1993 in Northern Ireland, to provide supplementary information to toxicity tests under current Regulations. The Food Standards Agency (FSA) is the competent authority in the UK for compliance with the EU Shellfish Hygiene Regulations; the FSA contract this work out to various laboratories. The Centre for Environment, Fisheries and Aquaculture Science (Cefas) carry out the analysis for potentially toxic phytoplankton in England and Wales funded by the FSA, the Scottish Association for Marine Science (SAMS) do the same for FSAS (FSA Scotland) and the Agri-Food and Biosciences Institute (AFBI) conduct this work for the FSA NI (FSA Northern Ireland).

Both the Urban Waste Water Treatment and Nitrates Directives are statutory policy drivers with a phytoplankton monitoring element. The requirement is to undertake measurements of phytoplankton and/or nuisance macroalgae as part of the process of putting forward candidate sensitive (eutrophic) areas.

The WFD that came into force in 2000 introduced a new regime requiring monthly sampling throughout the year in transitional and coastal waters (out to 3 nautical miles in Scotland, 1 nautical mile elsewhere in the UK) for phytoplankton and chlorophyll (but not zooplankton). In June 2008 the Marine Strategy Framework Directive that addresses all European seas was adopted. This is the first directive that requires a systematic assessment of the ecological state of all European regional seas. The aim is to determine ‘Good Environmental Status’ targets by 2012, the implementation of a monitoring programme by 2014 and the achievement of Good Environmental Status by 2020. Monitoring programmes must include a systematic description of the seasonal and geographical variability of chlorophyll and species and communities of phytoplankton (including Harmful Algal Blooms (HABs)), zooplankton and non-indigenous species, amongst many other variables (MSFD, Annex III).

Unlike the WFD, the Marine Strategy Framework Directive (MSFD) operates at a regional sea scale, with the UK and Ireland being part of the Northeast Atlantic/North Sea region (MSFD Article 4, Section 1). Although each Member State has responsibility to define its own ‘Good Environmental Status’ objectives, the MSFD requires that monitoring programmes and methodologies used must be compatible within and between regional seas and consistent with existing monitoring programmes at a regional and international level. In addition the MSFD (Annex III) specifically requests the monitoring of phytoplankton and zooplankton communities and of indicators that provide information on fish population structure, invertebrate benthic fauna, HABs, biodiversity, and non-indigenous species. Information on all of these can be derived from planktonic indicators.

The MSFD also emphasizes that the natural variability of biological indicators must be considered – this is only possible for long time-series. The Continuous Plankton Recorder (CPR) survey data will contribute towards some of these crucial requirements. The CPR time-series is >75 years for UK waters, a consistent sampling and analysis methodology has been employed during this time and the CPR, if towed with water samplers attached, could be used to contribute information to at least 5 of the 11 descriptors of Good Environmental Status required by the MSFD in a cost-effective manner. However limitations to the CPR data exist. The large plankton mesh size means that the CPR only samples a subset of the plankton species in the environment. Some important phytoplankton groups e.g. raphidophytes will not be sampled at all and sampling for larger or fragile zooplankton is very poor or impossible with the CPR. In addition, the CPR only samples in the top 7m of the water column, thus information on plankton species that regularly inhabit deeper waters will not be provided. There are observable differences in day and night CPR catches due to the diel migrations of some taxa to and from deeper layers. Whilst the CPR provides a measure of phytoplankton and zooplankton abundance over a long time-series, more recent quantitative time-series have been obtained for chlorophyll and associated physical and chemical data from other instruments. For examples; there are high resolution (weekly) time series of plankton sampled at Plymouth and near Aberdeen. Also continuous in situ measurement of chlorophyll, sediments, nutrients, light attenuation, temperature and salinity with real time transmission of data have been developed since 2000 as part of the Smart Buoy programme at Cefas in both the southern North Sea and Liverpool Bay. Similar measurements are available from a number of European Ferrybox routes since 2000, and a reliable time-series of satellite colour imagery for oceanic waters is also available for the past decade. The data from all these series and others is also being used to validate and incorporate field data into ecosystem models. These various models in turn model processes and are allowing wider data synthesis, interpretation and scenario testing based on the field data and experimental observations.

1.4.2 Non-statutory mandatory drivers

The most important policy driver requiring information on plankton under this heading is the Eutrophication Strategy of the OSPAR Convention. The monitoring programme associated with this strategy requires the measurement, at least once a year during the phytoplankton growing season, of chlorophyll as well as the composition of phytoplankton species/genera and nuisance/potentially toxic species in ‘Problem’ and ‘Potential Problem’ areas. Similar measurements of chlorophyll and eutrophication indicator species are also needed to determine Ecological Quality Objectives for eutrophication under the OSPAR Biological Diversity and Ecosystem Strategy. Concern over the inadvertent trans-oceanic transfer of plankton, their resting stages or benthic organisms (non-native species) in the ballast water of ships led to the adoption of the International Maritime Organisation (IMO) Ballast Water Management Convention in 2004. Article 6 of the Convention includes a call to signatory states to promote and facilitate research and monitoring of the effects of ballast water management in waters under their jurisdiction. Ballast water treatment facilities are now available and the UK has started the process to ratify the convention, but this is expected to take up to two years.

The Scottish Government funds a coastal ecosystem monitoring programme undertaken by Marine Scotland where the phytoplankton community is monitored alongside physical and chemical environmental variables at six sites around the Scottish coast; the zooplankton community is also sampled at two of these sites. These time series have been established to generate the information needed to identify and understand long-term changes in the marine ecosystem and they vary in length, with the longest, the Stonehaven time series, in operation since 1997. Some investigative and site specific surveys for phytoplankton have been undertaken by the Environment Agency (EA) and the Countryside Council for Wales (CCW) at Natura 2000 sites however, plankton is not included in the condition monitoring required under the Habitats Directive at these sites by the conservation agencies.

1.5 OSPAR/UKMMAS Assessment framework background

The assessment framework developed by JNCC was first presented to the OSPAR Convention's Biodiversity Committee in February 2007 and has since gained wide support across OSPAR as a tool to guide the development of a strategic approach to biodiversity monitoring. It has been particularly welcomed for its potential benefit in meeting the needs of the Marine Strategy Framework Directive (MSFD).

The framework takes the form of a matrix which relates ecosystem components (e.g. deep-seabed habitats) to the main pressures acting upon them (e.g. physical disturbance to the seabed). The ecosystem components have been correlated with components used by OSPAR and the MSFD. The columns of the matrix are a generic set of pressures on the marine environment, which are based on those used by OSPAR, MSFD and the Water Framework Directive (WFD). A 3-point scale of impact (low, moderate, high) reflects the degree of impact each pressure has on an ecosystem component. Each cell of the matrix has additionally been populated with a set of known indicators[1,] derived from statutory and non-statutory sources, which are used to monitor and assess the state of that ecosystem component. The assessment matrix helps to highlight priorities for indicator development and monitoring programmes, based on the likely degree of each impact on the ecosystem component in question.

Since 2007 this approach has also been introduced to the UK's Marine Monitoring and Assessment Strategy (UKMMAS) and is being further developed by the Healthy and Biologically Diverse Seas Evidence Group (HBDSEG). The intention has been to have parallel development at UK and OSPAR levels which will help ensure similar biodiversity strategies are developed at national and international levels. It is also envisaged that the development process will benefit from wide input across OSPAR Contracting Parties.

The overall goal of the UKMMAS is to implement a single monitoring framework that meets all national and international multiple policy commitments (UKMMAS, 2007). This will identify if there are any significant gaps in the current monitoring effort and aim to minimise costs by consolidating monitoring programmes. To help meet this goal, the assessment matrix has been developed with HBDSEG to provide a useful framework that analyses components of an ecosystem and their relationships to anthropogenic pressures. The framework aims to encompass three key issues: an assessment of the state of the ecosystem

[1] Note: cells of the matrix where impacts have been identified currently contain a number of species and habitats on protected lists (OSPAR, Habitats Directive), which could potentially be used as indicators of the wider status of the ecosystem component which they are listed against. Should this be appropriate, certain aspect of the species or habitat (e.g. its range, extent or condition) would need to be identified to monitor/assess.

and how it is changing over space and time, an assessment of the anthropogenic pressures on the ecosystem and how they are changing over space and time, and an assessment of the management and regulatory mechanisms established to deal with the impacts.

The further development of the assessment framework has been divided into five shorter work packages: 1) assessment of pressures, 2) mapping existing indicators to the framework, 3) review of indicators and identification of gaps, 4) modifying or developing indicators and 5) review of current monitoring programmes. The following work will contribute to work package 3 and will critically review indicators, identify gaps and recommend an overall suite of the most effective indicators for the ecosystem component in question.

1.6 Definitions used within the report and analysis

Definitions of activity, pressure, state change/ecological impact and ecosystem structure and function are used within this report as follows (adapted from the 2008 CP2 methodology[2)]:

Activity – Human social or economic actions or endeavours that may have an effect on the marine environment e.g. fishing, energy production.

Pressure - the mechanism (physical, chemical or biological) through which an activity has an effect on any part of the ecosystem e.g. physical disturbance to the seabed.

State change/ecological impact – physical, chemical or biological condition change at any level of organisation within the system. This change may be due to natural variability or occurs as a consequence of a human pressure e.g. benthic invertebrate mortality.

Ecosystem structure and function – ecosystem level aspects of the marine environment (i.e. structural properties, functional processes or functional surrogate aspects) which are measured to detect change at higher levels of organisation within the system (i.e. changes at ecosystem scales), that is not attributable to any pressure or impact from human activity e.g. natural changes in species' population sizes.

Defined pressures list:

The standard list of pressures against which indicators for this ecosystem component are reviewed is taken from the generic pressures list in the latest version (v11) of the UKMMAS / OSPAR assessment framework. Those pressures which are relevant to the ecosystem component (i.e. those that cause any impact on it) are used within the critical indicators review, gap analysis and this report.

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[2] Robinson, L.A., Rogers, S., & Frid, C.L.J. 2008. *A marine assessment and monitoring framework for application by UKMMAS and OSPAR – Assessment of Pressures and impacts* (Contract No: C-08-0007-0027 for the Joint Nature Conservation Committee). University of Liverpool, Liverpool and Centre for the Environment, Fisheries and Aquaculture Science, Lowestoft.

2 Methods & data sources

2.1 Data sources

Two primary information sources were used to compile the set of plankton indicators included here:

Edwards, M., Reid, P.C., McQuatters-Gollop, A., Helaouet, P., Kirby, R. and Frederiksen, M., 2008. Indicator review for pelagic ecosystems (phytoplankton and zooplankton): Report to the Healthy and Biologically Diverse Sea Evidence Group (HBDSEG). Sir Alister Hardy Foundation for Ocean Science, Plymouth, UK, 22 pp.

This report was produced by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) and provides an overview of MSFD-relevant plankton indicators for the Northeast Atlantic. All indicators provided in the report have been developed by SAHFOS using data from the Continuous Plankton Recorder (CPR) survey to address European and UK policy needs.

Reid, P.C., Edwards, M., McQuatters-Gollop, A., Beaugrand, G., Bresnan, E., Brierley, A., Davidson, K., Delany, J., Eloire, D., Forster, R., Fox, C., Frederiksen, M., Gowen, R., Halliday, N., Hardman-Mountford, N., Hátún, H., Hay, S., Hartman, S., Helaouët, P., Johns, D., Kirby, R., Lampitt, R., Larkin, K., Licandro, P., Lindley, A., Lucas, C., McCollin, T., Miller, P., Milligan, S., Mills, D., Pitois, S., Prior, A., Rees, A., Smyth, T., Smythe-Wright, D., Stevens, D. and Widdicombe, C., in press. Biological indicators of state: the plankton, *Charting Progress 2: An Integrated Assessment of the State of UK Seas*. Defra, London, UK, 69 pp.

Charting Progress 2 was also produced by SAHFOS, but it offers an integrated assessment of plankton monitoring efforts, from the CPR survey as well as other programmes, around the UK. Charting Progress 2 also offers a policy perspective on plankton monitoring in the British Isles.

2.2 Methods

For the purposes of this report, the indicators presented here have been divided into two categories.

CPR indicators: These indicators have been developed by SAHFOS using data from the Continuous Plankton Recorder (CPR) survey (Batten *et al* 2003). The CPR survey is one of the longest ecological time-series in the world (>75 years), with over 2.5 million samples analyzed for more than 500 plankton taxa in the Atlantic, North Sea and North Pacific. The CPR's long time-series and extensive spatial coverage enable the development of statistically significant complex multivariate indicators encompassing many levels of ecosystem state, structure, and functioning. Uniquely, the CPR is able to provide large-scale regional information (as opposed to single station monitoring programmes which can only provide information on plankton dynamics at one single point).This large scale information can aid in interpretation of data from localized monitoring programmes by putting local data into context. The CPR also has sister surveys in the Southern Ocean, Australia and USA. The CPR indicators addressed in this report are:

- Phenology index (CPR) (604)
- Biogeographical shifts/Northward movement index (CPR) (652)
- Spatial and temporal changes in primary production and the marine growing season (CPR) (653)
- Phytoplankton community change (CPR) (654)
- Zooplankton community change (CPR) (655)
- Plankton as indicators of future climate scenarios (CPR) (656)
- Geographical distribution and trends in biodiversity (CPR) (657)
- Invasive species (CPR) (1114)
- Ecosystem stability and non-linear climate change impacts (CPR) (1127)
- Harmful Algal Bloom taxa (CPR) (1128)
- Calcareous taxa change (CPR) (1130)
- Fish and plankton interactions (CPR) (1131)
- Plankton-wildlife interactions (prey fields) (CPR) (1132)

Non-CPR indicators: This group contains plankton indicators which have not been developed from CPR data. They come from various sources and are generally simpler in design than CPR indicators. Due to their limited spatial scale (with the exception of remotely sensed chlorophyll) they are only able to provide information on one (or few) single geographic points. The time-series lengths are generally less than 20 years.

- Phytoplankton chlorophyll from remote sensing (as proxy for biomass) (1137)
- Plankton community change (non-CPR) (1139)
- In situ phytoplankton chlorophyll (as proxy for biomass) (1147)
- Harmful Algal Bloom taxa (non-CPR) (1148)
- Phytoplankton multi-metric toolkit for the Water Framework Directive (1286)

Standard scientific and economic evaluations were conducted for all indicators via the methods detailed in section 3.2.

3 Review of the existing indicators and critical evaluation

3.1 Current indicators summary

Table 1. Indicators summary

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Phenology index (CPR)	Population species community	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive; EU Water Framework Directive Reference: SAHFOS Ecological Status Report, European Environment Agency, DEFRA, Scottish Natural Heritage, IPCC Marine Climate Change Impacts, Edwards, M. & Richardson A.J. (2004). "Impact of climate change on marine pelagic phenology and trophic mismatch." Nature 430(7002): 881-884.	In use (for seven years); used outside UK	North Atlantic	Month of occurrence of peak abundance of 500 plankton taxa recorded by CPR Month of occurrence of peak abundance of plankton taxa groups recorded by CPR	Phenology, repeated seasonal lifecycle events, is a highly sensitive indicator of climate warming. Many plankton taxa are moving forward in their seasonal cycles in response to climate warming. In some cases a shift in seasonal cycles of > six weeks was detected. Temperate pelagic environments are particularly vulnerable to phenological changes caused by climatic warming because the recruitment success of higher trophic levels is dependent on synchronisation with pulsed planktonic production. Furthermore in the marine environment the response to regional climate warming is varied between different functional groups and trophic levels, leading to mismatch in timing between trophic levels. For example, while the spring bloom has remained relatively stable in seasonal timing over five decades (due to light limitation and photoperiod rather than temperature dictating seasonality) many zooplankton organisms including fish larvae have moved rapidly forward in their seasonal cycles.	Phenology indices can be developed for each CPR taxon (approx 500) and group of taxa (such as echinoderm larvae, diatoms, dinoflagellates, meroplankton, etc). This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton - offshore Zooplankton - coastal (WFD) Zooplankton - offshore Fish	fish larvae		Temperature changes - regional/national		Trophic mismatch	Community structure		Change in distribution of plankton taxa Change in ecosystem structure and functioning Potential impacts on higher trophic levels change in phenology of plankton taxa trophic mismatch	Eco system Structure/Functi on

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Biogeographical shifts/Northward movement index (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: EU Common Fisheries Policy; EU Marine Strategy Directive; EU Water Framework Directive Reference: SAHFOS Ecological Status Report, European Environment Agency, DEFRA, IPCC Marine Climate Change Impacts, Beaugrand, G., P. C. Reid, *et al.* (2002). "Reorganization of North Atlantic marine copepod biodiversity and climate." Science 296(5573): 1692-1694	in use for 7 years, used outside the uk	North Atlantic	Abundance of 36 copepod taxa recorded by CPR Distribution of 36 copepod taxa recorded by CPR Diversity of 36 copepod taxa recorded by CPR	During the last fifty years there has been a northerly movement of warmer water plankton by 10° latitude in the north-east Atlantic and a similar retreat of colder water plankton to the north. This geographical movement is much more pronounced than any documented terrestrial study, mainly due to advective processes and in particular the shelf-edge current running north along the northern European continental shelf. The rapid movement of plankton northward is only seen along the continental shelf, where deeper water is warming much more rapidly. Further along the shelf, plankton are upwelled from this deeper water to make an appearance in the surface plankton community. Hence the plankton have moved 10° latitude northward via mainly deep water advective processes not seen in the movement of surface isotherms. This change in distribution and biodiversity could have impacts on higher trophic levels and similar biogeographical changes in fish have been observed.	This indicator is well developed and currently used. Similar indicators measuring biogeographical shifts in diversity could be developed for other plankton groups and assemblages (such as all zooplankton, phytoplankton, *Ceratium* spp., dinoflagellates, etc). This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto plankton - coastal (WFD) Phyto plankton - offshore Zooplankton - coastal (WFD) Zooplankton - offshore			Temperature changes - regional/national Water flow changes – regional/national	Primary production Secondary production Trophic complexity		Range and distribution (species or habitats) Species diversity Species richness Community Structure Habitat extent		Change in distribution of plankton taxa Change in ecosystem structure and functioning Trophic impacts	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Spatial and temporal changes in primary production and the marine growing season (CPR)	Community habitat/ biotope	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; ; EU Marine Strategy Directive; EU Water Framework Directive Reference: SAHFOS Ecological Status Report, European Environment Agency, DEFRA, Scottish Natural Heritage, Edwards, M., Reid, P.C. *et al.* (2001). "Long-term and regional variability of phytoplankton biomass in the Northeast Atlantic (1960-1995). " ICES Journal of Marine Science **58(1)**: 39-49.	In use (for 7 years); used outside UK	North Atlantic	Phytoplankton Colour Index recorded by the CPR	Phytoplankton as algal primary producers, are the main structural components of marine ecosystems. Their seasonal and interannual abundance is tightly coupled to the physical and chemical environment and may integrate signals of climate change. Seasonal variability is also impacted by grazing from the zooplankton. Inter- and intra-annual changes in phytoplankton biomass have occurred at different magnitudes in different regions of the north Atlantic. Changes in biomass of the phytoplankton impact carbon cycling, and trophic interactions and could lead to changes in other trophic levels. Changes in the annual phytoplankton biomass and the extension of the seasonal growth-period already appear to be having considerable impacts on the overall biological production, food-web structures and marine trophic levels (e.g. fisheries and benthos).	This is a key indicator of change in phytoplankton biomass. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto plankton - coastal (WFD) Phyto plankton - offshore		Waste disposal - liquid - industrial & agri-cultural liquid discharges Waste disposal - liquid - sewerage (human & agri-cultural)	Atmospheric climate change Temperature changes - regional/national Water clarity changes Nitrogen & phosphorus enrichment Organic enrichment	Primary production Export of detritus and dissolved organic material		Biomass Habitat extent		Extended phytoplankton growing season Eutrophication effects (hypoxia, etc) Trophic impacts Spatial change in phytoplankton biomass interannual change in phytoplankton biomass Intraannual change in phytoplankton biomass	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Phytoplankton community change (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; ; EU Marine Strategy Directive; EU Water Framework Directive Reference: SAHFOS Ecological Status Report, European Environment Agency, DEFRA, Scottish Natural Heritage, McQuatters-Gollop, A., Raitsos, D.E. *et al*. 2007. "Spatial patterns of diatoms and dinoflagellate seasonal cycles in the North - East Atlantic Ocean." Marine Ecology Progress Series **339**: 301-306.	In use (for 5 years); used outside UK	North Atlantic	Total diatom abundance from the CPR Abundance of Harmful Algal Bloom species form the CPR Total dinoflagellate abundance from the CPR Total dinoflagellate distribution from the CPR Total diatom distribution from the CPR Abundance of approximately 300 phytoplankton species from the CPR Distribution of approximately 300 phytoplankton species from the CPR Distribution of HAB species from the CPR	Phytoplankton are the main structural components of marine ecosystems. Their seasonal and interannual composition and abundance is tightly coupled to the physical and chemical environment and may integrate signals of climate change. Since the 1980s some regions of the North Atlantic have experienced an increase in dinoflagellate abundance, while the abundance of diatoms has decreased. This pattern is particularly prevalent in the North Sea where the increasing dominance of dinoflagellates has resulted in increased abundance of some HAB species. In the North Sea, these changes, along with an increase in winter diatom abundance, have been linked to the marked increase in SST occurring in the late 1980s. Changes in phyto community composition and structure could have severe consequences on higher trophic levels as not all taxa/groups are trophically useful to higher organisms. Some of these changes in phyto community composition are thought to be linked to eutrophication.	This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton - offshore		Waste disposal - liquid - industrial & agri-cultural liquid discharges Waste disposal - liquid - sewerage (human & agri-cultural)	Atmospheric climate change pH changes Temperature changes - regional/national Salinity changes - regional/ national Water flow changes (tidal & ocean currents) - regional/national Nitrogen & phosphorus enrichment Organic enrichment Introduction of microbial pathogens Introduction or spread of non-indigenous species & translocations	Primary production Trophic complexity Gas exchange		Range and distribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Changes in distribution, seasonality, and/or abundance of the above listed ecosystem components Trophic impacts	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Zooplankton community change (CPR)	Population species community	Source: SAHFOS Policy Driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strat Direct Ref: SAHFOS Eco Status Report, European Environment Agency, DEFRA, Scottish Natural Heritage, ICES Status Reports, UK Public Service Agreement, Pitois, S.G. & Fox, C.J. 2006. "Long-term changes in zooplankton biomass concentration and mean size over the Northwest European shelf inferred from Continuous Plankton Recorder data. "ICES Journal of Marine Science **63(5)**, 785-798.	In use (for 5 years); used outside UK	North Atlantic	*Calanus helgolandicus* abundance *Calanus finmarchicus* abundance *Calanus helgolandicus/ Calanus finmarchicus* ratio zooplankton biomass holoplankton abundance meroplankton abundance Copepod distribution Meroplankton distribution Holoplankton distribution Total zooplankton distribution *Calanus finmarchicus* distribution *Calanus helgolandicus* distribution Copepod abundance (275 taxa) measured by CPR Abundance of all (approximately 400) zooplankton taxa recorded by CPR Distribution of all (approximately 400) zooplankton taxa recorded by CPR	Since 1960s, notable decline in copepods around N Atlantic. Copepods trophically important component of zooplankton community & decrease in abundance may have consequences on higher trophic levels. In late1980s zooplankton comm shifted from coldboreal community to warm temperate community, a change accompanied by decreased zooplankton biomass. Other changes in zooplankton comm included influx of ocean species, increased warm water zooplankton species, shift from holoplankton to meroplankton dominance. Warming climate has impacted geographic distribution of two key Calanus species in N Atlantic. The abundance of *C. finmarchicus*, coldwater copepod, has decreased while abundance of *C. helgolandicus*, a warm water species, increased. This is observable as north-progressing shift in the proportion of these two species, with *C. hel* replacing *C. fin*. Because *C. fin* has higher energy content, this has had impact on growth, recruitment and survival of other trophic levels such as seabirds and fish.	This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Zooplankton - coastal (WFD) Zooplankton - offshore	Calanus fin-marchicus Calanus helgo-landicus Holo-plankton Mero-plankton Copepod taxa		Atmospheric climate change pH changes Temperature changes - regional/national Salinity changes - regional/ national Water flow changes (tidal & ocean currents) - regional/national Introduction of microbial pathogens Introduction or spread of non-indigenous species and translocations	Secondary production		Range and distiribution (species or habitats) Species diversity Species richness Community structure		Impacts on higher trophic levels Change in zooplankton distribution, abundance and composition Change in zooplankton community structure Change in abundance and distribution of holoplankton Change in abundance and distribution of meroplankton Change in abundance and distribution of decapod larvae	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Plankton as indicators of future climate scenarios (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy Reference: Based on IPCC climate change scenarios, Helaouët, P. and G. Beaugrand (in press). "Physiology, ecological niches and species distribution." Ecosystems in press.	Indicator developed for some species, could be applied to others	North Atlantic	*Calanus finmarchicus* abundance *Calanus helgolandicus* abundance Calanus finmarchicus egg production rate (EPR) *Calanus helgolandicus* egg production rate (EPR) Calanus finmarchicus distribution *Calanus helgolandicus* distribution	Egg production rate is linked to SST and can be used to predict spatial distribution of species. The species *C. finmarchicus* is herbivorous copepod and key structural species which plays a crucial role in transferring primary production to higher trophic levels in the food web. *C. finmarchicus* is a key element for the larval survival of some commercial fish such as the Atlantic cod, herring and mackerel. Assessing future changes in the spatial distribution of the species is therefore a prerequisite to anticipate ecosystem changes and future potential impacts on living marine resources. Spatial distribution of abundance of *C. finmarchicus* is highly correlated at decadal scale with its EPR. When EPR is modelled as function of SST according to IPCC scenarios, results indicate that in the North Sea, the species could disappear by the end of the 21st century.	This indicator has been developed based on ecological niche modelling concept. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Zooplankton - coastal (WFD) Zooplankton - offshore	Calanus fin-marchicus		Temperature changes - regional/national	Secondary production Trophic complexity		Range and distiribution (species or habitats) Population size Community structure Habitat extent		Trophic impacts Changes in distribution, seasonality, and/or abundance of the above listed ecosystem components	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Geographical distribution and trends in biodiversity (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: UN Convention on Biological Diversity; EU Habitats Directive ; FAO Reykjavik Declaration; EU Marine Strategy Directive, EU Water Framework Directive Reference: Beaugrand, G., Ibanez, F., Lindley, J.A. and Reid, P.C. 2002. Diversity of calanoid copepods in the North Atlantic and adjacent seas: species associations and biogeography. Marine Ecology Progress Series, **232**: 179-195.	Indicator being developed from CPR data	North Atlantic	Abundance of all (approximately 500) plankton taxa recorded by CPR Distribution of all (approximately 500) plankton taxa recorded by CPR	SST and an increase in warming over the last few decades have been followed by increased diversity. In particular, increases in diversity are seen when previously low diversity systems like Arctic and cold-boreal provinces undergo prolonged warming events. The overall diversity patterns of pelagic organisms, peaking between 20° to 30° north or south, follow temperature gradients in the world's oceans. Similarly, phytoplankton show a relationship between SST and diversity which is linked to the phytoplankton community having a higher diversity but an overall smaller size-fraction and a more complex foodweb structure (i.e. microbial-based versus diatom based production) in warmer more stratified environments. Climate warming will therefore increase planktonic diversity throughout the cooler regions of the world's oceans as temperature isotherms shift poleward.	This indicator is actually an aggregation of many parameters measured by the CPR and can be broken down to look at changes in diversity of certain groups of taxa or species (such as just copepods, just diatoms, Ceratium spp., etc). Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton – offshore Zooplankton - coastal (WFD) Zooplankton - offshore			Atmospheric climate change Temperature changes - regional/national Water flow changes (tidal & ocean currents) - regional/national	Primary production Secondary production Trophic complexity Export of detritus and dissolved organic material		Range and distiribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Spatial change in plankton biodiversity Impacts on higher trophic levels Change in trophic complexity and interactions	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Ecosystem stability and non-linear climate change impacts (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: FAO Reykjavik Declaration For adaptive management purposes, it would be an advantage if we could anticipate non-linear abrupt ecosystem shifts. Reference: Beaugrand, G., Luczak, C., Edwards, M. 2009. Rapid biogeographical plankton shifts in the North Atlantic Ocean. Global Change Biology, in press.	Indicator in development by SAHFOS.	North Atlantic	Abundance of all (approximately 500) plankton taxa recorded by CPR Distribution of all (approximately 500) plankton taxa recorded by CPR	The concept of ecosystem stability refers to resistance to disturbance or resilience (the rate of recovery after disturbance) and constancy (degree of temporal stability). In this case we are concerned with measuring the temporal stability of ecosystems which is important because climate change does not manifest itself in marine ecosystems as a linear process but can materialise as step-wise shifts also known as ‘regime shifts’. This non-linear response can be very rapid, for example, a shift in an ecosystem, which has been stable for many decades, to a new system can happen within a few years. Recently, it has been speculated that the variability of a system’s behaviour changes in advance of regime shifts (measured by a system’s rising variance). For adaptive management purposes, it would be an advantage if we could anticipate non-linear abrupt ecosystem shifts.	This indicator is a measure of ecosystem variance and is therefore requires a significant amount of data (this data is all provided by the CPR). It is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto plankton – offshore Zooplankton - coastal (WFD) Zooplankton - offshore			Atmospheric climate change Temperature changes - regional/national	Primary production Secondary production Trophic complexity Export of detritus and dissolved organic material		Range and distribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Change in distribution of plankton taxa Change in ecosystem structure and functioning Change in phytoplankton distribution and composition Change in zooplankton distribution and composition Change in trophic complexity Change in ecosystem stability Change in ecosystem resilience Non-linear ecosystem change	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Harmful Algal Bloom taxa (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: UN Convention on Biological Diversity; EU Marine Strategy Directive; EU Shellfish Hygiene Regulations, EU Water Framework Directive Reference: Edwards, M. & Johns, D.G. *et al*. 2006. "Regional climate change and harmful algal blooms in the northeast Atlantic." Limnology and Oceanography **51(2)**, 820-829.	Can be developed from CPR data	North Atlantic	Frequency of occurrence of HAB species from CPR Distribution of HAB species from the CPR Abundance of HAB species from CPR (approx 10 spp) Abundance and distribution of dinoflagellate species (approx 100) from CPR	Increased abundance of HAB species has been linked with hydroclimatic conditions and can cause hypoxia and toxicity in fish. Increased HAB frequency may affect other trophic levels. Toxic HAB species can affect shellfish and potentially humans.	This indicator has been developed based on ecological niche modelling concept. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton - offshore	HAB species		Atmospheric climate change Temperature changes - regional/national	Export of detritus and dissolved organic material		Range and distribution (species or habitats) Population size Biomass Community structure Oxygen level	Poisoning of fish, shellfish, loss of animals due to hypoxia	Occurrence of HABs Change in abundance and distribution of HAB spp. Shellfish toxicity Toxicity in humans due to consumption of contaminated seafood Change in phytoplankton community composition	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Calcareous taxa change (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: EU Marine Strategy Directive; EU Water Framework Directive Reference: Raitsos, D.E., Lavender, S.J., Pradhan, Y., Tyrrell, T., Reid, P.C. & Edwards, M. 2006. Coccolithophore bloom size variation in response to the regional environment of the subarctic North Atlantic. Limnology and Oceanography, **51**: 2122-2130.	In development from CPR data	North Atlantic	Abundance of calcareous taxa collected by the CPR (approx 6 taxa) Distribution of calcareous taxa collected by the CPR (approx 6 taxa)	While temperature, light and nutrients are probably the most important physical variables structuring marine ecosystems, the pelagic realm will also have to contend with the impact of anthropogenic CO_2 directly influencing the pH of the oceans. Evidence collected and modelled to date indicates that rising CO_2 has led to chemical changes in the ocean which has led to the oceans becoming more acidic. Ocean acidification has the potential to affect the process of calcification and therefore certain planktonic organisms (e.g. coccolithophores, foraminifera, pelagic molluscs) may be particularly vulnerable to future CO_2 emissions. Potential chemical changes to the oceans and their affect on the biology of the oceans could further reduce the ocean's ability to absorb additional CO_2 from the atmosphere which in turn could affect the rate and scale of global warming. Change in plankton community composition could lead to change in ecosystem structure and functioning.	This indicator is actually an aggregation of several parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton – offshore Zooplankton - coastal (WFD) Zooplankton - offshore	Calcareous plankton		pH changes	Gas exchange	CO_2 absorption	Range and distribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Change in ecosystem structure and functioning Change in phytoplankton distribution and composition Change in zooplankton distribution and composition Changes in plankton biodiversity Change in trophic interactions	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Fish and plankton interactions (CPR)	Population species community	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive Reference: Beaugrand, G., Brander, K.M., Lindley, J.A., Souissi, S. & Reid, P.C. 2003. Plankton effect on cod recruitment in the North Sea. Nature, **426**: 661-664.	Can be developed (e.g. plankton biomass in space and time and carrying capacity of ecosystems).	North Atlantic	Abundance of fish larvae (appx 50 taxa) Distribution of fish larvae (appx 50 taxa) Abundance of all decapod taxa recorded by the CPR Distribution of all decapod taxa recorded by the CPR Jellyfish occurrence on CPR samples Jellyfish distribution on CPR samples Distribution of all (approximately 400) zooplankton taxa recorded by CPR Abundance of approximately 400 zooplankton taxa from the CPR	The abundance of fish top predators in the North Atlantic is affected by temperature both directly and indirectly through effects on zooplankton prey. Links between climate, plankton and fish can provide information about changes in trophic interactions and insight into climate effects on fisheries. Overfishing is also known to promote jellyfish proliferation, which feed on fish eggs, fish larvae and zooplankton, and this has become an indicator of marine ecosystem degeneration. The CPR's >50 year time-series of fish larvae abundance and distribution, which includes information on approximately 50 fish taxa, delivers information on changes in fish populations.	This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton – offshore Zooplankton - coastal (WFD) Zooplankton - offshore Fish	Fish larvae Decapod larvae Jellyfish	Fishing - benthic trawling Fishing - hydraulic dredging Fishing - pelagic trawling Fishing - potting/ creeling Fishing – recrea-tional Fishing - set netting Fishing - shellfish harvesting	Atmospheric climate change Temperature changes - regional/national Introduction or spread of non-indigenous species & translocations Removal of target species Removal of non-target species	Trophic complexity		Range and distiribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Change in distribution of plankton taxa Change in abundance and distribution of fish larvae Change in ecosystem structure and functioning Change in abundance and distribution of decapod larvae Change in trophic complexity and interactions	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Plankton-wildlife interactions (prey fields) (CPR)	Population species community habitat/ biotope	Source: SAHFOS Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive Reference: Frederiksen, M., Edwards, M., Richardson, A.J., Halliday, N.C. & Wanless, S. 2006. From plankton to top predators: bottom-up control of a marine food web across four trophic levels. Journal of Animal Ecology, **75**: 1259-1268. Witt, M.J., Broderick, A.C., Johns, D.J., Martin, C., Penrose, R., Hoogmoed, M.S. & Godley, B.J. 2007. Prey landscapes help identify potential foraging habitats for leatherback turtles in the NE Atlantic. Marine Ecology Progress Series, **337**: 231-244.	Can be developed at SAHFOS (e.g. spatial foraging fields and long-term carrying capacity)	North Atlantic	Abundance of sandeel (Ammodytes marinus) Abundance of jellyfish Distribution of jellyfish Distribution of sandeel (Ammodytes marinus) Distribution of copepod taxa recorded by CPR Abundance of copepod taxa recorded by CPR	Most megafauna prey has planktonic life stages such as the lesser sandeel (Ammodytes marinus) which is a key food source for many seabirds, gelatinous plankton which is consumed by sea turtles and calanoid copepods which are a key food source for basking sharks. Changes in climate impact abundance and distribution of the planktonic stages of prey for wildlife taxa which may have negative impacts on wildlife; understanding relationships between climate, plankton and marine wildlife may enable more effective conservation measures.	This indicator is actually an aggregation of many parameters measured by the CPR. Because the CPR has such an extensive spatio-temporal time-series, this indicator can be used at multiple spatial and temporal scales. The CPR survey is one of the few monitoring programmes to consistently and extensively monitor both offshore and near coastal waters in the North Atlantic, which is a requirement of the MSFD.	Phyto-plankton - coastal (WFD) Phyto-plankton - offshore Zooplankton - coastal (WFD) Zooplankton - offshore Fish - sharks, skates & rays Turtles Seabirds	Copepod taxa Fish larvae		Temperature changes - regional/national	Trophic complexity		Range and distiribution (species or habitats) Population size Species diversity Species richness Biomass Community structure Habitat extent		Change in abundance and distribution of sea turtles Change in abundance and distribution of basking sharks Change in abundance and distribution of seabirds Change in abundance and distribution of copepods Change in abundance and distribution of fish larvae	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Phytoplankton chlorophyll from remote sensing (as proxy for biomass)	Community	Source: SeaWIFS, MERIS, etc Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive	In use for 10 years (USA's SeaWifs - but satellite is expected to quit transmitting soon). MERIS in use since 2003 (European satellite).	North Atlantic, but works less well in high latitudes and during cloudy periods. Not useful in coastal waters due to sus-pended sedi-ments	Chlorophyll (mg/m3) from satellites (MERIS, Seawifs, AQUA-MODIS, etc)	Is an indicator of phytoplankton biomass in surface waters. Can provide some information on productivity, but satellites have many data limitations (see comments below).	Ocean colour satellites work less well in high latitudes and during cloudy periods. Not useful in coastal waters due to suspended sediments. Data is noisy and requires significant processing before it can be used. Only a short time-series is available.	Phyto-plankton - offshore	Phyto-plankton biomass		Temperature changes - regional/national	Primary production		Biomass		Increased phytoplankton biomass Change in phytoplankton growing season	State change/Impact

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Plankton community change (non-CPR)	Population species community	Source: Stonehaven, L4 (PML), DovePolicy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive, EU Water Framework Directive	In use for various amounts of time depending on length of time-series.	Most in situ datasets measure data in one or few loc-ations (West-ern Channel Observ-atory, Stone-haven, Dove) which are usually coastal so only provide infor-mation on local change.	Plankton abundance Plankton biomass	Plankton are key structural components of marine ecosystems. Their seasonal and interannual composition and abundance is tightly coupled to the physical and chemical environment and may integrate signals of climate change. Changes in the plankton can affect higher trophic levels.	Most monitoring programmes only sample at one (or few), usually coastal, sites so changes only reflect the local plankton community and little information can be provided on changes in distribution. Most programmes in the UK are <20 years in length. Plankton abundance and biomass data by themselves do not deliver as much information as collective indicators, particularly those developed based on long time-series.	Phyto-plankton - coastal (WFD) Zooplankton - coastal (WFD)			Temperature changes - local Salinity changes - localWater flow changes (inc. tidal currents) - local Water clarity changes Nitrogen & phosphorus enrichment Organic enrichment Introduction of microbial pathogens Introduction or spread of non-indigenous species & translocations	Primary production Secondary production		Population size Species richness Biomass Community structure		Changes in abundance and biomass of plankton	State change/ Impact

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
In situ phytoplankton chlorophyll (as proxy for biomass)	Community habitat/ biotope	Cefas (Smartbouy) Policy driver: FAO Reykjavik Declaration; EU Common Fisheries Policy; EU Marine Strategy Directive; EU Water Framework Directive	Chlorophyll is commonly used as a proxy for phytoplankton biomass. Most time-series in UK waters (e.g. Cefas SmartBouy, etc) are less than 20 years old.	Primarily single or few stations which provide information on local variability in chlorophyll.	Chlorophyll concentration	Is an indicator of phytoplankton biomass. Can provide some information on productivity but not change in community structure.	Phytoplankton biomass is a key indicator for marine ecosystems. However, most in situ datasets only offer local information and have short time-series.	Phyto-plankton - coastal (WFD)	Phyto-plankton biomass		Temperature changes - regional/national Nitrogen and phosphorous enrichment	Primary production		Biomass		Increased phytoplankton biomass Change in growing season	State change/ Impact
Harmful Algal Bloom taxa (non-CPR)	Population species community	Source: FRS Policy driver: UN Convention on Biological Diversity; EU Marine Strategy Directive; EU Shellfish Hygiene Regulations; EU Water Framework Directive	Most HAB time-series in the British Isles are less than 10 years long.	Samples taken at few locations per monitoring programme which are mostly coastal.	Abundance of HAB species	Increased abundance of HAB species has been linked with hydroclimatic conditions and can cause hypoxia and toxicity in fish. Increased HAB frequency may affect other trophic levels. Toxic HAB species can affect shellfish and potentially humans.	Most non-CPR monitoring programmes only collect samples at few sites which are mostly coastal.	Phyto-plankton - coastal (WFD)	HAB spp abundance		Atmospheric climate change Temperature changes - regional/national			Community structure Oxygen level	Poisoning of fish, shellfish, loss of animals due to hypoxia	Occurrence of HABs Shellfish toxicity Toxicity in humans due to consumption of contaminated seafood Change in abundance of HAB species	Ecosystem Structure/ Function

Indicator Name	Levels	Reference Sources	Status	Geographic Coverage	Parameters	Description	Comments	Ecosystem Components	Ecosystem Component Details	Activities	Pressures	Ecosystem Functions	Custom Ecosystem Functions	Ecosystem Structures	Custom Ecosystem Structures	State Changes Impacts	Indicator Type
Phytoplankton multi-metric toolkit for the Water Framework Directive	Community	Source: WFDUKTAG Policy driver: Water Framework Directive Reference: Devlin, M., Best, M., Coates, D., Bresnan, E., Boyle, S., Park, R., Silke, J., Cusack, C. & Skeats, J. 2007. Establishing boundary classes for the classification of UK marine waters using phytoplankton communities. Marine Pollution Bulletin **55**: 91–103	This method has been developed for UK coastal waters, and three phytoplankton tools are currently in use.	Can be applied to coastal waters	Phytoplankton biomass during the growing season Bloom frequency in respect of chlorophyll, individual taxa, total taxa and Phaeocystis. Seasonal succession of phytoplankton functional groups.	This indicator is a system for monitoring, assessing and classifying coastal waters based on phytoplankotn for the WFD. It only addresses the pressure of nutrient enrichment.	Only for costal waters, still awaiting information on if this indicator is currently in use and where. It is debatable whether Phaeocystis responds to nutrients or is climatically driven (Edwards *et al* 2006).	Phyto-plankton - coastal (WFD)		Waste disposal - liquid - industrial & agri-cultural liquid discharges Waste disposal - liquid - sewerage (human & agri-cultural)	Nitrogen & phosphorus enrichment Organic enrichment Temperature changes - local	Primary production Export of detritus and dissolved organic material		Population size Biomass Community structure		Increased phytoplankton biomass Increased phaeocystis Change in succession of phytoplankton functional groups	State change/ Impact

3.2 Evaluation of the effectiveness of indicators against standard scientific and economic criteria

3.2.1 Criteria used to evaluate indicators

In order to achieve a consistent critical appraisal of all indicators, the indicators for this ecosystem component have been reviewed and scored against the following set of criteria. These criteria have been built into the online indicators database application and the data has been stored electronically.

A. Scientific criteria:

The criteria to assess the scientific 'effectiveness' of indicators are based on the ICES EcoQO criteria for 'good' indicators. The scoring system is based on that employed within the Netherlands assessment of indicators for GES (2008)[3]. A confidence score of 3 – High, 2 – Medium, 1 – Low is assigned for each question. A comment is given on the reasons for any low confidence ratings in the comment box provided within the database. All efforts have been made to seek the necessary information to answer criteria questions to a confidence level of medium or high.

1. Sensitivity: Does the indicator allow detection of any type of change against background variation or noise:

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

2. Accuracy: Is the indicator measured with a low error rate:

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

If the indicator scores 1 or 2 for question 1 or 2, conclude that it is ineffective and do not continue with the evaluation –the indicator will still be stored within the database as considered but will be flagged as 'insensitive, no further evaluation required'

3. Specificity: Does the indicator respond primarily to a particular human pressure, with low responsiveness to other causes of change:

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

4. Performance:

For questions 4a-f, if a score of 1 is given, please consider if the indicator is of real use. Please justify (within the report) continuing if a score of 1 is given.

The following criteria are arranged with descending importance:

[3] Langenberg. V.T. & Troost T.A. (2008). Overview of indicators for Good Environmental Status, National evaluation of the Netherlands.

a) Simplicity: Is the indicator easily measured?

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

b) Responsiveness: Is the indicator able to act as an early warning signal?

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

c) Spatial applicability: Is the indicator measurable over a large proportion of the geographical to which the indicator metric it to apply to e.g. if the indicator is used at a UK level, is it possible to measure the required parameter(s) across this entire range or is it localised to one small scale area?

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

d) Management link: Is the indicator tightly linked to an activity which can be managed to reduce its negative effects on the indicator i.e. are the quantitative trends in cause and effect of change well known?

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

e) Validity: Is the indicator based on an existing body or time series of data (either continuous or interrupted) to allow a realistic setting of objectives:

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

f) Relatively easy to understand by non-scientists and those who will decide on their use:

Score	3	2	1	Confidence
Options	Usually	Occasionally	Rarely	

Thresholds for scientifically poor, moderate and good indicators:

Combine indicator evaluation scores for:

1. Sensitivity
2. Accuracy
3. Specificity
4. Performance

Evaluation Score	Indicator 'Effectiveness' Category
22-27	**Good**
16-21	**Moderate**
9-15 OR not all questions completed due to expert judgement not to continue	Poor

Further economic evaluation required - see section B below

B. Economic criteria:

Having identified the most scientifically robust indicators using the above stated criteria, a further economic evaluation of those most effective indicators (i.e. those falling in the good or moderate categories) is carried out using the criteria stated below.

1. Platform requirements

Score	4	3	2	1
Options	None e.g. intertidal sampling	Limited e.g. coastal vessel	Moderate e.g. Ocean going vessel or light aircraft	Large e.g. satellite or several ocean going vessels

2. Equipment requirements for sample collection

Score	4	3	2	1
Options	Simple equipment requirements e.g. counting number of organisms	Limited equipment requirements e.g. using quadrats on the shoreline	Moderate equipment requirements e.g. measuring physiological parameters	Highly complex method e.g. technical equipment operation

3. Amount of staff time required to plan collection of a single sample

Score	4	3	2	1
Options	Hours	Days	Weeks	Months

4. Amount of staff time required to collect a single sample

Score	4	3	2	1
Options	Hours	Days	Weeks	Months

5. Amount of staff time required to process a single sample

Score	4	3	2	1
Options	Hours	Days	Weeks	Months

6. Amount of staff time required to analyse & interpret a single sample

Score	**4**	**3**	**2**	**1**
Options	Hours	Days	Weeks	Months

7. Amount of staff time required to QA / QC data from a single sample

Score	**4**	**3**	**2**	**1**
Options	Hours	Days	Weeks	Months

Thresholds for economically poor, moderate and good indicators:

Evaluation Score	**Indicator 'Effectiveness' Category**
24-28	**Good**
19-23	**Moderate**
7-18	Poor

Those indicators which fall within the 'Good' or 'Moderate' economic category will then be tagged within the summary database as 'Recommended' indicators. Indicators can also be 'recommended' via expert judgement even if the evaluation of the indicator does not score well enough to be automatically recommended. This judgement will be justified within the report text.

3.2.2 Additional information on the critical analysis of indicators

None required. All relevant information is captured within the database and tables supporting this report.

4 Gap analysis – Review of indicators against relevant pressures and important aspects of ecosystem structure and function

4.1 Review of indicators against pressures and identification of gaps

Please see the associated spreadsheet gap analysis: FINAL Plankton Pressures.xls

This gap matrix was produced as a tool to aid authors in identifying significant gaps in current or potential indicators i.e. where important pressures on the ecosystem component have no suitable indicators associated with them. All recommended indicators have been prefixed with [R] and the cells containing them are coloured green.

It should be noted that if a single indicator is associated with more than one pressure within the pressures gap matrix, it may mean that this indicator responds to a range of pressures or the synergistic effects of a combination of pressures. Such an indicator would not necessarily be able to detect change which can be attributed to each individual pressure.

All plankton-relevant pressures are monitored by the indicators given in the tables listed in section 5.1. Indicators derived from the CPR survey address all relevant ecosystem structures and functions for waters around the UK. The CPR indicators are uniquely able to provide information on both temporal and spatial changes in pressures and when used as a suite are able to provide a robust assessment of each relevant pressure. The non-CPR indicators are less complex and well developed than the CPR indicators, but the sampling may occur more frequently, albeit at only a few near-coast stations and with shorter time-series. At a local scale some pressures may be monitored with non-CPR indicators, but the data provided is best interpreted with reference to wider geographic coverage and change in the open ocean as monitored by the CPR.

Climate is the primary pressure behind change in plankton around the UK and in the North Atlantic. The relevant regional climatic pressures (temperature change, pH change, atmospheric climate change, salinity change, and water flow change) are all associated with CPR indicators as the CPR survey regularly samples both open ocean and many nearer-shore waters (as required by the MSFD). Non-CPR indicators are mainly associated with localized hydrological changes (temperature change, salinity change, water flow change), but due to their sampling frequency can often offer higher temporal resolution than can CPR indicators. Locally-observed changes identified by non-CPR indicators are best interpreted against the regional-scale context provided by the CPR; together these two classes of indicators can provide the most comprehensive overview of plankton change at local and regional scales. An example is water clarity, which has been observed to increase in the North Sea at the regional-sea scale with impact on the North Sea phytoplankton community (as monitored by both CPR and non-CPR indicators). Pollutant pressures, such as nutrient and organic enrichment, are linked to both non-CPR indicators (measuring change in phytoplankton in a local, often coastal, area) and CPR indicators (provide regional context against which to interpret locally-observed changes). The introduction of microbial pathogens acts as a pressure on the zooplankton and phytoplankton communities by affecting the health of these organisms and therefore influencing species composition. The introduction or spread of non-indigenous species and translocations is best monitored through the CPR indicator for invasive species – in order to recognize a ‘new’ species a comprehensive inventory of regularly occurring native species is needed. The CPR indicator 'fish and plankton interactions' provides information on regional climate change pressures, as well as fishing pressure (target and non-target species) through change in abundance, species and distribution of fish larvae. Fish larvae from the Continuous Plankton Recorder, in collaboration with Cefas and Defra, are currently being reanalysed to provide more detailed spatial and temporal data on changes in key fish species around the British Isles. This information may help with the sustainable management of fisheries, particularly when linked with changes in climate and fishing pressure.

Additionally, the CPR indicator 'plankton-wildlife interactions' provides information on the effects of regional climate pressures on higher trophic levels such as sharks, turtles and seabirds. The CPR indicator 'ecosystem stability and non-linear climate change impacts' is in further development to enable the prediction of climate-driven ecosystem regime shifts and will be an invaluable tool for ecosystem managers.

4.2 Review of indicators against ecosystem structure & function aspects and identification of gaps

Please see the associated spreadsheet gap analysis: FINAL Plankton Ecosystem Structure_Function.xls

All plankton-relevant biotic ecosystem structures and ecological ecosystem functions are currently being or are able to be monitored by the indicators given in the tables listed in section 5.1. Indicators derived from the CPR survey address all relevant ecosystem structures and functions for both open ocean and many near-shore waters around the UK. In many cases CPR indicators have been developed specifically to address policy needs and due to the long time-series available, extensive spatial coverage and large (>500) number of parameters measured offer a more comprehensive picture of plankton dynamics than single station near-shore monitoring programmes. The CPR indicators are uniquely able to provide information on both temporal and spatial changes in ecosystem structure and function and when used as a suite are able to provide a robust assessment of each relevant aspect of ecosystem structure and function. The non-CPR indicators are less complex and well developed than the CPR indicators, and thus the information they can provide is more limited. However, some non-CPR programmes collect samples more frequently, albeit at only a few near-coast stations and with shorter time-series. At a local scale some ecosystem structure and function components can be monitored with non-CPR indicators, but the data provided is best interpreted with reference to wider geographic coverage and change in the open ocean as monitored by the CPR. However it should be noted that these coastal time series are increasing in length with every year. Also, there are areas in the West coast of Scotland where CPR coverage is poor and the CPR is not appropriate for shallow coastal sites.

Functional aspects addressed by plankton indicators:

CO_2 absorption and gas exchange: Ocean acidification has the potential to affect the process of calcification and therefore certain planktonic organisms (e.g. coccolithophores, foraminifera, pelagic molluscs) may be particularly vulnerable to future CO_2 emissions. Apart from climate warming, potential chemical changes to the oceans and their affect on the biology of the oceans could further reduce the ocean's ability to absorb additional CO_2 from the atmosphere which in turn could affect the rate and scale of global warming and have important impacts on ecosystem functioning. The CPR survey is providing a critical baseline indicator (both in space and time) of change in calcareous plankton taxa, through the monitoring of phytoplankton and zooplankton communities, and is currently keeping a close eye on these vulnerable organisms is case in the future these organisms start to show negative effects due to acidification. It should be noted that although the CPR survey mesh does not retain all cooccolithophore species, the proportional retention has remained constant over time (Batten *et al* 2003; Raitsos *et al* 2006).

Trophic mismatch: Phenology, the study of the timing of recurring natural phenomena (e.g. seasonal events) is a sensitive indicator of climate-induced ecosystem changes. As warmer temperatures cause a change in bloom timings of some, but not all, plankton taxa, trophic mismatch may occur, impacting food webs from the plankton to higher trophic levels. The CPR indicator 'Phenology index' has been developed to quantify phenological changes in the plankton and enable an assessment of mismatches in timing between phytoplankton prey and their zooplankton predators.

Trophic complexity: Trophic complexity can be assessed coarsely through changes in the plankton community, including invasive species, (both CPR and non-CPR indicators) or more thoroughly with CPR indicators such as geographical changes in biodiversity, ecosystem stability and non-linear climate change impacts, fish and plankton interactions, plankton-wildlife interactions, and plankton as indicators of future climate scenarios. The CPR indicators provide information on trophic interactions at a regional scale and can also offer an assessment of biogeographical changes in trophic complexity.

Harmful Algal Bloom (HAB) impacts (including oxygen level): HABs can affect ecosystem structure and functioning through the poisoning of shellfish and fish and by causing hypoxic conditions on the seabed, resulting in the loss of benthic organisms due to lack of oxygen. The monitoring of HAB taxa in coastal (CPR and non-CPR HAB indicators including the genera *Psuedo-nitzschia* and *Alexandrium*) and open (CPR HAB indicators including the genera *Dinophysis* and *Noctiluca*) waters can provide insight into the causes behind changes in HAB frequency of occurrence, species composition and magnitude. A regional context is provided by CPR data which helps interpret observed localized changes in some HAB species as climatically-induced or anthropogenically caused. Recently, molecular techniques have been developed to identify HAB species which have historically been inaccurately counted due to their small size or fragile nature. These techniques can be applied to archived CPR samples to retrospectively extract data.

Primary and secondary production: Temporal changes in primary and secondary production can be assessed by CPR indicators in near-shore and open sea waters and by non-CPR indicators in coastal, local areas. Spatial changes in primary and secondary production can only be monitored by indicators, such as those developed for the CPR, which contain regional-scale data (spatial and temporal changes in primary production and the marine growing season, phytoplankton community change, zooplankton community change, biogeographical shifts/northward movement index). Some information on spatial changes in primary production can be provided by remote sensing, but the time-series is short and does not work in coastal waters or if conditions are cloudy.

Biomass: Changes in plankton biomass can profoundly affect the ecosystem through alterations in water clarity, hypoxia/anoxia, change in food supply for higher trophic levels and HAB impacts. In situ non-CPR indicators are relatively simple and assess changes in biomass through change in plankton community composition, chlorophyll and HAB magnitude; these indicators are primarily monitored in coastal waters. The CPR takes a more comprehensive and geographically extensive approach to monitoring biomass as an ecosystem function and provides multivariate indicators examining spatial and temporal changes in primary production and the marine growing season, invasive species, ecosystem stability and non-linear climate change impacts, Harmful Algal Bloom taxa, and calcareous taxa change. The CPR's fish and plankton interaction and plankton-wildlife interaction indicators offer information on how alterations in plankton biomass affect higher trophic levels. Remotely sensed chlorophyll can also provide spatio-temporally resolved information on phytoplankton biomass in open sea waters.

Export of detritus and dissolved organic material: The export of detritus and dissolved inorganic material can be assessed with relevance to open sea and nearshore phyto- and zooplankton through several CPR indicators: spatial and temporal changes in primary production and the marine growing season, geographical distribution and trends in biodiversity, Harmful Algal Bloom taxa, invasive species, and ecosystem stability and non-linear climate change impacts.

4.2.1 Structural aspects addressed by plankton indicators:

Population size and community structure: Both CPR and non-CPR indicators assess change in population size and community structure through change in plankton community composition. The CPR indicators also monitor these parameters comprehensively at a regional scale with the phenology index, geographical distribution and trends in biodiversity, invasive species, changes in HABs and calcareous taxa, ecosystem stability and non-linear climate change impacts, and the interactions of plankton with wildlife and fish. The CPR's developed indicators provide information not only on the changes in plankton population size and community structure, but also on the impacts these changes have on the ecosystem. These indicators have been developed by SAHFOS using data from the Continuous Plankton Recorder (CPR) survey (Batten *et al* 2003). The CPR survey is one of the longest ecological time-series in the world (>75 years), with over 2.5 million samples analyzed for more than 500 plankton taxa in the Atlantic, North Sea and North Pacific. The CPR's long time-series and extensive spatial coverage enable the development of statistically significant complex multivariate indicators encompassing many levels of ecosystem state, structure, and functioning. Uniquely, the CPR is able to provide large-scale regional information (as opposed to single station monitoring programmes which can only provide information on plankton dynamics at one single point).This large scale information can aid in interpretation of data from localized monitoring programmes by putting local data into context.

Habitat extent and range and distribution: Assessment of changes in range and distribution and habitat extent require spatially comprehensive data which can only be provided by geographically large scale surveys like the CPR; Single station surveys can only provide information about change at one geographic point while coastal networks only provide information about coastal change; short time-series also limits identification and interpretation of range and distribution changes. A long time-scale for assessment is needed in order to confirm that changes observed are real and not just the result of natural interannual variability. Due to their complexity, these ecosystem structure components can only be addressed by highly-developed multivariate indicators, such as those provided by the CPR.

Species diversity and species richness: Species richness, simply the number of species per sample, is monitored through changes in plankton community composition via the CPR and localized sampling programmes. However, this is only one aspect of biodiversity. The assessment and quantification of change in biodiversity requires an extensive time-series and a wide range of parameters measured and which is highly dependent on sampling effort. An indicator assessing geographical distribution and trends in biodiversity has been developed using data from all 500 CPR taxa at a regional scale. CPR data are also used to assess change in diversity and species richness through other indicators including biogeographical shifts/northward movement index, invasive species, ecosystem stability and non-linear climate change impacts, and change in calcareous taxa. The ecosystem effects of changes in diversity and species richness are monitored through the CPR's plankton-wildlife interactions and fish and plankton interactions indictors.

Gaps identified:

One notable gap in plankton indicators currently in use around the UK is the lack of information concerning nanoplankton, picoplankton, bacterioplankton, and HAB species. These small size classes are under-monitored throughout existing programmes and are usually not included in indicators. In particular, HAB species are often poorly taxonomically resolved in both CPR and non-CPR datasets, resulting in an information gap. SAHFOS is refining new molecular techniques to address this particular issue; these techniques allow the identification of small sized plankton through retrospective analysis of CPR silks. Additionally, a water sampler, which uses the CPR as a deployment platform, is now being deployed on some routes in order to better sample smaller sized plankton.

Spatial gaps also exist in all indicators. Although the CPR monitors extensively at a regional scale, some locations around the UK are particularly undersampled (around northern Scotland, some areas of the Channel and North Sea).

5 Conclusions and recommendations

5.1 Database report tables

Please see attached Excel files:

Plankton all indicators.xls
Plankton Ecosystem Structure and Function.xls
Plankton pressures.xls

5.2 Identification of an effective indicator set

It is clear from the tables in section 5.1 and the scientific and economic scores in table 1 that the CPR indicators represent the most cost efficient and comprehensive indicator suite for monitoring planktonic GES components for the MSFD. The CPR's extensive spatio-temporal scale, large (>500) number of parameters routinely monitored, and unchanged methodology have enabled SAHFOS to develop these high-level indicators for plankton phenology, biogeographical shifts, changes in primary production and the marine growing season, phytoplankton and zooplankton community composition, geographical distribution and trends in biodiversity, invasive species, ecosystem stability and non-linear climate change impacts, HABs, calcareous plankton, and interactions between plankton and fish, and plankton and wildlife (such as sharks, seabirds and turtles). The complex nature of these indicators offers more information on ecosystem changes than each individual parameter could on its own and if used together in a suite will comprehensively assess all relevant aspects of ecosystem structure and function. The CPR indicators are complex multivariate indicators of ecosystem state, function and structure, that have been designed to be policy-relevant to meet both EU and UK requirements (Brander *et al* 2003). Not only have these indicators been regularly used to inform policy bodies such as OSPAR (OSPAR Commission, 2000; Edwards *et al* 2009), Defra (Edwards and Reid, 2001; Department for Environment Food and Rural Affairs, 2008), the UK Environment Agency (Reid, 2007), the European Environment Agency (Edwards, 2008), DG-Environment (McQuatters-Gollop, 2009), the FAO (McQuatters-Gollop, 2008) and the IPCC (M.L. Parry, 2007), they were developed and have been applied through scientific research published in the peer-reviewed literature (Beaugrand *et al* 2002; Beaugrand *et al* 2003; Richardson and Schoeman, 2004; Hays *et al* 2005; Edwards *et al* 2006; McQuatters-Gollop *et al* 2007; Reid *et al* 2008), including in the context of the MSFD (McQuatters-Gollop *et al* 2009).

Although there are a number of important long-term coastal research stations sampling plankton around the British Isles, the CPR survey is the only plankton monitoring programme to regularly sample both near-coast and open ocean waters around some areas of the British Isles – this is in compliance with the MSFD which requires the monitoring of GES indicators at the regional sea scale. Regional scale data such as that provided by the CPR is needed in order to put local scale data (such as coastal sampling stations) into context. The comparison of indicators between open ocean and near-shore waters ensures that regionally-occurring changes are not misinterpreted as localized anthropogenic impacts – for example, the sudden increased phytoplankton biomass observed in coastal North Sea waters in the late 1980s may have been attributed to anthropogenic eutrophication instead of a climatically-driven North Atlantic regime shift if the same pattern of change had not been simultaneously observed in oceanic data (Beaugrand, 2004; McQuatters-Gollop *et al* 2007). The comprehensive spatial scale at which the CPR sample also enables the development of complex biogeographic indicators (such as for range shifts, distribution changes, spatial changes in biodiversity) that cannot be developed from parameters measured at a single sampling station, no matter how frequently samples are collected.

Table 2. Scientific and economic scores calculated during assessment.

ID	Indicator	Created	Modified	Scientific	Economic	Recommended
1286	Phytoplankton multi-metric toolkit for the Water Framework Directive	28/09/09	28/09/09	21	21	Yes
1148	Harmful Algal Bloom taxa (non-CPR)	04/09/09	28/09/09	23	27	Yes
1147	In situ phytoplankton chlorophyll (as proxy for biomass)	03/09/09	28/09/09	23	19	Yes
1139	Plankton community change (non-CPR)	03/09/09	28/09/09	24	27	Yes
1137	Phytoplankton chlorophyll from remote sensing (as proxy for biomass)	03/09/09	22/09/09	4		No
1132	Plankton-wildlife interactions (prey fields) (CPR)	03/09/09	22/09/09	27	28	Yes
1131	Fish and plankton interactions (CPR)	03/09/09	22/09/09	27	28	Yes
1130	Calcareous taxa change (CPR)	03/09/09	24/09/09	25	28	Yes
1128	Harmful Algal Bloom taxa (CPR)	03/09/09	24/09/09	27	28	Yes
1127	Ecosystem stability and non-linear climate change impacts (CPR)	03/09/09	22/09/09	27	28	Yes
1114	Invasive species (CPR)	01/09/09	24/09/09	27	28	Yes
657	Geographical distribution and trends in biodiversity (CPR)	01/09/09	24/09/09	27	28	Yes
656	Plankton as indicators of future climate scenarios (CPR)	01/09/09	24/09/09	27	28	Yes
655	Zooplankton community change (CPR)	01/09/09	24/09/09	27	28	Yes
654	Phytoplankton community change (CPR)	01/09/09	24/09/09	27	28	Yes
653	Spatial and temporal changes in primary production and the marine growing season (CPR)	01/09/09	24/09/09	27	28	Yes
652	Biogeographical shifts/Northward movement index (CPR)	01/09/09	24/09/09	27	28	Yes
604	Phenology index (CPR)	14/08/09	24/09/09	27	28	Yes

The MSFD specifically requests the continuation of established monitoring programmes where possible and the provision of information on natural variability of biological indicators which is only possible through long-term monitoring programmes. With its unchanged methodology and more than 75 years of data, the CPR survey is in a unique position to provided information on natural variability of regional plankton. This baseline data has allowed the identification of major ecosystem reorganization, such as the late 1980s North Sea regime shift (Reid *et al* 1998). Additionally, CPR samples are archived after initial analysis, which enables the retrospective analysis of samples if new information is needed at a later data. For example, genetic and molecular techniques are currently being applied to historic CPR samples in order to identify smaller plankton classes that are unable to be counted during routine CPR analysis. This storage of samples and availability for retrospective analysis could also enable the 'creation' of an indicator time-series for future policy requirements.

The cost-effectiveness of indicators developed from CPR data is a result of the CPR's simple method of sample collection and plankton analysis. CPRs are towed using ships of opportunity (such as ferries and cargo ships) which keeps costs to a minimum as expensive research vessels are not needed. The CPR body and sampling mechanism are also of a simple design which has remained unchanged for more than 75 years. As a result, the purchase and repair of CPR bodies and parts is also inexpensive. Because the method of plankton analysis is virtually unchanged since the survey began in 1931, no expensive technology is needed to count and identify the plankton. This methodology allows data regarding more than 500 plankton taxa, as well as phytoplankton biomass, to be obtained from each CPR sample.

Although the CPR indicators provide information on a wide variety of pressures and ecosystem structures and functions at a regional scale, localized monitoring programmes are also important. The non-CPR indicators addressed in this report may not be as well developed as the CPR indicators, but they are often sampled with a higher temporal frequency and therefore provide critical information on plankton change in coastal areas. CPR indicators can be used to provide perspective to localized indicators; both types are needed in order to most adequately assess plankton dynamics in UK waters. A monitoring strategy integrating large-scale CPR indicators with localized coastal monitoring will therefore provide the most powerful and comprehensive indicator suite to allow robust assessments of marine ecosystem status to be made in future. The plankton indicators recommended for inclusion in the final plankton indicator suite, and their reasons for inclusion or exclusion are shown in table 3.

Table 3. Indicator conclusions and recommendations table.

Indicator Name	Recom-mended	Accepted (yes or no)	Reason for Decision
Phenology index (CPR)	yes	yes	Cost effective, sensitive indicator of regional climate impacts, long time-series, good spatial coverage
Biogeographical shifts/Northward movement index (CPR)	yes	yes	Cost effective, complex indicator of regional climate driven change in plankton, long time-series, good spatial coverage
Spatial and temporal changes in primary production and the marine growing season (CPR)	yes	yes	Cost effective, unique indicator of inter-and intra-annual spatial change in phytoplankton biomass at the regional scale, long time-series, good spatial coverage
Phytoplankton community change (CPR)	yes	yes	Cost effective, unique indicator of inter-and intra-annual spatial change in phytoplankton community at the regional scale, long time-series, good spatial coverage
Zooplankton community change (CPR)	yes	yes	Cost effective, unique indicator of inter-and intra-annual spatial change in zooplankton community at the regional scale, long time-series, good spatial coverage
Plankton as indicators of future climate scenarios (CPR)	yes	yes	Cost effective, complex indicator enabling prediction of future climate impacts, long time-series, good spatial coverage
Geographical distribution and trends in biodiversity (CPR)	yes	yes	Cost effective, complex indicator of regional climate driven change in plankton biodiversity, long time-series, good spatial coverage
Invasive species (CPR)	yes	yes	Cost effective, unique indicator compositional change in plankton community at the regional scale, long time-series, good spatial coverage
Ecosystem stability and non-linear climate change impacts (CPR)	yes	yes	Cost effective, complex indicator of regional climate driven change in plankton, in further development to enable prediction of regime shifts, long time-series, good spatial coverage
Harmful Algal Bloom taxa (CPR)	yes	yes	Cost effective, indicator of inter-and intra-annual spatial change in HABs at the regional scale, long time-series, good spatial coverage
Calcareous taxa change (CPR)	yes	yes	Cost effective, indicator of inter-and intra-annual spatial change in calcareous taxa at the regional scale, long time-series, good spatial coverage
Fish and plankton interactions (CPR)	yes	yes	Cost effective, indicator of inter-and intra-annual spatial change in fish larvae at the regional scale, long time-series, good spatial coverage
Plankton-wildlife interactions (prey fields) (CPR)	yes	yes	Cost effective, indicator of inter-and intra-annual spatial change in interactions between plankton and higher trophic levels (seabirds, sharks, turtles) at the regional scale, long time-series, good spatial coverage
Phytoplankton chlorophyll from remote sensing (as proxy for biomass)	no	no	Expensive, short time series, doesn't work in coastal waters, weather dependent
Plankton community change (non-CPR)	yes	yes	Offers information on change in near-coast plankton
In situ phytoplankton chlorophyll (as proxy for biomass)	yes	yes	Offers (often high frequency) information on change in near-coast plankton
Harmful Algal Bloom taxa (non-CPR)	yes	yes	Offers information on change in near-coast HAB species
Phytoplankton multi-metric toolkit for the Water Framework Directive	yes	yes	Provides information on coastal change in phytoplankton for fulfilment of WFD requirements

5.3 Recommendations for areas of development to address significant gaps

The development of an integrated plankton monitoring strategy would allow a greater understanding of the changes in the plankton of UK waters and would systematically link large scale surveys such as the CPR with inshore sampling programmes (such as Cefas SmartBouys and at Stonehaven, Plymouth, etc). An integrated monitoring strategy would enable the development of more robust ecological indicators which could be used to assess the performance of policy requirements.

The lack of a forum for UK plankton data to be discussed and evaluated on a regional scale in terms of identifying GES is therefore a critical gap. Much of the data from UK plankton monitoring time series (such as the L4 time series, the CEFAS Smart Buoy time series, the Dove time series, the Marine Scotland - Science time series, the Scottish Association of Marine Science time series, the Port Erin time series) has not been published in the peer reviewed literature and in some instances it is also not available in any of the ‘grey’ literature. While there have been a number of smaller specific plankton initiatives within the UK over the last 5 – 10 years there has yet to be a meeting of all the main holders of UK plankton data to discuss:

- The status of their time series
- What (if any) trends/changes they are seeing
- If the causes of any changes can be identified
- If any additional/complimentary monitoring needs to be performed to enhance/supplement their time series on a UK regional scale.

The indicators included here have been developed specifically to address policy needs, and future indicators should be developed in the same fashion.

Sampling effort and effort to develop suitable indicators for smaller plankton groups (such as nanoplankton, picoplankton and HAB species) should be expanded. These smaller size classes cannot be counted in the same way as larger plankton groups and are not routinely monitored in most plankton monitoring programmes; however, with the aid of new molecular techniques, retrospective analysis of archived CPR samples would allow development of new indicators based on these plankton groups. A deeper understanding of plankton size structures would allow further insight into the causes and effects of plankton community change and HAB dynamics.

Spatially, CPR sampling could be increased further to reduce geographic gaps in data collection and provide better coverage in UK waters. This would ensure that CPR indicators would be as spatially representative as possible and provide more robust indicators of marine environmental status.

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