OSPAR COMMISSION

Food webs Thematic Assessment

OSPAR QUALITY STATUS REPORT 2023

2023

OSPAR's Quality Status Report 2023

Food webs Thematic Assessment

Contributors

Lead authors: Ulrike Schückel, Izaskun Preciado

Supporting authors: Christopher Lynam, Murray Thompson, Ger-Jan Piet, Joey Volwater, Federico Cornacchia, Rob van der Veeren, Quentin Nogues, Nathalie Niquil, Joana Brito, Telmo Morato, Emily Corcoran, Maria A. Torres, Gro I. van der Meeren, Eva Varkevisser, Matthew Holland, Arnaud Louchart, Abigail McQuatters-Gollop and Luis Felipe Artigas

Supported by: Intersessional Correspondence Group on the Coordination of Biodiversity Assessment and Monitoring (OCG-COBAM), Biodiversity Committee (BDC), Intersessional Correspondence Group on the Quality Status Report (ICG-QSR), Intersessional Correspondence Group on Ecosystem Assessment Outlook (ICG-EcoC), Intersessional Correspondence Group on Economic and Social Analysis (ICG-ESA), and OSPAR Commission Secretariat.

Citation

OSPAR, 2023. *Food webs Thematic Assessmen*t. In: OSPAR, 2023: Quality Status Report 2023. OSPAR Commission, London. Available at: https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/thematic-assessments/food-webs-ta/

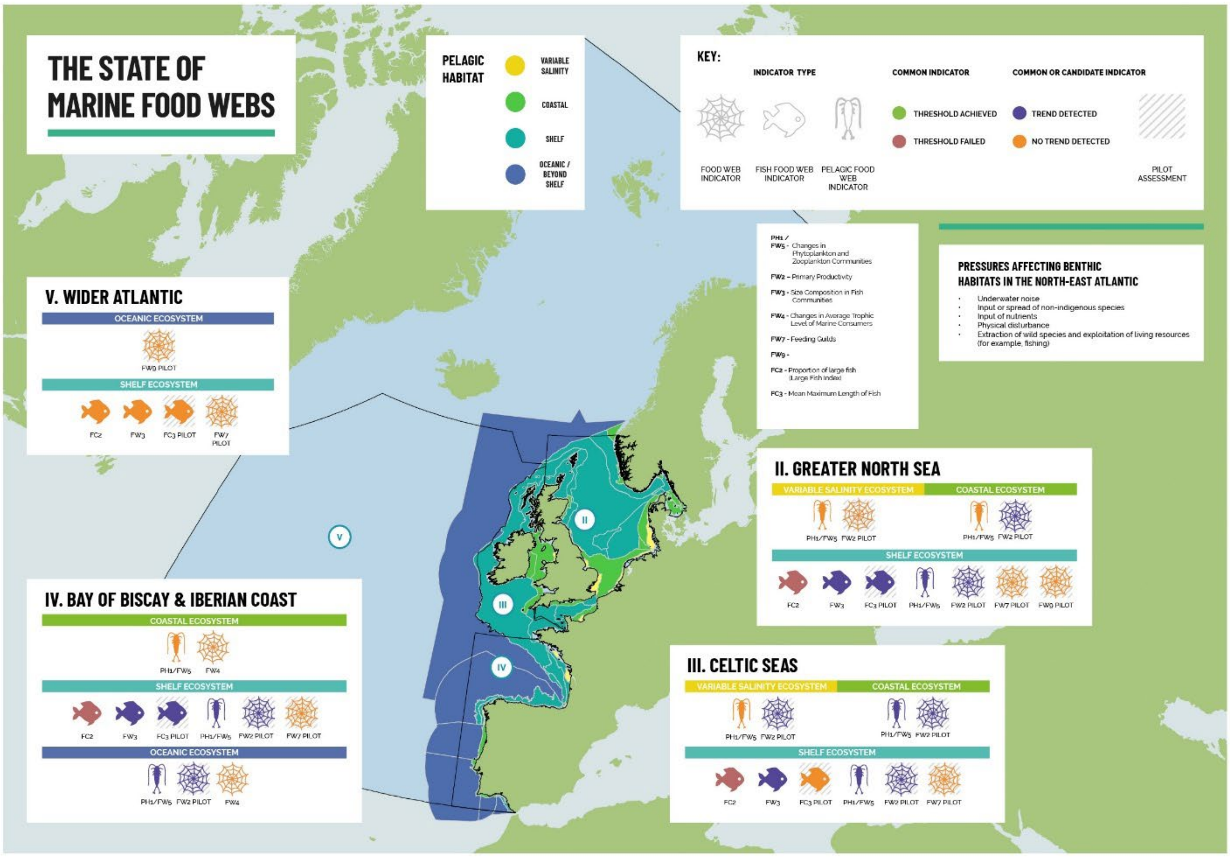
Contents

Executive Summary

The functioning of a marine ecosystem is highly dependent on the structure, diversity and integrity of its components and their interactions. Food webs represent networks of feeding interactions between predators and their prey at different levels in the ecosystem.

Environmental and anthropogenic pressures alter the balance between organisms. Any human activity that has an impact on biota in our marine ecosystems is also likely to have an impact on food webs, and this impact can be local or far away from the site of the pressure. Trends in primary production have been mainly driven by reduced nutrient availability and increasing sea surface temperatures. The latter is the main pressure associated with trends in plankton functional groups. Trends in fish communities are mainly linked to fishing pressures. Marine food webs and the ecosystem's carrying capacity support not only the diversity of life in our seas and oceans, but also many of the ecosystem services that humans very much depend on. Knowledge of the structure and functioning of food webs is therefore not only key for understanding marine ecosystem functioning and how it may be conserved or restored but also for facilitating sustainable use of our seas in the future.

In this thematic assessment a set of food web indicators demonstrates that the abundances, distribution and productivity of key groups representing different trophic levels are in flux in many of the assessed areas. The production of phytoplankton as well as the second layer of food webs are assessed by analysing changes in zooplankton and ratios between plankton life forms. Fish communities are also assessed, in terms of size structure, species composition and biomass of feeding guilds linking lower trophic levels to predators. The effects of fishing pressures on the structure of demersal fish were analysed by assessing the status of different trophic levels including mesopredators and top predators. Finally, the existing knowledge of all compartments, trophic levels and their interactions is integrated into an assessment of the state of the whole food web.



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

In the study of marine food webs, the distribution, productivity and abundance of all marine biota and the relationships between them are of relevance, as they in a sense integrate the status of all the ecosystem components. Given the comprehensive nature of food web status, the human activities affecting food webs span the width of those affecting the status of marine birds, marine mammals, fish, benthic and plankton communities, and non-indigenous species.

Society's need for food results in fishing activities in the OSPAR Maritime Area, involving the extraction of commercially important species, as well as by-catch of non-commercial species. This can cause imbalances in predator-prey relationships, with consequent negative effects on the food web. Fishing can also cause physical disturbance of the seabed, impacting the benthic communities on which some fish species depend as a food source.

Society's need for energy and to mitigate climate change, requires new infrastructure to be built in the marine environment. Construction can impact benthic and pelagic food web components through alteration of habitats and changes to hydrological and hydrodynamic conditions, with negative effects for nutrients.

Society's need for trade and movement of goods and the associated increase in shipping can result in the translocation of non-indigenous species and introduces underwater noise. Non-indigenous species have the potential to compete with native species for space and food, affecting trophic levels and negatively affecting primary productivity.

Underwater noise can also impact fish and top-predator communities and alter the behaviour of marine mammals, which in turn affecting lower trophic levels.

Climate change is also affecting the food web. As the waters warm, they are changing the distribution and range of many species in the food web throughout the OSPAR Maritime Area. This has already affected the primary production rates and species composition of phytoplankton and zooplankton, which in turn will trigger changes at other trophic levels. In addition, climate change alters species phenology and life-cycle events and leads to a desynchronization of biotic interactions, in particular predator-prey relationships.

These stressors may have a greater impact in some regions than in others, but given the level of globalization in human activities, all OSPAR Regions are affected to a greater or lesser extent.

Non-indigenous species introduced by shipping have the potential to compete with native species for space and food, affecting trophic levels and negatively affecting primary productivity. © Shutterstock

Q2. What has been done?

Food webs are the umbrella that connects all biodiversity components, from primary producers to apex predators, and their various interactions and energy transfers across trophic levels must be taken into account. This makes food webs particularly hard to investigate and assess. Understanding food web structure and changes is critical in order to formulate policy that can lead to appropriate management responses. Responses that address climate change, fishing, pollution and eutrophication have been identified as important for supporting good environmental status of food webs in the North-East Atlantic.

OSPAR has not adopted any specific measures with the explicit objective of supporting the state, function or resilience of food webs. There are, however, several examples of measures that could have particular relevance to ecosystem function and resilience. These include the OSPAR MPA network and Other Effective Conservation Measures (OECMs).

Q3. Did it work?

The ambition to apply an ecosystem approach to the management of human activities is central to the work of OSPAR, but implementation remains challenging. Even though, arguably, every measure to improve the state of the marine environment is ultimately (also) aimed at conserving or restoring food webs to good status, connecting response measures to (positive or negative) effects on food webs is complex, also because the impact is seldom direct in nature. It is critically important to continue to improve food web indicators in order to inform the development and implementation of responses that take a more integrated approach.

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

The food web is key to the health of the marine ecosystem. Significant impacts on one element of the food web can impact the whole ecosystem through knock-on and cascading effects. A well-balanced food web is a key factor underpinning a healthy marine ecosystem. A suite of indicators has therefore been used to address the differing trophic levels in the food web under a holistic approach that aims to build an overall picture of food web status. This assessment covers all OSPAR Regions, and the overall results indicate that food webs are not in good environmental status.

In the Greater North Sea, the indicators for demersal fish communities have not achieved the threshold indicating good status, which suggests that this component of the food web is under pressure. Plankton community indicators show a decreasing trend of primary production and a mixed picture for various plankton lifeforms, with some showing increasing trends and others decreasing. The fish feeding guild indicator shows an increasing trend in planktivore biomass in shelf ecosystems between 1997 to 2020. There is a mixed picture for other guilds that feed largely on benthos and fish: their biomass generally shows increasing trends in the southern part of the Greater North Sea and decreasing trends in its northern part. The multitrophic level indicator demonstrates that primary productivity has been the main driver of changes in trophic functioning in coastal ecosystems. Different trends were observed in Ecological Network Analysis-related indices, resulting in unknown status for the trophic network.

In the Celtic Seas, the indicators for demersal fish communities have not achieved the thresholds indicating good status, suggesting a long term status decline in the Region. Plankton community indicators show a decreasing trend for primary production and for virtually all plankton lifeforms. The fish feeding guild indicator shows an increasing trend in the biomass of three of the four guilds investigated in the northern part of the Region. Contrasting trends in the biomass of fish that feed largely on the benthos were found, with generally increasing trends in the southern part of the Celtic Seas and decreasing trends in the northern part of the Region.

In the Bay of Biscay and Iberian Coast, the indicators for demersal fish communities demonstrate no clear patterns. Top predators and mesopredators show signs of recovery although they display contrasting trends at sub-division level, which implies unknown status. Plankton community indicators show a significant downward trend in primary production, and a mixture of upward and downward trends for different plankton lifeforms. These decreasing trends can be linked to rising sea surface temperatures. The fish feeding guild indicator shows that the biomass of fish guilds is generally highest in the northern part of the Region.

In the Wider Atlantic, the indicators for demersal fish communities demonstrate no long term changes. The fish feeding guild indicator shows that benthivore biomass was the same in the two survey areas. Planktivore and piscivore biomass are generally highest in the southern area. The pilot assessment with the multitrophic level indicator conducted in the area of the Azores shows a decreasing trend for biomass at all trophic levels in this food web model. Changes to the indices in modelled ecosystem network analyses indicate that, for the area studied in this pilot assessment, the resilience of the ecosystem is decreasing over time.

A different but equivalent approach was taken in Arctic Waters, where the Common Indicators were not available. This assessment used evidence taken from other sources (Arctic Council / AMAP / ICES) and indicates that climate change is currently the strongest driver of change in the marine food web in this Region.

The food web assessment results indicate potential risks of both bottom-up and top-down effects impacting ecosystem function.

Q5. What do we do next?

The NEAES 2030 operational objective SX.O2 commits OSPAR to initiating discussions on the development of a practical approach for regional-scale ecosystem-based management, including through the Collective Arrangement and in cooperation with fishery management bodies and other competent organisations. The objective is to strengthen ecosystem resilience to climate change and to safeguard the marine environment, its biodiversity and ecosystem services. Progress in the implementation of this objective will be an important contribution to developing appropriate responses for food webs.

The development of a practical approach to ecosystem-based management (EBM) will provide the opportunity and the mechanism to share evidence and common objectives for more sustainable use of the marine environment. Working with interested partners and drawing on international best practice, OSPAR will design and implement a pilot project on EBM in one of the OSPAR Regions. In addition, more knowledge of the potential future impacts of windfarms on trophic structure and food web functioning is needed.

There are opportunities for OSPAR to strengthen its response to support food webs, including by taking a broader ecosystem approach to the implementation of actions to strengthen the status of OSPAR listed species and habitats, further developing the OSPAR MPA network, including OECMs, and implementing the strategic objectives which address eutrophication. Strengthening cooperation with those bodies that have competence for managing human activities outside of OSPAR’s mandate will be critical to success.

Ecosystem restoration provides another potential opportunity to support healthy food webs in line with NEAES Strategic Objective 6, to “Restore degraded benthic habitats in the North-East Atlantic when practicable to safeguard their ecosystem function and resilience to climate change and ocean acidification”.

With regard to the OSPAR MPA network, understanding the management effectiveness of MPAs within the network, and the network itself, remains an important gap to address, particularly from an ecosystem function and food-web perspective. By 2022, OSPAR aimed to identify barriers to the effective management of MPAs, and by 2024 it will take appropriate steps to enable all OSPAR MPAs to achieve their conservation objectives (NEAES S5.O2). The contribution of OECMs and improvement in the management of MPAs within and outside national jurisdiction will be an important response for food webs.

For OSPAR MPAs in Areas Beyond National Jurisdiction (ABNJs), continued effort will be needed to further the Collective Arrangement (OSPAR Agreement 2014-09) and to cooperate through other mechanisms, such as Memoranda of Understanding, with relevant competent management authorities to help them consider appropriate management actions for delivering the conservation objectives for OSPAR MPAs in ABNJs.

D - Drivers

Social and economic drivers affecting marine food webs

The global demand for food and energy has risen and continues to rise, resulting in intensive exploitation of marine resources and the use of the sea for the production of renewable energy. In addition to intensive fishing and the renewable energy infrastructures, accelerated climate change including atmospheric warming and changes in precipitation is projected for this region during the 21st century. Mitigating climate change increases the need for renewable energy. Furthermore, adaptation to climate change potentially drives changes in marine life by changing the seascape to provide for flood protection. Additionally, globalization and increased consumerism resulting in shipping and pollution are other important driving forces in this region as these activities influence the different trophic levels of the food web.

All social and economic drivers have the potential to influence the quality status of complex food webs.

With the world population projected to grow from 7,3 billion to approximately 9,7 billion by 2050, as consumption per capita increases and available natural resources decrease (Powlson et al., 2010), research suggests that 40% more protein from the sea will be needed by 2030. Fishing is a direct response to society's need for food. Current policies focus on fishing at sustainable levels to protect fish stocks; however, some practices lead to adverse impacts on the marine ecosystem, and this requires management.

In addition, the growing population increases society's need for energy. The introduction of infrastructure associated with renewable and non-renewable energy to the marine environment has the potential to either directly or indirectly affect marine life. An example of such direct impact is the localised temperature changes associated with power station outputs. Water used as a coolant may alter the distribution and abundance of organisms at different trophic levels, including food sources. Energy security activities, such as modifications to water courses or effects from renewable energy installations, might also drive impacts on marine organisms. Moreover, hydrological changes (stratification and mixing regime) from wind farms can impact both benthic and pelagic habitats and diversity in different trophic guilds.

The marine food webs leading to seafood species are among the many goods and services generated by marine ecosystems. Their utilisation has been a characteristic of human societies since the earliest times. Threats to all marine species in the food web drive public pressure for political debate and action, because of society's needs and its appreciation of nature and biodiversity. Pelagic and benthic species play critical functional roles in biogeochemical processes. They are particularly important in secondary production, both as a direct food source (e.g. clams) and as major food sources for pelagic and bottom-feeding species that are commercially fished.

The multiple factors driving activities that can create climate change impacts include the burning of fossil fuels, industrialised farming practices and deforestation, and these also drive impacts on fish. Society's need to mitigate the effects of climate change has led to the expansion of renewable energy technologies. The introduction of the associated infrastructure to the marine environment can either directly affect benthic trophic guilds or directly or indirectly affect fish species. In addition, coastal and flood protection, sea defences, levees and dikes are being increasingly introduced, driven by society's need to adapt to the effects of climate change. Again, such infrastructure has the potential to either directly or indirectly affect fish species and their habitats.

The production of goods and services helps to meet society's need for stable economies. The manufacturing and processing of goods can introduce pollutants to the marine environment which can affect lower, upper and apex trophic guilds, either directly or indirectly.

Society's need to manufacture and process goods drives their trade and movement, their shipment by sea, and navigational dredging in support of shipping. However, each can contribute to the input or remobilisation of contaminants in the marine environment. Vessel movements may disturb fish and marine mammals.

Population demands for goods requiring manufacturing and processing, and for services such as waste treatment and disposal, are on the increase. These are driven by society's need for health and wellbeing. However, these activities can introduce pollutants (including plastics) to the marine environment that can become concentrated in marine resources. Plastic litter is now one of the most serious threats to the marine environment. Over 690 marine species have been impacted by plastic debris, with small plastic particles being observed in the digestive tracts of organisms from all different trophic levels. Growing populations are increasing the demand for housing and utilities, and therefore increasing society's need for materials and their processing. The manufacturing and processing of goods can introduce pollutants to the marine environment. Activities such as mineral extraction and infrastructure installation lead to the restructuring of seabed morphology, which can drive impacts on benthic and fish habitats.

A – Activities

Activities affecting marine food webs

Human activities are distributed widely across the North-East Atlantic, but the intensity of activities and of the pressures they impose on the marine environment varies greatly between OSPAR Regions and sub-divisions. Some sea areas are affected by many activities; in others, only a few may be significant. Activities are reflected in the spatial scale of their potential impacts on food webs. The key human activities affecting food webs are extraction of living resources, transport and shipping, water management activities, agriculture, aquaculture, renewable energy and extraction of non-living resources.

Widespread activities

Extraction of living resources:
Society's need for food is a driver of fishing activity. The different gears and methods used to extract living resources include benthic trawling, scallop dredging, netting (e.g. fixed nets), pelagic trawls, potting / creeling, suction (hydraulic) dredging, bait digging, seaweed and saltmarsh vegetation harvesting, and hand

collection of bird eggs and shellfish. These activities directly and/ or indirectly interact with food web components and can alter food web structure and functioning and therefore their balance.

Transport - shipping:
Society's need for the trade and movement of goods drives transport activities, reflecting the need for stable economies and the supply and demand of goods and services. Transport and shipping involve activities such as the dumping of litter and debris, the production of shipping wastes, particularly emissions of greenhouse gases, and also mooring, beaching and launching, as well as the operation of ferries. Litter and debris (including plastics) can injure or kill marine and coastal wildlife or can be ingested and move through the marine food web. Shipping can introduce non-indigenous species through ballast water discharge, which impacts food web structure and functioning.

Lobster and crab creels. © Shutterstock

Local activities

Physical restructuring of rivers, coastline or seabed (water management):
Dredging the seabed can cause localised increases in nutrients and turbidity. This eutrophication impact can change the pelagic system, including changes in food webs and changes of energy transfer from pelagic systems to higher trophic levels. The dredging and depositing of materials at sea and in local marine areas, predominantly associated with the maintenance of navigable channels and associated disposal at marine sites, will directly interact with benthic habitats and influence bottom-up control in food webs. Furthermore, coastal areas used as spawning areas are negatively impacted by physical disturbance. Benthic communities play a central role in the transfer of materials, from primary production by phytoplankton, microphytobenthos, benthic macrophytes and coastal wetlands through the detrital pool to higher trophic levels in the food web, including commercially exploitable fish.

Agriculture and Aquaculture [Cultivation of living resources]:

Society's need for food drives marine aquaculture, freshwater aquaculture, and terrestrial agriculture. Agricultural run-off can lead to the input of toxicological substances to the environment, including nutrients and fertilisers. In localised areas, nutrient run-off from industry and sewage can cause significant eutrophication impacts on pelagic habitats, which can alter food web structure and functioning (OSPAR Eutrophication Thematic Assessment). Aquaculture can also provide vectors for the spread of introduced diseases and parasites. Parasites have the potential to uniquely alter food web structure in terms of chain length, interaction strength, and energy transfer.

Renewable energy generation (wind, wave and tidal power), including infrastructure [Production of energy]: This includes the construction and operation of offshore wind farms and other renewable energy developments designed to harness both wave and tidal energy, including the associated infrastructure. The construction, operation, and decommissioning activities associated with renewable energy developments may directly interact with benthic and pelagic food web components. The introduction of infrastructure to the marine environment alters benthic habitats and can cause hydrological and hydrodynamic changes influencing nutrients, primary production and plankton species distributions. Fish and top-predator communities are impacted by the construction of offshore wind farms and underwater noise.

Extraction of minerals, Extraction of oil and gas [Extraction of non-living resources]:
The extraction of aggregate materials (mining, polymetallic nodules, sand, gravel and crushed rock), oil and gas from the seabed is necessary for the construction industry and low-carbon technologies. Materials extracted from the seabed directly interact with benthic habitats in the locations where the materials are collected and are likely to modify the consumer-resource (trophic) and substrate-providing (non-trophic) interactions within the food web.

Military operations (subject to Article 2(2)) [Security/defence]:
These activities include the production of contaminants, military training, disposal at sea of munitions and the construction of complex infrastructure projects. They have potential consequences for food web structure and functioning, including habitat degradation, soil erosion, environmental pollution and disturbance, and have contributed to population declines and biodiversity losses arising from both acute and chronic effects in marine systems (Lawrence *et al*., 2015).

P – Pressures

Pressures affecting marine food webs

The main pressures affecting marine food webs are the extraction of wild species and exploitation of living resources, physical disturbance, input of nutrients, non-indigenous species, underwater noise and global warming. The main pressures alter the structure and dynamics of food webs and can have cascading effects through the overall marine food web.

Extraction of wild species and exploitation of living resources [Extraction of living resources]:
Fishing pressure exerts a direct impact on food web functioning by extracting commercial and non-commercial species from the sea, causing individual mortality or injury. Extraction through unsustainable fishing leads to changes in balance across food webs by altering predator-prey interactions and, ultimately, the resilience of the ecosystems. The removal of predatory fish can cause a disproportionate increase in forage fish (plankton feeders), which in turn may deplete the biomass of some zooplankton life forms, leading to imbalances in plankton communities. Fishing not only impacts directly target and by-catch

species, but the effects of unsustainable fishing can propagate down through the food web, restructuring the entire ecosystem. The extent to which a disturbance is diminished as it propagates through a food web varies widely between ecosystems, and there is no formal theory as to why this should be so (Heath et al., 2014). Additional effects involve food web processes related to prey availability, competition for food resources, utilization of discards by some species, and / or parasitism. Deterioration in the condition of some fish species due to complex biological and chemical interactions has also been observed. Nevertheless, the intrinsic complexity of food webs makes it particularly difficult to quantitatively discern the effects of fisheries, climate change and environmentally driven variables on ecosystem functioning, even when categorized by low, medium or high fisheries pressure. Ecologically sustainable fishing should not impact resilience. In fact, it should have the opposite effect of mainly removing individuals from abundant stocks, thereby limiting some of the cycling that may otherwise occur in natural populations.

Physical disturbance to seabed (temporary or reversible) [Physical]:
This pressure is strongly related to the extraction of wild species and exploitation of living resources, since one of the main human pressures with a direct impact on the seafloor is fishing. Fishing gears such as trawls and dredges can greatly alter the seabed and exert impacts on the benthic communities and upper trophic levels that feed on small organisms dwelling in or on the seafloor. The magnitude and extent of the impact depends on the gear type and the persistence of the impact. In the OSPAR Maritime Area, bottom trawling is among the main pressures on the seabed. Physical disturbance, no matter the cause, can impact pelagic habitats through changes in stratification / mixing processes that affect primary productivity and trophic relations in the plankton / pelagic compartments (as in the case of offshore wind farms). The extraction of minerals (rock, gravel, sand) may also cause alterations of seabed topography, changes of sediment composition and the removal of organisms. This may lead to shifts in the spatial distribution of species and changes in predator-prey interactions, altering bentho-pelagic coupling and the overall functioning of bentho-demersal ecosystems.

Fishing gears such as trawls and dredges can greatly alter the seabed © Shutterstock

Input of nutrients - diffuse sources, point sources, atmospheric deposition [Substances, litter and energy]:
Classical food web theory suggests that nutrients affect the food web from the bottom up, with top-down effects, through predation, controlling the biomass at each trophic level (Odum, 1969). Therefore, an enhanced input of nutrients may trigger a bottom-up cascade effect by increasing primary production and consequently phytoplankton biomasses and / or changes in their associated diversity, which will impact the upper trophic levels. However, due to the highly complex nature of food web processes it is difficult to demonstrate consistent biological changes based on cause-effect relationships, for example increased nutrient availability leading to increasing biomass of zooplankton and planktivorous fish. Nevertheless, Capuzzo *et al.* (2018) have demonstrated that concurrent declines in time-series data for primary production, the biomass of copepods and an index of fish recruitment in the North Sea during the 1990s correlated with total oxidized nitrogen in riverine inputs from the Rhine. Through food web modelling of the European Seas, Piroddi *et al.* (2021) found that planned management measures to reduce nutrients further would have minimal effects on the pelagic offshore marine food web. There may also be consequences for seafloor food webs through increasing sedimentation rates in organic material due to sinking from enhanced plankton production. This ‘marine snow’ can cause increasing oxygen consumption through microbial processes and remineralization in deeper water layers, leading to large areas of oxygen deficiency. Oxygen depletion may also affect the remineralisation capacity of benthic fauna, as well as the distribution and reproduction of higher trophic level organisms.

Input or spread of non-indigenous species [Biological]:
The introduction of non-indigenous species can impact food webs in different ways, for example through the alteration of nutrient concentration and availability, alteration of habitat structure (for example, structural changes of blue mussel beds into mixed beds caused by the Pacific oyster), and competition with native species for food resources and space. The appearance, and especially the proliferation, of a non-indigenous species may cause a cascading effect: high abundances of a non-indigenous species may lead to over-predation of specific prey which in turn could affect other species that feed on the same resource, triggering changes in predator-prey interactions (diet shifts, increased competition–diet overlap–with other species). These cascading effects may change the spatio-temporal dynamics of native species and, ultimately, lead to lower trophic levels and primary productivity, altering the overall functioning of food webs.

Input of anthropogenic sound (impulsive, continuous) [Substances, litter and energy]:
Many marine mammals and other species rely on their hearing for survival. They use sound to communicate, avoid predation, locate prey or navigate. The noise pollution produced by offshore infrastructure, transport and shipping, ferries, cruise ships and recreational vessels or military activities may alter the behaviour of marine mammals, causing changes in their distribution and migration which in turn may trigger top-down effects by releasing predation over lower trophic levels. Underwater noise may also alter breeding habits and cause injuries or even death to many marine organisms. Although little is known about the direct impact on food webs, some studies point towards a drop in commercial catches due to noise, with larger fish vacating disturbed areas, which can lead to top-down effects (removal of top predators can lead to unwanted abundances at lower trophic levels). The acoustic effects may also increase by-catches, with a consequent impact on food webs through the removal of important compartments of the ecosystem. Underwater noise from commercial shipping is considered one of the most pervasive noise sources. Underwater distribution and noise effects are still unknown; however, impacts have been observed at all trophic levels, from invertebrates to fish, marine mammals, and diving seabirds (Machado *et al*., 2021).

S – State

Changes in state of marine food webs

Food webs have shown widespread changes in the OSPAR Maritime Area in recent decades. Fishing and climate change represent the main human pressures affecting trophic networks and OSPAR marine ecosystems. There has been a general pattern of decreasing phytoplankton and zooplankton abundance and / or biomass across the Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast, which might have consequences for upper trophic levels. Demersal fish communities have not achieved good status in any of the assessed Regions. Due to widespread human pressures across multiple compartments of the ecosystem, the food web ecosystems in the four OSPAR Regions assessed in the present Thematic Assessment are indicatively considered not to be in good status according to the definition and categorisation of quality status described in McQuatters-Gollop *et al.*, (2022).

Table S.1: Confidence assessment results across the five OSPAR Regions, determined using the methodology outlined in the QSR guidance

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

OSPAR acts as a coordination platform in the North-East Atlantic for the regional implementation of the EU Marine Strategy Framework Directive (MSFD) that aims to achieve a Good Environmental Status (GES) in European marine environments, as well as for the coordination of other national frameworks. The characteristics of GES are determined by the individual EU member states, based on criteria elements, threshold values and methodological standards set regionally or at EU level.

Norwegian, Icelandic, United Kingdom, Greenlandic and Faroese marine areas are not covered by the MSFD.

Food webs are key to our understanding of changes in ecosystem structure and functioning. Changes in marine food web structure and functioning can affect the provision of ecosystem services, as outlined in the Ecosystem Services section.

The food web common and candidate indicators briefly described below address the EU Marine Strategy Framework Directive Descriptor 4 criteria, as outlined in **Table S.3**. In Arctic Waters (OSPAR Region I) a different set of information was used and therefore not included in the assessment overviews for indicators.

Food webs are key to our understanding of changes in ecosystem structure and functioning. Changes in marine food web structure and functioning can affect the provision of ecosystem services, as outlined in the Ecosystem Services section.

The food web common and candidate indicators briefly described below address the EU Marine Strategy Framework Directive Descriptor 4 criteria, as outlined in **Table S.3** (Norwegian, Icelandic and United Kingdom marine areas are not covered by the MSFD). In Arctic Waters (OSPAR Region I) a different set of information was used and therefore not included in the assessment overviews for indicators.

The assessment of the state of food webs in OSPAR Regions was undertaken using a variety of indicators (common and candidate), methods and spatial scales. A set of indicators focusing on different trophic levels (e.g., primary production, zooplankton, fish, whole food web) was independently assessed. No integration method was used for the assessment results. Results are described for each ecosystem: variable salinity, coastal, shelf and oceanic / deep-sea (**Figure S.1, Tables S.3-S.6**). Assessment units represent OSPAR

Regions or their sub-divisions (specified areas that reflect biogeographic / hydrological characteristics of the sub-region). This assessment provides a descriptive summary of the results of each indicator rather than an integrated assessment of food webs. The main results for each indicator in each OSPAR Region are summarised in **Figure S.1**. The status assessment is based on expert judgement, since most indicators have no agreed threshold value.

Indicators representing differing trophic levels of the food web have been developed to create an overall perspective of change. The indicators for Primary production (FW2) as well as Phytoplankton and zooplankton abundance (PH1 / FW5 and FW6) capture change in bottom-up processes often linked to climate change and eutrophication. The Biomass of feeding guilds indicator (FW7) links the base of the food web to higher predators (e.g. through typically smaller fish that feed on plankton to typically larger fish that feed on fish) and to the seabed (through fish that feed on benthos) and can capture the cumulative impacts of human activities on essential fish habitats and those from the direct removal (harvesting), in addition to climate impacts from the base of the food web that may favour planktivory over benthivory or vice versa, depending on the status of the ecosystem. Potentially, fishing impacts on planktivores can also cascade down the food web and impact the planktonic community and cascade up the food web to marine birds (Lynam *et a*l., 2017).

Fishing also preferentially targets larger individuals and, over time, a sustained increase in the mortality of a population will lead to a reduction in the proportion of large individuals in the ecosystem. Furthermore, as species that can grow large are depleted, particularly those which are slow-growing such as demersal sharks, for example tope (*Galeorhinus galeus)*, the biomass of smaller bodied species such as dab (*Limanda limanda)* can increase to fill the ecological niche. The indicators of these highly diverse demersal fish communities (FC2, FC3, FW3) can capture such wider impacts of fishing on the resultant size structure (FC2 and FW3) and composition of species (FC3). In the Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast, the proportion of large fish (FC2) in a survey has been shown to track change in fishing mortality over long periods. This indicator (FC2) requires a specific threshold in order to determine a large fish with the tendency to reflect change in the biomass of larger species targeted by fisheries (e.g. cod, *Gadus morhua,* and saithe, *Pollachius virens,* in the North Sea). The indicator for typical length of fish (FW3) complements that for proportion of large fish (FC2), since typical length is a consistent metric over both time and space for a specific survey and can be used to demonstrate where changes in the fish community are leading to an overall failure in the proportion of large fish (FC2). This can help to determine which process is leading the change (e.g., climate, or fisheries or habitat change).

Changes in average trophic level of marine consumers (FW4) is an ecological indicator that characterises change in the trophic pyramid and can integrate the cumulative effects of fishing pressure and other drivers on the trophic structure of food webs. Conceptually, this indicator has aimed at highlighting unsustainable fishery practices in past decades. The lack of trends found in many scenarios with this assessment does not necessarily indicate lack of impact. Rather, this needs to be further investigated in order to determine whether such absence can be attributed to resilience of the ecosystem or other possible causes. Ecological Network Analysis (ENA) is a system-ecology oriented approach to analyse all trophic interactions (flows in energy or carbon) among all compartments of a food web. ENA and its related ENA indices (FW9) enable assessment of the structure and functioning of food webs based on the analysis of all interactions among the living and the non-living compartments (detritus carbon pools). The food web is represented by a network of quantified interactions (flows) between nodes (trophic compartments, gathering organisms having similar preys and predators and metabolic rates). This indicator can successfully capture the effects of cumulated pressures and has shown its capacity to detect changes in food webs and ecosystems due to climate change, eutrophication, fisheries, hypoxia events or invasive species.

These food web indicators used to assess the state of marine food webs **(Figure S.1)** are briefly described below, followed by a more extensive overview of the status assessments for each Region.

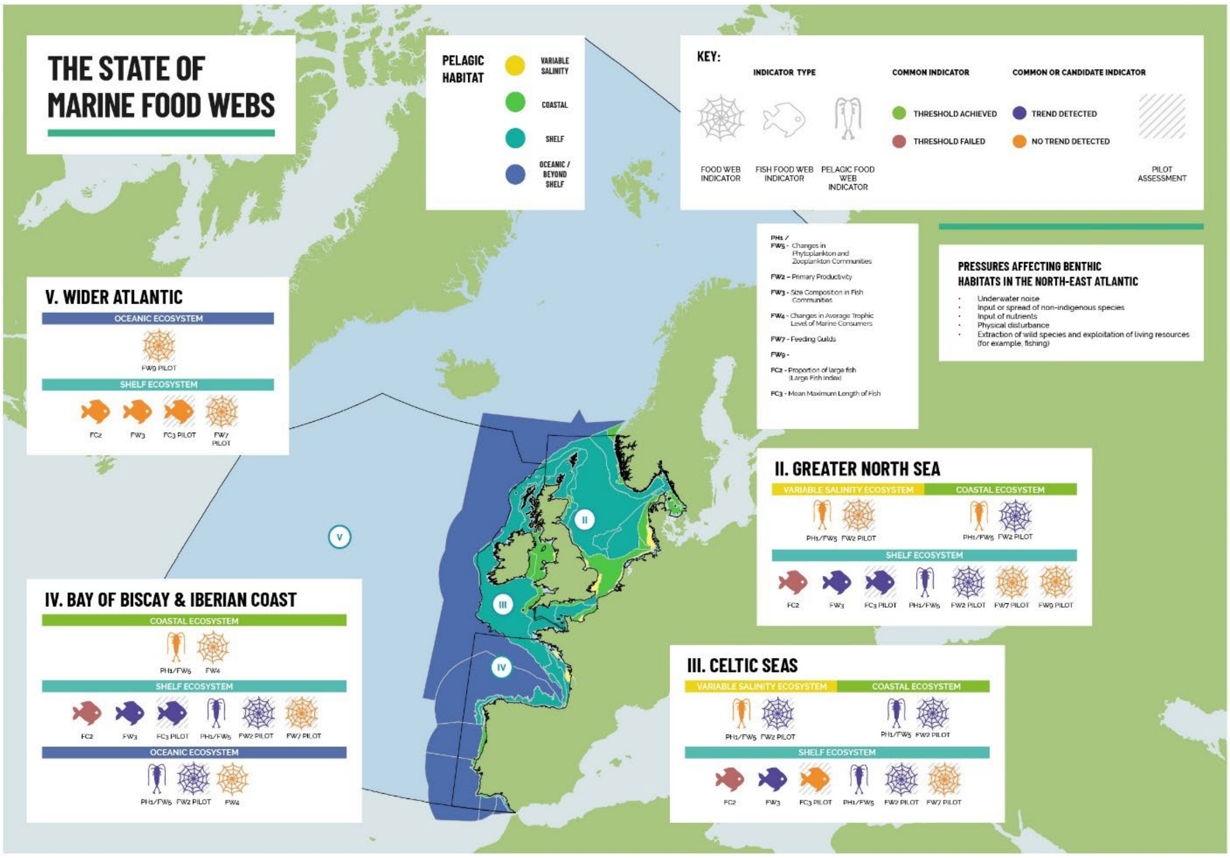


Figure S.1: Indicator results schematic for food web ecosystems (variable salinity, coastal, shelf, and oceanic / beyond shelf) within the OSPAR Regions. For the OSPAR food web biodiversity indicators there was variability among indicators, ecosystem habitats, and OSPAR Regions. Icons have been coloured according to indicator trends. Not all indicators were assessed in some Regions due to lack of data or because the habitat type was not present within the OSPAR Region. Grey background colour indicates that a candidate indicator was used and a pilot assessment conducted. The common indicator 'proportion of large fish' (FC2) has agreed threshold values in the North Sea and Celtic Sea and the icon is coloured accordingly. The candidate indicator 'ecosystem network modelling'(FW9) is excluded from Figure S.1 since this pilot assessment in Regions II and V focused on specific areas and not on whole Regions. An explanation of the meaning of any observed trend or change for each indicator assessment in each habitat type and Region is given in table headings 3-6

Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5): This Common Indicator includes phytoplankton and zooplankton lifeform abundance data. The main human pressures on these lifeforms are climate change and eutrophication.

Pilot Assessment of Primary Productivity (FW2): This Candidate Indicator includes phytoplankton productivity data; the main human activities / pressures on phytoplankton productivity are climate change and eutrophication, even though hydrodynamical changes can be important by changing mixing/stratification as well as light conditions, especially in coastal and variable salinity habitats.

Size composition and spatial distribution of zooplankton (FW6): This Candidate Indicator targets zooplankton biomass and body size. In the current OSPAR cycle, this indicator could not be assessed because of insufficient data. However, efforts have been made to automate the collection of size and biomass data from fisheries surveys and test the approach (e.g. Pitois *et al.*, 2021).

Proportion of Large Fish (Large Fish Index) (FC2) and Size Composition in Fish Communities (FW3): These Common Indicators include many species of demersal fish (including elasmobranchs) and summarise the change in the size structure of the fish community at the scale of regional seas and within spatial sub-divisions (FW3 only). The main human activities / pressures affecting demersal fish communities are trawl fisheries, since fishing mortality reduces biomass and the proportion of larger and older fish, but climate change may act to hinder the growth of typically larger cold-water species (e.g. Queirós *et al.,* 2018). FC2 has agreed threshold values for the North Sea and Celtic Sea

Mean Maximum Length of Fish (FC3): This Candidate Indicator includes demersal fish (including elasmobranchs) and summarises change in the relative biomass of species, where species are weighted by their ability to grow large (using the stationary trait of maximum body length), since larger species are vulnerable to depletion through additional mortality. The main human activities / pressures affecting the assessed fish are fisheries (Spence *et al.*, 2021) and climate change.

Changes in Average Trophic Level of Marine Consumers (FW4): This Common Indicator includes fish, cephalopods and benthic invertebrates dwelling in sediment bottoms of the circalittoral zone. The main human activities / pressures that were identified are fisheries and climate change. Eutrophication and invasive species can also be of relevance in specific areas.

Feeding Guilds (FW7): Due to data availability, this Candidate Indicator currently includes pelagic and demersal fish and elasmobranchs only, but in future it will include data on higher and lower trophic levels. This indicator tracks the change in biomass and diversity of taxonomic groups that share similar prey items (e.g., planktivores, benthivores and piscivores) and have similar functional roles in the food web (Thompson *et al.,* 2020). The main human activities / pressures are fisheries and climate change, which can interact to alter the strength of energy pathways through the food web (Thorpe *et al*., 2022).

Ecological Network Analysis Indices (FW9): This Candidate Indicator is a multitrophic level indicator. It includes pelagic elements (phytoplankton, zooplankton), benthic elements, fish, seabirds and mammals. Ecological Network Analysis (ENA) is a system-ecology oriented approach for analysing all trophic interactions (e.g. flows in energy or carbon) among all compartments of a food web (Ulanowicz, 2004; Safi *et al*., 2019). ENA and its related indices (FW9) enable assessment of the structure and functioning of food webs based on the analysis of all interactions among the living and the non-living compartments (detrital carbon pools). The food web is represented by a network of quantified interactions (flows) between nodes (trophic compartments, gathering organisms having similar preys and predators and metabolic rates).

Table S.2: Food web indicators in relation to EU Marine Strategy Framework Directive Descriptor 4 criteria

	Common indicator				Candidate indicator				
	FC2	FW3	FW4	PH1/FW5	FC3	FW2	FW6	FW7	FW9
D4C1 – Primary: The diversity (species composition and their relative abundance) of the trophic guild is not adversely affected due to anthropogenic pressures.					X			X	X
D4C2 – Primary: The balance of total abundance between the trophic guilds is not adversely affected due to anthropogenic pressures.			X	X			X	X	X
D4C3 – Secondary: The size distribution of individuals across the trophic guild is not adversely affected due to anthropogenic pressures.	X	X							
D4C4 – Secondary (to be used in support of criterion D4C2, where necessary): Productivity of the trophic guild is not adversely affected due to anthropogenic pressures.						X		X	X

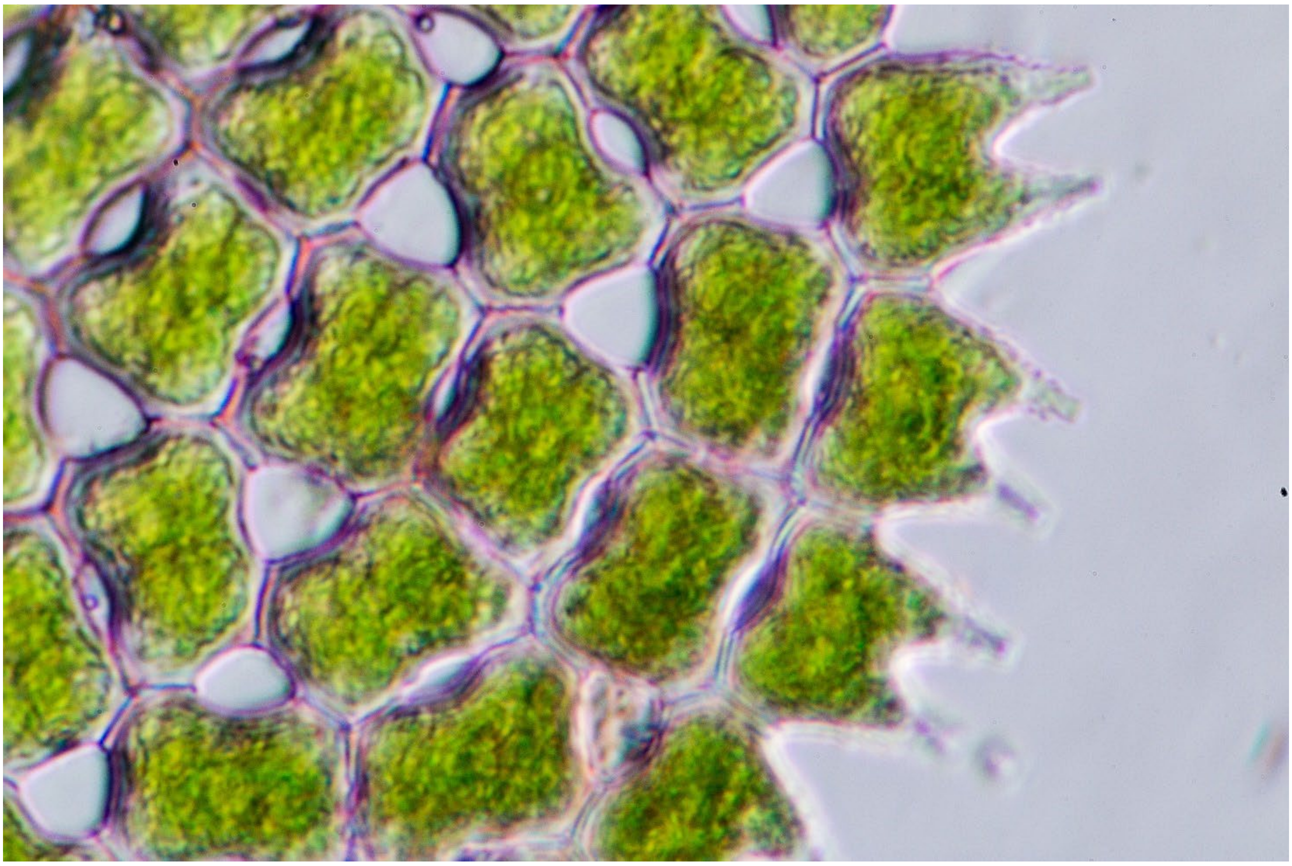
OSPAR acts as a coordination platform in the North-East Atlantic for the regional implementation of the EU Marine Strategy Framework Directive (MSFD) that aims to achieve a Good Environmental Status (GES) in European marine environments, as well as for the coordination of other national frameworks. The characteristics of GES are determined by the individual EU member states, based on criteria elements, threshold values and methodological standards set regionally or at EU level.

Norwegian, Icelandic, United Kingdom, Greenlandic and Faroese marine areas are not covered by the MSFD.

The current food web ecosystem status of the five OSPAR Regions is summarized in the section below from the key information for each indicator considered. Results and information are presented per ecosystem per OSPAR Region with the intention of providing a qualitative description of the parameters that have been assessed. It has not yet been possible to provide an integrated assessment of the state of the ecosystems.

Overall, in the 38 assessments conducted over four Regions all the indicators showed either a failed threshold, trends associated with human activities or a unknown result. Moreover, none of the indicators assessed for food web currently has achieved a threshold value which would be an expression of the desired status of the particular parameter. No integration was done and none of the ecosystems can be assessed for good or not good environmental status. Overall, these results clearly show the need for further data collection and research to support the mitigation of food web effects arising from the impacts of human activities. The results indicate risks for both bottom-up and top-down effects. Trophic cascades affect the entire food web and thereby the functioning of the entire ecosystem.

The status of the Arctic Waters Region is illustrated through region-relevant peer-reviewed literature as well as expert knowledge since it was not possible to assess the region using OSPAR Common Indicators at this time.



Phytoplankton under microscope. © Shutterstock

Arctic Waters (Region I)

The assessments for the Arctic Waters ecosystems are based on third party sources (Arctic Council / (AMAP) / ICES regional sea reports). The assessments constitute a different set of information from the OSPAR Common Indicators.

A novel assessment method is being developed in Norway for evaluating the ecological condition of ecosystems (Jepsen *et al.*, 2020). It will be applied to all of Norway's three seas: the Barents Sea, the Norwegian Sea and the Norwegian sector of the North Sea. The overall question that the assessment aims to answer is whether there has been a change from the defined reference condition ("intact nature", i.e. a situation where the ecosystem is largely unimpacted by modern industrial activities) which can be attributed to anthropogenic impacts. This is done by selecting indicators for seven ecosystem characteristics: primary productivity, biomass distribution among trophic levels, functional groups within trophic levels, functionally important species and biophysical structures, landscape-ecological patterns, biological diversity and abiotic factors. Food webs are thus represented mainly by the indicators of primary productivity (e.g. annual net primary production, timing of spring bloom) and biomass distribution across trophic levels (e.g. in the Barents Sea Arctic and Sub-Arctic ecosystems, the biomass of low trophic level zooplankton, benthos suspensivores, pelagic planktivorous fish and high trophic level seabirds, among others). These indicators are calculated from satellite data (for primary productivity) and from stock assessment and surveys available in the Region. For benthic suspensivore biomass, for example, the indicator is represented by the sum of biomass (kg/km^2)

of megabenthic species (sampled with bottom trawl), weighted by a fuzzy coding for their degree of suspension feeding. Fuzzy coding is a method of indicating to what extent a taxon exhibits selected trait categories, in this case suspension feeding; some functional trait-related indicators such as the ratio of gelatinous zooplankton to krill, or fish size in the community, are also included in other characteristics of the assessment. This last indicator is represented by biomass-weighted community mean body length at maturity. Species-specific lengths at maturity were taken from the literature (Wiedmann *et al*., 2014). Climate change is considered currently to be a stronger driver of change than fishing for the food web in the Barents Sea*, with substantially increasing air and water temperatures causing loss of sea ice and habitats for ice-associated species in the Arctic region.* There is strong evidence of important changes in the upper and lower trophic levels, suggesting important changes in trophic structure, in the Norwegian sector of the Arctic Barents Sea. However, in the sub-Arctic part, there is low or intermediate evidence of changes in parts of the upper (high trophic level seabirds) and lower (suspension feeders) trophic levels. There are major uncertainties linked to the short time series available for most of the biological groups.

Following the assessment of the seven ecosystem characteristics (primary productivity, biomass distribution among trophic levels, functional groups within trophic levels, functionally important species and biophysical structures, landscape-ecological patterns, biological diversity and abiotic factors) a panel of fisheries, oceanographic and marine biology experts concluded that primary production, biomass distribution within trophic levels, landscape-ecological patterns and abiotic factors showed substantial deviations from the reference conditions. By contrast, the panel found more limited deviation for functional groups within trophic levels and biological diversity, and no deviation for functionally important species and biophysical structures. In the Atlantic region of the Barents Sea, substantial deviations were assessed for landscape-ecological patterns and abiotic factors, while the remainder were found to have no deviation from expected characteristics (Siwertson *et al.*, in prep, 2022).

Greater North Sea (Region II)

In the Greater North Sea Region, one Common Indicator failed its threshold value, and the other Common Indicators and Candidate indicators show a trend that is associated with human activities (**Table S.3**). The two indicators for the first two layers of the food web (FW2 and PH1 / FW5) revealed trends within coastal and shelf ecosystems and unknown trend within the variable salinity ecosystem. All indicators for demersal fish communities either fail the threshold value or show a declining trend associated with human activities, indicating that this component of the food web is under pressure.

Table S.3: Trends for Common and Candidate Indicators within each ecosystem for Greater North Sea based on each indicator's results. NA = Not Assessed; FC2 = threshold failed in shelf ecosystems; FW3 = downward trend (deteriorating state) in shelf ecosystems; FW5 = downward trends in holoplankton and upward trends in meroplankton in shelf ecosystems; FW2 = downward trends in variable salinity, coastal and shelf ecosystems; FC3 = downward trend (deteriorating state) in shelf ecosystems; FW7 = downward trend (deteriorating state) for planktivorous fish and no trend (unknown implications) for sub-apex demersal predators in shelf ecosystems; and FW9= no trend (unknown implications) in coastal and shelf ecosystems, *This pilot assessment was done in specific areas and did not cover the whole region

Greater North Sea	Common indicator			Candidate indicator				
	FC2	FW3	PH1/FW5	FW2	FC3	FW7		FW9
Trophic guild	Sub-apex demersal predators	Sub-apex demersal predators	Pelagic primary producer; Secondary producer	Pelagic primary producer	Sub-apex demersal predators	Planktivorous fish	Sub-apex demersal predators	Pelagic primary producers; Secondary producer; Benthic filter feeding invertebrate; Benthic feeding invertebrate; Planktivorous fish and invertebrate; Sub-apex pelagic predators; Sub-apex demersal predators; Mammal apex predators; Fish apex predators
Variable salinity ecosystems	N/A	N/A	no trend	trend	N/A	N/A	N/A	N/A
Coastal ecosystems	N/A	N/A	no trend	trend	N/A	N/A	N/A	no trend*
Shelf ecosystems	threshold failed	trend	trend	trend	trend	trend	no trend	no trend*
Oceanic/beyond shelf ecosystem	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Variable salinity ecosystems

Plankton community assessment:

For variable salinity ecosystems, the Common Indicator Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) indicated that dinoflagellates and larval fish have been increasing in abundance according to long-term trends. Holoplankton, large copepods and small copepods indicated significant downward trends; however, plankton monitoring datasets were only available for a limited number of assessment units, with significant gaps in time series. Therefore, lower confidence must be assigned to these results, particularly for the zooplankton lifeform time-series. For this Common Indicator, no clear links could be made between changes in lifeform abundance and anthropogenic pressures, owing to the generally low internal confidence among the assessed time-series. Contrary to the PH1 / FW5 Common Indicator, it was possible to complete the Candidate Indicator Pilot Assessment of Primary Productivity (FW2) for a large proportion of assessment units (89% of assessment units covered). The results revealed a significant downward trend in primary production, as also evidenced by the long-term evolution of primary production in the North Sea (e.g., Capuzzo *et al*., 2018). As with the decreasing phytoplankton biomass for the common indicator Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2), the most important predictor of decreasing primary production was decreasing concentration of dissolved inorganic phosphate.

Coastal ecosystems

Plankton community assessment

For coastal ecosystems, the Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) Common Indicator revealed significant upward trends in meroplankton and larval fish abundance, which may have been associated with rise in sea surface temperatures and increasing salinity, respectively. While the data used to assess trends exhibited a high degree of confidence and the majority of assessment units were well represented, except for the gelatinous zooplankton lifeform, a high degree of variability resulted from linking trends in lifeform abundance with environmental pressures, and thus the associations with change in sea surface temperature and salinity lacked confidence. The Candidate Indicator Pilot Assessment of Primary Productivity (FW2) revealed a significant downward trend in primary production which was attributed to increasing sea surface temperature. Similar results were evidenced by the long-term evolution of primary production in the North Sea (e.g., Capuzzo *et al*., 2018).

Multitrophic level assessment

Changes in trophic structure and functioning derived by Ecological Network Analysis (ENA) indices, (Candidate Indicator Pilot Assessment of Ecological Network Analysis Indices, FW9) are very much linked to changes in primary productivity. In the coastal North Sea, primary production decreased from 2009 to 2014 but has increased since 2015. This has been accompanied by an increase in the biomass of benthic filter feeding invertebrates and benthic feeding birds (in 2016), which probably benefit from the increasing biomass of filter feeding invertebrates. However, an overall decrease in benthic filter feeding invertebrates was found over time. The Detritivory: Herbivory ratio has increased since 2015. Flow diversity is a measurement of the number of interactions and evenness of energy flows. As with the biodiversity index, a high value shows a highly diverse and well-developed system. Since all models have the same number of compartments, energy flows between trophic guilds seem to be more unevenly distributed. As in the case of the coastal North Sea food web, ENA indices in the Seine Bay model are linked to changes in primary production and to the biomass of phytoplankton. By contrast with the Elbe Plume, the Finn Cycling Index decreased from 2000 to 2014 while the Detritivory:Herbivory ratio increased from 2000 to 2006 / 2007 but then decreased until 2015. These changes mainly related to the pelagic parts of the food web, including a strong increase in the biomass of zooplankton, bacteria and zooplanktivorous fish.

Shelf ecosystems

Plankton community assessment

For shelf ecosystems, the Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) Common Indicator revealed that diatoms, meroplankton, and larval fish underwent significant upward long-term trends, while dinoflagellates, holoplankton, and small copepods experienced significant downward trends. For meroplankton and holoplankton, the abundance trends were linked to rising sea surface temperatures with a high degree of consistency, while the increase in larval fish abundance was associated with decreasing light attenuation. While no data were available to assess trends for gelatinous zooplankton, there was high confidence and high representation of assessment units for all time-series assessed. The results revealed a significant downward trend in primary production, the most important predictor of this being an increase in the ratio of nitrogen to phosphorous (N/P ratio). In turn the latter is a consequence of efforts to combat eutrophication, with greater reductions achieved for phosphorous loading than for nitrogen. The results presented some deviation, as long-term decrease in primary production in the North Sea has not been linked to increasing N/P ratio (e.g., Capuzzo *et al*., 2018).

Demersal fish community assessment

The fish community indicators of size structure, namely Proportion of Large Fish (Large Fish Index) (FC2) and Size Composition in Fish Communities (FW3), and of species composition, namely the Candidate Indicator Pilot Assessment of Mean Maximum Length of Fish (FC3), demonstrated long-term decline of this ecosystem component in the Greater North Sea. The assessments show a common pattern of decreases between the

1980s and 2000 that was consistent between scientific surveys and indicators and that has been linked to high levels of fishing mortality in demersal fish stocks (Greenstreet *et al*., 2011).

Within sub-divisions of the Greater North Sea, the Candidate Indicator Pilot Assessment on Mean Maximum Length of Fish (FC3) showed overall patterns of decline that were driven by a loss of the species that grow large in the southern North Sea sub-divisions, with no change overall in the north. The typical length of fish (FW3) Common Indicator demonstrated an overall decline in the observed sizes of individual fish in all areas that was followed by a recovery in the northern North Sea (north-eastern and Orkney-Shetland sub-divisions) during the 2000s and a variable pattern with no clear trend in the 2010s. The depletion of species that can grow large in the south (FC3) suggests that the recovery in community size structure (FW3) back towards the previous high proportion of large fish in the early 1980s (FC2) may have been hindered. However, provided that all commercial species are fished under fishing mortality targets consistent with Maximum Sustainable Yield, increases towards a new higher equilibrium are expected within two decades (Spence *et al*., 2021).

Evidence of continued recoveries in the eastern part of the Channel sub-division were evident in the proportion of large fish (FC2) and species composition (FC3), with mixed patterns in typical length (FW3).

Feeding guild assessment

The spatial gradient for planktivore biomass and species richness showed an increasingly northward trend in the shelf ecosystem of the Greater North Sea, with high points in the north-western North Sea and Kattegat, in the Candidate Indicator Pilot Assessment of Feeding Guilds (FW7). Benthivore biomass was uniformly distributed across the Region, with higher species richness in the north-western North Sea and Kattegat. The spatial gradients for pisco-crustivore (i.e., fish that feed omnivorously, largely preying on crustaceans and fish) and piscivore biomass and species richness increasingly moved north and west across the Region. These patterns are probably heavily influenced by natural, large-scale gradients in environmental conditions. The temporal dynamics of planktivore biomass showed an increase in the Channel and a minor decrease in the north-western North Sea but no significant change elsewhere. Planktivore species richness was increasing across the northern North Sea, Kattegat and the Channel with no significant change elsewhere. Benthivore biomass showed increases in the southern North Sea and decreases in the Kattegat, with little change elsewhere. Benthivore species richness was increasing in the English Channel, decreasing in the north-eastern North Sea and Kattegat with limited change elsewhere. Pisco-crustivore biomass was increasing in the southern North Sea but decreasing across much of the north, with increases in species richness in the north-west, the English Channel and the south-east but decreases elsewhere. Piscivore biomass showed contrasting directions of change in the western North Sea, with decreases off the east coast of Scotland and northern England but increases further south, with limited change elsewhere. Piscivore species richness was increasing across the north and the Kattegat but decreasing in the west, with limited change in the southern North Sea.

Oceanic / beyond shelf

Although the Greater North Sea (Region II) intersects with a small portion of an Oceanic / beyond shelf assessment units, this ecosystem was not assessed for the Greater North Sea since the ecosystem shares far greater overlap with the Bay of Biscay and Iberian Coast (OSPAR Region IV).

Celtic Seas (OSPAR Region III)

In the Celtic Seas Region, one Common Indicator failed the threshold value and the other indicators show trends that are associated with human activities (**Table S.4**). Within coastal ecosystems, only the lower trophic levels of the pelagic food web were assessed and showed trends that were considered linked to negative impacts from human activities.

Table S.4: The trends for Common and Candidate indicators within each ecosystem for Region III are given based on each indicator results. NA = not assessed; FC2 = threshold failed in shelf ecosystems; FW3= downward trend (deteriorating state) in shelf ecosystems; FW5 = downward trends for four plankton lifeforms in coastal ecosystems, with downward trends in dinoflagellates and holoplankton and upward trends in meroplankton in shelf ecosystems; FW2= downward trends in variable salinity and shelf ecosystems and no trend in coastal ecosystems; FC3 = no trend (unknown implications) in shelf ecosystems; and FW7= no trend (unknown implications) for planktivorous fish and increasing trend (improving state) for sub-apex demersal predators in shelf ecosystems

Celtic Seas	Common indicator			Candidate indicator			
	FC2	FW3	PH1/FW5	FW2	FC3	FW7	
Trophic guild	Sub-apex demersal predators	Sub-apex demersal predators	Pelagic primary producer; Secondary producer	Pelagic primary producer	Sub-apex predators demersal	Planktivorous fish	Sub-apex demersal predators
Variable salinity ecosystems	N/A	N/A	no trend	trend	N/A	N/A	N/A
Coastal ecosystems	N/A	N/A	trend	no trend	N/A	N/A	N/A
Shelf ecosystems	threshold failed	trend	trend	trend	no trend	trend	no trend
Oceanic/beyond shelf ecosystem	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Variable salinity ecosystem

Plankton community assessment

For variable salinity ecosystems in the Celtic Seas, the Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) revealed that dinoflagellates have been undergoing significant upward long-term trends, while all other planktonic lifeforms have undergone significant downward trends. However, there was very low representation of assessment units for all zooplankton lifeforms. For diatoms, downward abundance trends were linked to an increase in the ratio of nitrogen to phosphorous. For large copepods, which were only assessed at a single fixed-point monitoring station, the downward trend was linked to a rise in sea surface temperature. For the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), the pilot assessment results revealed a significant decrease in primary production linked to a modelled decreasing trend in pH. Relevant literature on primary production trends in the area is scarce. While the present assessment identifying a decrease in primary production is congruent with Tilstone *et al.,* (2022), Hernvann *et al.,* (2020) have noted long-term stability in primary production in the Celtic Sea. In addition, the existing literature has not yet investigated the link between ocean acidification and primary production over long-term timescales. Changes in pH arise from concentration of dissolved inorganic carbon, which in turn depends on phytoplankton activity (resulting in the balance between production and respiration) and CO_2 level. Since phytoplankton activity within coastal ecosystems (including variable salinity and coastal habitats) is subject to large diel variability but is CO_2 neutral over long timescales (Duarte *et al*., 2013), it is unclear at this stage if the decrease in primary production in the variable salinity and coastal habitats assessed here is due to decreasing pH or if it is the cause of decreasing pH. Further investigations should untangle the links between phytoplankton activity (production and respiration) and long-term concentration of dissolved inorganic carbon and anthropogenic CO_2.

Coastal ecosystems

Plankton community assessment

For coastal ecosystems, the Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) showed that dinoflagellates, holoplankton, large copepods and small copepods all underwent significant downward trends linked to rising sea surface temperatures, and for holoplankton, to decreasing modelled pH. No data were available for the gelatinous zooplankton lifeform. There was high confidence for all assessed time series and high spatial representation of assessment units. For the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), the pilot assessment results revealed a significant downward trend in primary production probably linked to decreasing modelled pH. For the same reason as stated with variable salinity habitats, it is currently unclear whether the decrease in primary production detected in this assessment was the consequence of ocean acidification.

Shelf ecosystems

Plankton community assessment

For shelf ecosystems of the Celtic Seas, the Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) revealed that meroplankton underwent significant upward trends, while dinoflagellates and holoplankton indicated significant downward trends. For dinoflagellates, the changes were linked to an increase in the ratio of nitrogen to phosphorous. For meroplankton, the changes were linked to increasing sea surface temperature, and for holoplankton the changes were linked to ocean acidification. No data were available for gelatinous zooplankton; however, there was high confidence for all time-series assessed and high spatial representation of assessment units. The Candidate Indicator Pilot Assessment of Primary Productivity (FW2) pilot assessment results revealed a significant downward trend in primary production linked to a decreasing trend in modelled pH in shelf ecosystems. While the present assessment identified a decrease in primary production congruent with Tilstone *et al*., (2022), Hernvann *et al*., (2020) noted long-term stability in primary production in the Celtic Sea. The decrease in primary production in this assessment is probably related to shallower mixed layer depth, which is predicted in the future for the Irish Sea (Olbert *et al*., 2012).

Demersal fish community assessment

The fish community indicators of size-structure, Proportion of Large Fish (Large Fish Index) (FC2) and Size Composition in Fish Communities (FW3), demonstrate long term decline in status in the Region. Since the results are all at a lower level than during previous assessment they indicate a status that cannot be interpreted as good. No clear pattern was evident in the species composition Candidate Indicator Pilot Assessment of Mean Maximum Length of Fish (FC3).

Following the depletion observed in the 1980s, some surveys of the Proportion of Large Fish (Large Fish Index) (FC2) in the Region show evidence of ongoing recoveries during the 2000s and 2010s. At smaller spatial scales, mean maximum length (FC3) and size composition (FW3) found evidence of mixed patterns, with increases in some sub-divisions (including the Irish Sea, Bristol Channel and much of the area south of Ireland) and decreases elsewhere (including the deeper waters at the shelf edge).

Feeding guild assessment

Planktivore biomass was highest off the north-west coast of Scotland and around the north and west coast of Ireland, while their species richness was highest off the north-west coast of Scotland and in the north of the Celtic Sea in the Candidate Indicator Pilot Assessment of Feeding Guilds (FW7). Benthivore biomass was highest in the Irish Sea and off the west coast of Ireland, with their species richness highest in the Irish Sea and in all coastal areas across the Region. Pisco-crustivore and piscivore biomass and species richness tended to increase northwards and westwards across the region.

Regarding temporal changes, planktivore biomass was increasing to the west of Scotland and north of the island of Ireland, with minor patchy increases in the north-eastern Celtic Sea and similarly patchy decreases in the north-western Celtic Sea and limited change elsewhere. Planktivore species richness was increasing in the southern Irish Sea and north-eastern Celtic Sea, but decreasing off the north-west coast of Ireland and remaining relatively stable elsewhere. Benthivore biomass showed updard trends, from the north-eastern Celtic Sea through the Irish Sea and to the West of Scotland, with one area south of Ireland showing a slight decrease and insignificant change elsewhere. Benthivore species richness showed contrasting directions of change, with increases in the south and decreases in the north, with insignificant change in the areas between them. Pisco-crustivore biomass was increasing over much of the study region, with one area between Scotland and Northern Ireland showing a slight decrease. Pisco-crustivore species richness was increasing in the south west of the region and to the north but decreasing around Northern Ireland and in the Bristol Channel. Piscivore biomass was also increasing over much of the study region, with a relatively small area of decline along the west coast of Ireland. Piscivore species richness was increasing in the south of the region, with limited change elsewhere.

Oceanic / beyond shelf

While the Celtic Seas (Region III) intersects a small portion of an Oceanic / beyond shelf assessment units, this ecosystem was not assessed for the Celtic Seas, since it shares far greater overlap with the Bay of Biscay and Iberian Coast (OSPAR Region IV).

Bay of Biscay and Iberian Coast (OSPAR Region IV)

In the Bay of Biscay and Iberian Coast Region, one Common Indicator fails the threshold value and three other showing trends that are associated with human activities. Plankton-related indicators (PH1 / FW5; FW2) were assessed in shelf and ocean / deep ecosystems showing trends associated with human activities in both ecosystem types. The status of fish-related indicators was classed as unknown for all habitat types assessed. An overall resilient bentho-demersal community due to persistent pressure over time could explain the stable trends observed in this specific ecosystem compartment.

Table S.5: The trends for each Common and Candidate indicator within each ecosystem for Region IV are given based on each indicator result. NA = not assessed; FC2 = no trend (unknown implications) in shelf ecosystems; FW4 = no trend (unknown implication) in the three habitat types assessed; FW3 = no trend (unknown implications) in shelf ecosystems; FW5 = downward trends for holoplankton, small copepods and large copepods in shelf ecosystems, and downward trends in small and large copepods in oceanic/beyond shelf ecosystems; FW2 = downward trend in shelf and oceanic/beyond shelf ecosystems; FC3 = no trend (unknown implications) in shelf ecosystems; and FW7 = downward trend (deteriorating state) for planktivorous fish and upward trend (improving state) for sub-apex demersal predators in shelf ecosystems

Bay of Biscay and Iberian Coast	Common indicator				Candidate indicator			
	FC2	FW4	FW3	PH1/FW5	FW2	FC3	FW7	
Trophic guild	Sub-apex demersal predators	Benthic filter feeding invertebrates; Benthic feeding invertebrates; Planktivorous fish and invertebrates; Sub-apex pelagic predators; Sub-apex demersal predators	Sub-apex demersal predators	Pelagic primary producer; Secondary producer	Pelagic primary producer	Sub-apex demersal predators	Planktivorous fish	Sub-apex demersal predators
Variable salinity ecosystems	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Coastal ecosystems	N/A	no trend	N/A	no trend	N/A	N/A	N/A	N/A
Shelf ecosystems	no trend	no trend	no trend	trend	trend	no trend	trend	trend
Oceanic/beyond shelf ecosystem	N/A	no trend	N/A	trend	trend	N/A	N/A	N/A

Variable salinity habitat

Plankton community assessment

For variable salinity habitats, there were no suitable plankton monitoring data available to evaluate the pelagic habitat indicators. For the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), the assessment was also not possible because of lack of data.

Coastal ecosystems

Plankton community assessments

For coastal habitats, only phytoplankton data were available to inform Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1/FW5). Further, trends in diatoms and dinoflagellates in this case had to be represented by a dataset which only recorded specimens from the genera Pseudo-nitzschia and Dinophysis. This indicator showed that dinoflagellates have undergone significant upward long-term trends. While the assessed time-series had moderate confidence, there was poor spatial representation of assessment units and no clear links could be drawn between changes in lifeform abundance and environmental pressures. For the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), assessment was not possible due to lack of data.

Changes in average trophic level of marine predators assessment

The Common Indicator Assessment on Changes in Average Trophic Level of Marine Consumers (FW4) was assessed in coastal ecosystems in only two sub-divisions of the Region: French shelf and Gulf of Cadiz.

Regarding the upper trophic levels, the MTL indicator showed a significantly increasing trend in the southernmost areas of the French sub-division, whereas no significant trend was observed in Gulf of Cadiz. Taking into account other scenarios (including mesopredators), downward trends were detected in Gulf of Cadiz. Regarding the spatio-temporal approach at local scale, no significant changes were observed in coastal areas under any of the scenarios in the French shelf. In Gulf of Cadiz however, downward trends were detected in the temporal approach, concentrated in local coastal areas. The contrasting trends observed in coastal areas indicate an uncertain status for MTL in this ecosystem.

Shelf ecosystems

Plankton community assessment

For shelf ecosystems in the Bay of Biscay and Iberian Coast, the Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1 / FW5) revealed that diatoms, holoplankton, meroplankton, large copepods, and small copepods all showed significant downward trends. No data were available to assess the gelatinous zooplankton lifeform from the Continuous Plankton Recorder; however, there was generally high confidence across the assessed time-series and moderate spatial representation of assessment units. The decreasing trends in holoplankton, large copepods, and small copepods were all linked to rising sea surface temperatures. Concerning the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), the pilot assessment results revealed a significant downward trend in primary production. Spatial assessment was limited to one area (representing 17% of all sub-divisions in the habitat), resulting in low confidence in those results. Primary production in the Bay of Biscay and Iberian Coast is subject to large uncertainty regarding their future projection (Holt *et al*., 2014). The decrease identified in primary production reported in the current assessment was associated with a decrease in wind speed, which is contradictory to the increasing wind speed in the Bay of Biscay shown by Chust *et al*., (2022).

Demersal fish community assessment

The fish community indicators of size-structure, namely Proportion of Large Fish (Large Fish Index) (FC2), Size Composition in Fish Communities (FW3), and of species composition, namely the Candidate Indicator Pilot Assessment of Mean Maximum Length of Fish (FC3), demonstrated no clear pattern of change in the Bay of Biscay and Iberian Coast. This result has unclear implications.

Changes in average trophic level of marine consumers assessment

Considering top predators alone, the Common Indicator Assessment on Changes in Average Trophic Level of Marine Consumers (FW4) showed significant upward trends in the French and Gulf of Cadiz shelves, in contrast to the downward trends observed in the North Iberian and Portuguese shelves. However, when including mesopredators in the calculations, the trends became positive or stable in most of scenarios. In the spatio-temporal approach, a decline of the indicator was observed in the westernmost area of the North Iberian sub-division, more pronounced in shelf ecosystems than in deeper waters. In the Portuguese sub-division, little evidence of MTL changes at the local scale was observed in any of the scenarios, with a very small number of significant trends scattered across the area. These results at the local scale mostly agree with the temporal trends obtained when analysing the sub-division as a whole, which highlights the greater stability/resilience of the Portuguese sub-division in relation to the adjacent areas. Gulf of Cadiz displayed significant positive trends for top predators and mesopredators in this ecosystem, scattered across the southern part of the sub-division. Overall, the contrasting trends observed in the different scenarios by sub-division indicate an uncertain status for this indicator in shelf ecosystems.

Feeding guild assessment

The Candidate Indicator Pilot Assessment of Feeding Guilds (FW7) results showed that planktivore biomass and species richness was highest in the Bay of Biscay, decreasing southwards. Benthivore biomass was also highest in the Bay of Biscay and decreased southwards, whereas benthivore species richness was highest in the north of the Bay of Biscay and along the coast of northern Spain. Pisco-crustivore biomass and species richness was highest in the north of the Bay of Biscay and along the coast of northern Spain. Piscivore biomass was highest in the Bay of Biscay and along the coast of Portugal, with species richness highest in the north of the Region.

Temporal changes showed that planktivore biomass had decreased across the Bay of Biscay, increasing at the north-western tip of Spain but relatively constant elsewhere. Change in planktivore species richness and benthivore biomass and species richness was limited to patchy increases along the west coasts of Portugal and Spain. There were increases in pisco-crustivore and piscivore biomass and species richness in the Bay of Biscay and in patches along the west coasts of Portugal and Spain, with patchy decreases in piscivore species richness along the north coast of Spain.

Oceanic/beyond shelf

Plankton community assessment

For oceanic / beyond shelf ecosystems, the Common Indicator Assessment on Changes in Phytoplankton and Zooplankton Communities (PH1/FW5) demonstrated that meroplankton underwent significant upward trends. All other lifeforms underwent significant downward trends except for gelatinous zooplankton, which were not assessed due to a lack of data. Downward trends in holoplankton, large copepods, and small copepods were all linked to rising sea surface temperature. Despite the low spatial representation of assessment units for informing PH1/FW5, the assessment units considered for this pelagic habitat were spatially extensive and incorporated a very large quantity of samples. Further, there was high confidence in the time-series used to assess PH1/FW5. Concerning the Candidate Indicator Pilot Assessment of Primary Productivity (FW2), the pilot assessment results revealed a significant downward trend in primary production. Spatial assessment was limited to one area representing 20% of all sub-divisions in the habitat, resulting in low confidence in those results. Primary production in the Bay of Biscay and Iberian Coast is subject to large uncertainty as to its future projection (Holt et al., 2014). The decrease in primary production identified in the current assessment was associated with a decrease of light in the water column. If phytoplankton productivity (FW2) is linked to the relevant pelagic and eutrophication assessments, the increase in light attenuation could be due to increase in chlorophyll-a concentration, which was evidenced by the Common Indicator Assessment Concentrations of Chlorophyll-a in the Greater North Sea, Celtic Seas and Bay of Biscay and Iberian Coast but not by the Common Indicator Assessment of Changes in Phytoplankton Biomass and Zooplankton Abundance (PH2) assessment.

Changes in average trophic level of marine predators assessment

Contrasting trends were observed in the evolution of the indicator when looking at top predators, showing a decline in deeper areas of the North Iberian sub-division in contrast to the positive trends observed in Gulf Cadiz for the Common Indicator Assessment on Changes in Average Trophic Level of Marine Consumers

(FW4). When mesopredators are included, positive trends emerge in all sub-divisions except for Portuguese slope, which displayed stable trends. Regarding the spatio-temporal approach, trends appeared heterogeneously and patchily distributed in all sub-divisions. Again, the contrasting trends of the indicator observed in deeper areas seemed to indicate an unclear status for the average trophic level of the bentho-demersal communities in this habitat type.

Wider Atlantic (OSPAR Region V)

In the Wider Atlantic Region, the results of the assessment showed that the two Common Indicators that were assessed had an unknown status due to no trend being detected and the reference condition not being known. Although, this might seem more positive compared with the other Regions, the result is due to the lack of data, and this should be taken into account in the interpretation of the outcome.

Table S.6: The trends for Common and Candidate indicators within each ecosystem for Region V based on each indicator result. NA = Not Assessed; FC2 = no trend (unknown implications) in shelf ecosystems; FW3 = no trend (unknown implications) in shelf ecosystems; FC3 = no trend (unknown implications) in shelf ecosystems; FW7 = increasing trends (improving state) for planktivorous fish and sub-apex predators in shelf ecosystems; and FW9 = no trend (unknown implications) in oceanic/beyond shelf ecosystems, * This pilot assessment was done on a specific area and did not cover the whole Region

Wider Atlantic	Common indicator		Candidate indicator			
	FC2	FW3	FC3	FW7		FW9
Trophic guild	Sub-apex demersal predators	Sub-apex demersal predators	Sub-apex demersal predators	Planktivorous fish	Sub-apex demersal predators	Pelagic primary producers; Secondary producer; Benthic filter feeding invertebrates; Benthic feeding invertebrates; Planktivorous fish and invertebrates; Sub-apex pelagic predators; Sub-apex demersal predators; Mammal apex predators; Fish apex predators
Variable salinity ecosystems	N/A	N/A	N/A	N/A	N/A	N/A
Coastal ecosystems	N/A	N/A	N/A	N/A	N/A	N/A
Shelf ecosystems	no trend	no trend	no trend	trend	trend	N/A
Oceanic/beyond shelf ecosystem	N/A	N/A	N/A	N/A	N/A	no trend*

Shelf ecosystems

Demersal fish community assessment

No long-term changes were evident in the Wider Atlantic for the size-structure and community composition indicators Proportion of Large Fish (Large Fish Index) (FC2), Size Composition in Fish Communities (FW3) and the Candidate Indicator Pilot Assessment of Mean Maximum Length of Fish (FC3). The implications are unknown.

Feeding guild assessment

The Candidate Indicator Pilot Assessment of Feeding Guilds (FW7) showed that planktivore and piscivore biomass was high in the Wider Atlantic in the Porcupine Bank survey, and lower to the west of Scotland at the Rockall Bank. Benthivore biomass showed no clear gradient of change between the two surveyed areas in the Wider Atlantic, whereas pisco-crustivore biomass was highest in the Rockall Bank survey. The species richness of planktivores, benthivore and piscivores was higher to the west of Ireland and lower to the west of Scotland, with no clear gradient in pisco-crustivore species richness between the surveyed areas.

Temporal changes of planktivores showed patchy increases in biomass and species richness across the surveyed areas. Benthivore biomass was increasing in the Rockall Bank survey and decreasing to the west in the Porcupine Bank survey, with limited change elsewhere. Benthivore species richness was increasing in the Porcupine Bank survey, with no clear change elsewhere. Pisco-crustivore biomass was increasing in the Rockall Bank survey, but there was limited change in biomass elsewhere and no change in species richness across either the Rockall Bank or the Porcupine Bank surveys. Piscivore biomass and species richness showed increases across both Rockall Bank and Porcupine Bank surveys.

Oceanic / beyond shelf

Multitrophic Level assessment

The Candidate Indicator Pilot Assessment of Ecological Network Analysis Indices (FW9) was assessed for a deep-sea ecosystem in the Wider Atlantic. A globally decreasing trend for biomass at all trophic levels was evident in the Azores food web model. An overview of the relative contribution by the low and mid-trophic level groups that shape the biomass spectra to the diets of top predators (TL>4) suggests two distinct energy pathways reaching the top of the chain. Model-derived ENA indicators were estimated between 1997 and 2018. The inter-annual variability of the indicators was strongly influenced by the availability of primary production in the system. No significant changes of ENA indices were found over time. The only exception was the resilience indicator, suggesting that the resilience of the ecosystem is decreasing.

Knowledge gaps and way forward towards an integrated assessment of food webs

The functioning of marine food webs, and particularly the assessment of their status, is a complex task owing to the intrinsic complexity of marine networks and trophic interactions. To better assess the state of food webs an integrated approach should be developed and implemented, taking into account all trophic guild compartments of the ecosystem. Rigorous, consistent and coordinated monitoring programmes are being implemented by Contracting Parties in some cases (e.g., groundfish surveys). However, many trophic guilds are still under-sampled (e.g., zooplankton biomass, which is used in the candidate indicator FW6) and are therefore underrepresented in indicators and models worldwide. Most of the food web indicators developed so far focus on specific functional groups (e.g., phytoplankton, fish). However, to assess a network where every node is interconnected, information on as many compartments as possible is needed. From an operational point of view, this is a difficult task which has emerged as one of the main challenges in the assessment of food web status. The complexity of assessing the structure and functioning of food webs is a common issue in all OSPAR Regions.

Further development of food web indicators should be directed towards more integrative and process-based indicators, operationalising the ENA approach. Most of the existing monitoring data can be used to construct the network to be analysed through the model, and most food web, benthic and pelagic habitat indicators can benefit from monitoring of the parameters needed for ENA indices. Future efforts should focus on making this mutual benefit a reality. To do this, the spatial scale and resolution of the assessments (regional vs local) should be agreed among the Contracting Parties. Food web indicators should also be understandable for policy makers and the general public. How to convey the results of the set of indicators developed under ENA indices (FW9), turning complexity into simplicity, is an issue that needs to be addressed in the future.

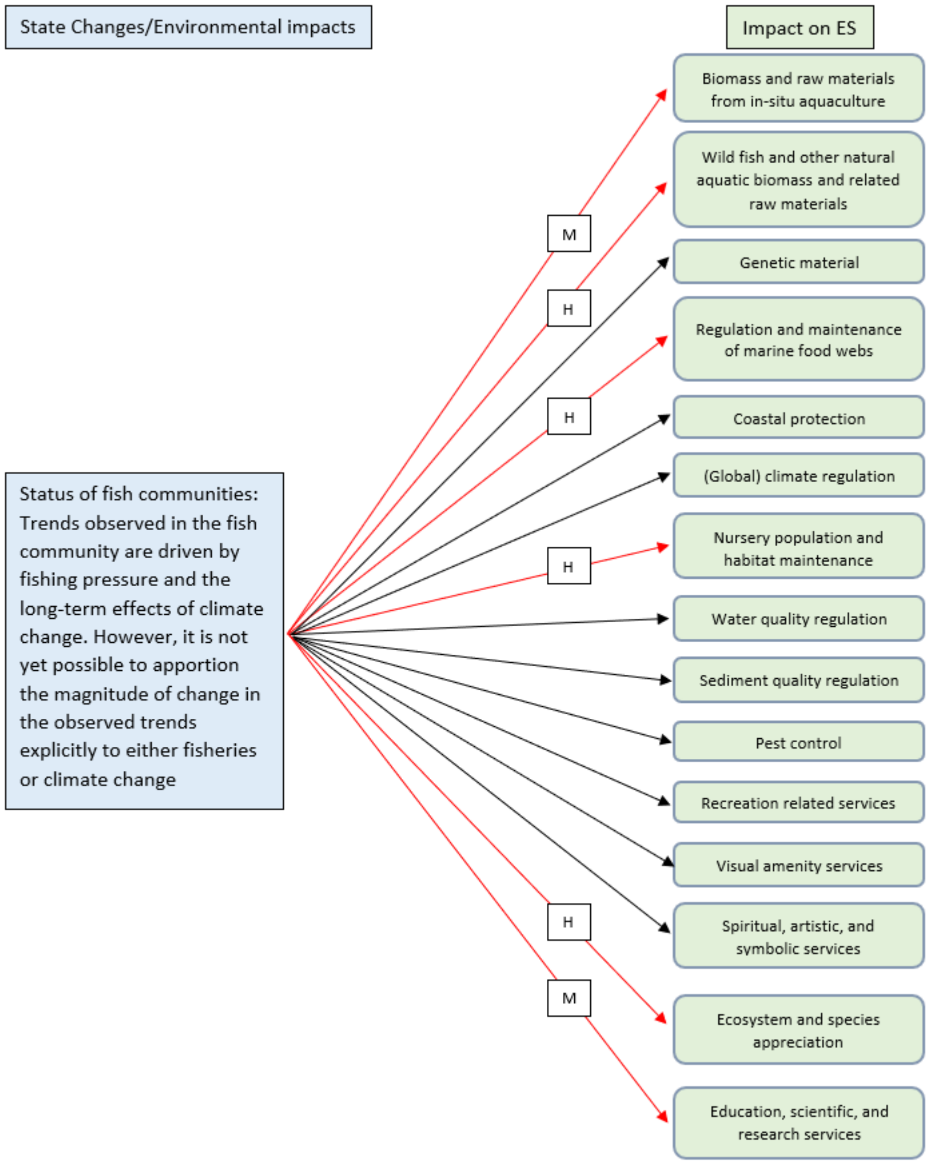
In the next five years future work will explore the changes in food web indicators due to climate change impacts within IPCC scenarios. In order to capture the impacts of human activities and climate change on food webs, in terms of changes in trophic and non-trophic interactions and the supply of ecosystem services, there is a need to develop integration methods and cumulative effects assessments further (e.g., Piet *et al*., 2021). As an example, further development of ecosystem modelling approaches will allow the exploration of different scenarios addressing the impacts of fishing and climate change on food webs (Thorpe *et al*., 2022; Spence *et al.*, 2021).

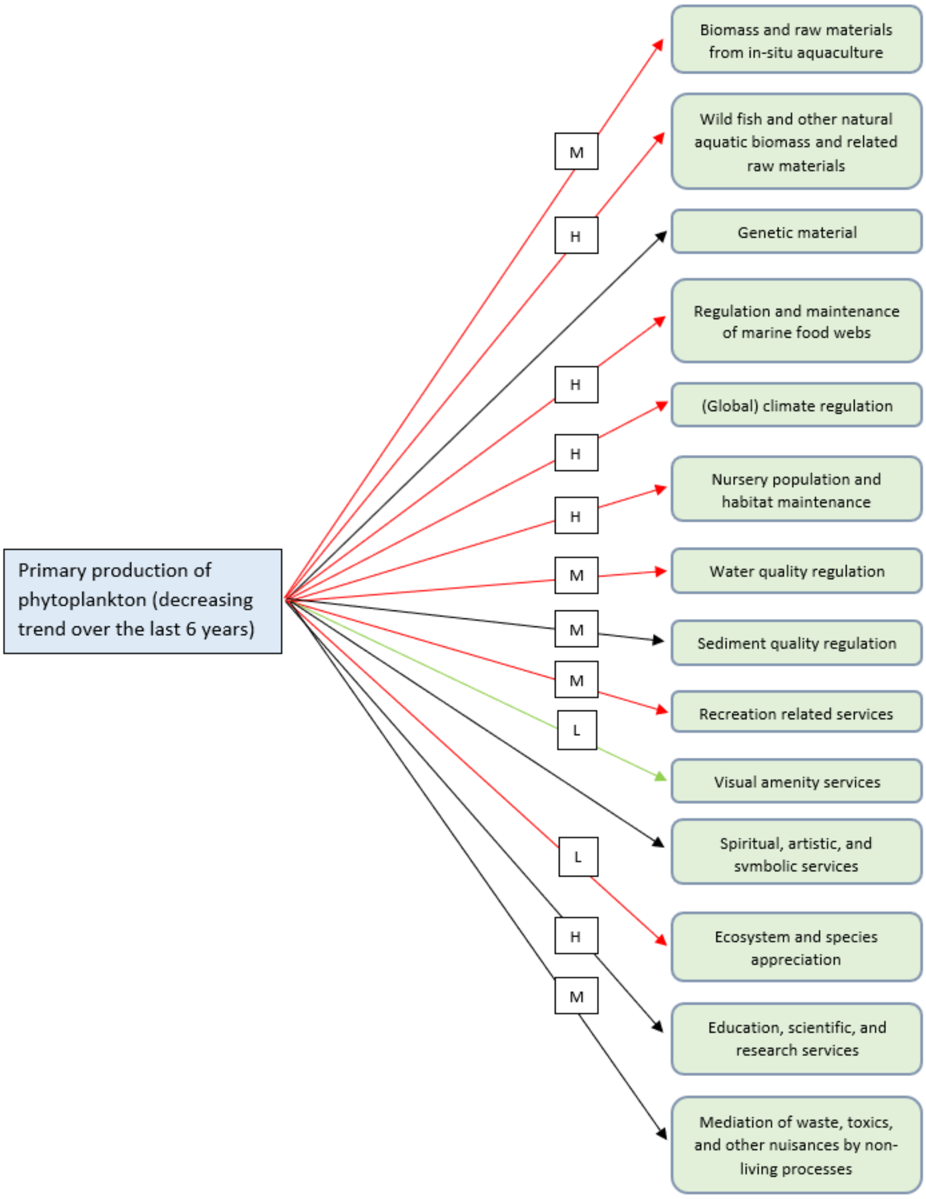
I – Impact (on ecosystem services)

Impacts on the provision of ecosystem services by marine food webs

Given the current changes occurring in marine food webs, no positive outcome for the ecosystem services they provide are observed or expected, except that research and education activities will probably increase due to the generally unknown status of food webs. In addition to climate change, fishing pressures, physical disturbance, nutrient inputs, introduction of non-indigenous species and underwater noise can all impact food web structure and functioning. Adverse changes in marine food web structure, richness and functioning can affect the provision of ecosystem services by species including all trophic levels in marine ecosystems.

This section evaluates the impact that changes in the environmental state of food webs, as described in the '<u>State</u>' section, have on the ecosystem services that the North-East Atlantic provides. The section was developed on the basis of a literature review combined with expert judgement, using the same methodology across all thematic assessments. Several workshops involving ecosystem services experts and food-web experts were held to discuss and agree the presented results. A detailed description of the anthropogenic pressures that impact food-web state, and thus the provision of ecosystem services, is provided in the '<u>Pressures</u>' section. The following section provides further details of the role that food webs (and their state) play in relation to the provision of the ecosystem services outlined in **Figure I.1**.


State Changes/Environmental impacts
Impact on ES
Status of fish communities: Trends observed in the fish community are driven by fishing pressure and the long-term effects of climate change. However, it is not yet possible to apportion the magnitude of change in the observed trends explicitly to either fisheries or climate change
M
H
H
H
H
M
Biomass and raw materials from in-situ aquaculture
Wild fish and other natural aquatic biomass and related raw materials
Genetic material
Regulation and maintenance of marine food webs
Coastal protection
(Global) climate regulation
Nursery population and habitat maintenance
Water quality regulation
Sediment quality regulation
Pest control
Recreation related services
Visual amenity services
Spiritual, artistic, and symbolic services
Ecosystem and species appreciation
Education, scientific, and research services


Primary production of phytoplankton (decreasing trend over the last 6 years)
Biomass and raw materials from in-situ aquaculture
Wild fish and other natural aquatic biomass and related raw materials
Genetic material
Regulation and maintenance of marine food webs
(Global) climate regulation
Nursery population and habitat maintenance
Water quality regulation
Sediment quality regulation
Recreation related services
Visual amenity services
Spiritual, artistic, and svmbolic services
Ecosystem and species appreciation
Education, scientific, and research services
Mediation of waste, toxics, and other nuisances by non-living processes
M
H
H
H
H
M
M
M
L
L
H
M

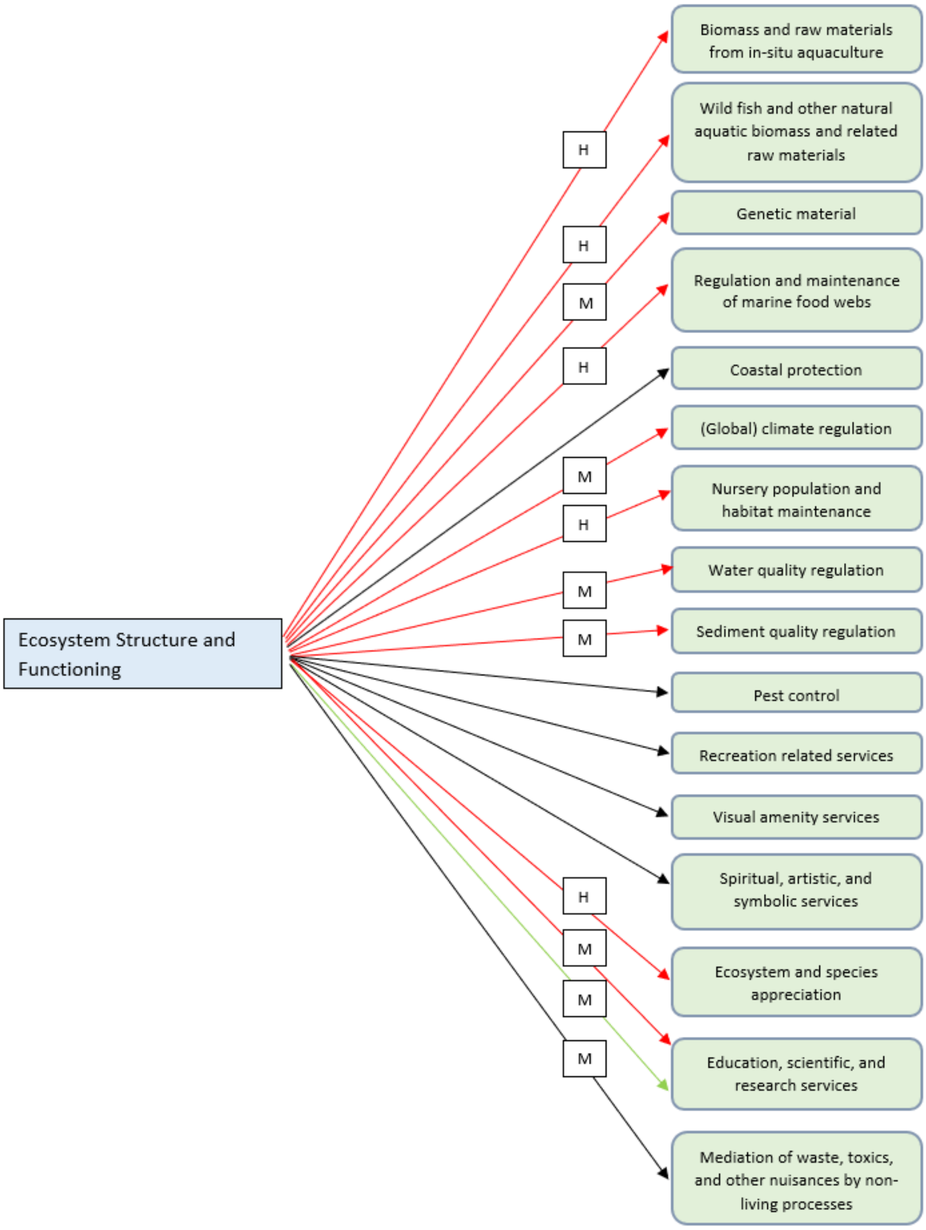


Figure I.1: Schematics depicting the 'State (changes)' - 'Impacts on ES' linkages for the Food Webs thematic assessment, using three trophic guild state changes as the starting point. The ecosystem services shown are those considered most relevant in relation to the Food Webs thematic assessment. Each arrow also denotes an expert estimate of the nature and magnitude of the impact (black arrow = recognition of the existence of the impact but no clear negative or positive impact (uncertain nature); red arrow = negative impact; green arrow = positive impact; H = high impact; M = medium impact; L = low impact; U = unknown impact)

Detailed rationale for the role that food webs (and their state) play in relation to the provision of ecosystem services

Marine food webs are made up of and sustained by all the organisms that make up marine ecosystems. Accordingly the various trophic guilds, be they marine mammals, marine invertebrates, fish, phytoplankton, zooplankton and others, play differing and important roles in sustaining the dynamics of marine food webs.

The following section provides further details of the ecosystem services associated with food webs and their state.

The original concept of Mean Trophic Level (Common Indicator Assessment on Changes in Average Trophic Level of Marine Consumers, FW4) was known as "fishing down marine food webs". A decline in the Middle Trophic Level of a fishery indicates a shift from intense fishing pressure on higher trophic levels to increasing fishing pressure on lower trophic levels, due to a decline in the biomass of higher trophic levels; this can have cascading consequences for marine food webs and consequently for the ecosystem services supported by their balanced functioning (Essington *et al*., 2006; OSPAR, 2017h). Fishing mortality also limits the age structure of fish communities, reducing the proportion of older and larger individuals. In addition to the average trophic level of marine predators, the indicators Proportion of Large Fish (Large Fish Index) (FC2), Candidate Indicator Pilot Assessment of Mean Maximum Length of Fish (FC3) and Size Composition in Fish Communities (FW3) are used to monitor the impacts of fishing mortality and, by providing information on the status of fish communities they also provide useful information on the status of marine food webs.

It has been shown that declines in predatory fish generate significant increases in their prey, considerably modifying the interactions between higher trophic levels and potentially inducing cascading effects on lower levels, including decreases in zooplankton and increases in phytoplankton (Eriksson *et al.*, 2011). For example, decreases in the biomass of predators in offshore areas can lead to increases in the abundance of mesopredators along the coast. Coastal mesopredators can regulate the abundance of crustacean and gastropod herbivores (mesograzers), with consequent effects on marine vegetation. Accordingly, it has been observed how an increase in coastal mesopredators, leading to a decrease in important mesograzers and in combination with nutrient growth due to coastal eutrophication, can lead to declines in beds of eelgrass (Eriksson *et al.*, 2011). In addition, there is the example of the central Baltic Sea, where in the past a mesopredator increase following a decrease of their predators (cod) led to a trophic cascade, including a 50% decrease in zooplankton and a doubling in phytoplankton biomass. This can lead to an increase of carbon fixation associated with increased primary productivity ((Global) climate regulation) (Eriksson *et al*., 2011; Holmlund and Hammer, 1999). In the context of OSPAR IA 2017, an increase in the biomass of marine predators was observed. An increase in the availability of predators in the marine ecosystem can reduce the vulnerability of the ecosystem to natural or human-induced pressures (OSPAR, 2017h). However, a significant increase in predators could lead to a decrease in zooplanktivorous predators, and thus to an increase in zooplankton, leading in turn to a decrease in phytoplankton and the associated primary productivity.

The food-web cascading effects could locally and negatively affect the ecosystem service of '(global) climate regulation'. Similar reasoning can be applied to marine predators in general (whales, large pelagic fish, sea birds, pinnipeds, etc.) which, through food web interactions, have been shown to be essential in supporting the provision of ecosystem services by coastal plant communities including 'coastal protection', '(global) climate regulation', 'habitat maintenance' and the balance of the food web itself (Atwood and Hammill, 2018). Thus, it is evident that changes in the balance of food webs can have cascading effects leading to shifts in the structure of food webs and consequently to alterations in the provision of ecosystem services underpinned by different organisms.

To add to the relationship between the chosen indicators and the food web dynamics, large fish can contribute to food web maintenance and the enhancement of primary productivity via nutrient transport (Tavares *et al*., 2019). In this regard, fish species with a large body size that are particularly sensitive to the additional mortality associated with contribute effectively to the maintenance of food webs (OSPAR, 2017h; Tavares *et al*., 2019). It has been observed that decreases in fish body size due to environmental pressures and impacts associated with human activities can have negative consequences for traits such as egg production and nutrient transport, and in turn for ecosystem services such as 'regulation and maintenance of marine food webs' and 'wild fish and other natural aquatic biomass and related raw materials' (Oke *et al*., 2020; Tavares *et al*., 2019). In a similar way, a decline in the abundance of such species can negatively affect food webs (Tavares *et al.*, 2019).

In the context of the present work, few direct links were found in the existing scientific literature between the individual state indicators and the provision of specific ecosystem services. It follows that, links to the ecosystem services that are in most cases cited as being provided by the dynamics of marine food webs can be assumed. In fact, state changes such as an alteration in the proportion of large fish (FC2) and depletion of the mean maximum length of fish (FC3)), combined with greater scarcity of individual fish and species, can lead to altered food-web structures (Tavares *et al*., 2019). As shown by the Candidate Indicator Pilot Assessment of Feeding Guilds (FW7), large fish are typically piscivorous, so their depletion could be expected to lead to an increase in their prey within the planktivore and benthivore guilds, with potential ramifications for pelagic and benthic habitats.

Primary production of phytoplankton:
Marine phytoplankton is a well-known provider of ecosystem services, crucially contributing to the climate cycle and functions of the marine ecosystem and beyond. Phytoplankton is one of the main marine ecosystem components that contributes most to providing the ecosystem service of '(global) climate regulation'. Some phytoplankton species produce dimethylsulfoniopropionate (DMSP), a precursor to dimethyl sulphide (DMS), important to the process of cloud formation. Phytoplankton is also a major contributor to the carbon fixation process and its sequestration in sediments and ocean depths, by capturing CO_2 from the atmosphere (Tweddle *et al.*, 2018). At the same time, as a food source for pelagic herbivores (including larval stages), phytoplankton also forms the basis of most marine food webs ('regulation and maintenance of marine food webs'), supporting the production and supply of biomass from the upper trophic levels, including biomass produced in the marine aquaculture or mariculture contexts (wild fish and other natural aquatic biomass and related raw materials and biomass and raw materials from in-situ aquaculture). Spatial variability in primary productivity and phytoplankton abundance can influence the spatial distributions of upper trophic levels, including fish, birds, and marine mammals, and indirectly the local provision of ecosystem services by these organisms (See: Marine Birds Thematic Assessment, Marine Mammals Thematic Assessment, and Fish Thematic Assessment for more details about these ecosystem services). It can therefore be argued that the functioning and balance of food webs underpinned by the primary production of phytoplankton has the capacity to indirectly support the provision of ecosystem services by all those marine organisms that are part of the food web itself. For this reason, it can also be argued that the maintenance of balanced food webs can positively contribute to the provision of all the marine ecosystem services considered in the QSR 2023, including 'pest control' and all 'cultural ecosystem services'.

As confirmation, in relation to this specific thematic assessment, visual links to several ecosystem services (e.g., cultural ecosystem services) have been provided, even if all the ecosystem services have not been individually addressed in the narrative. This is due to the overall importance of balanced food web functioning in ensuring the good status of marine ecosystems and thus their provision of ecosystem services. All the ecosystem service mechanisms mentioned in Marine Birds Thematic Assessment, Marine Mammals Thematic Assessment, Fish Thematic Assessment, Benthic Habitats Thematic Assessment, Pelagic Habitats Thematic Assessment flow into this thematic assessment and vice versa, because all marine ecosystem components contribute to food webs.

Shelf areas support most oceanic primary production and they are at the same time the areas affected by most human activities and related pressures (e.g. oil and gas, wind energy, wave and tidal renewable energy, aquaculture, aggregate dredging and waste dumping; Tweddle *et al*., 2018). However, the Candidate Indicator Pilot Assessment of Primary Productivity (FW2) showed several site-specific changes that do not permit a generalised conclusion for the whole OSPAR Maritime Area. This means that areas where a downward trend in annual phytoplankton production was observed, the provision of associated ecosystem services (described above) is likely to decrease. The opposite can be said for areas where high phytoplankton production can lead to an increase in the local provision of ecosystem services such as support for biomass production from shellfish farming activities (OSPAR, 2017h). In the current assessment cycle, primary production is decreasing in many assessment units. Given the general trend for the OSPAR Maritime Area, the impact of the current state of phytoplankton primary production in the OSPAR area on the related ecosystem services is mainly represented with red arrows (**Figure I.1**), indicating a negative impact on most of those services. Nevertheless, some of the relationships between the impact on ecosystem services and primary production remained unclear, represented by black arrows (**Figure I.1**). Declining primary production is likely to increase water clarity which, in turn, may have a positive effect on visual ecosystem services. This relationship is represented by the green arrow (**Figure I.1**).

Despite the overall trend of decreasing primary production, the role played by anthropogenic pressures and their impacts in relation to food webs and components such as phytoplankton must be kept in mind, as they nevertheless act in the background. For example, phytoplankton is essential in the benthic-pelagic coupling that is crucial to the functioning and balance of food webs, as it involves functions from nutrient cycling to energy transfer between habitats (Griffiths *et al*., 2017). At the same time, anthropogenic pressures and related environmental impacts (addressed in the pressure-related thematic assessments) influence benthic-pelagic coupling through their impacts on the physical and biological components of the marine ecosystem, including phytoplankton. For example, a climate change-related increase in water temperature may cause changes in the timing, and decrease the magnitude, of phytoplankton blooms, which in turn may lead to a decrease in the transport of organic matter to the benthos and reduce the release of inorganic nutrients from the marine sediment. Meyer *at al*., (2018) found changes in macrofauna community structure in the south-eastern North Sea caused by increasing sea surface temperature and de-eutrophication effects between 1986, 2000, 2010 and 2015. De-eutrophication effects in line with food limitation caused by decreasing phytoplankton biomass and pelagic and benthic primary production strengthen the dominance of opportunistic species such as *Phoronis* spp. and *Spiophanes bombxy (*Meyer *et al.*, 2018). Overfishing can impact, for example, oyster reefs, resulting in a reduction in the water filtration processes which in turn triggers an increase in phytoplankton production and a reduction in water quality and clarity (Griffiths *et al.*, 2017). These components of the marine ecosystem, as a result of environmental impacts from human-related pressure, can alter the structure and dynamics of food webs and consequently the provision of ecosystem services.

Changes in phytoplankton communities and biomass and changes in zooplankton communities and abundance:

Phytoplankton communities are directly linked to zooplankton communities. The presence and abundance of the zooplankton influences the production of biomass at higher trophic levels (‘wild fish’ and other ‘natural aquatic biomass’ and related ‘raw materials’) and of the biomass in maricultural contexts (‘biomass and raw materials from in situ aquaculture’). The contribution of zooplankton in sustaining the balance of the food web itself (‘regulation and maintenance’ of marine food webs) is also detectable in its role as a grazer for algae and bacteria and as a provider of nitrogen and phosphorus (‘nutrient cycling’) that has positive effects on the primary productivity of phytoplankton. In addition, zooplankton, through processes such as the export of particles by grazing, the fractioning of sinking particles and the transport of particulate organic carbon at depth through its diel vertical migration, plays a crucial role in the functioning of the oceanic biological carbon pump that contributes to the ecosystem service of regulation of atmospheric CO_2 levels ('(Global) climate regulation') (Lomartire *et al.*, 2021). Changes in the ratio of planktonic life forms, as well as changes in their absolute and relative abundance, can be used to detect changes in community functioning, which in turn can inform changes in ecosystem services (Bedford *et al.*, 2020; McQuatters-Gollop *et al.*, 2019).

OSPAR assessments have shown that over the most recent period (since 2000) zooplankton abundance has tended to decrease while phytoplankton biomass has tended to increase (OSPAR, 2017i). In addition, OSPAR assessments in studies of planktonic life forms have shown that plankton communities (phytoplankton and zooplankton) have experienced significant changes, indicating alterations in ecosystem functioning (OSPAR, 2017i). However, although these assessments show that important changes have occurred, they are preliminary, and it is difficult to draw conclusions about extent and direction, and what the consequences are for overall marine ecosystem dynamics and the provision of ecosystem services in the OSPAR Maritime Area. For this reason, the links between the trends observed for phytoplankton (biomass and primary production) and zooplankton (abundance) and ecosystem services are represented as links that exist but whose nature cannot yet be clearly defined as overall positive or negative for the OSPAR area (black arrows **Figure I.1**). However, by presenting and describing the ecosystem services underpinned by phytoplankton and zooplankton it is possible to at least identify which of the ecosystem services may be altered as a result of major changes in phytoplankton biomass and productivity and zooplankton abundance and community functioning (Bedford *et al.*, 2020).

The above-mentioned structural changes in the different ecosystem components of a food web due to climate change and anthropogenic pressures are linked to changes in the trophic structure and functioning of food webs. For example, food webs at higher temperatures will become less organized and shift towards detritus-based food webs (Baird *et al.*, 2019). Results have shown, inter alia, an intensification of detrital production and consumption, a substantial increase in total system throughput, a decline in consumption of phytoplankton and macrophytes, and an increase in community respiration (Baird *et al.*, 2019). Non-indigenous species influence the production and biomass of wild animals, which in turn changes ENA indices and food web system attributes. ENA indices show declines in the number of trophic cycles and in trophic efficiency, ascribed to the impact of non-indigenous species on system organization and function (Baird et al., 2012; Jung *et al.*, 2020).

As the supply of ecosystem services depends on the functioning of ecosystems and the ecological groups composing them, using Ecological Network Analysis (Candidate Indicator Pilot Assessment of Ecological Network Analysis Indices, FW9) to quantify the provisioning of ecosystem services can provide multiple benefits. It considers the interconnectivity of marine and coastal ecosystems to adequately forecast the effects of ecosystem changes, it can quantify simple ecological functions, like secondary production, as well as more complex ones, and it can assess a wide range of ecosystem services owing to their holistic and integrative nature (Nogues *et al.*, 2022). For this reason, in Nogues et al. (under review), ENA was used to quantify the potential effects of climate change on species distribution and the reef and reserve effects of an offshore wind farm on the provision of ecosystem services. Multiple ecosystem services were considered, such as 'food supply' from fisheries (through catches), 'cultural benefits' from the production of flagship species such as marine mammals and seabirds, and the ability of the system to withstand disturbance through redundant trophic pathways (relative redundancy). The use of ENA enabled the observation of connections between ecosystem services. As the offshore wind farm increased habitat heterogeneity, the biomass of multiple benthic and demersal species increased, with a beneficial effect for catches, but also for culturally important species such as dolphins and porpoises. This was due to the increased amount of potential prey available to these high trophic level groups within the offshore wind farm, leading to higher production of these iconic species (Nogues et al., under review). This demonstrates how useful ENA could be in the context of ecosystem services quantification.

R – Response

Responses to improve the state of marine food webs

Food webs are the umbrella that connects all biodiversity components from primary producers to apex predators, and their various interactions and energy transfers across trophic levels must be taken into account. Understanding food web structure and changes is critical in order to formulate policy that can lead to appropriate management responses. Responses that address climate change, fishing and pollution, in particular eutrophication, have been identified as important for supporting good environmental status of ecosystems representing food webs in the North-East Atlantic. Because of these complex networks of interactions, pressures and management responses can have both direct and indirect effects on living organisms, leading to cascading effects along the food chains. This is why it is crucial to adopt an integrated view of the food webs which gives global consideration to this complexity.

There are opportunities for OSPAR to strengthen its response to support food webs, including by taking a broader ecosystem approach to the implementation of actions to strengthen the status of OSPAR listed species and habitats and by further developing the OSPAR MPA network, including OECMs, and implementing the strategic objectives to address eutrophication. Strengthening cooperation with those bodies that have competence for managing human activities outside of OSPARs mandate will be critical to success.

Food webs are the umbrella that connects all biodiversity components from primary producers to apex predators, and their various interactions and energy transfers across trophic levels must be taken into account. Understanding food web structure and changes is critical in order to formulate policy that can lead to appropriate management responses. Responses that address climate change, fishing and pollution, in particular eutrophication, have been identified as important for supporting good environmental status of ecosystems representing food webs in the North-East Atlantic. Because of these complex networks of interactions, pressures and management responses can have both direct and indirect effects on living organisms, leading to cascading effects along the food chains. This is why it is crucial to adopt an integrated view of the food webs which gives global consideration to this complexity.

There are opportunities for OSPAR to strengthen its response to support food webs, including by taking a broader ecosystem approach to the implementation of actions to strengthen the status of OSPAR listed species and habitats and by further developing the OSPAR MPA network, including OECMs, and implementing the strategic objectives to address eutrophication. Strengthening cooperation with those bodies that have competence for managing human activities outside of OSPARs mandate will be critical to success.

Section overview

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

Food webs are the umbrella that connects all biodiversity components from primary producer to apex predator, and their various interactions and energy transfers across trophic levels must be taken into account. Understanding food web structure and changes is critical in order to formulate policy that can lead to appropriate management responses. Responses that address climate change, fishing and pollution, in particular eutrophication, have been identified as important for supporting good environmental status of food webs in the North-East Atlantic (Machado *et al.*, 2021).

This section considers the responses taken to ensure the maintenance of healthy and functioning food webs across all regions of the OSPAR Maritime Area, including those in the coastal and shelf seas as well as deep seas within and outside national jurisdiction. In many cases, the objective of sustaining functioning food webs is not expressed explicitly as measures, but rather presented implicitly in the context of applying the ecosystem approach, one of the core principles guiding the work of the OSPAR Commission.

The primary focus is on responses that have been adopted by the OSPAR Commission to implement the Contracting Parties' commitments under the OSPAR Convention and the strategic objectives of the North-East Atlantic Environment Strategy. Article 22 of the OSPAR Convention requires the Contracting Parties to report to the OSPAR Commission at regular intervals on the steps they have taken to implement OSPAR Decisions and Recommendations, the effectiveness of those measures and the problems encountered in their implementation. This section aims to describe the progress made in the implementation of these measures and whether these measures are working in terms of achieving the ambitions set out in the North-East Atlantic Environment Strategy (NEAES) 2030. The section attempts to set OSPAR's responses in the wider policy context and looks at responses by other competent organisations, where these address food webs in the context of the North-East Atlantic.

In NEAES 2030, safeguarding ecosystem function and resilience features in three of the 12 strategic objectives and is implied in others that aim to avoid adverse effects on the marine environment.

Strategic Objective 5: Protect and conserve marine biodiversity, ecosystems and their services to achieve good status of species and habitats, and thereby maintain and strengthen ecosystem resilience;

Strategic Objective 6: Restore degraded benthic habitats in the North-East Atlantic when practicable to safeguard their ecosystem function and resilience to climate change and ocean acidification;

Strategic Objective 9: Safeguard the structure and functions of the seabed/marine ecosystems by preventing significant habitat loss and physical disturbance due to human activities.

SX.O2: By 2024 OSPAR will initiate discussions on the development of a practical approach for regional-scale ecosystem-based management, including through the 'Collective Arrangement' and in cooperation with fisheries management bodies and other competent organisations, in order to strengthen ecosystem resilience to climate change and to safeguard the marine environment, its biodiversity and ecosystem services.

There are cross-linkages to all other biodiversity thematic assessments Marine Birds Thematic Assessment, Marine Mammals Thematic Assessment, Fish Thematic Assessment, Benthic Habitats Thematic Assessment, Pelagic Habitats Thematic Assessment, Non Indigenous Species Thematic Assessment as well as the Eutrophication Thematic Assessment.

The reader is referred to the following feeder reports for additional information on some of the key human activities affecting food webs: Feeder Report 2021 - Fisheries, Feeder Report 2021 - Offshore Renewable Energy Generation.

Responses addressing the State of marine food webs

OSPAR has not adopted any specific measures with the explicit objective of supporting the state, function or resilience of food webs. There are, however, several examples of measures that could have particular relevance to ecosystem function and resilience.

The implementation status of all OSPAR Measures was reported on in 2021: Implementation of OSPAR Measures, A Progress Report.

Addressing species and habitats in decline and under threat

The OSPAR Contracting Parties have identified 18 habitats of particular concern in the North-East Atlantic, which have been included in the OSPAR List of Threatened and/or declining species and habitats (Agreement 2008-06) (the OSPAR List). This list, first adopted in 2003 and updated in 2008 and 2021, guides the OSPAR Commission in setting priorities for its further work on the conservation and protection of marine biodiversity in implementing Annex V to the OSPAR Convention. Recommendations for actions to protect and conserve 16 of these habitats were adopted by OSPAR between 2010 and 2016. Kelp forests and *Haploops* habitats on muddy seabeds were included in the OSPAR List at the OSPAR Ministerial Meeting in 2021 and Recommendations for their protection and conservation were adopted in parallel.

The purpose of these Recommendations is to agree actions to be taken nationally and collectively to strengthen the protection of the listed habitats, recover their status and ensure that they are effectively conserved in the OSPAR Maritime Area. A common understanding of the Recommendations was adopted in 2013 (Agreement 2013-13). They are broad in nature, addressing a range of human activities and pressures. The actions to be taken nationally include steps to ensure appropriate national legislation for the protection of a given species or habitat, consideration of how to strengthen the knowledge base, monitoring and assessment, steps to manage key human activities, calls for the designation of MPAs within their jurisdiction, and awareness raising. The collective actions include coordination of monitoring and assessment, enhancing knowledge exchange, collaborating and maintaining cooperation with relevant competent organisations on how to address key pressures (such as fishing and shipping), and research.

From a food web perspective, this set of measures is significant, as it aims to retain species and habitats that are functionally important in the north-east Atlantic, particularly certain apex predators and habitats. The significance of the interconnection between protection of habitats and species has been identified in reporting: for example, the Netherlands has highlighted the importance of eel grass (*Zostera spp)* restoration as a precursor to the return of the long nosed seahorse in its waters.

Are these measures working?:

The reporting by Contracting Parties demonstrates that the OSPAR Recommendations on protection and conservation have generated conservation action at the national level. Contracting Parties are stepping up the protection of features that are threatened on a regional scale through various awareness-raising activities and by introducing national measures and legislation to regulate the human activities that causing pressures on these features and establishing monitoring programmes to assess their status. Many of these actions are also being taken as part of national responses to EU legislation such as the EU Habitats Directive. It is difficult to separate out the actual effects of such actions and to evaluate the impact of the OSPAR measures.

The adoption of the 2017-2025 Roadmap for the implementation of collective actions within the Recommendations for the protection and conservation of OSPAR listed Species and Habitats (The

Roadmap) has supported the collaborative efforts made across thematic boundaries within OSPAR as well as inform or support the actions implemented at national level. However, it is not yet possible to report on the impact or effectiveness of these collective actions.

The most recent implementation reporting took place in 2019, with the next reporting due in 2025. A detailed overview of the scope and range of actions implemented in this reporting round can be found in OSPAR Overview assessment of implementation reporting.

Kelp. © Scottish National Heritage

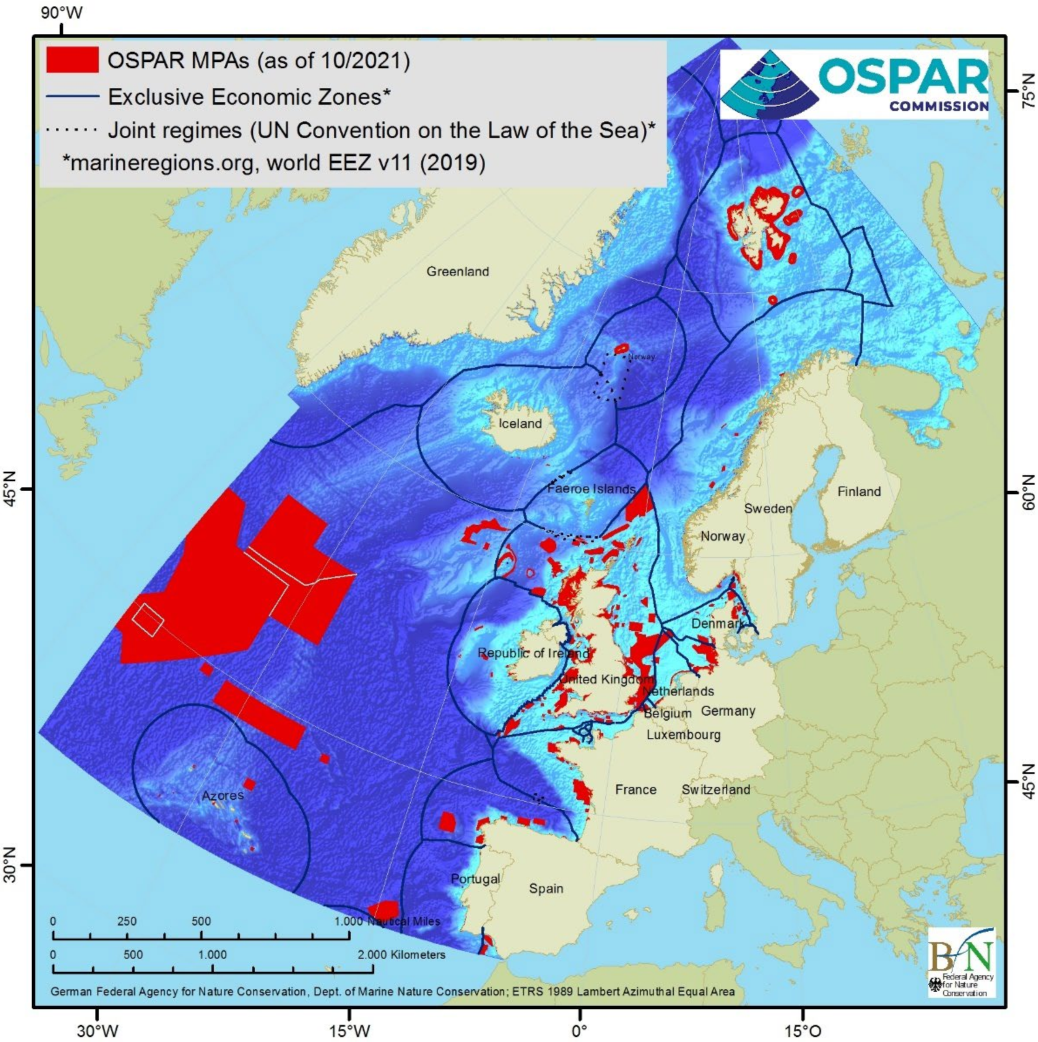
The OSPAR network of Marine Protected Areas and their role in supporting food webs

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

MPAs as a response to conserve food webs

Signs of recovery among predator species have been observed in the MPAs protecting coral reefs (Dell *et al*., 2015), with an expected increase in higher trophic levels and larger species/ guilds such that fish within MPAs feed higher up the food chain than those in adjacent non-MPAs. This may be the result of more diverse food webs and hence greater prey choice and availability in MPAs, and implies that MPAs affect not only ecosystem structure (abundance and diversity) but also functioning (through consumption, growth and production) (Dell *et al*., 2015). As a result, the designation of effectively managed MPAs has been identified as a valid management response for strengthening food web structure and functioning (Soler *et al*., 2015). Modelling has suggested that highly protected MPAs benefit not only biodiversity but also fishery yields and the sequestering of blue carbon (Sala, 2021).

Further examples exist of Other Effective Conservation Measures (OECMs) and fishery closures being used to manage fishing pressure and protect seabird prey species in order to support the marine food web. Thus, fishing for sandeels has been limited in Scottish coastal waters in order to protect black-legged kittiwakes and other dependent predators (see Case Study by Daunt *et al*., 2008, and also Greenstreet *et al*., 2006).



OSPAR Network of MPAs (as of 1 October 2021). Source: Report and assessment of the status of the OSPAR network of Marine Protected Areas in 2021

Case study: The East Coast UK Sandeel Closure: an OECM contributing to the conservation of marine food webs

Due to their importance as a food source for seabird species, following advice from the ICES, in 1999 the United Kingdom Government called for a moratorium on sandeel fishing adjacent to North Sea seabird colonies, due to concerns over declining seabird numbers (primarily kittiwakes [1]. This resulted in the precautionary closure of all commercial sandeel fisheries in 2000 over an extensive area of the east coast of the United Kingdom (**Figure R.1** in red).

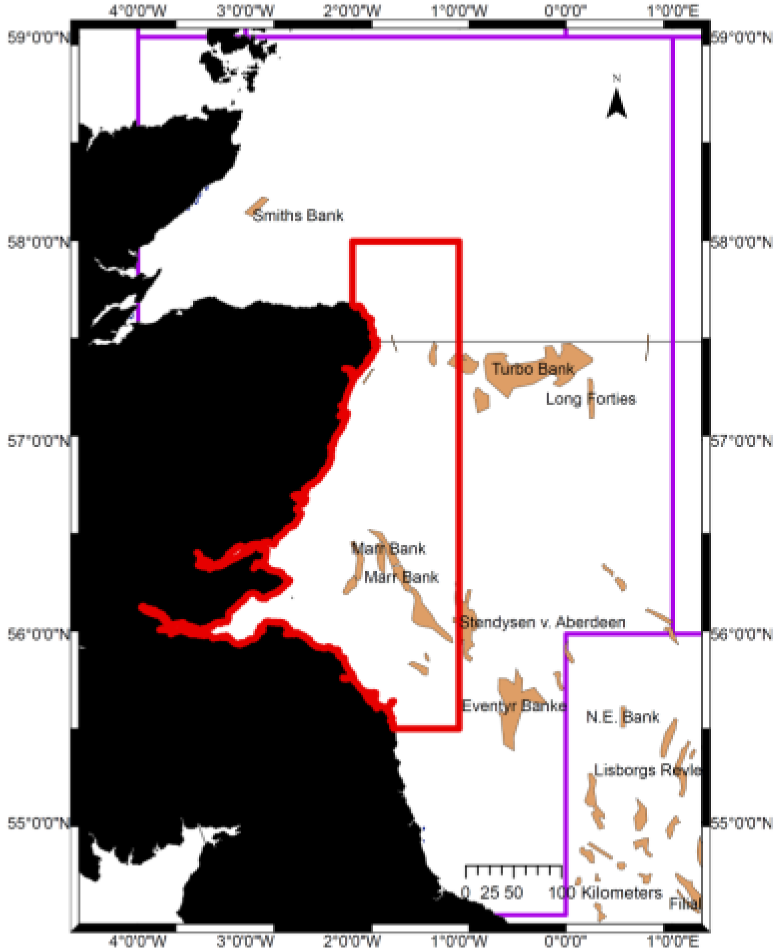


Figure R.1: East Coast UK Sandeel Closure. Reproduced from ICES (2017)

The East Coast UK Sandeel Closure remains in place, and the ICES has advised that the reopening threshold is that the breeding success of seabirds (particularly kittiwakes) should be greater than '0,7 fledged chicks per well-built nest'. However, this threshold has not been accepted by the European Commission and no further reopening criteria have been proposed or approved [3]. This means that the measure is likely to remain in place in the longer term – a key factor in the success of an OECM.
The above-mentioned recommendation by the ICES resulted in an 'Ecological Quality Objective (EcoQO)' issued by OSPAR in respect of sandeels. The EcoQO 'seeks to maintain safe levels of fish species by management of fisheries based on the precautionary principle' [4].

The closure is enforced under the following European legislation:

- Article 29a of Council Regulation (EC) No. 850/98 of 30 March 1998 for the conservation of fishery resources through technical measures for the protection of juveniles of marine organisms [5];
- Regulation (EU) No 227/2013 of the European Parliament and of the Council of 13 March 2013, amending Council Regulation (EC) No 850/98 and Council Regulation (EC) No 1434/98 specifying conditions under which herring may be landed for industrial purposes other than direct human consumption [5];
- Division 5, Annex III of Council Regulation (EC) No 41/2007 of 21 December 2006 fixing for 2007 the fishing opportunities and associated conditions for certain fish stocks and groups of fish stocks, applicable in Community waters and, for Community vessels, in waters where catch limitations are required [6];
- The restriction has been retained following the exit of the United Kingdom from the EU and is mentioned in Annex V (North Sea), Part C of Regulation (EU) 2019/1241 of the European Parliament and of the Council [7].

The target for this management measure is that sandeel biomass must be sufficient to ensure no impairment to recruitment levels while also ensuring adequate prey availability to support and sustain healthy seabird populations [1, 3]. Since the closure in 2000, surveys have identified both an increase in sandeel numbers and improved kittiwake breeding success [6].

Sandeels (*Ammodytes marinus* and *A. tobianus*) © Keith Mutch Marine Scotland

Sandeels, *Ammodytes marinus* and *A. tobianus*, specifically the lesser sandeel (*A. marinus*), are an important food source for many seabirds, in particular kittiwakes. Research studies have determined that once sandeels become established on the seabed, they will stay within a small range and their removal from these areas can quickly deplete their populations. A study by Wright et al. (1998)[8] identified that the sandeels in this area are 'reproductively isolated' from other aggregations in Sandeel Area 4, which makes them more vulnerable to decline.

By providing protection for sandeels in the North Sea, this OECM offers an indirect conservation benefit to seabird numbers and therefore supports the marine food web.

References

[1] https://www.ices.dk/sites/pub/Publication Reports/Expert Group Report/acom/2016/WKSAND/WKSAND_2016.pdf ICES. 2017. Report of the Benchmark on Sandeel (WKSand 2016), 31 October - 4 November 2016, Bergen, Norway. ICES CM 2016/ACOM:33. 319 pp. https://doi.org/10.17895/ices.pub.7718

[2] https://stecf.jrc.ec.europa.eu/documents/43805/44876/07-09_SG-MOS+07-03+-+Evaluation+of+closed+areas+II.pdf

[3] https://www.rspb.org.uk/globalassets/downloads/documents/campaigning-for-nature/rspb2021_the-case-for-stronger-regulation-of-sandeel-fisheries-in-uk-waters.pdf

[4] https://www.ospar.org/documents?v=7169

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A01998R0850-20140101

[6] https://www.legislation.gov.uk/eur/2007/41/annex/III/part/A/division/5

[7] https://www.legislation.gov.uk/eur/2019/1241#f00033

[8] Wright, P., Verspoor, E., Anderson, C., Donald, L., Kennedy, F., Mitchell, A., Munk, P., Pedersen, S.A., Jensen, H., Gislason, H. and Lewy, P. 1998. Population structure in the lesser sandeel (*Ammodytes marinus*) and its implications for fishery-predator interactions. Final report to DG XIV 94/C 144/ 04 Study Proposal No. 94/071, October 1998

N.B. new information is available in the WKTOPS workshop report on OECMs from 2021. One of the case studies used was the North East UK Sandeel Closed Area. (Report on pages 11 and 94)

OSPAR has made progress in managing the MPA network. The 2021 status assessment showed that 88% of OSPAR MPAs have either full or partial management information in place which is publicly documented. The assessment reveals a 17% rise, to 83%, in the implementation level of measures considered necessary for achieving conservation objectives, since assessments began in 2016. Another area of improvement is the increase in monitoring to be able to detect progress made towards achieving the conservation objectives. The assessment showed that 75% of OSPAR MPAs have either full or partial monitoring programmes, although these are largely based on the ability to monitor sea users' compliance with the rules and regulations associated with OSPAR MPAs, as opposed to direct site-condition monitoring, which is costly. Nearly half of OSPAR MPAs are thought to be moving towards achieving their conservation objectives. It is important to note that the percentage of OSPAR MPAs achieving or moving towards their conservation objectives has increased over time, from 36% to 44% and then 49%, for 2016, 2018 and 2021, respectively. Despite improvements in understanding the management status of the MPA network, it is still difficult to determine whether the protected features in OSPAR MPAs are moving towards their conservation objectives, owing to lack of site-specific information or long-term monitoring programmes, as noted above.

For OSPAR MPAs in ABNJs, efforts should be made to further the Collective Arrangement (OSPAR Agreement 2014-09) and to cooperate through other mechanisms, such as Memoranda of Understanding, with relevant competent management authorities, so that they can consider appropriate management actions to help deliver the conservation objectives for OSPAR MPAs in ABNJs.

Is this measure working?:

OSPAR is progressing towards establishing key metrics in terms of area-based protection; however, there are still gaps in geographic coverage (particularly in the Arctic region), ecological coherence and in the understanding of whether or not management is effective. Under the North-East Atlantic Environment Strategy (NEAES) 2030, the Contracting Parties have committed to further develop the OSPAR network of MPAs and other effective area-based conservation measures (OECMs) by 2030 so as to cover at least 30% of the OSPAR Maritime Area and ensure that it is representative, ecologically coherent and effectively managed to achieve its conservation objectives (Objective S5.O1). This ambition is in line with the global target under negotiation within the Convention on Biological Diversity.

The mandate of OSPAR is restricted when it comes to the management of certain human activities, and thus effective implementation relies on action taken by the Contracting Parties in areas within national jurisdiction, and with other competent organisations in areas beyond national jurisdiction. However, the common ambition of a regionally coherent network is important and brings useful attention to the protection of threatened and /or declining habitats. Within NEAES 2030, OSPAR has committed to establishing a mechanism by 2024 whereby, when Contracting Parties are seeking to authorise human activities under their jurisdiction or control that may conflict with the conservation objectives of OSPAR MPAs in an ABNJ, those activities are subjected to an Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA).

There is still a need to improve the availability of the data relating to the OSPAR MPA network for those that have the responsibility to manage different human activities. This includes not only information on the features that are protected but also the management objectives and the plans that are in place, to ensure that the MPAs are delivering expected conservation outcomes. This will be a requirement for Contracting Parties to deliver on NEAES S11.O2. By 2023, and every six years thereafter, OSPAR will assess at a regional scale the OSPAR network of MPAs in respect of the resilience of marine biodiversity to climate change, with the aim of ensuring that the network provides a good representation of species and habitats and that its spatial design and management regime remains relevant.

Other OSPAR measures responding to relevant human activities and pressures:
Fish and shellfish harvesting (professional, recreational) [Extraction of living resources]:
As set out in Article 4, Annex V of the Convention, OSPAR has agreed that no programme or measure concerning a question relating to the management of fisheries must be adopted under that Annex. However, where the Commission considers that action is desirable in relation to such a question, it must draw that question to the attention of the competent authority or international body. Where action within the competence of the Commission is desirable to complement or support action by those authorities or bodies, the Commission must endeavour to cooperate with them (see section 3).

Eutrophication:

Eutrophication Thematic Assessment

The input of nutrients to eutrophication can arise from a number of human activities: agriculture [Cultivation of living resources]; industrial uses [Urban and industrial uses] and waste treatment and disposal [Urban and industrial uses]. Changes in nutrient input can affect phytoplankton primary production and trigger a bottom-up trophic cascade in which changes in primary production then impact fish populations. The effect of eutrophication or nutrient input is measured through a series of pelagic food web indicators: FW2, FW6 and FW9.

The eutrophication status of the OSPAR Maritime Area has improved as a result of the OSPAR response to eutrophication and the subsequent implementation of measures adopted by the EU, the European Economic Area and other international forums, including the Urban Waste Water Treatment Directive (91/271/EEC); the Nitrates Directive (91/676/EEC); the Water Framework Directive (2000/60/EC); and the Marine Strategy

Framework Directive (2008/56/EC). There are, however, still regional variations and local problem areas, particularly in areas sensitive to nutrient inputs such as estuaries, fjords and bights and in areas affected by river plumes. Work to "Tackle eutrophication, through limiting inputs of nutrients and organic matter to levels that do not give rise to adverse effects on the marine environment" remains a strategic objective for OSPAR within NEAES 2030 (Strategic Objective 1). One of the NEAES operational objectives focuses on the application of nature-based solutions to safeguard the natural capacity of the ecosystem to sequester nutrients through the conservation and restoration of estuarine, coastal and marine habitats (S1.O6).

Introduction or spread of non-indigenous species (NIS)
The introduction of NIS can alter or change the structure and functioning of food webs. Since the 2010 QSR, significant progress has been made in the responses to address NIS; however, they continue to be introduced and this issue will require continued effort to prevent further introductions. Continued implementation of the joint response by OSPAR and HELCOM, the EU MSFD, the Invasive Alien Species Regulation and the International Maritime Organization Ballast Water Management Convention should ensure that some of the gaps identified in monitoring are addressed and also strengthen the monitoring required to reduce bias and data gaps.

Other important measures

General conservation measures:
Under Article 13 of the EU Marine Strategy Framework Directive (2008/56/EC) (MSFD), EU Member States are required to take measures to achieve or maintain good environmental status by 2020. The status assessments under Article 8 and environmental targets under Article 10 help to identify where these measures are needed. The MSFD notes the importance of coherence and connects to action under the Habitats Directive (including the Natura2000 network). The inclusion of food webs as one of the 11 descriptors is a novel feature of the MSFD. Descriptor 4 requires that for good environmental status *"All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity".* In the 2018 evaluation of the programmes of measures reported by Member States, Descriptor 4 was grouped with other biodiversity descriptors according to main species and habitat types (European Commission, 2018), making it difficult to identify those measures taken to address broader ecosystem function and resilience. The 2018 report did, however, identify that Member States had not yet established sufficient linkage between measures to reduce negative impacts from human activities and measures to address the state of marine biodiversity.

Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning sets a high-level ambition: "Healthy marine ecosystems and their multiple services, if integrated in planning decisions, can deliver substantial benefits in terms of food production, recreation and tourism, climate change mitigation and adaptation, shoreline dynamics control and disaster prevention." Action under this directive is considered relevant for food webs.

In the Arctic region, the ecosystem approach was adopted as an overarching principle and approach by Arctic Council Ministers in 2004 as part of the Arctic Marine Strategic Plan (AMSP). In 2011, the Ministers established an expert group on Arctic ecosystem-based management (EBM), which reviewed the ecosystem approach (or EBM) concept and provided a definition along with principles and recommendations that were adopted as part of the Kiruna Declaration in 2013. At Iqaluit in 2015, and at Fairbanks in 2017, the Arctic Council Ministers recognized the need for an ecosystem approach and requested the development of practical guidelines. The first guidelines were published in 2019 to assist scientists, policy-makers, managers and communities in implementing an ecosystem approach for Arctic marine ecosystems, recognising the interconnectivity of marine systems and the role of humans within them.

Climate change measures:

Climate Change Thematic Assessment

The impacts of climate change can drastically affect the structure and function of marine food webs, with implications for ecosystem services (Ullah *et al*., 2018). The primary global response to addressing climate change is the Paris Agreement, adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in Paris on 12 December 2015. This is a legally binding international treaty on climate change adopted by 196 Parties with the goal of limiting global warming to well below 2˚C above pre-industrial levels, and preferably to 1,5˚C above pre-industrial levels. To achieve this long-term temperature goal, countries are aiming to reach a global peaking of greenhouse gas emissions as soon as possible so as to achieve a climate-neutral world by mid-century. The outputs of the IPCC sixth climate assessment cycle show that, at the current rate of progress, the world is not on track to meet the Paris Agreement goal and climate change action needs to be massively increased if we are to do so.

Fish and shellfish harvesting (professional, recreational) [Extraction of living resources]:

OSPAR Feeder Report 2021 – Fisheries

The management of fisheries has particular relevance for food web dynamics. Fishing activities remove different elements of the food web, which, depending on the target species, will affect different trophic levels and have different implications for food web structure. This can lead to trophic cascades. The assessment of a number of food web indicators can inform management responses from a fish perspective; these include FW3, FW4, FW7 and FW9 (see State section).

Fisheries management responses are set within the context of the global framework for fisheries management and the common principles set out in the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which includes a call for a maximum sustainable yield (MSY) approach to managing fisheries; by the 1992 United Nations Conference on Environment and Development (UNCED), including Chapter 17 of Agenda 21 which highlights a precautionary approach; and the 1995 United Nations Straddling Fish Stocks Agreement (known as the UN Fish Stocks Agreement or UNFSA) and the 1995 FAO Code of Conduct for Responsible Fisheries, which both call for a precautionary approach. Within the North-East Atlantic, the key responses are the national fisheries management legislation for those OSPAR Contracting Parties that are not EU Member States, and the Common Fisheries Policy (CFP) under Regulation (EU) No. 1380/2013 of the European Parliament and of the Council, as amended by Regulation No. 2017/2092 of the same bodies, for those Contracting Parties that are also EU Member States. Other responses include the Regional Fisheries Management Organisations (RFMOs) that manage particular aspects of fisheries within the North-East Atlantic, including the North East Atlantic Fisheries Commission (NEAFC), which regulates certain fisheries outside of national jurisdiction, the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the North Atlantic Salmon Conservation Organisation (NASCO).

The importance of having an ecosystem approach to fisheries management is accepted. However, fisheries management measures tend to focus on the sustainable management of stocks to achieved Maximum Sustainable Yield, and not on maintaining ecosystem function and resilience.

Fisheries management regulations have resulted in less focus on maximising fish-stock harvesting and greater focus on moving to levels considered sustainable, together with a shift from a fish-stock management to an ecosystem-based perspective, including the introduction of measures to protect vulnerable habitats and species. However, there are still concerns, including in relation to by-catch, the need to integrate concepts of ecosystem function into fisheries management regulation, such as the idea of trophic cascades, and how management regimes can take account of the impact of fisheries on food webs.

Regional differences

Many of the responses addressing food webs, or more broadly ecosystem function and resilience, are applicable to EU coastal waters, although some, such as the EU Water Framework Directive, are more confined to the coastal zone. Fisheries management in non-EU Member States that are OSPAR Contracting Parties is also applied at the national level and in shelf and deep waters.

The OSPAR MPA network applies across the OSPAR Maritime Area, although with significant gaps in the Arctic and with remaining challenges relating to the management of MPAs in the area beyond national jurisdiction.

Gaps and opportunities

Are we doing enough?:
The ambition to apply an ecosystem approach to the management of human activities is central to the work of OSPAR, but implementation remains challenging. The continued improvement of indicators to inform the development and implementation of responses that take a more integrated approach is critical.

Could other types of responses be undertaken by OSPAR to improve the status of food webs?:
Policy and management response to ensure good environmental status for food webs will require increased integration of monitoring, assessment and action, across all of OSPAR's strategic objectives. There is also need for appropriate management of human activities and their associated pressures, in particular fisheries and eutrophication, and where these activities fall outside of OSPAR's mandate to strengthen effective cooperation with those relevant organisations that do have competence.

NEAES 2030 operational objective SX.O2 commits OSPAR to initiate discussions on the development of a practical approach for regional-scale ecosystem-based management, including through the Collective Arrangement and in cooperation with fisheries management bodies and other competent organisations, in order to strengthen ecosystem resilience to climate change and to safeguard the marine environment, its biodiversity and ecosystem services. Progress in the implementation of this objective will be an important contribution to developing appropriate responses for food webs.

There are opportunities to apply an ecosystem approach more widely in implementing actions to protect and conserve the OSPAR listed species and habitats. Ecosystem restoration provides another opportunity to support healthy food webs in line with NEAES Strategic Objective 6: "Restore degraded benthic habitats in the North-East Atlantic when practicable to safeguard their ecosystem function and resilience to climate change and ocean acidification".

With regard to the OSPAR MPA network, understanding the management effectiveness of the MPAs within the network, and the network itself, remains an important gap to address, particularly from the perspective of ecosystem functioning and food webs. By 2022, OSPAR will identify the barriers to effective MPA management, and by 2024 will take steps to address them appropriately to enable all OSPAR MPAs to achieve their conservation objectives (NEAES S5.O2). The contribution of OECMs and improved management of MPAs within and outside national jurisdiction will be an important response for food webs.

With regard to OSPAR MPAs in ABNJs, efforts should continue to further the Collective Arrangement (OSPAR Agreement 2014-09) and to cooperate through other mechanisms, such as Memoranda of Understanding with the relevant competent management authorities, enabling the latter to consider appropriate management actions to help deliver the conservation objectives.

The new approach to ecosystem state being taken by Norway in Region I incorporates several indicators that may be applicable to OSPAR food web assessment. This could be further investigated, to test if these indicators may be applicable to future OSPAR integrated assessments.

Cumulative Effects

Interactions between food web pressures

Food webs are processes which involve the transfer of energy and trophic interactions between compartments, rather than components, of the ecosystem. The intrinsic complexity of interconnections in trophic chains makes it difficult to perform an assessment based on a bow-tie analysis. Drivers, Activities and Pressures can be linked to many different compartments and interact across many levels of the ecosystem, which may trigger cascading effects (e.g., topdown, bottom up). For bow-tie analysis to be effective, the use of a complex food web assessment is needed in order to better identify specific links. Bow-tie analysis was therefore not included in the QSR 2023 food web thematic assessment. An indication of these interactions can be gained from the individual thematic assessments for: Marine Birds Thematic Assessment, Marine Mammals Thematic Assessment, Fish Thematic Assessment, Benthic Habitats Thematic Assessment, Pelagic Habitats Thematic Assessment.

Climate Change

Impacts of climate change on food webs

Climate change represents one of the main factors currently affecting marine ecosystems and their feeding interactions. Declines observed in the biomass and abundance of phytoplankton and zooplankton might have important implications for upper trophic levels due to cascading effects. Additionally, changes in the spatial distribution patterns and displacement of marine species, towards either northern areas or greater depths, represent an important driver that is affecting food web interactions. Besides triggering ocean warming, climate change has increased the terrestrial dissolved organic carbon load into coastal ecosystems, altering primary productivity, and has increased ocean acidification, with effects on shell-forming species. Synergies between these stressors may contribute to ecosystem food web stabilization and alter food web energy flow and material cycling (Chapman *et al.*,2020).

The warming of the Arctic Waters has resulted in substantial changes in the ecosystem (ICES ecoregion overviews for the sub-regions Greenland Sea, Icelandic Waters, Norwegian Sea, Barents Sea and the Arctic Ocean) (Berge *et al.*, 2012; Edwards *et al.*, 2016; Fossheim *et al*., 2015; González-Pola *et al*., 2019; IPCC 2019; Jørgensen *et al*., 2022; Kunisch *et al*., 2020; Stige *et al.*, 2019). Some Arctic endemic and ice-associated species are more strongly impacted. For example, the polar cod population has declined, owing in part to the loss of sea ice, its spawning habitat, in the Region. In the meantime, large predators or generalist species such as the north-east Arctic cod have progressed northwards across the whole region. The record high cod stock is in need of wider feeding space. As the ice has contracted, the area available to the north and north-east of Svalbard has now become additional feeding grounds for cod. Both near eastern Greenland and in the Iceland

Waters and Norwegian Sea, temperate fish species like mackerel and blue-finned tuna, and sea birds like eider ducks, are also extending their northern ranges. Minke whales are declining near Iceland, probably owing to less food availability. The thinning and reduction in ice cover has resulted in changes in ice biota communities. These include a reduction in the territory and ice conditions needed for seals to give birth and increased risk of killer whale attack. It is feared that the impacts on Arctic Sea mammal species, both seals and whales, will lead to major changes in food webs (ICES WGICA 2018; ICES WGIBAR 2021; ICES WGINOR 2022).

Climate change is expected to affect primary production rates and trends but also the composition of phyto and zooplankton species, which may trigger potential changes in trophic interactions. Since the 2017 Intermediate Assessment, several new analyses of primary production sensitivity to environmental controlling variables have been published for the North Sea and/or the North Atlantic in the context of climate change and involving comparison of computational models. Temperature, light climate, mixing layer depth, nutrient availability, and grazing pressure of secondary herbivorous producers are the variables most frequently mentioned to explain the dynamics of primary productivity calculated in relation to climate change scenarios. Overall, this work shows a decreasing trend in primary productivity for the North Atlantic (Tagliabue *et al.*, 2021) and the North Sea (Capuzzo *et al.*, 2018). Concerning the latter ecosystem, there is uncertainty about the type of model to use in order to accurately reproduce primary production (Spence *et al.*, 2022). The decreasing trend in primary productivity characterized for several OSPAR Regions is consistent with the results of the global model of Lotze *et al.*, (2019), while contrasting with the results from the ecosystem modelling by Thorpe *et al.,* (2022) for the North Sea (upward trend). As summarized in Sathyendranath *et al.*, (2020), there are still uncertainties about the nature of the climate change-related primary production trend, both for ecosystem models in climate change studies and for models based on satellite data. This latest study highlights the accuracy of satellite-based calculations and discusses whether it could be improved by more intense measurements of key parameters and processes (such as underwater light field, chlorophyll-carbon ratio θ, photosynthesis-irradiance parameters and photoacclimation). Finally, the recent study by Spence *et al.*, (2022) recommends, consistent with the conclusions of Sathyendranath *et al.* (2020) and the work of Capuzzo et al. (2018), developing regional models including processes occurring over short time scales (biological parameters cited above). Similarly, Thorpe *et al.,* (2022) recommend that further work be done to improve the representation of bottom-up processes to ensure that ecosystem models can capture limitation by nitrogen and other elements, and not only food/energy uptake, particularly in higher trophic level models developed to understand the impact of fisheries.

It should be noted that the work of Capuzzo *et al.*, (2018) as well as the Candidate Indicator Pilot Assessment of Primary Productivity, which use some empirical models based on chlorophyll-a (Chla) and light (with local parametrization), show downward trends that can actually vary across hydrodynamic regions of the North Sea. Negative correlations are also obtained between this process and temperature, while positive correlations are highlighted with the smallest copepods (herbivores, from CPR records) as well as an index of recruitment from seven commercially valuable fish species (sandeel, sprat, herring, Norway pout, cod, haddock and whiting from the ICES stock assessment report, 2016). This work has therefore concluded in favour of bottom-up control (from physics to plankton, to planktivorous fish) of the food web, as did the previous work of Lynam *et al.,* (2017). In conjunction with declining food web base biomass, increased energy demand from organisms, related to increased temperature, may also explain the decrease in fish biomass (Bryndum-Buchholz *et al.*, 2019; Carozza *et al.*, 2019; Lotze *et al.*, 2019). In addition, it can be caused by predator-prey decoupling between primary and secondary production. This will cause the phytoplankton to sink to the sea bottom and then be lost to secondary production (Morrison *et al.*, 2019).

Changes in the spatial distribution patterns of marine species are being affected by global warming and increasing temperatures at an unprecedented rate in marine environments (Cheung *et al*., 2009; Burrows *et al*., 2011; Punzón *et al*., 2020). The distribution ranges of marine species are shifting towards higher latitudes in processes of tropicalization (Horta e Costa *et al*., 2014), meridionalization (Punzón *et al*., 2016) and borealization (Fossheim *et al*., 2015). These regions are becoming increasingly dominated by species with warmer affinities (Lenoir *et al*., 2011; Simpson *et al*., 2011).

The displacement of species toward greater depths is an additional change detected in the distribution of those species that seek a better niche condition (Dulvy *et al*., 2008; Hofstede *et al*., 2010). With temperatures displaying marked spatial gradients in latitude, longitude and depth, the thermal niche arises as a fundamental factor in the distribution of fish species (Righton *et al*., 2010; Bruge *et al*., 2016; Kleisner *et al*., 2017).

Changes in the distribution of species, whether in latitude, longitude or depth, may cause changes in predator-prey interactions. Food webs should be seen as networks where all compartments are interconnected. Therefore, the disappearance of specific prey for some predators and/or changes in the distribution of top predators could lead to changes in trophic interactions and thus in ecosystem structure (in the trophic level of the species) and, ultimately, functioning. As the species in an ecosystem have different environmental preferences, climate change does not impact them homogeneously. This means that the trophic network will be impacted in different ways by climate change depending on species composition, but also on temporal and spatial dynamics (Nogues *et al*., 2022). The potentially strong structuring effect of climate change on both the functioning and the spatial and temporal organization of ecosystems thus calls for climate variables (e.g. seawater temperature, salinity, current velocity, precipitation, change in winds, depth of thermocline) to be implemented in the models, which will shed light on the impact that climate change may have on trophic levels at the population, community and ecosystem levels.

Global warming has been shown to be a vector that enhances invasions of a marine environment by new species, since most of them originate from warmer oceanic and coastal regions. Food web models using Ecological Network Analysis indices show that the arrival of non-indigenous species change the fate of organic matter within the ecosystem, with higher cycling, relative ascendency and a chain-like food web. It causes new trophic interactions in the food web that could lead to competition and thus modify food-web structure and functioning, with lower omnivory and higher detritivory (Le Marchand *et al*., 2022). Results from ENA indices show a decline in trophic efficiency which can be linked to a possible ecosystem shift caused by invasive species (Baird *et al*., 2012). Studies by Jung *et al*., (2020) used ENA to establish that increasing biomass of the invasive Atlantic jackknife clam (*Ensis leei)* coincided with a 70% increase of trophic carbon transfer from primary to secondary producers and an 80% increase from secondary producers to detritus in a western Wadden Sea food web. Carbon flows from secondary producers to higher trophic levels were reduced by more than 60% (Jung *et al*., 2020). Baird *et al*., (2019) used ENA to evaluate networks and their quantitative trophic interactions between living and non-living components at different temperature scenarios. Results from the trophic analysis revealed that detritivores clearly showed persistent increases in higher temperature scenarios, as did the Detritivory: Herbivory ratio. A similar trend was observed in the amount of detrital material returned to the detrital pool from the integer trophic levels, suggesting a shift in the system's trophic activity to lower trophic levels. The main reason for these trophic shifts was the increased metabolic and katabolic physiological processes which are expected to occur at increased ambient temperatures (Baird *et al*., 2019).

In Nogues *et al*., (2022), ENA was applied to a spatialized food web model (Ecospace model) of the Seine Bay to assess the impact of changing species distribution. This showed a significant impact by climate change for many ENA indices like trophic efficiency, system omnivory, system recycling and the relative redundancy of trophic pathways. The effect of climate change in the Seine Bay differed depending on the studied time frame, but the results tended to indicate that in the long run (2100), climate change will have a negative effect on ecosystem functioning by reducing its ability to resist external perturbations (Nogues *et al*., 2022). Moreover, climate change seems to have a structuring effect on the ecosystem of the Seine Bay, in terms of both network topology and spatial organization. Changes in ecosystem functioning may also impact the way in which other subsequent ecosystem drivers impact trophic network. This could lead to unexpected cumulative effects on ecosystems, where climate change is combined with other drivers. In this connection, numerous non-additive effects were observed on ENA indices when climate change was combined with the reef and reserve effect of an operating offshore wind farm in the Seine Bay (Nogues *et al*., 2021).

The impacts of climate change on the marine ecosystem are expected to reach the deepest parts of the ocean. Projections point to significant changes in deep-water mass properties worldwide (Sweetman *et al*., 2017). In the North Atlantic, such changes could include a decrease in seawater temperature, a loss of dissolved oxygen, a decrease in the flux of particulate organic matter to the seafloor, a decrease in pH and saturation of the minerals involved in the carbon cycle (e.g., calcite and aragonite) (Gehlen *et al*., 2014; Sweetman *et al*., 2017; Perez *et al*., 2018). The multitude of impacts caused by changes in these environmental properties are difficult to predict. Nevertheless, several studies have demonstrated climate-driven effects on the productivity, biodiversity, metabolism and distribution of various deep-sea organisms (Levin & Le Bris, 2015; Levin *et al*., 2019; Xavier *et al*., 2019; Morato *et al*., 2020; Puerta *et al*., 2020). Climate-driven changes in the spatial distribution of deep-sea fauna raise important questions about associated ecosystem-wide impacts. For example, climate change could reduce suitable habitat for cold-water corals and deep-sea fishes, forcing them to shift to northern latitudes (Morato *et al*., 2020). As this shift occurs, new interactions could emerge as immigrant and resident species from northern habitats interact (Kortsch *et al*., 2015). These interactions could result in new food web configurations that might affect ecosystem functioning, as already documented (Beaugrand *et al*., 2015; Blanchard *et al*., 2015). Thus, it is critical to channel research efforts into seeking an understanding (among other questions) (a) of how poleward shifts in deep-sea fauna might affect food web structure and (b) of the extent to which such changes might affect the ability of the deep-sea ecosystem to provide essential services.

An important step towards answering such questions is to improve current capabilities for modelling deep-sea ecosystems through network analysis or trophic models. To date, the development of complex, holistic modelling tools specific to deep-sea systems has been limited (Morato *et al*., 2016; Woodstock *et al*., 2022). This is primarily because these models are very data-intensive, which naturally limits their application to traditionally data-poor systems such as deep-sea ecosystems. New information on the life histories, feeding preferences and habitat use of different deep-sea species/functional groups is therefore of paramount importance to operationalize the development of models suitable for examining the ecosystem-wide impacts of climate change on deep-sea ecosystems. This is one of the priorities of the modelling efforts currently underway in the Azores.

Climate warming has significantly altered the phenology of a wide range of taxa across ecosystems, but responses frequently vary among species, potentially disrupting the synchronisation of key trophic interactions in the food web. In particular, failure of a predator to overlap the period of peak resource demand (typically breeding) with peak prey availability may lead to 'trophic mismatch,' and such decoupling may alter food web structure and ecosystems. One example is mismatch between the timing of seabird prey occurrence and periods of peak energy-demand (e.g. chick-rearing) (Burthe *et al*., 2012).

Besides ocean warming, ocean acidification can have an impact on food web interactions, with consumers expected to be affected by changes to the nutritional quality of their prey (Rossoll *et al.*, 2012). Anthropogenic CO_2 can function as a resource that boosts productivity throughout food webs, while warming can reverse this effect by acting as a stressor to trophic interactions (Goldenberg *et al.*, 2017).

References

Atwood, T. B. and Hammill, E. (2018). The Importance of Marine Predators in the Provisioning of Ecosystem Services by Coastal Plant Communities. Frontiers in Plant Science, 9(1289). doi:10.3389/fpls.2018.01289

Baird, D., Asmus, H. and Asmus R. (2012). Effect of invasive species on the structure and function of the Sylt-Rømø Bight ecosystem, northern Wadden Sea, over three time periods. Marine Ecology Progress Series 462,143-162.

Baird, D., Asmus, H., Asmus, R., Horn, S. and De la Vega, C. (2019). Ecosystem response to increasing ambient water temperatures due to climate warming in the Sylt-Romo Bight, northern Wadden Sea, Germany. Estuarine, Coastal and Shelf Science 228, 106322

Beaugrand, G., Edwards, M., Raybaud, V., Goberville, E. and Kirby, R.R. (2015). Future vulnerability of marine biodiversity compared with contemporary and past changes. *Nature Climate Change*, *5*(7), pp.695-701.

Blanchard, J.L., 2015. A rewired food web. *Nature*, *527*(7577), pp.173-174.

Bruge, A., Alvarez, P., Font´an, A., Cotano, U. and Chust, G. (2016). Thermal niche tracking and future distribution of Atlantic mackerel spawning in response to ocean warming. Front. Mar. Sci. 3 https://doi.org/10.3389/fmars.2016.00086.

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K. M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J. and Richardson, A.J. (2011). The pace of shifting climate in marine and terrestrial ecosystems. Science 334 (6056), 652–655.

Burthe, S., Daunt, F., Burler, A., Elston, D.A., Frederikson, M. et al. (2012). Phenological trends and trophic mismatch across multiple levels of a North Sea pelagic food web. Marine Ecology Progress Series 454: 119-133

Capuzzo, E., Lynam, C. P., Barry, J., Stephens, D., Forster, R. M., Greenwood, N., McQuatters-Gollop, A., Silva, T., van Leeuwan, S. M. and Engelhard, G. H. (2018). A decline in primary production in the North Sea over 25 years, associated with reductions in zooplankton abundance and fish stock recruitment. *Global change biology*, *24*(1), e352-e364.

Chapman, E.J., Byron, C.J., Rasher-Lasley, R., Lipsky, C., Stevens, J.R. and Peters, R. (2020). Effects of climate change on coastal ecosystems food webs: implications for aquaculture. Marine Environemental Research 162, https://doi.org/10.1016/j.marenvres.2020.105103

Cheung, W.W., Lam, V.W., Sarmiento, J.L., Kearney, K., Watson, R., Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish. 10 (3), 235-251

Chust, G., González, M., Fontán, A., Revilla, M., Alvarez, P., Santos, M., Cotano, U., Chifflet, M., Borja, A., Sagarminaga, Y., Caballero, A., de Santiago, I., Epelde, I., Liria, P., Ibaibarriaga, L., Garnier, F., Franco, J., Villarino, E., Irigoien, X., Fernandes-Salvador, J. A., Uriarte, A., Esteban, X., Orue-Echervarria, D., Figueira, T. and Uriarte, A. (2022). Climate regime shifts and biodiversity redistribution in the Bay of Biscay. *Science of The Total Environment*, *803*, 149622.

Daunt, F., Wanless, S., Greenstreet, S.P.R., Jensen, H., Hamer, K.C., Harris, M.P. (2008) The impact of the sandeel fishery closure on seabird food consumption, distribution, and productivity in the northwestern North Sea. Canadian Journal of Fisheries and Aquatic Sciences 65: 362-381

Duarte, C. M., Hendriks, I. E., Moore, T. S., Olsen, Y. S., Steckbauer, A., Ramajo, L., Carstensen, J., Trotter, J. A. & McCulloch, M. (2013). Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, *36*(2), 221-236.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R. and Skjoldal, H.R. (2008). Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. J. Appl. Ecol. 45 (4), 1029–1039

European Commission (2018). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL assessing Member States' programmes of measures under the Marine Strategy Framework Directive (COM/2018/562 final) accessed https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0562&from=EN

Eriksson, B., Sieben, K., Eklöf, J., Ljunggren, L., Olsson, J., Casini, M. and Bergström, U. (2011). Effects of Altered Offshore Food Webs on Coastal Ecosystems Emphasize the Need for Cross-Ecosystem Management. Ambio, 40, 786-797. doi:10.1007/s13280-011-0158-0

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R.B., Aschan, M.M. and Dolgov, A. V. (2015). Recent warming leads to a rapid borealization of fish communities in the Arctic. Nat. Clim. Change 5 (7), 673–677

Gehlen, M., Séférian, R., Jones, D.O., Roy, T., Roth, R., Barry, J., Bopp, L., Doney, S.C., Dunne, J.P., Heinze, C. and Joos, F. (2014). Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk. *Biogeosciences*, *11*(23), pp.6955-6967.

Goldenberg, S.U., Nagelkerken, I., Ferreira, C.M., Ullah, H. and Connell, S.D. (2017). Boosted food web productivity through ocean acidification collapses under warming. Global change biology 23: 4177-4184

Greenstreet, S.P.R., Armstrong, E., Mosegaard, H., Jensen, H., Gibb, I., Fraser, H., Scott, B., Holland, G. and Sharples, J. (2006). Variation in the abundance of sand eels Ammodytes marinus off southeast Scotland: an evaluation of area-closure fisheries management and stock abundance assessment methods. ICES J. Mar. Sci. 63: 1530-1550

Greenstreet, S. P. R., Rogers, S. I., Rice, J. C., Piet, G. J., Guirey, E. J., Fraser, H. M. and Fryer, R. J., (2011). Development of the EcoQO for the North Sea fish community. *ICES Journal of Marine Science* 68: 1–11.

Heath, M.R., Speirs, D.C. and Steel, J.H. (2014). Understanding patterns and processes in models of trophic cascades. Ecologica letters, 17(1), 101-114

Hernvann, P. Y., Gascuel, D., Grüss, A., Druon, J. N., Kopp, D., Perez, I., Piroddi, C. and Robert, M. (2020). The Celtic Sea through time and space: Ecosystem modeling to unravel fishing and climate change impacts on food-web structure and dynamics. *Frontiers in Marine Science*, 1018.

Hofstede, T.R., Hiddink, J.G. and Rijnsdorp, A.D. (2010). Regional warming changes fish species richness in the eastern North Atlantic Ocean. Mar. Ecol. Prog. Ser. 414, 1–9.

Holt, J., Allen, J. I., Anderson, T. R., Brewin, R., Butenschön, M., Harle, J., Huse, G., Lehodey, P., Lindemann, C., Memery, L., Salohoglu, B., Senina, I. and Yool, A. (2014). Challenges in integrative approaches to modelling the marine ecosystems of the North Atlantic: Physics to fish and coasts to ocean. *Progress in Oceanography*, *129*, 285-313

Horta e Costa, B., Assis, J., Franco, G., Erzini, K., Henriques, M., Gonçalves, E.J. and Caselle, J.E., 2014. Tropicalization of fish assemblages in temperate biogeographic transition zones. Mar. Ecol. Prog. Ser. 2014 (504), 241.

Jepsen, J.U., Arneberg, P., Ims, R.A., Siwertsson, A. and Yoccoz, N.G. (2020). Panel-based Assessment of Evosystem Condition (PAEC) – Technical protocol version2. NINA Report 1980. Norwegian Institute for Nature Research

Johannesen E., Yoccoz, N., Tveraa, T., Schackell, N.L., Ellingsen, K., Dolgov, A.V. and Frank, K.T., (2020). Resource-driven colonization by cod in a high Arctic food web. Ecology and Evolution 10: 14272–14281. DOI: https://doi.org/10.1002/ece3.7025.

Jung, A.S., van der Veer, H.W., Philippart, C.J.M., Waser, A.M., Ens, B.J., de Jonge, V.N. and Schückel, U. (2020). Impacts of macrozoobenthic invasions on a temperate coastal food web. Marine Ecology Progress Series 653: 19-39.

Kleisner, K.M., Fogarty, M.J., McGee, S., Hare, J.A., Moret, S., Perretti, C.T. and Saba, V.S. (2017). Marine species distribution shifts on the U.S. Northeast Continental Shelf under continued ocean warming. Prog. Oceanogr. 153, 24–36.

Kortsch, S., Primicerio, R., Fossheim, M., Dolgov, A.V. and Aschan, M. (2015). Climate change alters the structure of arctic marine food webs due to poleward shifts of boreal generalists. *Proceedings of the Royal Society B: Biological Sciences*, *282*(1814), p.20151546.

Lawrence, M.J., Stemberger, H.L.J., Zolderdo, A.J., Struthers, D.P. and Cooke, S.J. (2015). The effects of modern war and military activities on biodiversity and the environment. Environ. Rev 23: 443-460

Lenoir, S., Beaugrand, G. and Lecuyer, E. (2011). Modelled spatial distribution of marine fish and projected modifications in the North Atlantic Ocean. Glob. Change Biol. 17, 115–129.

Le Marchand, M. Ben Rais Lasram, F., Araignous, E., Saint-Béat, B., Lassalle, G., Michelet, N., Serre, S., Safi, G., Lejart, M., Niquil, N. and Le Loc´h, F. (2022). Potential combined impacts of climate change and non-indigenous species arrivals on Bay of Biscay trophic network structure and functioning. Journal of Marine Systems 228, https://doi.org/10.1016/j.jmarsys.2022.103704

Levin, L.A. and Le Bris, N. (2015). The deep ocean under climate change. *Science*, *350*(6262), pp.766-768.

Levin, L.A., Wei, C.L., Dunn, D.C., Amon, D.J., Ashford, O.S., Cheung, W.W., Colaço, A., Dominguez-Carrió, C., Escobar, E.G., Harden-Davies, H.R. and Drazen, J.C. (2020). Climate change considerations are fundamental to management of deep-sea resource extraction. *Global change biology*, *26*(9), pp.4664-4678.

Lynam, C.P., Llope, M., Möllmann, C., Helaouët, P., Bayliss-Brown, G.A. and Stenseth, N.C. (2017). Interaction between top-down and bottom-up control in marine food webs. Proceedings of the National Academy of Sciences 114 (8): 1952-1957

Machado, I., Costa L.J.and Cabral, H. (2021). Response of food-webs indicators to human pressures, in the scopre of the Marine Strategy Framework Directive. Front. Mar.Sci., https://www.frontiersin.org/articles/10.3389/fmars.2021.699566/full

Meyer, J., Nehmer, P., Moll, A.and Kröncke, I. (2018). Shifting south-eastern north Sea macrofauna community structure since 1986: A response to de-eutrophication and regionally decreasing food supply? Estuarine, Coastal and Shelf Science 213: 115-127

Morato, Telmo, José-Manuel González-Irusta, Carlos Dominguez-Carrió, Chih-Lin Wei, Andrew Davies, Andrew K. Sweetman and Gerald H. Taranto. (2020). "Climate-induced changes in the suitable habitat of cold-water corals and commercially important deep-sea fishes in the North Atlantic." *Global Change Biology* 26, no. 4: 2181-2202.

Machado I., Costa J.L., and Cabral, H. (2021). Response of Food-Webs Indicators to Human Pressures, in the Scope of the Marine Strategy Framework Directive. Front. Mar. Sci. 8:699566. doi: 10.3389/fmars.2021.699566

Morato, T., Lemey, E., Menezes, G., Pham, C.K., Brito, J., Soszynski, A., Pitcher, T.J. and Heymans, J.J. (2016). Food-web and ecosystem structure of the open-ocean and deep-sea environments of the Azores, NE Atlantic. *Frontiers in Marine Science*, *3*, p.245.

Nogues, Q., Raoux, A., Araignous, E., Chaalali, A., Hattab T., Leroy, B., Ben Rais Lasram, F., David, V., Le Loc'h, F., Dauvin, J.C. and Niquil, N. (2021). Cumulative effects of marine renewable energy and climate change on ecosystem properties: Sensitivity of ecological network analysis. Ecological Indicators, 121, 107128.

Nogues, Q., Araignous, E., Bourdaud, P., Halouani, G. and Raoux, A. (2022). Spatialized ecological network analysis for ecosystem-based management: effects of climate change, marine renewable energy, and fishing on ecosystem functioning in the Bay of Seine. ICES Journal of Marine Science 79: 1098-1112

Odum E. P. 1969 *Science*, New Series, Vol. 164, No. 3877. pp. 262-270

Olbert, A. I., Dabrowski, T., Nash, S. and Hartnett, M. (2012). Regional modelling of the 21st century climate changes in the Irish Sea. *Continental Shelf Research, 41, 48-60.*

Perez, F.F., Fontela, M., García-Ibáñez, M.I., Mercier, H., Velo, A., Lherminier, P., Zunino, P., De La Paz, M., Alonso-Pérez, F., Guallart, E.F. and Padin, X.A. (2018). Meridional overturning circulation conveys fast acidification to the deep Atlantic Ocean. *Nature*, *554*(7693), pp.515-518.

Piet G. J., Tamis J. E., Volwater J., de Vries P., van der Wal J. T. and Jongbloed, R. H. (2021). A Roadmap Towards Quantitative Cumulative Impact Assessments: Every Step of the Way. *Sci. Total Environ*. 784, 146847. doi: 10.1016/j.scitotenv.2021.146847

Piroddi, C., Akoglu, E., Andonegi, E., Bentley, J. W., Celić, I., Coll, M. and Tsikliras, A. C. (2021). Effects of nutrient management scenarios on marine food webs: a Pan-European Assessment in support of the Marine Strategy Framework Directive. *Frontiers in Marine Science*, 8, 179.Pitois SG, Graves CA, Close H, Lynam C, Scott J, Tilbury J, van der Kooij J, Culverhouse P. (2021). A first approach to build and test the Copepod Mean Size and Total Abundance (CMSTA) ecological indicator using in-situ size measurements from the Plankton Imager (PI), *Ecological Indicators* 123, 107307. https://doi.org/10.1016/j.ecolind.2020.107307

Puerta, P., Johnson, C, Carreiro-Silva, M., Henry, LA, Kenchington, E., Morato, T., Kazanidis, G., Jose Luis Rueda, J.L., Urra, J., Ross, S., Wei, C.-L., González-Irusta J.M., Arnaud-Haond, S. and Orejas, C. (2020). Influence of water masses on the biodiversity and biogeography of deep-sea benthic ecosystems in the North Atlantic. *Frontiers in Marine Science 7*, 239.

Punzón, A., Serrano, A., Sánchez, F., Velasco, F., Preciado, I., González-Irusta, J. and López-López, L. (2016). Response of a temperate demersal fish community to global warming. J. Mar. Syst. 161, 1–10.

Punzón A., López-López L., González-Irusta J.M., Preciado I., Hidalgo M., Serrano A., Tel E., Somavilla R., Polo J., Blanco M., Ruiz-Pico S., Fernández-Zapico O., Velasco F.and Massutí, E., (2020). Tracking the effect of temperature in marine demersal fish communities. Ecological indicators (doi: https://doi.org/10.1016/j.ecolind.2020.107142)

Queirós, A.M., Fernandes, J., Genevier, L. and Lynam, C.P. (2018). Climate change alters fish community size-structure, requiring adaptive policy targets. Fish and Fisheries 2018: 1-9, https://doi.org/10.1111/faf.12278

Righton, D.A., Andersen, K.H., Neat, F., Thorsteinsson, V., Steingrund, P., Svedang, H., Michalsen, K., Hinrichsen, H.H., Bendall, V., Neuenfeldt, S., Wright, P., Jonsson, P., Huse, G., van der Kooij, J., Mosegaard, H., Hüssy, K. and Metcalfe, J. (2010). Thermal niche of Atlantic cod Gadus morhua: limits, tolerance and optima. Mar. Ecol. Prog. Ser. 420, 1–13.

Rossoll D, Bermu´dez R, Hauss H, Schulz KG and Riebesell, U. (2012) Ocean Acidification-Induced Food Quality Deterioration Constrains Trophic Transfer. PLoS ONE 7(4): doi:10.1371/journal.pone.0034737

Safi, G., Giebels, D., Arroyo, L., Heymans, J., Preciado, I., Raoux, A., Schückel, U., Tecchio, S., de Jonge V.N. and Niquil, N. (2019). Vitamine ENA: A framework for the development of ecosystem-based indicators for decision-makers. Ocean, Coastal and Management 174:116-130

Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P.-J., Sims, D.W. and Genner, M.J. (2011). Continental shelf-wide response of a fish assemblage to rapid warming of the sea. Curr. Biol. 21, 1565–1570

Soler, G.A., Edgar, G.J., Thomson, R.J., Kininmonth, S., Campbell, S.J. and Dawson, T.P. (2015). Reef Fishes at All Trophic Levels Respond Positively to Effective Marine Protected Areas. PLoS ONE10(10): e0140270. doi:10.1371/journal.pone.0140270. Available from: https://www.researchgate.net/publication/282943302_Reef_Fishes_at_All_Trophic_Levels_Respond_Positively_to_Effective_Marine_Protected_Areas[accessed May 30 2022].

Spence, M.A., Griffiths, C.A., Waggitt, J.J., Bannister, H.J., Thorpe, R.B., Rossberg, A.G. and Lynam, C.P. (2021). Sustainable fishing can lead to improvements in marine ecosystem status: an ensemble-model forecast of the North Sea ecosystem. Marine Ecology Progress Series 680:207-221. https://doi.org/10.3354/meps13870

Spence, M.A., Lynam, C.P., Thorpe, R.B., Heneghan, R.F. and Dolder, P.J. (2022). Synthesizing Empirical and Modelling Studies to Predict Past and Future Primary Production in the North Sea. Frontiers in Marine Science 9:828623. https://doi.org/10.3389/fmars.2022.828623

Sweetman, A.K., Thurber, A.R., Smith, C.R., Levin, L.A., Mora, C., Wei, C.L., Gooday, A.J., Jones, D.O., Rex, M., Yasuhara, M. and Ingels, J. (2017). Major impacts of climate change on deep-sea benthic ecosystems. *Elementa: Science of the Anthropocene*, *5*.

Tavares, D. C., Moura, J. F., Acevedo-Trejos, E. and Merico, A. (2019). Traits Shared by Marine Megafauna and Their Relationships with Ecosystem Functions and Services. Frontiers in Marine Science, 6(262). doi:10.3389/fmars.2019.00262

Thompson, M.S.A., Pontalier, H., Spence, M., Pinnegar, J.K., Greenstreet, S., Moriarty, M., Hélaouët, P. and Lynam, P.C. (2020). A feeding guild indicator to assess environmental change impacts on marine ecosystem structure and functioning. Journal of Applied Ecology 57 (9): 1769-1781, https://doi.org/10.1111/1365-2664.13662

Thorpe, R.B., Arroyo, N.L., Safi, G., Niquil, N., Preciado, I., Heath, M., Pace, M.C. and Lynam, C.P. (2022). The Response of North Sea Ecosystem Functional Groups to Warming and Changes in Fishing. Frontiers in Marine Science 9:841909. https://doi.org/10.3389/fmars.2022.841909

Tilstone, G. H., Land, P. E., Pardo, S., Kerimoglu, O. and Van der Zande, D. (2022). Threshold indicators of primary production in the north-east Atlantic for assessing environmental disturbances using 21 years of satellite ocean colour. *Science of The Total Environment*, 158757.

Ulanowicz, R. E. (2004). Quantitative methods for ecological network analysis. Computational biology and chemistry 28: 321–339

Ullah, H., Nagelkerken, I., Goldenberg, S.U. and Fordham, D.A. (2018). Climate change could drive marine food web collapse through altered trophic flows and cyanobacterial proliferation. PLOS Biology 16(1): e2003446. https://doi.org/10.1371/journal.pbio.2003446

Woodstock, M.S. and Zhang, Y. (2022). Towards ecosystem modeling in the deep sea: A review of past efforts and primer for the future. *Deep Sea Research Part I: Oceanographic Research Papers*, p.103851.

Xavier, J., Carreiro-Silva, M., Colaço, A., Le Bris, N. and Levin, L. (2019). *Chapter 6. Vulnerabilities: Invertebrate taxa (VME indicators)*, In Deep-ocean climate change impacts on habitat, fish and fisheries, by Lisa Levin, Maria Baker, and Anthony Thompson (eds). FAO Fisheries and Aquaculture Technical Paper No. 638. Rome, FAO. 186 pp. Licence: CC BY-NC-SA 3.0 IGO.

Thematic Metadata

Field	Explanation
Linkage	DAPI list and definitions https://www.ospar.org/documents?v=48497 Key papers FW7 https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.13662 Climate https://doi.org/10.3389/fmars.2022.841909 FC2/FC3/FW3 https://doi.org/10.3354/meps13870 FW2 https://doi.org/10.3389/fmars.2021.596797 FW6 https://doi.org/10.1016/j.ecolind.2020.107307

OSPAR's Quality Status Report 2023

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

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

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

Publication Number: 959/2023