The importance of sprat to the wider marine ecosystem in the North Sea and English Channel (ICES Subarea 4 and Divisions 7.d–e)

Defra request for advice

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Defra Request

In February 2024, Defra Quota Policy & Negotiations Team sought Natural England advice as regards the ecosystem role of sprat and appropriateness of applying Ecosystem-Based Fisheries Management (EBFM) approaches to the management of sprat fisheries. This report has been requested to support the North Sea and Channel Sprat Fishery Management Plan (FMP).

As well as explaining the ecosystem role of sprat, the objective of this report was to identify both the positive and negative impacts of changes to the biomass of sprat on individual trophic marine species including seabirds. Lastly, advice was sought on what management instruments would deliver the most benefit to the wider marine ecosystem, focusing on what these might be where there is not a full prohibition on fishing for sprat.

Core advice

The core advice generated from this report is that:

- Sprat (*Sprattus sprattus*) are an important forage fish in the North Sea and English Channel marine ecosystems. Sprat are 1) predators of zooplankton, 2) competitors with other forage fish (e.g., herring), 3) prey for piscivorous fish, marine mammals, and seabirds, and 4) a resource for economically important commercial fisheries. There is evidence to suggest sprat recruitment and growth is driven by environmental variation, notably changes in temperature and food availability.
- An ecosystem model of the North Sea (Ecopath with Ecosim) was used to simulate the impact of changes in sprat biomass on the wider ecosystem. Both direct and indirect responses were estimated: direct responses were linked to the availability of sprat as prey (e.g., for whiting, mackerel, and common guillemot) while indirect responses were linked to changes in biomasses of other species, and the associated impacts of predation pressure and food availability (e.g., herring increased when sprat decreased due to the increased availability of limited copepod prey for herring).
- In the Northeast Atlantic, we possess the necessary tools and expertise to provide evidence to underpin Ecosystem-Based Fisheries Management (EBFM) that recognises the impacts of environmental variation on production and assesses the performance of different management strategies against ecosystem objectives such as the potential trade-offs between forage fish harvest and predator carrying capacities. Four pragmatic EBFM approaches are presented in this report which could be further explored to operationalise EBFM for sprat.
- The nature of the evidence request underpinning this report is not unique, with similar requests having recently been completed (e.g., for sandeels) and further requests anticipated in the future as Defra explore EBFM options for other forage species. Considering this context, it would be advisable for Defra to lead the development of a UK Forage Fish Approach which sets out clear objectives and principles applicable to both existing and potentially new UK forage fish fisheries.
- Defra could accelerate momentum towards EBFM by asking their scientific advisers (which includes requests to ICES) ambitious, ecosystem-focused questions that consider multiple objectives across sustainable use and conservation policies (e.g., the Fisheries Act 2020 and UK Marine Strategy Regulations 2010).

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Preface and report overview

Sprat Fishery Management Plan (FMP)

This report has been requested as a supporting document for the North Sea and Channel Sprat (*Sprattus sprattus*) Fishery Management Plan (FMP). The objective of this report is to provide additional information on potential advice pipelines and research options to adopt Ecosystem-Based Fisheries Management (EBFM) approaches (**Objective 2 of the FMP**).

In line with the Fisheries Act 2020 ecosystem objective, Statutory nature conservation bodies (SNCB) advice recommended that the FMP should explore ecosystem-based approaches for the management of sprat stocks which will 1) contribute to Good Environmental Status (GES) for multiple targets set by the UK Marine Strategy (UKMS), 2) have benefits for the designated features of Marine Protected Areas (MPAs), and 3) have the potential to reflect the multiple, potentially conflicting, social, cultural, and ecological objectives and the trade-offs between the diverse needs of people and the marine food web. The FMP has embedded these recommendations, and options for short-, medium-, and long-term actions, within five goals to achieve the overall vision for the FMP.

This report provides additional ecosystem-based information and research options relative to the goals of the FMP, particularly in-line with recommendations to:

- Explore options to move away from single-species models (under FMP Goal 2)
- Bring together existing information on the ecosystem role of sprat (under FMP Goal 3)
- Progress contribution towards achieving Good Environmental Status (GES), compatible with targets set by the UK Marine Strategy (UKMS) (under FMP Goal 3)
- Consider research into how an ecosystem-based approach could be incorporated into future iterations of the FMP (under FMP Goal 3)
- Develop ecosystem-based fisheries management approaches for sprat fishing that are robust to the effects of climate variability (under FMP Goal 5)

UK policy landscape and environmental objectives

Ecosystem-Based Fisheries Management (EBFM) is a systematic approach to fisheries management that sets out to enhance the resilience and sustainability of the marine ecosystem by 1) recognising the physical, biological, economic, and social interactions among the fishery-related components of the ecosystem, including humans, and 2) developing strategies to optimise benefits and trade-offs across a diverse set of societal goals and policy objectives (Link et al., 2002; Pikitch et al., 2004; NOAA et al., 2016). Compared to traditional single-species approaches, EBFM is relatively esoteric, however, frameworks are available to guide the delivery of specific EBFM actions (e.g., ICES Framework for Ecosystem-Informed Science and Advice; FEISA; Roux and Pedreschi, 2024) and guidelines have been proposed to help decision makers formulate effective EBFM advice requests (e.g., Pew 2024).

North Sea and English Channel Sprat, along with other forage fish in UK waters, play a critical role in marine ecosystems by serving as a primary conduit for energy transfer from plankton to higher trophic levels, while also supporting commercially important fisheries (Pikitch et al., 2014; Englehard et al., 2014). EBFM for sprat and other forage fish is of direct and indirect relevance to multiple, interacting UK environmental objectives and policy areas. These are summarised below.

The Environmental Improvement Plan (EIP)

The 2023 Environmental Improvement Plan (EIP) sets out how the framework and vision described in the 25 Year Environment Plan, will be delivered. Goal 6 of the EIP commits the UK to using resources from nature sustainably. Specifically, the plan identifies the need to manage fisheries more sustainably by applying an ecosystem-based approach to marine and fish stock management. It identifies the need to “consider how best to use our forage fish, to support the wider ecosystem”.

The EIP also suggests that FMPs should contribute to the appropriate objectives of the UK Marine Strategy (UKMS) by promoting selectivity, reducing negative impacts on the ecosystem, and helping to deliver the recovery of fish stocks.

The UK Marine Strategy (UKMS)

The UK Marine Strategy Regulations 2010 (SI 2010/1627) provide the policy framework for delivering marine environmental policy at the UK level and set out how the Governments vision of clean, healthy, safe, productive, and biologically diverse oceans and seas will be achieved. Good Environmental Status (GES) establishes a ‘benchmark’ for our seas which seeks to ‘protect the marine environment, preventing its deterioration and restoring it where practical, while allowing sustainable use of marine resources'. For each of the GES descriptors, there are several practical targets and indicators that facilitate assessment of our delivery towards GES.

UKMS descriptors include those for biodiversity (D1) and food webs (D4) which in turn include indicators for birds, fish, marine mammals, and pelagic habitats. The UKMS Part 3 (the programme of measures) identifies fisheries as one of the contributing activities to the failure to reach GES for these descriptors.

Furthermore, recent advice from statutory nature conservation bodies ('SNCBs') to inform the development of the Strategic Environmental Assessment for the North Sea and Channel Sprat FMP identified that sprat fisheries were likely to pose a 'moderate' risk to D1, D4 birds and D1, D4 marine mammals, through possible reductions in prey availability.

The Fisheries Act 2020

A link between the UKMS and fisheries is established in the ecosystem objective of the Fisheries Act 2020. The ecosystem objective specifies that:

> *"Fish and aquaculture activities are to be managed using an ecosystem-based approach so as to ensure that their negative impacts on marine ecosystems are minimised and, where possible, reversed, and (b) incidental catches of sensitive species are minimised and, where possible, eliminated."*

Within the Fisheries Act, an ecosystem approach is defined as one which:

> (a) *ensures that the collective pressure of human activities is kept within levels compatible with* ***the achievement of good environmental status*** *(within the meaning of the Marine Strategy Regulations 2010 (S.I. 2010/1627)), and*
>
> (b) *does not compromise the capacity of marine ecosystems to respond to human-induced changes.*

The Joint Fisheries Statement (JFS)

The JFS acknowledges that fisheries are fully reliant on the ecosystems in which they operate, and that ecosystems can be compromised by human-induced pressures. It expands the definition of the ecosystem-based approach to one that explicitly supports the achievement of the sustainability, precautionary and ecosystem objectives in the Fisheries Act, as well as necessitating a contribution to the achievement of GES. It specifies that such an approach will include measures to sustainably manage fisheries, maintain healthy populations of target species, recover populations of vulnerable species, and protect key forage fish species. Furthermore, the JFS recognises the importance of managing fishing activity to account for natural change, to allow for the dynamic nature of marine ecosystems and improve resilience to fishing pressure, natural variation, and climate change.

One of the JFS's key principles of international fisheries negotiations is to secure outcomes consistent with wider obligations for the conservation and sustainable use of the marine environment including the UKMS, and international commitments such as those within the Convention on Biological Diversity (CBD), the OSPAR Convention, and the UN Sustainable Development Goals.

The JFS establishes that the primary focus of all FMPs will be achieving the long-term, sustainable harvesting of our stocks. However, it also acknowledges that the scope of an FMP may be extended to consider wider fisheries management issues covering environmental, social, and economic concerns.

The English Seabird and Recovery Pathway

The English Seabird Conservation and Recovery Pathway (ESCaRP) recently assessed species' sensitivity and exposure to activities and pressures to understand the relative potential of different activities to affect their populations (Natural England. 2024). The report makes a series of recommendations to restore seabird populations and help the UK meet GES targets stemming from the UKMS. One of these recommendations is to develop a Forage Fish Policy (or similar mechanism) to implement an ecosystem approach to fisheries management decisions that appropriately considers the importance of prey for seabirds, including the use of predator reference points (Natural England. 2024).

The Environmental Targets (Biodiversity) (England) Regulations 2023

Sprat is listed in Schedule 2 of The Environmental Targets (Biodiversity) (England) Regulations 2023, which were brought in as a requirement under Section 3 of the Environment Act (2021). The species included in Schedule 2 contribute to the relative species abundance indices which are used to measure progress towards two targets, namely the 2030 species abundance target and the long-term biodiversity target.

Marine Protected Areas

When managing Marine Protected Areas (MPAs) in the UK, 'Conservation Objectives' are used to ensure that designated features (and the site as a whole) are maintained and kept in good condition. Conservation Objectives are used as targets to ensure designated species and habitats are maintained or progress towards favourable conservation status (FCS), as per the Habitats Regulations and the Conservation of Offshore Marine Habitats and Species Regulations 2017 (as amended). The Habitats Regulations explicitly require the relevant SNCBs to advise on the conservation objectives for SACs and SPAs. This more detailed and site-specific information is known as Supplementary Advice on Conservation Objectives[1] (SACOs).

The Southern North Sea SAC for harbour porpoise and marine seabirds at five designated sites in the North Sea and three designated sites in the English Channel all have SACOs identifying sprat as a key prey target to be maintained. SNCB advice to the North Sea and Channel sprat FMP therefore identified this fishery as posing moderate risks to the designated features of these MPAs. In addition, whiting, a predator of sprat, are mentioned in the SACO advice on targets relating to maintaining the abundance of preferred food items of harbour seals (*Phoca vitulina*).

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[1] Designated sites portal: Site Search (naturalengland.org.uk)

Evidence review

Sprat ecology and drivers of production

Previous experimental, modelling, and field studies have demonstrated that temperature and the availability of zooplankton prey can impact the recruitment and growth of sprat (e.g., MacKenzie and Köster 2004; Daewel et al., 2008, Hunter et al., 2019, Fernandes et al., 2020). An inverse relationship between temperature and sprat has been identified in the North Sea (Hunter et al., 2019; Clausen et al., 2018) and Bristol Channel (Henderson and Henderson, 2017). Henderson and Henderson (2017) highlight that the rapid increase in spring temperature and inshore temperatures in the Bristol Channel can be above growth and survival optima for sprat early stages. Similarly, Hunter et al (2019) referenced the increased metabolic costs associated with rising temperatures in the North Sea and how growth rates may decline as thermal thresholds are exceeded. Engelhard et al. (2014) noted variation in the optimum thermal windows for sprat at different stages of development and responses to changing temperature regimes depending on the position within the species geographic range. Temperature also affects the synchrony between timing of fish reproduction and that of their zooplankton prey, with mismatches resulting in small year-classes (Wright et al., 2020). The 2018 ICES benchmark workshop on sprat (WKSPRAT, ICES, 2018) performed an exploratory statistical analysis to identify environmental indicators of North Sea sprat stock status. The results of their analysis supported their expectations that temperature and food availability, as well as density-dependence (e.g., Croll et al., 2023), have impacts on both the recruitment success and growth of sprat.

The historical harvest rate of sprat in the North Sea has oscillated between 5% and 30%, despite which, the stock biomass has recovered from historically low levels, inferring a strong dependence on the environment and less so on the fishery, whose catches have remained relatively stable (ICES, 2019). Short-lived species such as sprat are strongly dependent on spasmodic recruitment events, including survival of early life stages, which are not necessarily related to the adult stock size (Campanella & Van der Kooij, 2021). An impairment of these recruitment events, a change in the frequency of high recruitment events occurring, or a change in the magnitude of these events, might indicate a change in the ecosystem or the occurrence of a regime shift, which can subsequently lead to impacts on the biomass of predators dependent on these species.

In the North Sea, major fish predators of sprat include mackerel (*Scomber scombrus*), horse mackerel (*Trachurus trachurus*) and whiting (*Merlangius merlangus*) (e.g., Hislop., 1991; Timmerman et al., 2023; Van Ginderdeuren et al., 2014). Other predators include marine mammals and seabirds (e.g., Ransijn et al., 2021; Wanless et al., 2018). Predation levels in the North Sea do not show the dramatic variation from year-to-year that can occur in the Baltic (ICES, 2018). Predation impacts are considered explicitly in the stock assessment for North Sea sprat by including annual estimates of natural mortality imposed by predators based on predator abundances, prey preferences, and abundances of other prey stocks. The inclusion of variable natural mortality can be seen as a step towards EBFM (Trenkel et al., 2023), however it is an indirect application of EBFM because of advances in the best available science. The assessment priority remains to be single-species MSY; the forage needs of predators which might support recovery, for example, are not considered (ICES, 2023a). Impacts of changes in zooplankton communities and consequent changes in food densities for sprat are not included in the assessment. The ICES Herring Assessment Working Group (HAWG; ICES, 2023b) suggest that it may be useful to explore the possibility of including this, or a similar proxy bottom-up driver, in future sprat assessments.

Sprat and their role in the ecosystem

Forage fish such as sprat occupy an important niche in marine ecosystems; they are a high-energy prey that transfer energy from the lower trophic levels to the highest, including mammals, seabirds, and fish (Dickey-Collas et al., 2014). Forage fish may compete with each other for food, thus variations in the abundance of a single species affects that of other forage fish species, while the abundance of forage fish as a community affects the abundance of both their predators and the zooplankton they prey upon (Engelhard et al., 2014; Fauchald et al., 2011).

Some forage fish are a key food for certain predator species, whereby there is a direct correlation between their abundance and predator productivity or breeding success, such as the link between sandeels (particularly *Ammodytes marinus*) and blacklegged kittiwakes (*Rissa tridactyla*) (Carroll et al., 2017). However, for many predators, forage fish constitute part of a diet that includes multiple forage fish or other fish species, often in addition to non-fish prey (Barrett et al., 2007; Oceana, 2023). Such predators are more readily able to switch between alternative forage fish prey species, provided the conditions that make alternatives available are met, such as prey size and accessibility (Greenstreet, 1998). For example, harbour porpoise (*Phocoena phocoena*) and common guillemots (*Uria aalge*) have been found to switch to prey on sprat if sandeels are not available (Ransijn et al., 2021; Wanless et al., 2005).

Diets of predators may vary seasonally, thus the importance of different forage fish species can change through the year, for example, whiting and haddock

(*Melanogrammus aeglefinus*) prefer sprat over other, larger, forage fish prey during winter (Timmerman et al. 2020; Greenstreet, 1998) while seabirds select larger forage fish prey during the breeding season compared to their winter diets (Barrett et al., 2007). Finally, some predators show a preference for different age-classes of forage fish, such as fin whales (*Balaenoptera physalus*) and humpback whales (*Megaptera novaeangliae*) which prefer 0-1 year sprat (Ryan et al., 2014).

Thus, the relative importance of forage fish species to predators is likely to change with a) the availability of other prey species, b) their life stage or size, and c) season. Under these circumstances, correlations between the abundance of single forage fish species and the condition of predators are weak and the ecosystem role of one forage fish species is intrinsically linked to the abundance and availability of other forage fish. The availability and quality of forage fish available for predators can be affected by fishing, and as such, by fisheries management (Natural England, 2024).

English Channel sprat is a data-limited stock (ICES category 3) with there being many gaps in the fundamental understanding of the species' ecology in the area (Campanella & Van der Kooij, 2021). Data on the role of sprat in the English Channel ecosystem are therefore sparse. However, given the strength of evidence that sprat are important to multiple predators in the North Sea and Celtic Seas, it would be precautionary to assume that sprat in the Channel are capable of supporting a similar functional role. Several forage fish species found in the North Sea are less abundant or absent in the English Channel (Oceana, 2023), thus sprat may be relatively more important to that ecosystem. For instance, although sardine and anchovy schools were present in the western English Channel in autumn 2020, sprat were the dominant small pelagic fish species in the Lyme Bay area[2].

Sprat predate on fish eggs, including commercially important species (Wright et al., 2020); in the Irish Sea, sprat are a dominant predator of plaice (*Pleuronectes platessa*) eggs with consequences for their recruitment (Fox et al., 2012; Plirú et al., 2012). However, fish eggs may be only a small component of sprat diet in the North Sea and English Channel (Pinnegar et al. 2023; Kleinertz et al., 2012; Van Ginderdeuren et al., 2014). The available evidence on the role of sprat as prey for different predator groups in the North Sea and English Channel is presented below, with ecosystem links between sprat biomass and predators (in the North Sea, English Channel, Celtic Sea and Wadden Sea) summarised in

Table 1.

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[2] 2023 PELTIC survey results presented at South West Marine Ecosystems Webinar, 8 March 2024 (available online: SWME 2024 Webinar - Fisheries (youtube.com))

Marine mammals

Sprat are among the five most important prey for harbour porpoises in the North Sea (Mahfouz et al., 2017; Ransijn et al., 2021) and contribute considerably to harbour porpoise diet during the winter in the southern North Sea (Ransijn et al., 2019). There is evidence that sprat are also a minor prey item for harbour seals and grey seals (*Halichoerus grypus*) in the North Sea (Wilson & Hammond, 2019), however whiting, a predator of sprat, are a dominant prey item for grey seals in the Central and southern North Sea (Hammond & Wilson, 2016).

Sprat, particularly age 0-1, are preferred fish prey for humpback and fin whales in the Celtic Sea (Ryan et al., 2014); these whales are increasingly observed in the southern North Sea (Berrow & Whooley, 2022). Similarly, minke whales (*Balaenoptera acutorostrata*) feed on sprat in the Celtic Sea (Anderwald et al., 2011) and are seen in the English Channel (Reid, 2003). In European waters, sprat is a prey item of common bottlenose dolphins (*Tursiops truncatus*), which occur in both the English Channel and North Sea (Reid, 2003).

Marine mammals that switch prey depending on availability are unlikely to be affected by fluctuations in sprat populations (Dickey-Collas et al. 2014). However, the nature of these relationships is likely to be complex and sprat may become more important when other prey items are depleted. An example of this was noted by Ransijn et al. (2021), who found that a relative change in harbour porpoise predicted diet in the Southern North Sea between 2011-2020 was most notable for sandeels (-63%), whiting (+61%), herring (*Clupea harengus*) (-56%) and sprat (+50%). The change in prey availability was found to have a relatively small, predicted change in harbour porpoise daily consumption (~2%), but could lead to the requirement for increased biomass to meet energy requirements, or reduced energy intake. This was found to be because of prey switching behaviour primarily from sandeels to increased consumption of sprat and whiting, which have a reduced energetic quality relative to sandeels (

Table 1).

Seabirds

At a breeding colony on Coquet Island, Northumberland, sprat made up a quarter of prey items fed to common tern (*Sterna hirundo*) chicks; were one of only two species fed to Roseate tern (*Sterna dougallii*) chicks; and were a minor component of Arctic tern (*Sterna paradisaea*) chick diet (Robertson et al., 2014). Clupeids (i.e., sprat and herring) were the second most important prey item fed to common tern chicks at English Channel sites in Hampshire and Dorset, comprising 20-50% of prey;

indicating they may be an important alternative prey at times when sandeels are less available (Picksley, 2019).

Sprat made up nearly a quarter of prey items delivered to gannet (*Morus bassanus*) chicks at a breeding colony in the northern North Sea (Hamer et al., 2000); gannet also breed on the English North Sea coast (Natural England, 2024). Clupeids and particularly sprat are a prey item and important alternative to sandeels for guillemots, razorbills (*Alca torda*), puffins (*Fratercula arctica*), and kittiwakes during the breeding season in the northern North Sea (Anderson et al., 2013; Smout et al. 2013; Wanless et al., 2018). These species also breed on the English North Sea and Channel coasts (Natural England, 2024).

Additionally, sprat is a component in the diets of herring gull (*Larus argentatus*), greater (*Larus marinus*) and lesser black-backed gull (*Larus fuscus*) in the Celtic Sea and around the west coast of Scotland during the breeding season (Anderwald et al., 2011). These species also have breeding colonies in the English Channel and the North Sea (Natural England, 2024). Sprat are prey for critically endangered Balearic shearwaters (*Puffinus mauretanicus*) which have a growing presence in UK waters including the English Channel (Phillips et al., 2021). Sandwich tern (*Sterna sandvicensis*) are highly reliant on sprat in the Dutch Wadden Sea (Stienen 2006) and breeding populations are protected at multiple designated sites around the English south and North Sea coasts[Error! Bookmark not defined.].

During the breeding season, sprat are an important prey item for multiple seabird species and have become relatively more so due to reduced sandeel availability (

Table 1). Reduced food availability or quality can increase energy expenditure and time spent foraging away from chicks and can reduce body condition, chick growth rates, productivity, and survival (Natural England, 2024; Wanless et al., 2005). Forage fish may feature less in seabird diets outside of the breeding season (Barrett et al., 2007).

Finally, bycatch of the sprat fishery in the English Channel includes guillemot (tens of individuals per year), cormorant (species name not noted) (few individuals per year), and razorbill (few individuals per year) (Northridge, 2020).

Marine fish

Whiting are a major fish predator in the North Sea ecosystem, their diet varies with life-history stage and season (Knijn et al. 1993). Sprat form a key prey item for whiting over 25cm in length (Lauerburg et al., 2018). Hislop et al., (1991) found sprat were more common in whiting stomachs in the Southern North Sea (in line with their known distribution (Green, 2017; Englehard et al., 2014)), compared to northern and central North Sea regions. In the 1980s, sprat featured in the top three fish prey items of mackerel in the north-western and southern North Sea throughout most of the year (Mehl & Westgård, 1983). These findings are supported by Mackinson & Daskalov (2007), who noted that sprat is preferred by whiting, mackerel, and megrim (*Lepidorhombus whiffiagonis*), along with saithe (*Pollachius virens*). Engelhard et al., (2014) reported trophic interactions between North Sea forage fish, with anchovy (*Engraulis encrasicolus*) predating on sprat eggs and larvae as well as predation of sprat by horse-mackerel, whiting, grey gurnard (*Eutrigla gurnardus*), cod (*Gadus morhua*) and mackerel.

North Sea fish stomach content survey records show sprat predation by grey gurnard, mackerel, whiting, and haddock in the 2000's, whilst previously in the 1990’s it was whiting, haddock, cod, and saithe acting as key sprat predators (Pinnegar et al. 2023). Historical records show sprat was present in the stomachs of an additional five piscivorous fish species in the 1970s, although not found in grey gurnard during this time. Sprat were found in a further nine fish species in addition to whiting, haddock, and cod in stomach content surveys carried out between 1900-1910. In instances where clupeoids were identified but not to species level, the lesser weever fish (*Echiichthys vipera*) was an additional predator in the 2000’s along with tope shark (*Galeorhinus galeus*), starry ray (*Amblyraja radiata*) and dab (*Limanda limanda*) in historical records from 1885-1908 (Pinnegar, 2023). An atlas of North Sea fishes published by ICES in 1993 listed sprat predation by larger whiting, haddock and mackerel as well as bib (*Trisopterus luscus*), turbot (*Scophthalmus maximus*), hagfish (*Myxine glutinosa*) and twaite shad (*Alosa fallax*) (Knijn et al. 1993).

Stomach content surveys show sprat predation by whiting in 1992 in the English Channel while historical records show predation by black goby (*Gobius niger*) and sea trout (*Salmo trutta*) in the 1930s, and spurdog (*Squalus acanthias*) and brill (*Scophthalmus rhombus*) in 1901. Additionally, prey identified as clupeoid species were present in the stomach of blue sharks (*Prionace glauca*) in the 1970s, and in whiting, sea trout, flounder (*Platichthys flesus*), bib, brill, pollack (*Pollachius pollachius*), herring, spurdog, nurse hound (*Scyliorhinus stellaris*), and lesser spotted dogfish (*Scyliorhinus canicula*) between 1919 and 1937 (Pinnegar, 2023).

There is limited information on the sensitivity of piscivorous fish to reductions in sprat availability. Where pronounced effects on predatory fish have been demonstrated, it tends to occur in ecosystems where a key predator depends largely on one key prey species or at a localised scale (Engelhard et al., 2018; Lauerburg et al., 2018; Cormon et al. 2015; Engelhard et al., 2012). The North Sea food web has a high diversity of forage fish, resulting in complex dynamics. A review by Engelhard et al., (2014) reported that on average, the diet of the predatory fish species in the North Sea generally does not contain more than 20% of any single forage fish species (noting that local and seasonal percentages can be substantially higher or lower), therefore strong effects are less likely to occur.

In the early 2000s several North Sea forage fish stocks (sandeel, Norway pout (*Trisopterus esmarkii*), herring and sprat) simultaneously suffered from recruitment failures and subsequent declines in stock size. Lauerberg et al. (2018) (

Table 1) found a parallel decrease in combined forage fish abundance data and whiting length-at-age between 2000-2007, followed by subsequent increases in prey abundance and length-at-age after 2007. Several alternate factors were investigated e.g., size-selective mortality and water temperature, however the authors concluded that the most likely explanation for the observed decrease in length-at-age of adult whiting was a change in the abundance of forage fish serving as prey in the North Sea ecosystem.

Summary of ecosystem links

Table 1. Evidence of links between sprat and predators in the North Sea, English Channel, Celtic Sea and Wadden Sea, with relevance to the UK Marine Strategy (UKMS). In the UKMS part 2, objectives, targets, and indicators for Biological Diversity (Descriptor 1; D1) and Food Webs (D4) are delivered under the heading of 'Descriptors 1 and 4' for cetaceans, seals, birds, fish, and other ecosystem components. Links are also made below to D3: Commercial fish and shellfish. Table modified based on Dickey-Collas et al., 2014.

	Predator name	Reported effects of sprat biomass	Link to UKMS	Reference	Region
1	**Harbour porpoise** *Phocoena phocoena*	Requirement for increased daily biomass or decreased energy intake due to reduced consumption of sandeels, substituted mainly by an increase in consumption of sprat and whiting.	D1 and D4: Cetaceans	Ransijn et al., 2021	Southern North Sea
2	**Fin whale** *Balaenoptera physalus*, **Minke whale** *Balaenoptera acutorostrata*, **Humpback whale** *Megaptera novaeangliae*	Fin and baleen whale species presence was found to be positively correlated with sprat density.	D1 and D4: Cetaceans	Fariñas-Bermejo et al., 2023	Celtic Sea
3	**Common guillemot** *Uria aalge*	Breeding success dependent on quality and availability of sprat during low sandeel availability. Over the last two decades, guillemot have become increasingly dependent on sprat.	D1 and D4: Birds	Wanless et al., 2005; Harris et al., 2022, Anderson et al., 2013	North Sea
		Temperature constraints on sprat and sandeel resulting in decreases in mean body size, are being propagated up the food chain to impact seabirds including common guillemots.	D1 and D4: Birds	Wanless et al., 2018, Wanless et al., 2023	North Sea
4	**Sandwich tern** *Sterna sandvicensis*	Correlations between population fluctuations and availability of prey, including sprat.	D1 and D4: Birds	Stienen, 2006	Wadden Sea

	Predator name	Reported effects of sprat biomass	Link to UKMS	Reference	Region
5	**Balearic shearwaters** *Puffinus mauretanicus*	Sprat supporting northward range expansion of critically endangered Balearic shearwaters	D1 and D4: Birds	Phillips et al., 2021	English Channel, Celtic Sea
6	**Common tern** *Sterna hirundo*	Relationship between breeding numbers and sprat abundance.	D1 and D4: Birds	Jennings et al., 2012	Northern North Sea (Firth of Forth)
		Relationship between breeding success in the Wadden Sea and abundance of sprat, some of which may have spawned in the North Sea.	D1 and D4: Birds	Dänhardt & Becker, 2011	Wadden Sea, with links to North Sea sprat spawning grounds
7	**Whiting** *Merlangius merlangus*	The winter spawning migration of herring and sprat in the Eastern English Channel represents an important trophic opportunity for whiting during a nutrient-poor period.	D1 and D4: Fish D3	Timmerman et al., 2020	English Channel and the Southern North Sea
		Relationship found between forage fish availability (herring, sprat, sandeel sp. and Norway pout) and whiting growth.	D1 and D4: Fish D3	Lauerburg et al., 2018	North Sea

Ecosystem modelling

Ecopath with Ecosim

Overview

An Ecopath with Ecosim (EwE) model of the North Sea was used to simulate the dynamics of the marine ecosystem in response to changes in sprat biomass. **Note that the model only covers the extent of the North Sea (ICES divisions IVa, IVb, and IVc). The outputs from this model should not be used to infer understanding regarding the structure and function of marine ecosystems in other areas, e.g., the English Channel.**

EwE is a food web modelling suite used globally to simulate the ecosystem impacts of fishing and other drivers such as climate change and marine protection (Christensen and Walters, 2004). The North Sea model was initially built by Mackinson and Daskalov (2007) and subsequently updated and presented to the International Council for the Exploration of the Seas (ICES) Working Group on Multispecies Assessment Methods (WGSAM) to be used as an ICES advice product (ICES, 2013). The North Sea model was once again updated following Defra commissions to simulate the impacts of alternate sandeel fishing strategies.

The model comprises 76 functional groups, ranging from phytoplankton and benthos to commercial fish and marine mammals. A functional group can be a single species (such as cod), a group of species (such as demersal fish) or an age component of a species (such as juvenile cod). Functional group design is often driven by the question the model intends to answer as well as data availability. By encompassing all components of the food web, models such as EwE allow us to investigate the ecosystem impacts of management and policy options against objectives such as those under the UKMS (aiming to deliver GES).

Methodology

The temporal dynamic module of EwE is called Ecosim (Walters et al., 1997). Ecosim provides dynamic simulations of changes in ecosystem structure and function over time (past and future) in response to alternate management scenarios. Ecosim was used to simulate the changes in sprat biomass across depletion levels ranging from 0 to 50%. This depletion range encompasses the historical harvest rates for sprat, which have predominately been between 10-40%.

Simulations were generated for sprat, following previously published methods (Eddy et al., 2015), by projecting the model forward while exposing sprat to incrementally increasing harvest rates. Simulations were run for an extended period to allow the model to reach equilibrium. The harvest rates of all other exploited species were held constant at their 2020 levels. The level of depletion for sprat was calculated by comparing the biomass at each harvest rate to the biomass of sprat during a simulation where there was no harvest (for example, a depletion value of 50% means the biomass at that point is half of its unfished biomass).

While fishing harvest rates were used to drive the depletion of sprat in the model simulations, outputs have been presented in a way that they could also be viewed more generally as “what might happen if the sprat stock declines?”. Sprat depletion could occur in response to multiple drivers of mortality, such as climate change or changes in food availability.

The uncertainty in EwE input parameters was addressed by employing a Monte Carlo approach. Basic input parameters were assigned data pedigree credible intervals based on data origin (for example, if data were of poor quality, they were assigned a larger credible interval as they are more uncertain). This approach was used to produce 140 alternative parameter sets. Simulations were generated under each parameter set to produce a range of plausible model outputs. The results display this uncertainty in the form of 95% credible intervals, showing the range of plausible biomass changes as opposed to a single estimate.

Finally, we calculated the rates of change for sprat and other groups included in the EwE model to explore how the simulated ecosystem responded (either directly or indirectly) to a change in sprat biomass. Sprat was subject to incrementally increasing harvest rates (from 0% to 50%). The rates of change in the relative biomass of all groups in the EwE model were compared to the rate of change in the relative biomass of sprat at each incremental increase in harvest rate, following which an average rate of change was estimated for groups relative to the change in sprat biomass (**Equation 1**).

$$\frac{\sum_{i=1}^{h} {b_{i+1} - b_i}/{a_{i+1} - a_i}}{h}$$

Equation 1

where h is the number of harvest rates tested, a_i is the relative biomass of the group we want to compare rates of change against (in this case sprat), and b_i is the relative biomass of the group we are comparing against a_i. Average rates of change were estimated for each of the 140 alternative parameter sets to produce 95% credible intervals, showing a range of plausible responses to a change in the biomass of sprat.

Results and discussion

Consumption of sprat in the North Sea ecosystem

Sprat contributed to the diets of 36 functional groups in the North Sea EwE model, including marine mammals, seabirds, demersal fish, pelagic fish, squid and cuttlefish (**Figure 1).**

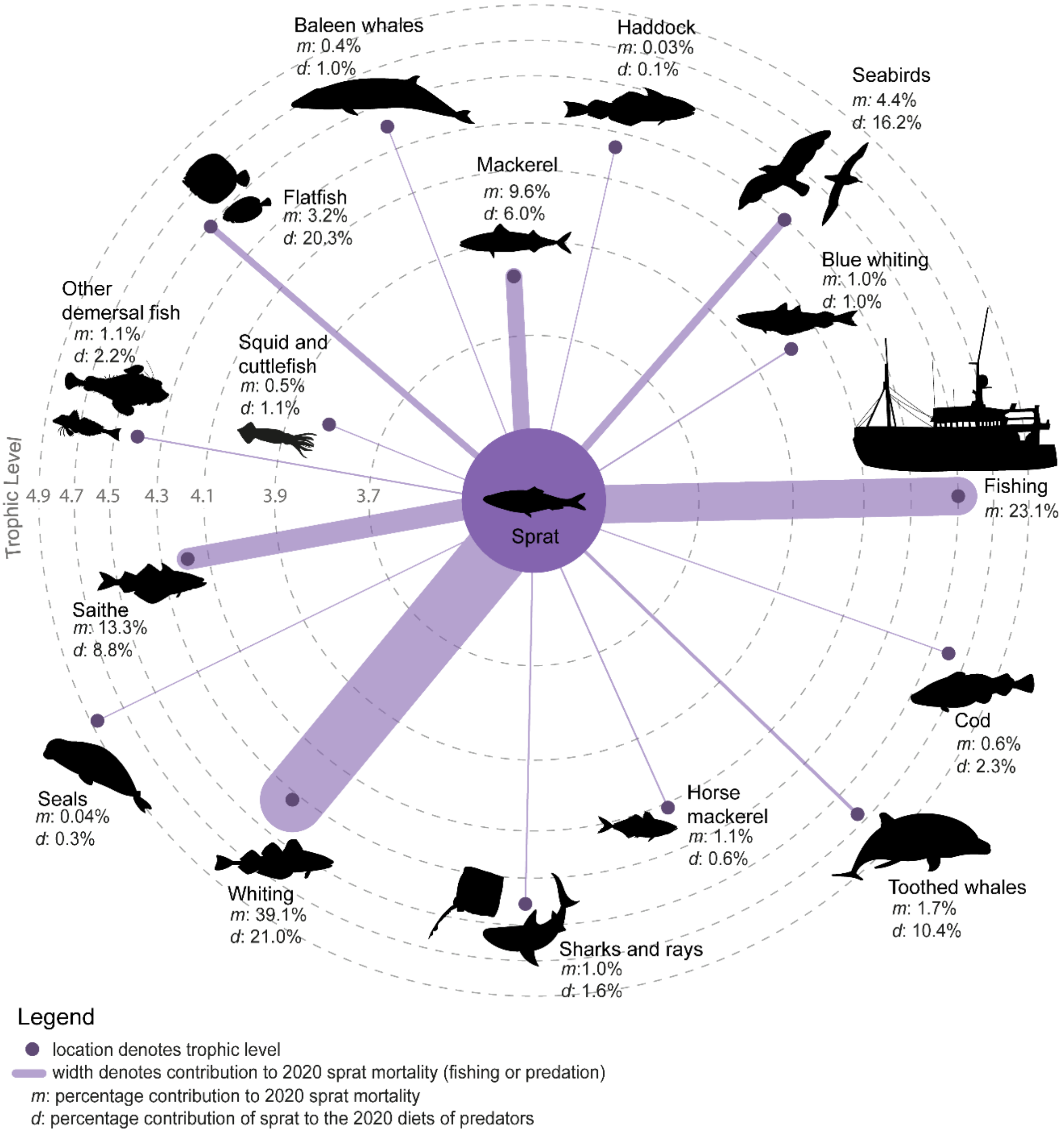


Figure 1. Sources of mortality (fishing and predation) for North Sea sprat in 2020, taken from the North Sea Ecopath with Ecosim model. Values indicate the contribution of ecosystem components to the mortality of sprat ($\boldsymbol{m}$) and the percentage contribution of sprat to the diets of predators in 2020 ($\boldsymbol{d}$). Sequential rings highlight the trophic level of the predators which consume/catch sprat. The trophic level of the pelagic fishery was calculated based on fleet catch composition.

Figure 1 provides a snapshot of the predation and fishing mortality for sprat in 2020, which is the final year of the model's calibration period (1991-2020). In 2020, the predators responsible for the greatest proportions of predation mortality in the model scenarios were 1) whiting, 2) saithe, 3) mackerel, and 4) seabirds. Sprat constituted a relatively large portion of the overall diets of these species, as well as the diets of some piscivorous flatfish groups (turbot and megrim). Fishing in the simulated year was responsible for 23.1% of the total mortality of sprat. Despite sprat being included in the diets of 36 functional groups, the consumption mortality from the four groups listed above, plus the mortality from the fishery, accounted for around 90% of the total mortality of sprat simulated for 2020.

Response of commercial fish species to changes in sprat biomass

The commercial species with the highest landings from the Greater North Sea include mackerel, herring, Norway pout, saithe, plaice, haddock, cod, and whiting (ICES, 2022a). **Figure 2** shows the biomass of these groups corresponding to levels of sprat depletion ranging from 0% to 50%.

Full descriptions of the direct and indirect mechanisms driving the responses in **Figure 2** can be found in **Annex 1**, **Table 2**. In summary, the direct consequences of reduced sprat availability as prey were seen for whiting and mackerel, whose biomasses declined with increasing sprat depletion. Sprat constitutes an important component of whiting and mackerel diets which could not be compensated by prey switching in the model. While saithe biomass also declined in some simulations due to reduced sprat availability, saithe showed greater capacity for prey switching, with increases in the availability of other forage fish dampening the negative impacts of reduced sprat biomass in some instances. Simulations for other forage fish (herring and Norway pout) showed increases in biomass due to the reduced competition for zooplankton prey. Cod and haddock also showed slight increases due to the increased availability of other prey, including sandeels which increased following a reduction in predation mortality from whiting and mackerel. Reduced sprat biomass, and the wider ecosystem consequences, had a very limited impact on the biomass of plaice, which experienced no notable changes in predation pressure or prey availability.

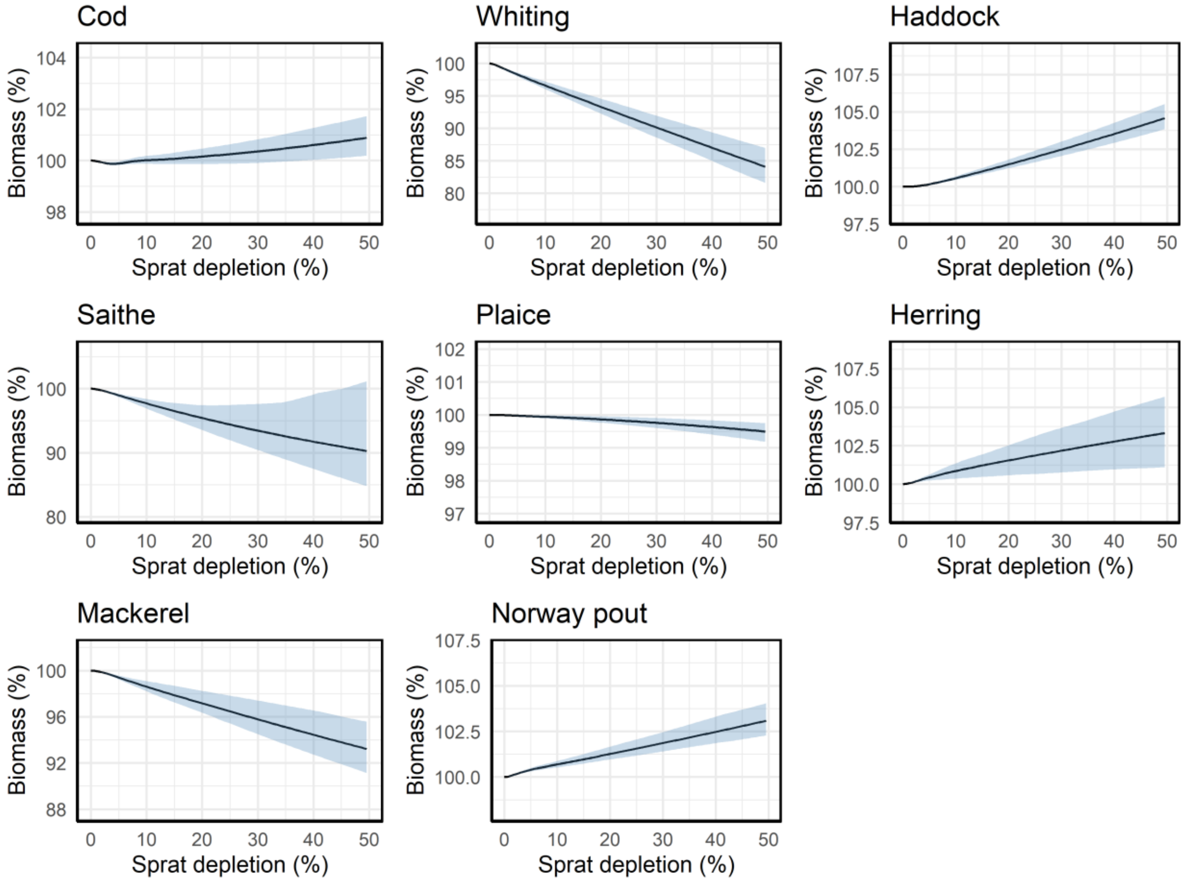


Figure 2. Impacts of sprat depletion on the relative biomass of commercial fish stocks in the North Sea (represented as the change in biomass compared to a scenario with no splat exploitation). Responses were simulated using an Ecopath with Ecosim model of the North Sea. The black line indicates the average response from a set of model parameterisations; the shaded area displays the 95% confidence intervals.

Response of marine mammals and seabirds to changes in sprat biomass

The responses of marine mammals and seabirds to changes in sprat depletion are shown in **Figure 3**. Marine mammals were split into three functional groups, including baleen whales, toothed whales, and seals. Seabirds have been included at a greater resolution following recent model updates to explore the cumulative impacts of fishing and offshore wind farms on seabird abundance. Seabird groups included single species groups (black-legged kittiwake, razorbill, common guillemot, Atlantic puffin, northern gannet, and northern fulmar (*Fulmarus glacialis*)) and aggregated groups (cormorant and shag (*Gulosus aristotelis*), gulls and skuas, and surface feeding terns).

Full descriptions of the direct and indirect mechanisms driving the responses in **Figure 3** can be found in **Annex 1**, **Table 2**. In summary, toothed whales, black-legged kittiwake, razorbill, common guillemot, northern gannet, and surface feeding terns declined as a direct response of the reduced availability of sprat prey. The negative response simulated for common guillemot was particularly severe given its dependency on sprat over other prey items. Other groups, including baleen whales, seals, Atlantic puffin, northern fulmar, and cormorant and shag, showed increasing biomass trends due to the increased availability of other forage fish, principally sandeels and herring.

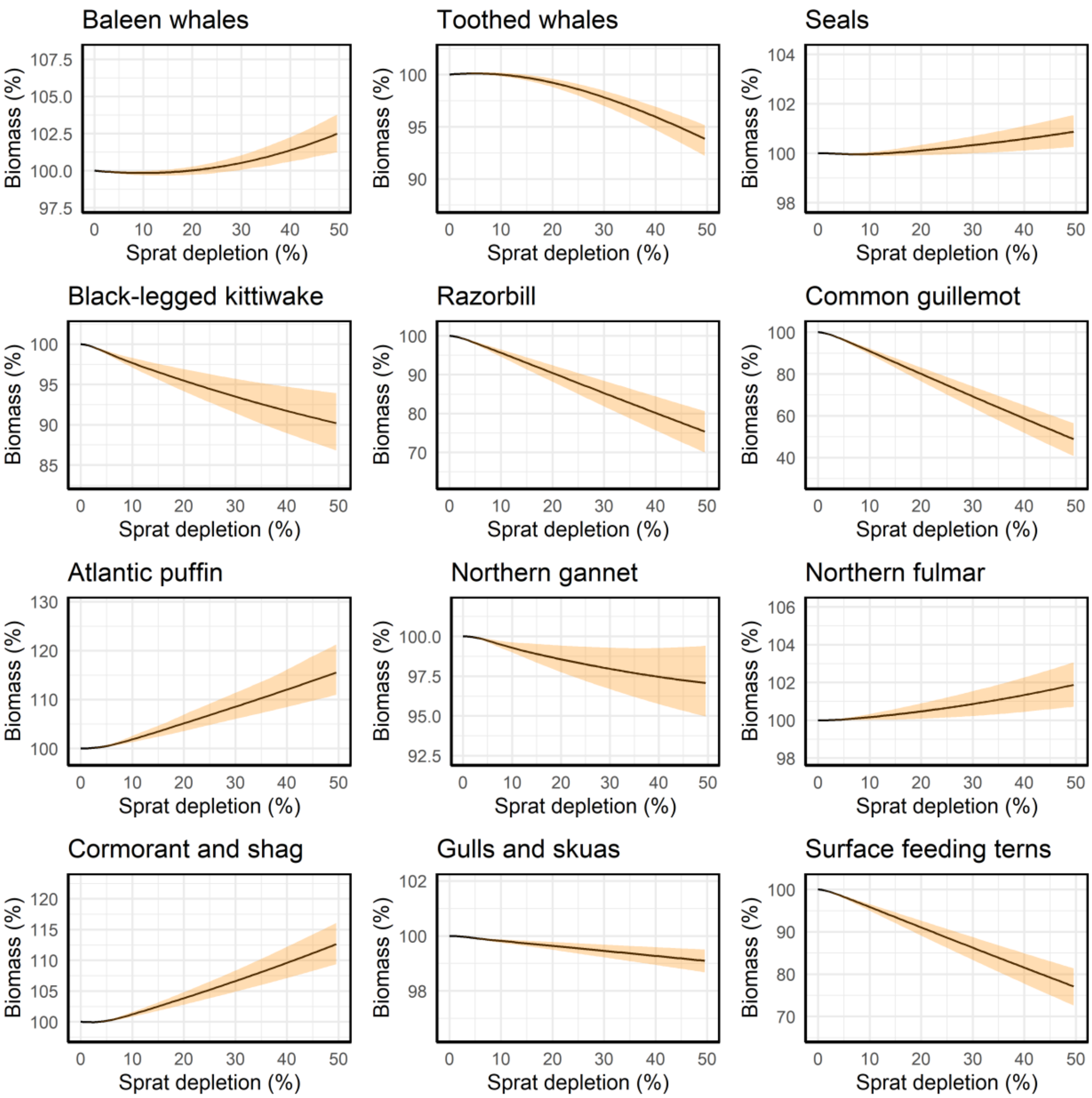


Figure 3. Impacts of sprat depletion on the relative biomass of marine mammals and seabirds in the North Sea (represented as the change in biomass compared to a scenario with no splat exploitation). Responses were simulated using an Ecopath with Ecosim model of the North Sea. The black line indicates the average response from a set of model parameterisations; the shaded area displays the 95% confidence intervals.

Response of feeding and trophic guilds to changes in sprat biomass

EwE can be used to assess the impact of fishing strategies and other pressures on targets for GES (e.g., Piroddi et al., 2021). To link the impacts of sprat through to GES targets, fish, marine mammals, and seabird groups were aggregated into feeding guilds using the categorisation proposed by Thompson et al. (2020). For multispecies functional groups (e.g., other demersal fish) it was not possible to represent the diversity of feeding guilds within the group, therefore, in such cases, feeding guilds were assigned based on the majority composition of the group. There are three feeding guild categories which reflect those suggested as indicators in the UKMS under Descriptor 4: Food webs. These include:

- **Piscivores**: species which feed predominately on other fish, which includes 1) commercially valuable species such as cod, whiting, hake (*Merluccius Merluccius*), and turbot, 2) top predators such as spurdog and starry ray, and 3) smaller taxa such as gurnards. We have separated mammals and seabirds into a separate **'apex piscivore'** category.
- **Benthivores**: species such as haddock, plaice, and sole (*Solea solea*) which feed predominantly on benthic prey, however generalist benthivores (e.g., lemon sole (*Microstomus kitt*) also feed on fish and plankton.
- **Planktivores**: species such as herring, sandeels, and Norway pout (forage fish) which feed predominantly on planktonic food, including zooplankton and phytoplankton, however generalist planktivores (e.g., herring and mackerel) may also feed on fish (e.g., sandeels). Sprat are planktivores, however they were omitted from the feeding guild in order to isolate the response of the wider planktovore community.

These groups provide summaries regarding balance of abundance between representative feeding guilds for fish, mammals, and seabirds. We have aggregated the remaining model groups into trophic guilds, which includes benthic invertebrates (**benthos**), **zooplankton**, and **phytoplankton.** The simulated responses of feeding guilds and trophic guilds to changes in sprat biomass are presented in **Figure 4**.

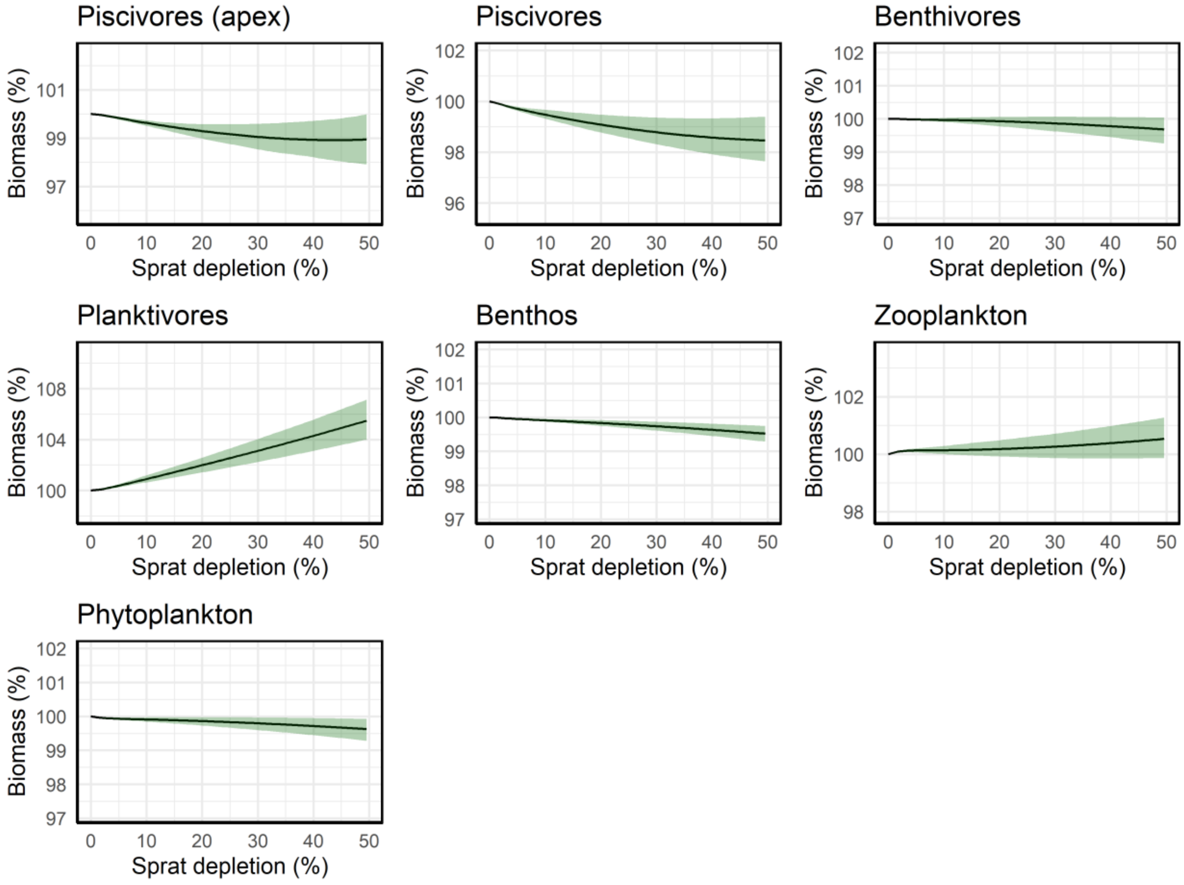


Figure 4. Impacts of sprat depletion on the relative biomass of feeding guilds, benthos, and plankton in the North Sea (represented as the change in biomass compared to a scenario with no splat exploitation). Responses were simulated using an Ecopath with Ecosim model of the North Sea. The black line indicates the average response from a set of model parameterisations; the shaded area displays the 95% confidence intervals.

Full descriptions of the direct and indirect mechanisms driving the responses in **Figure 4** can be found in **Annex 1**, **Table 2**. In summary, piscivores (apex and other) generally declined with increasing sprat depletion, albeit by a small margin (1-2%), due to the reduced availability of sprat as a prey item. Planktivores (which did not include sprat) increased as sprat were depleted. This increase was linked primarily to herring and Norway pout, which benefited from the increased availability of zooplankton prey and declines in predators including saithe, whiting, and toothed whales. Benthivores and benthos showed little to no response to changes in sprat biomass. Under some scenarios, zooplankton biomass increased due to the reduced predation pressure from sprat, which led to a decline in phytoplankton biomass due to increased predation pressure from zooplankton.

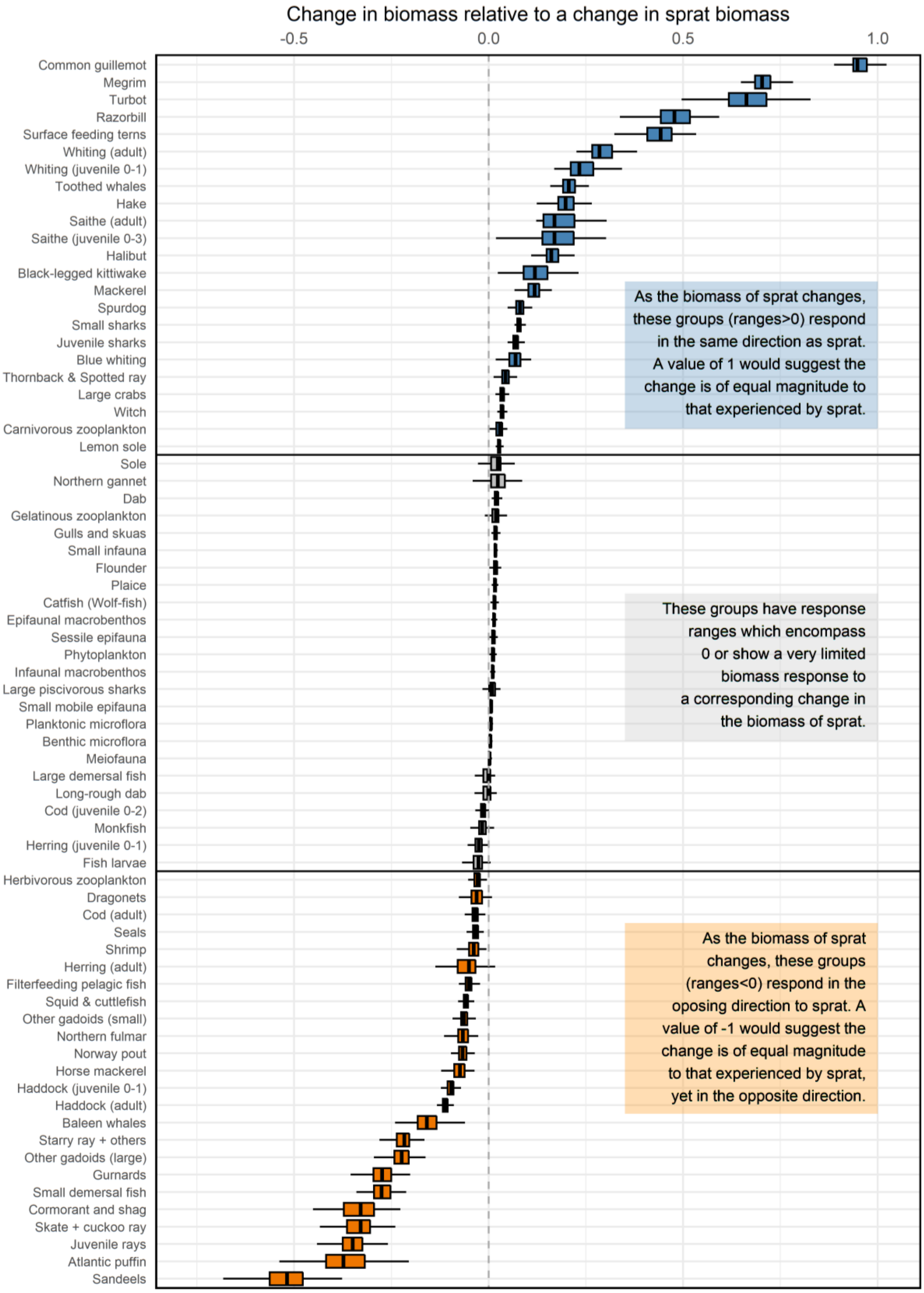
Ecosystem response to changes in sprat biomass

We compared the rates of change in sprat biomass, under incrementally increasing harvest rates, to the rates of change in the biomass of other groups in the model. Comparisons were made using relative biomass, where the biomass of all groups was equal to 100% under a sprat harvest rate of 0% (sprat at carrying capacity). All other drivers in the model (i.e., harvest rates for other species and environmental conditions) were held constant, thus the only driver which could impact the rates of change of other groups was the simulated variation in the biomass of sprat. **This analysis therefore quantified the net direct and indirect impact that a hypothetical change in biomass of sprat would have on every other model group.**

Figure 5 shows the impact of a change in sprat biomass on other model groups. The figure has been broken down into three sections to separate groups which 1) responded to changes in sprat biomass in the same direction at sprat (response range above 0), 2) showed little to no response to a change in sprat biomass (response range close to 0), and 3) responded to changes in sprat biomass but in the opposite direction to sprat (response range below 0). **Figure 5** quantifies the magnitude and direction of change in group biomasses relative to the change in sprat biomass; a value of 1 would indicate a change of the same relative magnitude, i.e., a 1% change in sprat biomass leads to a 1% change in the other groups biomass, in the corresponding direction. A value of -1 would indicate a change of the same relative magnitude but in the opposing direction.

Groups which responded in the same direction as sprat included common guillemot, megrim, turbot, whiting, toothed whales, terns, mackerel, saithe, and kittiwakes among others. Of these groups, changes in sprat biomass had the greatest impacts on the biomass of common guillemot. Many of these groups were identified in **Figure 2** and **Figure 3** as being directly impacted by the availability of sprat as prey. Groups which responded in the opposite direction to sprat included sandeels, Atlantic puffin, haddock, baleen whales, Norway pout, and herring. Many of these groups were identified in **Figure 2** and **Figure 3** as being driven more by the indirect consequences of changes in sprat biomass, such as changes in the availability of other preferred prey or changes in experienced predation pressures. Groups which showed negligible responses to changes in sprat biomass included primarily benthic invertebrates and benthivores but also some seabird groups, fish groups, bacteria groups, and plankton groups.

The values from **Figure 5** have also been tabulated in **Annex 2**, **Table 3**.



As the biomass of sprat changes, these groups (ranges>0) respond in the same direction as sprat. A value of 1 would suggest the change is of equal magnitude to that experienced by sprat.

These groups have response ranges which encompass 0 or show a very limited biomass response to a corresponding change in the biomass of sprat.

As the biomass of sprat changes, these groups (ranges<0) respond in the oposing direction to sprat. A value of -1 would suggest the change is of equal magnitude to that experienced by sprat, yet in the opposite direction.

Figure 5. Rate of change in the biomass of North Sea functional groups relative to the rate of change in the biomass of sprat.

Model caveats

There are several caveats to the modelling work which means it should be viewed in unison with the evidence provided by the wider literature. Model simulations are intended to raise awareness of the complexity of food web dynamics and highlight the structural role of sprat in the ecosystem.

Caveat 1

The model covers the extent of the North Sea only (ICES areas IVa, IVb, and IVc). We can therefore not infer anything from these results regarding the impacts of a change in sprat biomass would have on English Channel marine ecosystem. Further work is needed to develop a model specifically for this area to address specific policy and research questions related to the functioning of the English Channel ecosystem.

Caveat 2

The model simulates changes in the harvest rates of sprat and not changes in fishing effort, which may have additional indirect impacts such as bycatch and habitat disturbance. This means that indirect impacts or benefits which would likely change with sprat fisheries management (such as bycatch and habitat impacts) are not included in the impact analyses. The impact analysis presented here primarily acts to describe the role of sprat in the North Sea food web.

Caveat 3

The North Sea Ecopath with Ecosim model is not a ‘size structured model’. Simulations may overestimate the impacts of forage fish depletion by not accounting for cases where (1) predators take small forage fish that are unaffected by fishing and (2) forage fish and predators compete at different life stages (such as juvenile predator and adult forage fish).

Caveat 4

To rigorously quantify uncertainty in the strategic information derived from ecosystem models, it is preferable to use an ensemble of all available models for a given area. In this instance we have only used the North Sea EwE model to generate simulations.

Caveat 5

The model does not account for the spatial distribution of sprat. Fluctuations in forage fish abundance are often accompanied by changes in their distribution. Not accounting for this spatial component could mean we overestimate or underestimate some specific ecosystem impacts of changes in sprat biomass if, for example, even at low abundance forage fish occupy core areas local to important mammal or bird breeding sites. We may also underestimate localised benefits, which we might expect to be greater than the average benefit across the entire area due to the localised impacts of sprat biomass on predator condition and reproduction.

Caveat 6

The model forecasts simulations based on current environmental conditions and an understanding of past ecosystem dynamics. Simulations presented here do not consider how environmental variation may impact the dependency of predators on sprat, or how interspecific dynamics may vary under alternate environmental conditions.

Caveat 7

Some of the seabirds included in the model (e.g., kittiwakes) overwinter in different locations and are therefore not resident to the North Sea all year round. Annual migration is not included in the model as it is currently configured. This may impact estimates of seabird consumption of, and reliance on, prey in the North Sea. Additionally, environmental and ecosystem conditions in overwintering locations may impact seabird productivity, survivability, and therefore return rates and condition. Future work should attempt to incorporate seabird migration. It should be noted that prey availability in the North Sea during the seabird breeding period is likely to remain an important element of their productivity.

Options for an ecosystem-based approach for sprat

Sprat are an important part of the North Sea and English Channel ecosystems, as major predators of zooplankton, competitors with other forage fish (e.g., herring), and prey for piscivorous fish, marine mammals, and seabirds. Ensuring the sustainable exploitation of sprat by commercial fisheries in the North Sea and English Channel is therefore important for the health of the marine ecosystem and the wider UK fisheries sector. There is strong evidence to suggest sprat production is driven by environmental variation, notably changes in temperature and food availability. It is advisable to evaluate whether routes to operationalise EBFM could be implemented to improve current management and align with the UK's objectives to achieve GES. As part of this, it is important to explore whether:

1. single species advice enhanced with ecosystem information could improve the long-term viability of the stock and fishery,
2. the current and proposed advice framework can maintain sprat at a level which adequately satisfies the needs of predators, and
3. evaluate how alternate management strategies are expected to impact predator productivity and ecosystem resilience.

The exploitation of sprat and its resulting wider ecosystem impacts should be used to guide a risk-based ecosystem approach that reflects the multiple and potentially conflicting social, cultural, and ecological objectives and the trade-offs between the diverse needs of people and the marine food web. This approach necessitates early engagement with stakeholders, decision-makers, the International Council for the Exploration of the Sea (ICES), and Defra's arms-length bodies, as well as the development of interdisciplinary and pragmatic solutions which promote the application of ecosystem information and models alongside traditional methods for single-species assessment.

Defra could accelerate momentum towards EBFM by asking their scientific advisers (including requests to ICES) ambitious, ecosystem-focused questions that consider multiple objectives across sustainable use and conservation policies, as opposed to narrow questions that direct scientists to produce evidence focused only on individual fish populations and catches (Pew, 2024). This necessitates an awareness of the management options available, a few of which we have summarised below.

Pragmatic opportunities

In 2023, the European Union (EU) and United Kingdom (UK) jointly requested evidence from ICES to better understand how ecosystem considerations were integrated into single-stock advice for forage fish species. The response from ICES concluded that the primary route for the integration of predator-prey interactions was through the inclusion of quantitatively based and often time-varying predation mortality in forage species assessments, which aim to have high stock sizes capable of producing ‘pretty good yields’ (ICES, 2023a). The response noted that this may be enough to sustain predators and ecosystem services, however, it is also possible that it may not: specific analysis of whether forage fish biomass is kept high enough for specific predator requirements is not conducted as part of the advice currently delivered.

In the Northeast Atlantic, we possess the necessary tools and expertise to implement ecosystem-based approaches which recognise the impacts of environmental variation on production and assess trade-offs between forage fish harvest and predator carrying capacities. Tools such as Management Strategy Evaluation (MSE) and Ecological Reference Points (ERPs), informed by ecosystem modelling techniques, offer robust frameworks for assessing the potential impacts of alternative management strategies on both forage fish populations and their predators, facilitating informed decision-making, and promoting ecosystem resilience. These tools can be used to stress test the existing advice system and evaluate whether current advice can meet broader ecosystem goals.

We have provided an overview below of four pragmatic EBFM approaches which could be further explored for sprat in the North Sea and English Channel. These include:

1. ICES ecosystem-based fishing reference point (F_{eco}).
2. Ecological Reference Points (ERPs) for predator-prey trade-offs.
3. Management Strategy Evaluation (MSE).
4. Multispecies reference points.

ICES ecosystem-based fishing reference point (F_{eco})

In 2019, an ecosystem-based fishing reference point (F_{eco}) was proposed by the ICES benchmark workshop for the Irish Sea (WKIrish; ICES, 2020; Bentley et al., 2021; Howell et al., 2020). F_{eco} is an approach to allow ecosystem information or outputs of ecosystem models to be used to tune target species catch advice to account for medium term ecosystem driven variability in productivity. In many cases, this medium-term variability is not accounted for in assessment models and subsequent catch advice, meaning that there is a risk that the advised fishing pressure is out of step with the current state of the ecosystem. ICES WKREF2 (Workshop on ICES reference points; ICES, 2022b) recommended that ICES guidelines include the possibility to use an F_{eco} approach to adjust the catch advise based on ecosystem model information, given that 1) advise does not violate the precautionary principle, 2) the model used is reviewed by ICES WGSAM, and 3) the implementation is evaluated and reviewed via ICES benchmark processes.

F_{eco} entails identifying indicators (either physical or synthetic model outputs) which track stock productivity, and then using these indicators to scale up or down the predefined single species fishing mortality targets (**Figure 6**), while not exceeding the predefined limit reference points (i.e., ICES F_{lim} and B_{lim}). The F_{eco} approach is currently operational for Irish Sea cod (ICES, 2023c), which has an F_{eco} reference point responsive to changes in temperature: fishing mortality is reduced towards the lower end of the ‘pretty-good yield’ range when temperatures are above the long-term average, and vice versa. For North Sea and English Channel sprat, research suggests that variation in temperature and food availability can impact the productivity of sprat, making them potential candidate indicators for further exploration of the applicability of an F_{eco} reference point for sprat. It is important to note that only Category 1 stocks currently support ‘pretty-good yield’ ranges. Therefore, while F_{eco} may be applicable for the North Sea stock (Division 3.a and Subarea 4), a reference point could not currently be developed for English Channel sprat (Divisions 7.d and 7.e) as it is a data-limited stock (ICES Category 3).

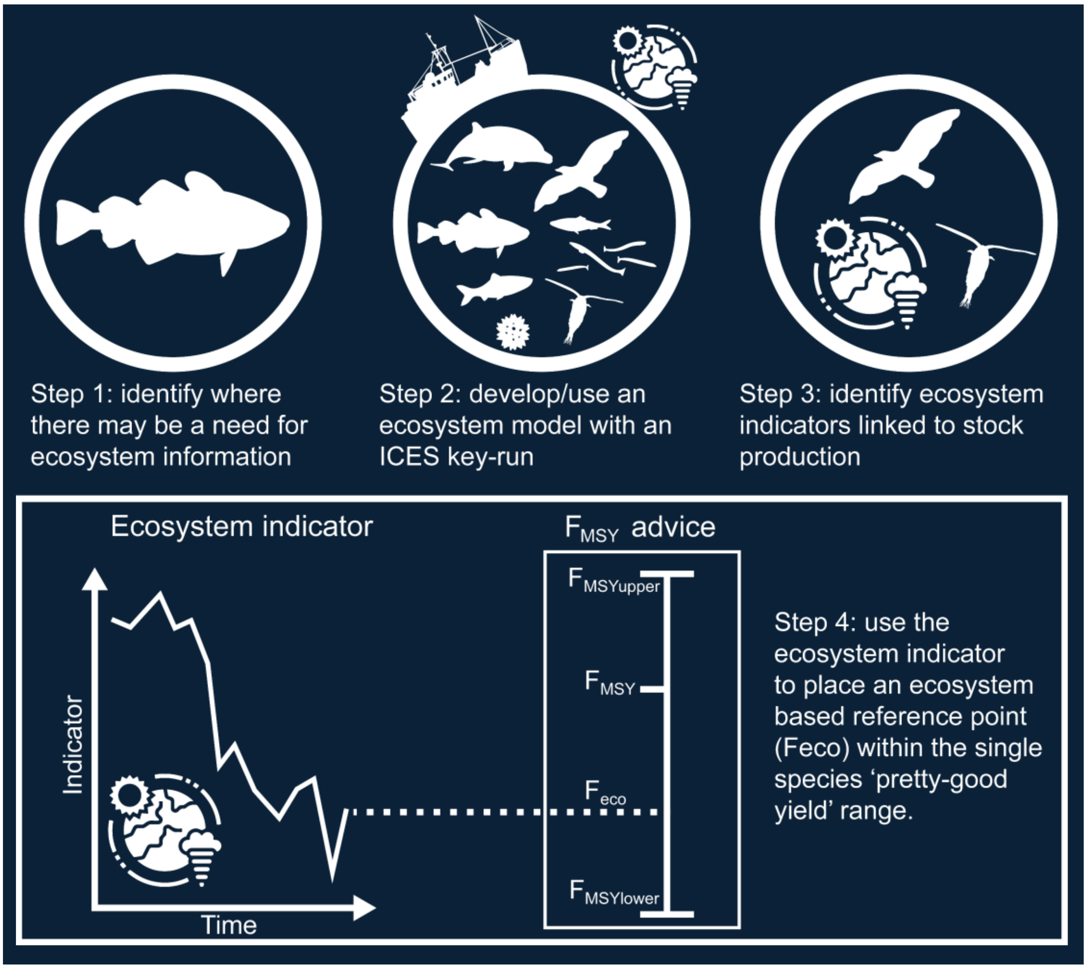


Figure 6. International Council for the Exploration of the Sea (ICES) ecosystem-based fishing reference point (F_{eco}). F_{eco} provides an option to adjust Total Allowable Catch advice, within the existing 'pretty good yield' range, in recognition of links between environmental/ecosystem variation and stock production.

Ecological reference points for predator-prey trade-offs

Ecological Reference Points (ERPs) can be developed to account for the dietary needs of forage fish predators. While quantitatively based predation mortality is often included in forage species assessments (Trenkel et al., 2023), specific analysis of whether forage fish biomass meets predator requirements is not systematically conducted (ICES, 2023a). ERPs provide a mechanism to enhance catch advice in recognition of the trade-offs between forage fish yield and predator carrying capacity.

As an example, the Atlantic States Marine Fisheries Commission (ASMFC) determined that ERPs were needed that accounted for the dietary needs of predators which were dependent on an important forage fish found along the U.S. Atlantic coast: menhaden (*Brevoortia tyrannus*) (Chagaris et al., 2020; Anstead et al., 2021). Managers and stakeholders were concerned that recent declines in several predator stocks, also managed by the ASMFC, were linked to insufficient prey, and wanted quantitative reference points that accounted for menhaden’s role as a forage fish to use for determining stock status and setting quotas. ERPs were established based on the trade-off between menhaden fishing mortality and the biomass of the most sensitive predator: striped bass (*Morone saxatilis*). ERPs were designed using ecosystem models to strategically inform assessment models, where, based on ecosystem information, the target fishing mortality could be scaled down to ensure enough prey remained for striped bass to reach their biomass target (**Figure 7**).

Our literature review and North Sea ecosystem model simulations identified multiple species which may be sensitive to the availability of sprat. These included whiting, mackerel, toothed whales, black-legged kittiwake, razorbill, common guillemot, and surface feeding terns. Further investigation into the dependencies between these predators and the availability of sprat, i.e., by using multiple models to rigorously quantify uncertainty, could support the development of ERPs which acknowledge the potentially necessary trade-off between target biomasses for predators and sprat yield.

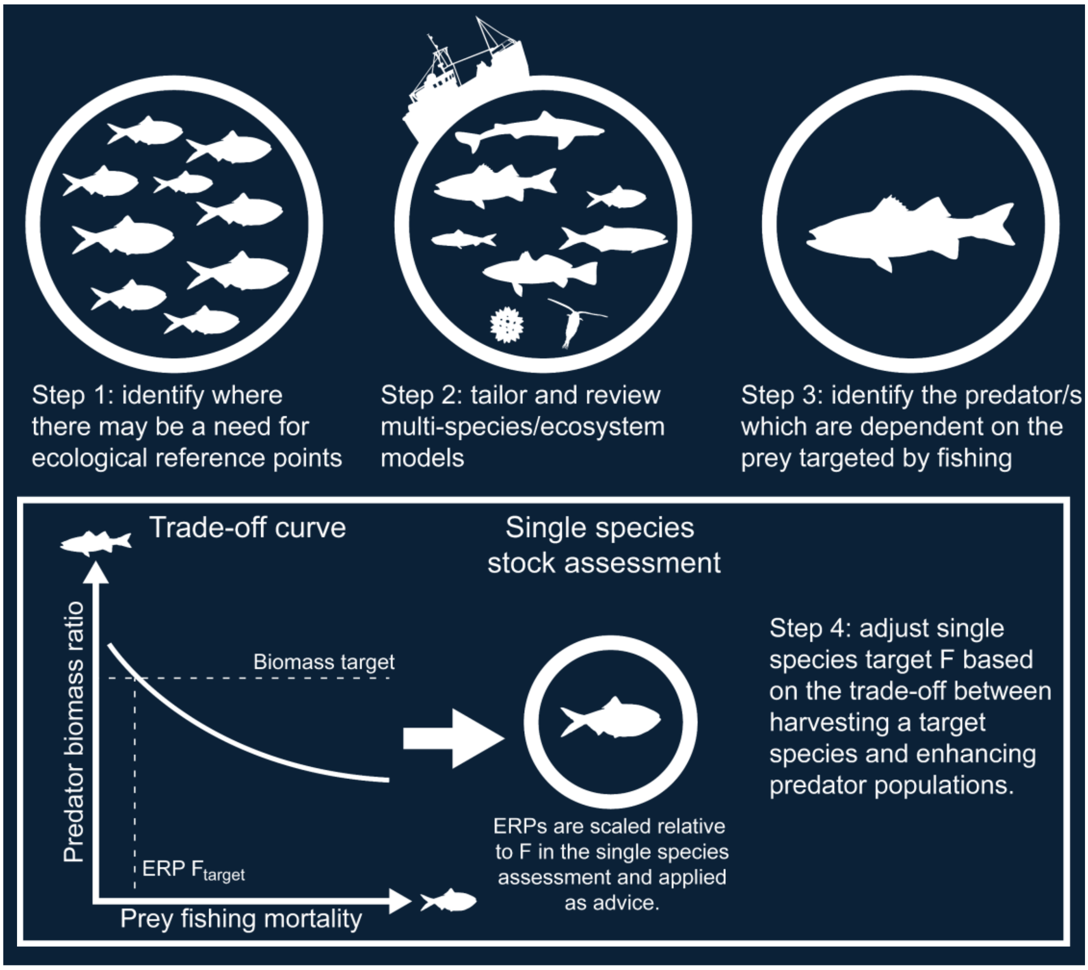


Figure 7. Ecological Reference Point (ERP) to adjust single species advice based on the trade-off between harvesting a target species and reaching predator biomass targets.

Management Strategy Evaluation (MSE)

Management Strategy Evaluation (MSE) has been used to develop management plans that are robust to uncertainty for a variety of data-rich stocks but also data-limited stocks such as English Channel sprat (Walker et al., 2023, Siple et al., 2021). MSE is a simulation approach that tests alternative options for management, monitoring, and assessment given the uncertainty in ecological, fishery, and survey observational processes. It has become a key method for evaluating trade-offs between management objectives, communicating with decision-makers, and has grown from a single-species approach to one relevant to multispecies and ecosystem-based management (Kaplan et al., 2021).

There are several ways in which ecosystem objectives and reference points for sprat could be evaluated and Operating Models (OM) conditioned when conducting MSE (**Figure 8**). The choice depends on the level of knowledge, data, and models available, summarised by de Moor (2023) and include:

1. Using an ecosystem model as an OM.
2. One-way coupling of a single-species OM with a Predator Model.
3. Splitting natural mortality into the background mortality and predation mortality.
4. Using performance statistics based on ecosystem thresholds.
5. Informing control parameters of the Harvest Control Rule.
6. Adjusting performance statistics related to the ecosystem.

Examples of sprat MSE have recently been published by Walker et al. (2023) and Kell et al. (in press), the latter of which 1) developed a seasonal OM to explore the impact of shorter lags between survey, advice and exploitation (allowing alternative management options such as in-season rules to be considered), and 2) used strategic information from ecosystem models in the OM to explore the trade-offs between fishing activities and ecosystem objectives.

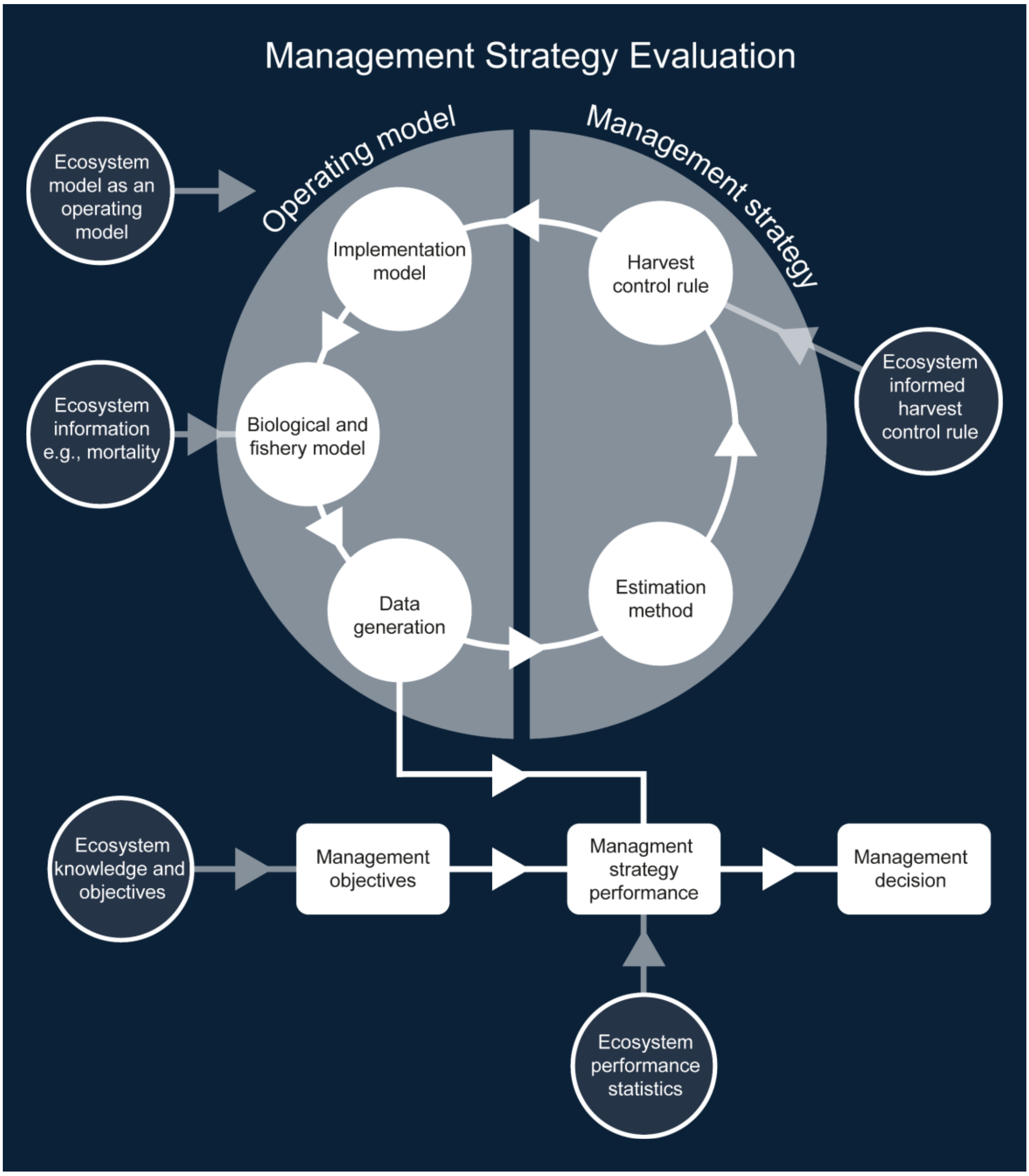


Figure 8. Routes for the integration of ecosystem information into Management Strategy Evaluation (MSE) to assess Ecosystem-Based Fisheries Management strategies.

Multispecies reference points

Following the precautionary approach, fishing mortality is considered precautionary if there is a less than 5% probability that Spawning Stock Biomass (SSB) will fall below B_{lim} in the long-term. However, as recognised for the development of ERPs, fishing on one species affects the biomass of other species. Single-species models largely disregard interspecific interactions when delivering estimates for MSY. This is problematic in a multispecies context (Fulton et al., 2021), as it is impossible for single species MSY to be simultaneously attained for different species whose maximum yields correspond to different ecosystem states (Link et al., 2018; Walters et al., 2005).

Alternative multispecies translations of single-species MSY have demonstrated how multispecies/ecosystem models can be used to account for species interactions to simultaneously maximise the yields of multiple species (e.g., Thorpe et al.,2019; Del Santo O’Neill et al., 2024). In the context of the ICES precautionary approach, it is possible to search for fishing mortality scenarios where multiple species are simultaneously precautionary. Doing so requires a rigorous quantification of uncertainty, which requires the use of an ensemble of ecosystem models to predict long-term spawning stock biomasses under alternate fishing mortalities (Spence et al., 2018; Spence et al., 2022).

Regarding management objectives for sprat and how fishing sprat impacts the wider ecosystem, it is important to understand how fishing strategies for multiple species 1) influence ecosystem trajectories and 2) constrain opportunities to meet objectives for multiple species. The use of multispecies models to simultaneously maximise yields, and ensemble models to quantify uncertainty, provides a path to overcome the current limitations of single-species MSY and deliver more holistic and rigorous approaches for EBFM.

UK Forage Fish Approach

The nature of the evidence request underpinning this report is not unique, with similar requests having recently been completed (e.g., for sandeels) and the potential for additional requests arising in the future as Defra explore EBFM options for other forage species. In this context, it would be advisable for Defra to lead the development a UK Forage Fish Approach that sets out clear objectives and principles for existing and new UK forage fish fisheries.

A UK Forage Fish Approach could provide an overarching framework, aligned with the objectives of the Fisheries Act 2020, to guide the integrated development of forage fish fishery management objectives for sustainable fisheries, ecosystem function, food security, climate resilience, and adequate monitoring operations.

There are lessons to be learnt from the U.S.'s Forage Fish Conservation Act[3] and Canada's Policy on New Fisheries for Forage Species[4], which both provide a definition for forage fish, acknowledge the central role of forage fish in marine ecosystems, and set specific and measurable objectives to support the role of forage fish in marine ecosystems.

The recently published ICES Framework for Ecosystem-Informed Science and Advice (FEISA; Roux and Pedreschi, 2024) provides a more general framework for ecosystem-informed advice which could be useful in the development of a forage fish approach. FEISA uses risk as a common currency for the inclusion and communication of ecosystem considerations into scientific advice. In terms of an EBFM approach for forage fish, risk could be considered in a few forms (Rice and Duplisea, 2014) to guide specific management decisions including:

1. **Trade-offs for management decisions:** what are the trade-offs between objectives and outcomes for food security, economic opportunities, and ecological risks; and how can this inform which management approach best accommodates interested parties with differing risk tolerances?

2. **Incorporating ecosystem information:** do management strategies accommodate key ecological concerns regarding fisheries on target forage fish (e.g., predator needs and productivity regimes)? Those strategies which do not may result in higher population or ecosystem risks, unless evidenced otherwise.

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[3] United States Forage Fish Conservation Act

[4] Canada's Policy on New Fisheries for Forage Species

3. **Management and assessment error:** what are the risks that management or assessment errors could lead to substantial increases in the risk of unsustainable fisheries or adverse ecosystem impacts?

It would be progressive for the UKs Forage Fish Approach to recognise that fishing is one of many anthropogenic pressures impacting population dynamics (Van de Kooij et al., 2021) and that cumulative impacts may influence the performance of management strategies. This includes pressures resulting from activities such as, fishing, renewable energy, aggregate extraction, water abstraction, and aquaculture, as well as diffuse pressures such as contaminants, marine plastic litter, noise, and climate change. Many of these pressures are linked and may exacerbate each other, however there is a general lack of specific knowledge on the impacts of these pressures on forage fish at either individual or population level. An improved understanding of cumulative impacts is needed to deliver EBFM (e.g., NOAA, 2016a, 2016b), which could better support efforts for an integrated spatial approach for fisheries management in alignment with other marine sectors.

Finally, the Marine Natural Capital and Ecosystem Assessments programme (mNCEA) is ambitious in its objective to transform marine decision-making by considering the value of natural resources and the ecosystem services they provide. A natural capital approach to policy and decision making considers the value of the natural environment for people and the economy. The UK Government has committed this joint economic and environmental approach (Hooper et al., 2019) and Government guidance suggests that public sector organisations interested in understanding the scientific and economic evidence around the natural environment should use natural capital approaches.

Lessons learnt from the mNCEA programme, and particularly the upcoming mNCEA FMP for pelagic fish in the Celtic Sea, may inform how we interpret and value the ecosystem role of forage fish and assess the risk of alternate fishery management strategies. For example, forage fish are an integral component of the biological carbon pump through deposition of carbon in faeces and carcasses and contribute to marine ecosystem function, including recycling nutrients, maintaining habitats via top-down control, and facilitating adaptation to climate change through production of alkali waste products that can buffer ocean acidification (Martin et al., 2023; ICES, 2024). Good fisheries management that incorporates and appropriately considers these ecosystem services could reduce the risk of loss of these services to wider society and deliver benefits for stakeholders, climate, and biodiversity (Andersen et al., 2024).

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Annex

Annex 1

Annex 1 includes a table (**Table 2**) which provides explanations for the trends observed in **Figure 2**, **Figure 3**, and **Figure 4**. The table explains why the species/groups presented in the figures followed trends, or showed no change, following reductions in sprat biomass.

Table 2. Descriptions to accompany Figures 2-4 which explain the direct and indirect mechanisms behind the simulated responses to a decline in sprat biomass.

Figure	Species	Biomass response description
Figure 2: Commercial species	Cod	Slight increase due to an increase in preferred prey (haddock and sandeels)
Figure 2: Commercial species	Whiting	Decrease due to the reduced availability of preferred prey (sprat)
Figure 2: Commercial species	Haddock	Increase due to an increase in preferred prey (sandeels: increases due to reduced predation pressure from whiting and mackerel)
Figure 2: Commercial species	Saithe	Decline but low confidence in magnitude due to uncertainty; in some scenarios saithe declines due to prey depletion (sprat), in others, the reduction is damped by reduced predation pressure (toothed whales) and increases in other prey (herring and Norway pout).
Figure 2: Commercial species	Plaice	Very limited response, in some scenarios we witnessed a slight decline due to increased predation pressure (cod and seals).
Figure 2: Commercial species	Herring	Slight increase due to a small increase in prey availability (copepods) and a decrease in predation pressure (saithe, spurdog).
Figure 2: Commercial species	Mackerel	Decrease due to the reduced availability of preferred prey (sprat).
Figure 2: Commercial species	Norway pout	Slight increase due to a small increase in prey availability (copepods) and a decrease in predation pressure (whiting, toothed whales).
Figure 3: Marine mammals and seabirds	Baleen whales	Increase due to an increase in preferred prey (sandeels).
Figure 3: Marine mammals and seabirds	Toothed whales	Decrease due to the reduced availability of preferred prey (sprat).
Figure 3: Marine mammals and seabirds	Seals	Very limited response, in some scenarios we witnessed a slight increase due to increased prey availability (sandeels).
Figure 3: Marine mammals and seabirds	Black-legged kittiwake	Decrease due to the reduced availability of one of their preferred prey (sprat).

Figure	Species	Biomass response description
Figure 3: Marine mammals and seabirds	Razorbill	Decrease due to the reduced availability of one of their preferred prey (sprat).
Figure 3: Marine mammals and seabirds	Common guillemot	Strong decline due to the reduced availability of their preferred prey (sprat).
Figure 3: Marine mammals and seabirds	Atlantic puffin	Increase due to an increase in preferred prey (sandeels).
Figure 3: Marine mammals and seabirds	Northern gannet	Decline with uncertainties in the magnitude of the decline. Declines due to reduced availability of prey (mackerel) may be offset by increases in other prey (sandeels and herring).
Figure 3: Marine mammals and seabirds	Northern fulmar	Slight increase due to a small increase in prey availability (herring).
Figure 3: Marine mammals and seabirds	Cormorant and shag	Increase due to an increase in preferred prey (small demersal fish and sandeels).
Figure 3: Marine mammals and seabirds	Gulls and skuas	Very slight decline in response to a slight reduction in prey (crabs: facing slightly increased predation pressure from rays, gurnards, and cod).
Figure 3: Marine mammals and seabirds	Surface feeding terns	Decrease due to the reduced availability of one of their preferred prey (sprat).
Figure 4: Feeding and trophic guilds	Piscivores (apex)	There are mixed responses within the feeding guild, however the overall signal is a slight decline, driven by declines in common guillemots, razorbills, terns, and toothed whales.
Figure 4: Feeding and trophic guilds	Piscivores	There are mixed responses within the feeding guild, however the overall signal is a slight decline, driven by declines in whiting, megrim, and turbot.
Figure 4: Feeding and trophic guilds	Benthivores	All groups in the benthivore feeding guild show little to no response to changes in sprat biomass. The overall trend is therefore muted.
Figure 4: Feeding and trophic guilds	Planktivores	Sprat were not included in the planktivore grouping to understand how changes in its biomass impacts the wider planktivore community. There are mixed responses within the feeding guild, however there is an overall increase which is driven by the response of herring and Norway pout.
Figure 4: Feeding and trophic guilds	Benthos	All groups in the benthos feeding guild show little to no response to changes in sprat biomass. The overall trend is therefore muted.
Figure 4: Feeding and trophic guilds	Zooplankton	Zooplankton showed little to no response to changes in sprat biomass. In some model parameterisations, gelatinous zooplankton and copepods increased due to reduced predation pressure.
Figure 4: Feeding and trophic guilds	Phytoplankton	Phytoplankton showed little to no response to changes in sprat biomass. In some model parameterisations, phytoplankton declined due to increased predation pressure from copepods.

Annex 2

Annex 2 provides the values (**Table 3**) from **Figure 5**. These values provide the average, lower, and upper estimated rates of biomass change in response to a change in the biomass of sprat. Positive values indicate that groups respond in the same direction as sprat, while negative values indicate that groups respond in the opposite direction to sprat. Values of 1 or -1 suggest the change is of the same relative magnitude (i.e., a 1% change in sprat biomass leads to a 1% change in the corresponding groups biomass).

Table 3. Rate of change in the biomass of North Sea functional groups relative to the rate of change in the biomass of sprat.

Guild	Group	Rate of change	Lower rate of change	Upper rate of change
Piscivores (apex)	Atlantic puffin	-0.374	-0.506	-0.262
Piscivores (apex)	Baleen whales	-0.159	-0.221	-0.094
Piscivores (apex)	Black-legged kittiwake	0.120	0.042	0.203
Piscivores (apex)	Common guillemot	0.952	0.900	1.005
Piscivores (apex)	Cormorant and shag	-0.334	-0.412	-0.256
Piscivores (apex)	Gulls and skuas	0.019	0.009	0.029
Piscivores (apex)	Northern fulmar	-0.066	-0.097	-0.037
Piscivores (apex)	Northern gannet	0.024	-0.025	0.068
Piscivores (apex)	Razorbill	0.476	0.362	0.566
Piscivores (apex)	Seals	-0.034	-0.051	-0.020
Piscivores (apex)	Surface feeding terns	0.437	0.343	0.505
Piscivores (apex)	Toothed whales	0.208	0.178	0.248
Piscivores	Cod (adult)	-0.035	-0.051	-0.021
Piscivores	Cod (juvenile 0-2)	-0.014	-0.030	-0.003
Piscivores	Gurnards	-0.275	-0.335	-0.217
Piscivores	Hake	0.198	0.142	0.250
Piscivores	Halibut	0.161	0.115	0.199
Piscivores	Horse mackerel	-0.076	-0.106	-0.051
Piscivores	Juvenile rays	-0.351	-0.410	-0.291
Piscivores	Juvenile sharks	0.070	0.058	0.082
Piscivores	Large demersal fish	-0.005	-0.028	0.009
Piscivores	Large piscivorous sharks	0.008	-0.012	0.025
Piscivores	Megrim	0.706	0.659	0.755
Piscivores	Monkfish	-0.016	-0.036	0.001
Piscivores	Other gadoids (large)	-0.226	-0.275	-0.184
Piscivores	Other gadoids (small)	-0.063	-0.078	-0.045
Piscivores	Saithe (adult)	0.135	-0.242	0.267

Guild	Group	Rate of change	Lower rate of change	Upper rate of change
Piscivores	Saithe (juvenile 0-3)	0.175	0.084	0.265
Piscivores	Skate + cuckoo ray	-0.334	-0.408	-0.267
Piscivores	Small demersal fish	-0.274	-0.314	-0.226
Piscivores	Small sharks	0.079	0.068	0.093
Piscivores	Spurdog	0.080	0.053	0.104
Piscivores	Squid & cuttlefish	-0.059	-0.075	-0.046
Piscivores	Starry ray + others	-0.218	-0.250	-0.181
Piscivores	Thornback & Spotted ray	0.043	0.021	0.062
Piscivores	Turbot	0.671	0.573	0.800
Piscivores	Whiting (adult)	0.291	0.238	0.351
Piscivores	Whiting (juvenile 0-1)	0.241	0.185	0.306
Benthivore	Catfish (Wolf-fish)	0.015	0.008	0.024
Benthivore	Dab	0.021	0.011	0.032
Benthivore	Dragonets	-0.031	-0.064	0.000
Benthivore	Flounder	0.018	0.008	0.028
Benthivore	Haddock (adult)	-0.112	-0.131	-0.096
Benthivore	Haddock (juvenile 0-1)	-0.098	-0.116	-0.080
Benthivore	Lemon sole	0.027	0.020	0.036
Benthivore	Long-rough dab	-0.004	-0.024	0.015
Benthivore	Plaice	0.016	0.010	0.023
Benthivore	Sole	0.021	-0.010	0.054
Benthivore	Witch	0.035	0.027	0.045
Benthos	Epifaunal macrobenthos	0.014	0.009	0.020
Benthos	Infaunal macrobenthos	0.010	0.005	0.016
Benthos	Large crabs	0.035	0.025	0.047
Benthos	Meiofauna	0.002	-0.002	0.005
Benthos	Sessile epifauna	0.012	0.004	0.021
Benthos	Small infauna	0.018	0.014	0.022
Benthos	Small mobile epifauna	0.006	0.003	0.010
Planktivore	Blue whiting	0.067	0.033	0.099
Planktivore	Filter feeding pelagic fish	-0.051	-0.070	-0.035
Planktivore	Herring (adult)	-0.056	-0.112	-0.008
Planktivore	Herring (juvenile 0-1)	-0.026	-0.048	-0.004
Planktivore	Mackerel	0.117	0.079	0.151
Planktivore	Norway pout	-0.065	-0.089	-0.037
Planktivore	Sandeels	-0.525	-0.647	-0.423
Zooplankton	Carnivorous zooplankton	0.027	0.007	0.046
Zooplankton	Gelatinous zooplankton	0.019	-0.003	0.040
Zooplankton	Herbivorous zooplankton	-0.029	-0.048	-0.010
Primary producers	Phytoplankton	0.011	0.004	0.019

Guild	**Group**	**Rate of change**	**Lower rate of change**	**Upper rate of change**
No guild	Benthic microflora	0.004	0.001	0.008
No guild	Fish larvae	-0.027	-0.057	-0.002
No guild	Planktonic microflora	0.005	0.002	0.010
No guild	Shrimp	-0.040	-0.071	-0.014