What are the ecosystem risks and benefits of full prohibition of industrial Sandeel fishing in the UK waters of the North Sea (ICES Area IV)?

Defra request for advice

Core advice on the ecosystem risks and benefits of full prohibition of industrial Sandeel fishing in the UK waters of the North Sea

This core advice generated from this report is that:

- if a full prohibition of sandeel fishing is implemented in UK waters of the North Sea, a viable alternative will be needed to monitor sandeels and the impacts of the area closure. This should capture the links between sandeels and food web dynamics and identify progress made towards Good Environmental Status (GES)
- Sandeel stocks experience high levels of natural fluctuation due to the influence of environmental variation on sandeel recruitment and production. A full prohibition of industrial sandeel fishing in the UK waters of the North Sea would offer some resilience at times of adverse natural conditions
- Sandeel availability has been linked to seabird breeding success and survival. Evidence from the literature and ecosystem modelling indicates that seabirds would be the biggest beneficiaries if sandeel fishing in the North Sea was prohibited. Ecosystem model simulations predict that a full prohibition of sandeel fishing in the UK waters of the North Sea would lead to an increase in seabird biomass of 7% in around 10 years, albeit under constant prevailing environmental conditions
- published research suggests increased sandeel biomass would have localised benefits for the condition of some commercial fish, however the impacts of prohibiting sandeel fishing on the overall stock biomasses of commercial fish would be limited and complex, with a mixture of positive and negative responses
- the risk of primary displacement (displacing sandeel fisheries to alternate sandeel fishing grounds) is greatest for sandeel management area 1r (SA1r) as this management unit is shared across the UK-EU EEZ border. Secondary displacement (displacement onto other species) would increase the risk of exploitation of other forage fish, particularly non quota species and stocks

Table of contents

Preface and advice overview

UK policy landscape and environmental objectives

Sandeels form a key component within the North Sea ecosystem and represent a major conduit of energy transfer from lower trophic levels (for example, plankton) to higher trophic levels including seabirds, marine mammals, and commercial fish species. This is UK legislation and a range of governmental strategies, designed to safeguard the functioning of the marine ecosystem, to which this advice has relevance. That legislation includes, The UK Marine Strategy Regulations 2010, The Conservation of Habitat Regulations 2017, The UK Environment Act 2021, The UK Fisheries Act 2020, and Scotland's Fisheries Management Strategy 2020 to 2030 (see Annex 1).

The Precautionary Objective of the UK Fisheries Act 2020 establishes the need to apply the precautionary approach to fisheries management, which the Fisheries Act defines as:

"An approach in which the absence of sufficient scientific information is not used to justify postponing or failing to take management measures to conserve target species, associated or dependent species, non-target species or their environment".

The evidence presented within this advice presents the current state of understanding of the role of sandeels and the potential impacts of a prohibition of industrial fishing for them in UK waters. The evidence does come with uncertainties and gaps and managers may therefore need to consider the level to which precautionary actions may be required, which can be informed by the risks identified in this report.

Forage fish in UK waters

Forage fish are small to intermediate sized species, occurring in schools or aggregations, that function as a main pathway for energy to flow from plankton to higher trophic level predators (Figure 1). Other species may be considered as forage fish for parts of their life cycle (for example juvenile gadoids such as cod and whiting) but are not intentionally targeted on an industrial scale. Many forage fish species are short lived, produce many eggs and have populations that can exhibit significant natural fluctuation in size and distribution, driven by environmental conditions as well as by anthropogenic factors; in addition, they can exhibit migratory behaviour over long distances (Campanella and van der Kooij 2021). Several forage fish species have been identified as current or potential targets for fisheries in waters around the

UK: sandeels (*Ammodytes spp*), Norway pout (*Trisopterus esmarkii*), blue whiting (*Micromesistius poutassou*), European sprat (*Sprattus sprattus*), Atlantic herring (*Clupea harengus*), horse mackerel (*Trachurus trachurus*), boarfish (*Capros aper*), sardine (*Sardina pilchardus*), and greater silver smelt (*Argentina silus*).

Figure 1: Forage fish in UK waters, their characteristics, catch statistics, and role in the ecosystem.

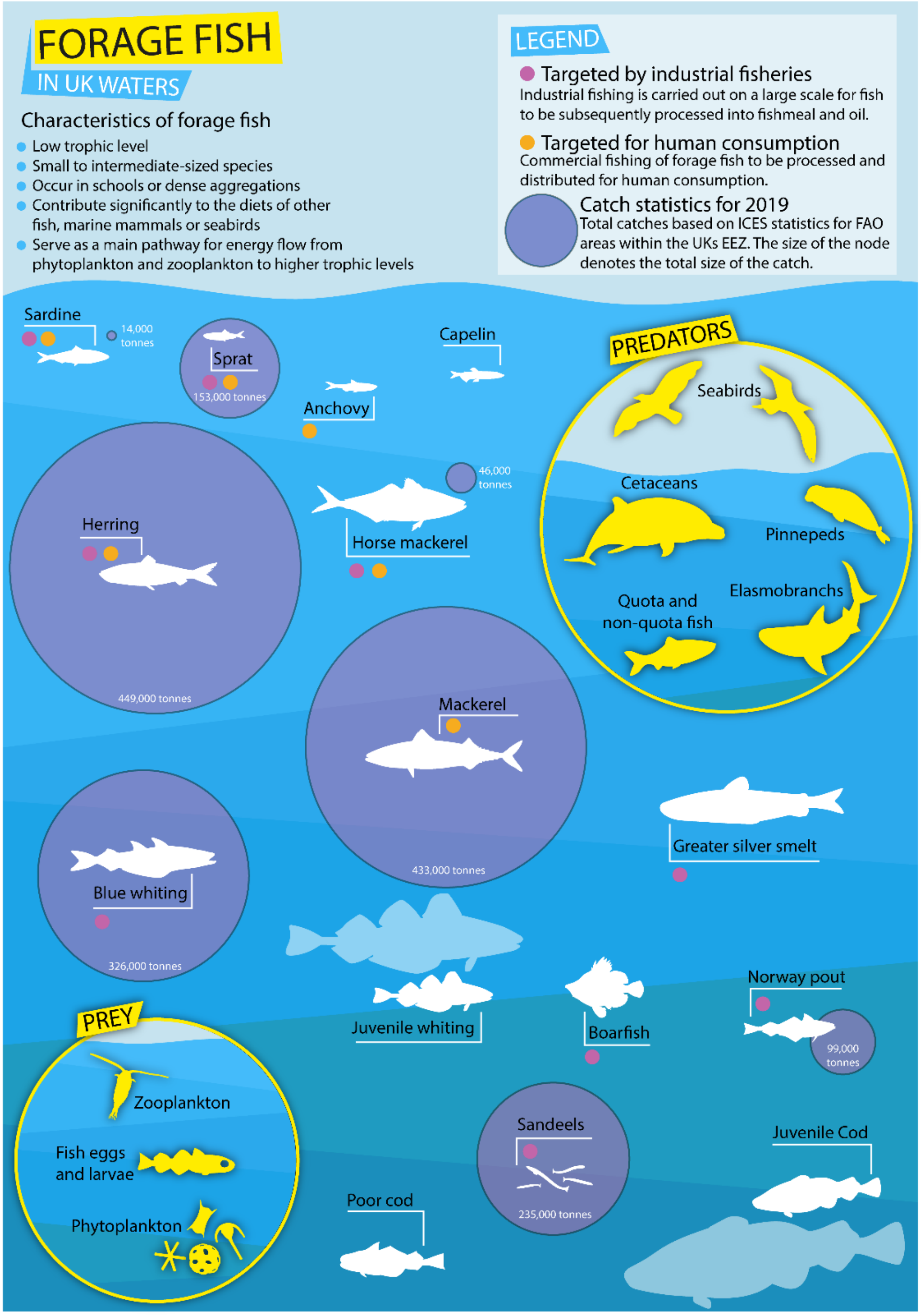

Figure 1 shows the forage fish species which can be found in UK waters. This includes herring, mackerel, blue whiting, sandeels, Norway pout, sprat, horse mackerel, capelin, anchovy, sardine, boarfish, poor cod, and greater silver smelt. Juvenile cod and juvenile whiting can also be considered forage fish, although they are not targeted commercially. The top 3 forage fish in terms of weight caught and landed are herring, mackerel, and blue whiting. Forage fish are caught for consumption and industrial purposes (such as being turned into fishmeal or fish oil). Key prey for forage fish include zooplankton, fish eggs and larvae, and phytoplankton. Forage fish are prey for seabirds, marine mammals, and quota and non-quota fish.

Industrial fishing is defined as commercial fishing where the harvested fish are destined to be processed into fishmeal and fish oil rather than for direct human consumption. Industrial fisheries rely on high levels of catches to remain commercially viable as market forces dictate that the value of the catch, per tonne, tends to be lower than fish typically caught for human consumption. In the context of the North Sea, there are specific fleet segments that specialise in this type of fishing for several forage fish species.

Evidence review

Sandeel fishery in the North Sea

3 species of sandeels occur in the North Sea of which *Ammodytes marinus* is the most common species and is considered to form 7 spatially distinct populations that are reproductively isolated and exhibit different population dynamics (Boulcott and Wright 2011). For commercial fishery purposes the populations have been separated into 7 sandeel assessment and management areas (SAs, Figure 2) (ICES 2010). Sandeels caught for industrial purposes are targeted with highly specific gears, usually large otter trawls of a pelagic or semi-pelagic design with cod end mesh sizes less than 16 millimetres (mm).

These gears have a high headline (typically more than 15 meters (m)) and are fished with relatively light ground gear and trawl doors. Vessels are typically large (more than 40m) operating multi-day trips. The North Sea sandeel fishery is primarily carried out by 2 countries, Denmark and Norway;,the majority of Norwegian operations take place in Norwegian waters while the majority of Danish landings come from within the UK EEZ (annual average of 60% from UK waters between 2002 and 2016, with a minimum of 31% and a maximum of 78%).

Figure 2: Sandeel assessment and management areas in the North Sea (ICES area IV). The borders of the UK and Norwegian Exclusive Economic Zones are shown as black lines. The closed part of Sandeel Area 4 is shown with hatched markings (adapted from ICES, 2022).

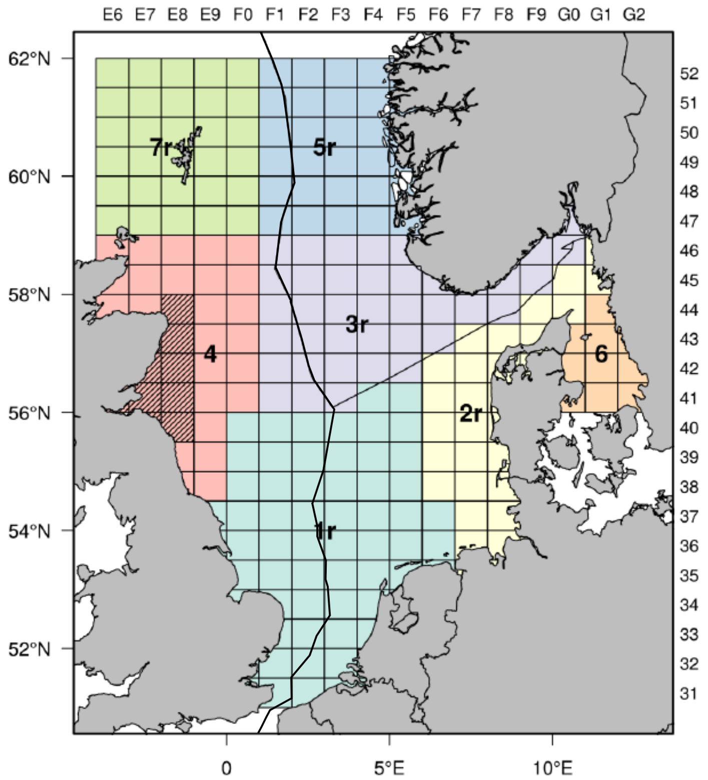

Figure 2 shows the separation of sandeel management areas in the North Sea. The North Sea is split into 7 distinct areas. Area 1r is the largest area and located between the East Coast of England and Northwest coasts of Belgium and the Netherlands. Area 2r extends up the west coast of Denmark. Area 3r falls mostly within Norway’s Exclusive Economic Zone (EEZ), bordering the south of the country. Area 4 falls entirely within the UKs EEZ and extends from the Northeast of England to Orkney. Area 5r sits mostly within Norway’s EEZ on the west coast of Norway. Sandeel area 6 is in the Skagerrak, Kattegat, and Belt Sea. Finally, area 7 is located around Shetland.

Sandeel landings from UK waters

To assess the proportion of sandeel landings taken from UK waters, the weight of sandeels landed within and outside the UK EEZ were taken from data published by the European Commission's Scientific, Technical and Economic Committee for Fisheries (STECF) and split between those caught within the UK Exclusive Economic Zone (EEZ) and those caught outside of the UK EEZ (Figure 3). To split landings, ICES rectangles were classified as being either inside or outside of the UK EEZ.

Where only part of a rectangle lay within the UK EEZ, the proportion of the landings caught within the UK EEZ were assumed to be proportional to the area of the rectangle that lay within the UK EEZ (for example, if 80% of the rectangle was within the UK EEZ, 80% of the sandeels caught within that rectangle would be assigned to UK waters and 20% to waters outside of the UK EEZ).

This assumption applies only to a small proportion of the total landings (Figure 3c), landings predominantly come from ICES rectangles that are exclusively within or outside the UK EEZ. Between 2003 and 2020, the average proportion of sandeel landings from UK waters was 58%. The upper (95^{th} percentile) and lower (5^{th} percentile) proportions were 73% and 38% respectively.

Figure 3: The (a) proportion of sandeel landings from 2003 to 2020 from within and outside of the UK EEZ and (b) the mean and 95% distribution of landings from within the UK from 2003 to 2020, (c) only a small proportion of landings (average of 10%) were taken from ICES rectangles that are shared by the UK and EU.

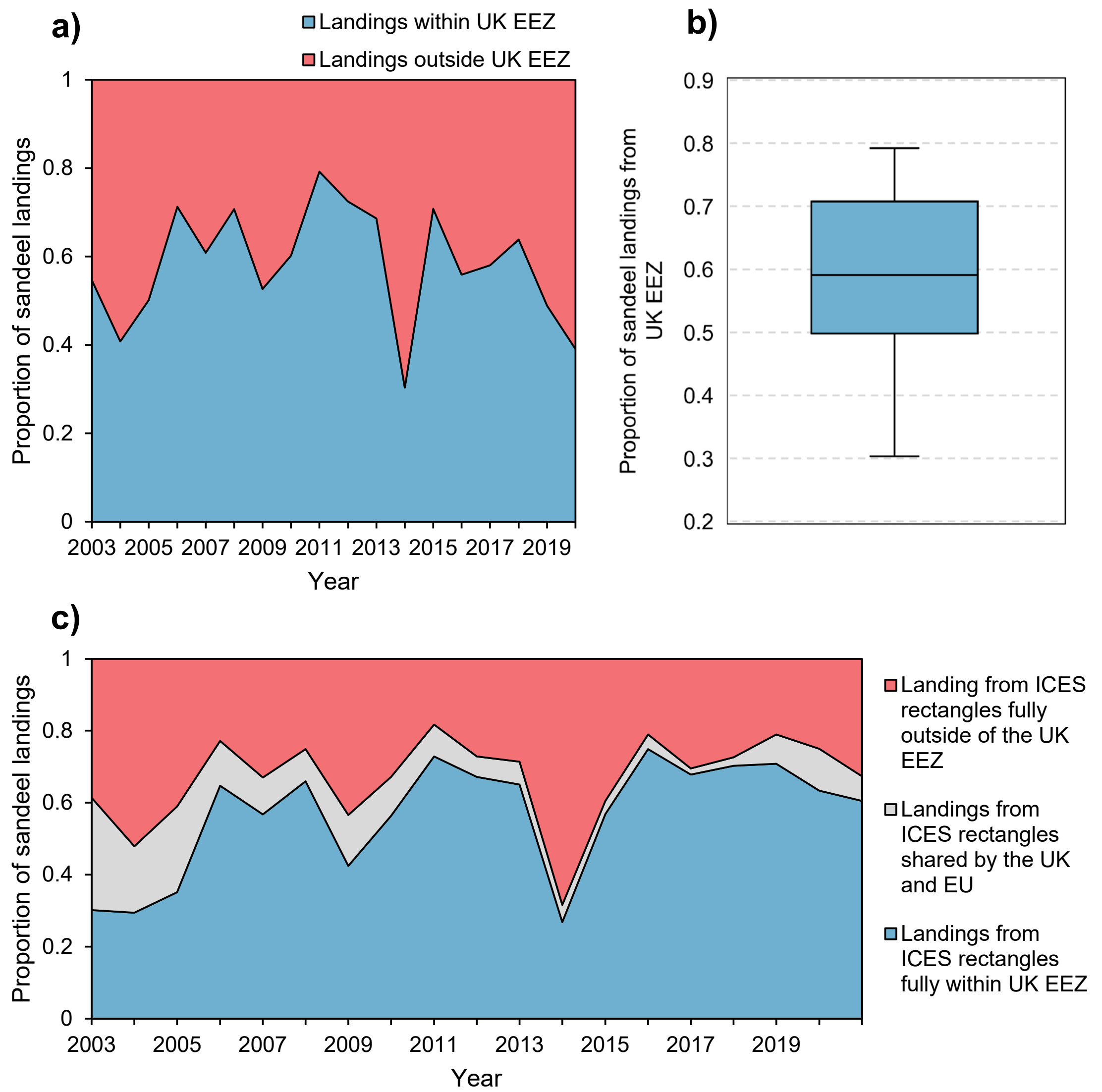

Figure 3 shows the proportion of sandeel landing within and outside of the UK EEZ from 2003 to 2020. On average, a larger proportion of annual landings is taken from within the UK EEZ (around 60% from within the UK EEZ), however in 2014 there was a notable increase in the landings proportion coming from outside the UK EEZ (roughly 70% from outside the UK EEZ). Only a small proportion of landings (average of around 10%) are taken from ICES rectangles that are shared by the UK and EU.

Sandeel dynamics

Sandeels have been described as the most important forage fish in the North Sea, contributing to the diets of mammals, seabirds, and predatory fish (Engelhard and others, 2014). Declines in sandeel abundance can negatively impact the survivability, condition, and reproduction of commercially and ecologically important species (see Table 1). In recognition of this, spatially restricted closures to sandeel fishing have been historically introduced, around Shetland and the southeast of Scotland. These closures have been linked to increases in the local sandeel population sizes (Wright and others, 1996; Greenstreet and others, 2006). However, fluctuations in sandeel stocks are driven by both top-down (such as predators and fishing) and bottom up (such as prey availability and hydroclimatic factors) processes.

Hydroclimatic factors, such as oceanic currents and the winter index of the North Atlantic Oscillation (NAO), have been linked to the number of juvenile sandeels which survive to become older, larger, and available to the fishery (for example, Arnott and others, 2002). The NAO is an irregular fluctuation of atmospheric pressure over the North Atlantic Ocean that has a strong effect on winter weather in Europe, Greenland, north-eastern North America, North Africa, and northern Asia. The impacts of extraneous factors on sandeel recruitment mean that even with low fishery exploitation pressure, the risk of population collapse still exists.

Poloczanska and others (2004) used aged structured population models which indicated that fishing sandeels at low levels (where recruitment is more than losses to fishery in 90% of simulated years) could lead to an increase in sandeel spawning stock biomass. They found that even at low levels of exploitation, sandeel populations still crashed (in 1 to 3% of scenarios) and the probability of poor seabird success was once in every 6 years. This study did not account for changes in predation mortality and how this may dampen any expected biomass gain, nor did it investigate the likelihood of sandeel collapse under zero fishing and thus whether the risk is any different from a low fishing scenario. However, they did find that the risk of collapse increased sharply under scenarios of higher fishing mortality.

Sandeel stocks in the North Sea have experienced a range of exploitation levels, peaking at over 1 million tonnes in the late 1990s although subsequent management regimes have reduced this and landings are more typically around 300 thousand tonnes (kt). Stock levels have varied considerably and have at times been below the levels considered appropriate for strong recruitment. The frequency of stocks being below the minimum acceptable biomass will likely increase with increasing fishing pressure, particularly when coupled to averse environmental conditions.

Sandeels and their role in the ecosystem

Marine mammals

Both grey seals (Halichoerus grypus) and harbour seals (Phoca vitulina) often show a preference for sandeels in their diets (Hammond and others, 1994; Thompson and others, 1996). Santos and Pierce (2003) suggest that demise of the herring stock has pushed North Sea harbour porpoise to become much more dependent upon Sandeels since the mid 1960's. Based on spatiotemporal energetic availability mapping for harbour porpoise (Phocoena phocoena) in the North Sea, it has been demonstrated that the distribution of porpoise is driven by availability of prey (Ransijn and others, 2019). As the main energetic contributions to the overall energy density in the North Sea are from whiting and sandeels, it is reasonable to conclude that distribution of harbour porpoise is strongly but not exclusively linked to sandeel availability in the North Sea. Indeed, the condition of harbour porpoise has been linked to sandeel availability (MacLeod and others, 2007).

The distribution and occurrence of other marine mammals has also been linked to the availability of sandeel prey. For example, observations of minke whale redistribution within the North Sea may be related to a decline in sandeel availability elsewhere in the North Sea (De Boer and others, 2010), while the decline in sandeels in the northern North Sea and re-invasion of the southern North Sea by sardine species might be affecting the distribution of harbour porpoise (Mahfouz and others, 2017).

Seabirds

The UK is globally important for many breeding seabird species. At the time of the last seabird census (Seabird 2000, 1998 to 2002), over 8 million seabirds of 25 species bred in Britain and Ireland each year. Since then, evidence of widespread declines in productivity (number of chicks fledged per pair) has emerged that may be driving declines in breeding population size. Sandeels are particularly important in the diets of many seabird species, especially during the breeding season and as food for growing chicks (Frederiksen and others, 2004).

The presence of an active fishery can have a detrimental effect on seabird populations (Cook and others, 2014) as the breeding success of some seabirds can be reduced dramatically when sandeel abundance decreases (for example, Philips and others, 1996; Rindorf and others, 2000; Miles and others, 2015; Carroll and others, 2017). In the context of other countries surrounding the North Sea, the UK is unique in terms of the large number of internationally important breeding colonies for several important, sandeel-dependant seabirds (Mitchell and others, 2004; Dunn, 2021). Furness and others (2013) suggest that the closure of sandeel and sprat fisheries in UK waters could increase the survival and productivity of kittiwakes, common guillemots, razorbills, and Atlantic puffins.

A full prohibition of sandeel fishing in UK waters would therefore serve to increase resilience of seabirds (for example, Poloczanska and others, 2004) which also face direct risk from pressures such as climate change (Mitchell and others, 2020) and diseases such as avian flu (Hunter, 2022).

Of the multiple species of seabirds studied, the links between sandeels and blacklegged kittiwakes appears to be one of the strongest. Frederiksen et al (2004) and Carroll and others (2017) found that lower temperatures and lower fishing mortality were positively associated with sandeel biomass, and higher sandeel biomass and lower fishing mortality were positively associated with kittiwake productivity. Sandeel recruitment is reduced in warm winters, which Frederiksen and others (2004) suggest explains the temperature effects on kittiwake survival and breeding success.

The breeding success of kittiwakes has also been shown to negatively correlate with the fishing effort of industrial sandeel fisheries, with fishery closures off the east coast of Scotland leading to increased breeding success (Frederiksen and others, 2008; Daunt and others, 2008). The focus of the industrial fishery is the Dogger Bank, with the major fishing grounds being approximately 100km from the UK coast and within the UK EEZ. Kittiwakes from eastern England forage throughout this area (approximately 60% of their diet here is sandeels) and their productivity is sensitive to sandeel fishing mortality (Carroll et al, 2017), although the exact mechanism in some cases is unclear as kittiwakes and fishers often target different sandeel age groups (Frederiksen et al, 2004).

Marine fish

The diet 'flexibility' and ability of predatory commercial fish to substitute diet shortfalls with other prey species suggests that they are less crucially dependent on local sandeel abundance than, for example, seabird colonies off Scotland (Frederiksen and others, 2005). This is supported by research showing that predatory fish tend to be generalist feeders and hence less reliant on a particular prey resource (Trenkel and others, 2005; Pinnegar et al, 2003).

Investigations note that some predator species in the North Sea (including cod, whiting, plaice, gurnards, lesser weaver, and haddock) showed better body condition indices (based on weight and length measurements) in years characterised by higher sandeel availability (Mackinson, 2007; Engelhard and others, 2013; Rindorf and others, 2008). Moreover, the condition of some species (such as, whiting, lesser weever, gurnards) has been shown to positively correlate with the number of sandeels consumed (Engelhard and others, 2013). As body condition relates to growth, reproduction, and survival chances, it is expected that fish in good condition would likely have a better fitness.

The stock rebuilding of forage fish has been linked to unanticipated consequences for other commercially or ecologically important species. For example, as forage fish grow, their ecological role changes, and at some stage during their life cycle they may compete with juvenile predators for limited zooplankton resources (Engelhard and others, 2014).

This follows the cultivation-depensation hypothesis (Walters and Kitchell, 2001) which suggests that adult prey species often consume or compete with juvenile predator species and that the depletion of adult predators from fishing can result in the release of prey from predation. This results in an increase in prey abundance while predator productivity declines. Strong evidence for cultivation depensation effects have been found between cod (predator) and herring (prey) where an increase in herring negatively impacts the biomass of young cod (Minto and Worm, 2012).

There is little evidence to suggest sandeels competing for food with juvenile predators has had any detrimental impact on other commercial species. If there is a risk of increased competition for limited resources, then an increase in sandeel biomass could have complex consequences on other commercially important species.

Summary of ecosystem risks and benefits

Table 1: Substantiated links between marine predators and sandeels and links 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 and others, 2014.

Example	Predator name	Reported effects of sandeel biomass	Link to UKMS	Reference
1	Harbour porpoise *Phocoena phocoena*	A lower proportion of sandeels in their diet in spring increases likelihood of starvation	D1 and D4: Cetaceans	MacLeod and others, 2007
2	Grey seal *Halichoerus grypus*	Condition of breeding females linked to sandeel abundance	D1 and D4: Seals	Smout and others, 2020
3	Harbour seal *Phoca vitulina*	Declines have been seen in the populations of harbour seals where their diets are reliant on declining sandeel stocks. Harbour seal populations are not declining in areas where they have more diverse diets.	D1 and D4: Seals	Wilson and Hammond, 2016
4	Great skua *Catharacata skua*	Reproductive success influenced by local sandeel abundance	D1 and D4: Birds	Furness, 2007

Example	Predator name	Reported effects of sandeel biomass	Link to UKMS	Reference
5	European shag *Phalacrocorax aristotelis*	Reproductive performance strongly depends on local sandeel availability	D1 and D4: Birds	Rindorf and others, 2000
6	Common guillemot *Uria aalge*	Reproductive performance influenced by local abundance and quality of sandeel	D1 and D4: Birds	Wanless and others, 2005
7	Black-legged kittiwake *Rissa tridactyla*	Reproductive performance strongly depends on local sandeel availability	D1 and D4: Birds	Frederiksen and others, 2004 Carroll and others, 2017
8	Arctic tern *Sterna paradisaea*	Reproductive success influenced by local sandeel abundance	D1 and D4: Birds	Furness, 2007
9	Arctic skua *Stercorarius parasiticus*	Reproductive success (chick growth and chicks fledged per pair) influenced by local sandeel abundance	D1 and D4: Birds	Phillips *and others* 1996
10	Razorbill *Alca torda*	Adult return rates (a suitable proxy for adult survival) influenced by local sandeel abundance	D1 and D4: Birds	McGregor et al 2022

Example	Predator name	Reported effects of sandeel biomass	Link to UKMS	Reference
11	Atlantic Puffin *Fratercula arctica*	Reproductive success declined significantly 1987 to 2013 in tandem with declines in 1) mean mass of food loads delivered, 2) mean mass of individual fish in loads, 3) mean number of fish loads delivered per day and 4) an increase in the number of individual fish per load.	D1 and D4: Birds	Miles et al 2015
12	Sandwich tern *Thalasseus sandvicensis*	Positive relationship between productivity and sandeel abundance: higher productivity was found at east Scottish colonies following the closure of the local sandeel fishery	D1 and D4: Birds	Frederiksen and Wanless, 2006
13	Whiting *Merlangius merlangus*	Positive correlations between local sandeel abundance and condition: decline in abundance of sandeels has been linked to a decrease in the length at age of whiting	D1 and D4: Fish D3	Engelhard and others, 2013 Lauerburg and others, 2018
14	Haddock *Melanogrammus aeglefinus*	Positive correlations between local sandeel abundance and condition	D1 and D4: Fish D3	Engelhard and others, 2013

Example	Predator name	Reported effects of sandeel biomass	Link to UKMS	Reference
15	Plaice *Pleuronectes platessa*	Positive correlations between local sandeel abundance and condition	D1 and D4: Fish D3	Engelhard and others, 2013
16	Cod *Gadus morhua*	Positive correlation between overlap with sandeel and growth in the North Sea	D1 and D4: Fish D3	Rindorf and others, 2008
17	Grey gurnard *Eutrigla gurnardus*	Positive correlations between local sandeel abundance and condition	D1 and D4: Fish D3	Engelhard and others, 2013

Table 2: Review of the ecosystem benefits and risks of a reduction in pressure from industrial Sandeel fishing in the UK waters of the North Sea.

Impact type	Impact number	Impact	Summary of ecosystem impact
Benefit	B1	Increased sandeel resilience	Fluctuations in sandeel stocks are largely driven by extraneous factors (such as hydroclimatic factors). Even if fishery exploitation rates are low, the risk of stock collapse exists. However, the risk of collapse increases with increasing exploitation pressure. Reducing exploitation by prohibiting fishing in UK waters may increase sandeel resilience.
Benefit	B2	Increased seabird resilience	Increased population resilience for seabirds for which increased sandeel availability can positively impact on reproductive success (such as kittiwakes).
Benefit	B3	Increased occurrence of marine mammals within UK EEZ	Previous studies have linked the abundance of sandeels to the distributions of marine mammals in the North Sea, Therefore, if management actions led to an increase of sandeels in the UK EEZ, we might expect to observe an increased occurrence of marine mammals in UK waters.

Impact type	Impact number	Impact	Summary of ecosystem impact
Benefit	B4	Improved condition of other commercial fish	Predatory fish have flexible diets and are likely to compensate for declines in sandeel availability. However, increased sandeel availability and consumption has been shown to positively correlate with the body condition of some commercial fish (such as whiting, haddock, and plaice) which relates to growth, reproduction, and survival chances.
Benefit	B5	Progress towards GES	Several substantiated links have been made between the abundance of sandeels and the survival and breeding success of birds, mammals, and commercial fish, linking to the targets and indicators of the UKMS and GES descriptors (D1, D3 and D4).
Risk	R1	Sandeels reducing available prey for other commercial species	Changes in the magnitude of fisheries removal of sandeels may have potentially complex and unanticipated consequences on other commercially or ecologically important species (for example, if species compete with sandeels for limited prey resources).

Ecosystem modelling

Ecosystem models were used to simulate the full prohibition of sandeel fishing in UK waters of the North Sea to better understand the potential ecosystem benefits and risks.

Ecopath with Ecosim

Overview

An Ecopath with Ecosim (EwE) model of the North Sea was used to simulate the impacts of sandeel depletion (the reduction of sandeel biomass due to fishing mortality) on important commercial stocks and trophic guilds. 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. 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 for the purpose of this work, bringing simulations to 2020 by updating the underlying time series data (Driver time series: fishing effort and mortality and Calibration time series: catch and biomass).

The model comprises 69 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 UK Marine Strategy leading to Good Environmental Status (GES).

Sandeels are a key prey group in the EwE model of the North Sea, contributing to the diets of 36 of the 69 functional groups (Figure 4). Several predators predate heavily on sandeel, including mammals, seabirds, seals, elasmobranchs, and other commercial species. It is estimated that of these, whiting remove the most sandeel biomass. Due to the wide range of sandeel predators, it has been suggested that changes in predation by one predator would likely to be dampened by variation in other sources (Englehard et al, 2014). For some predators (including whiting, mackerel, haddock, gurnards, rays, seabirds, toothed whales, baleen whales, seals) sandeels are responsible for more than 25% of their prey biomass. These predators may be more vulnerable to bottom up control, where changes in the availability of sandeels impact predator production.

Figure 4: Biomass flow from sandeels to predators (consumption) and industrial fisheries (fishing mortality) in the North Sea calculated using Ecopath with Ecosim base estimates. Values indicate the proportion of sandeel biomass consumed by predators (s) and the contribution of sandeels to the total consumption of predators (p). Links between sandeels and food web and fishery components are proportional to the flow of biomass from sandeels. Sequential rings highlight the trophic level of the predators which consume sandeels. The trophic level of the industrial fishery is calculated based on fleet catch composition.

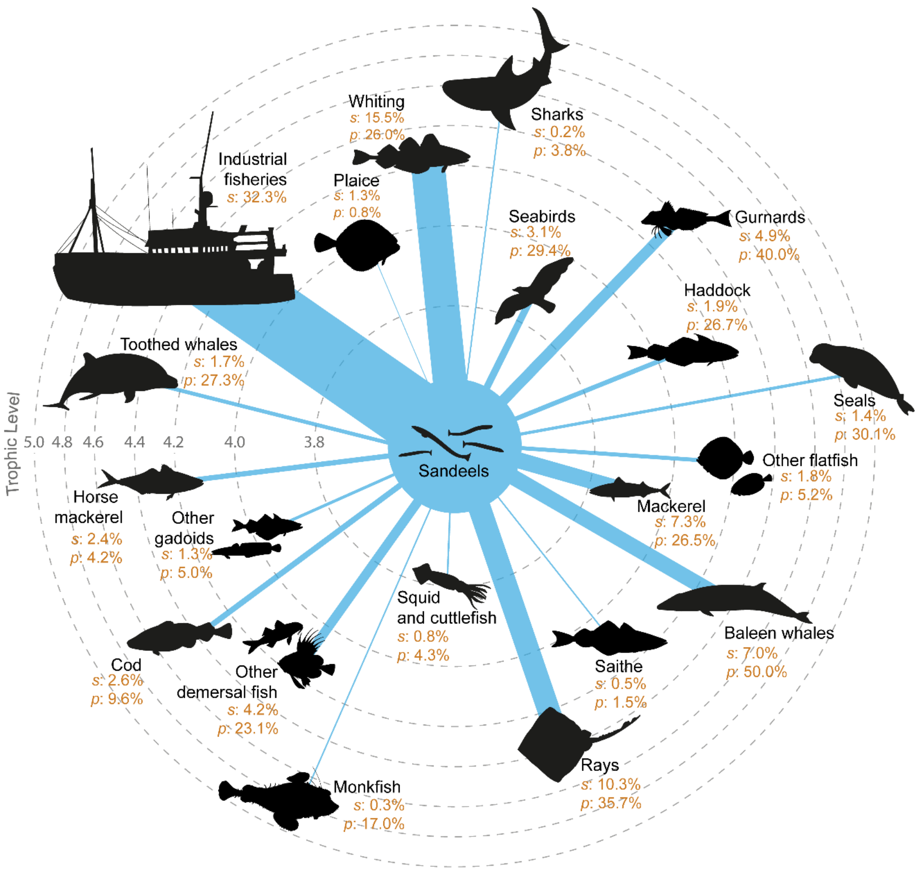

Figure 4 provides a summary of the consumption of sandeels by predators (including fishing) in the North Sea in terms of the proportion of sandeel biomass that is consumed or extracted by fishing. The fishing industry takes the largest proportion of sandeel biomass (32.3%) followed by whiting (15.5%), rays (10.3%), mackerel (7.3%), and baleen whales (7%). Sandeels constitute different percentages of the overall diets of its predators, for example, while baleen whales only consume 7% of the sandeel biomass, this constitutes around 50% of the total biomass consumed by baleen whales. Other species which depend heavily on sandeels as a core component of their diet includes gurnards (40%), rays (35.7%), seals (30.1%), seabirds (29.4%), toothed whales (27.3%), haddock (26.7%), and whiting (26%).

Methodology

The temporal dynamic module of EwE is called Ecosim (Christensen and Walters, 2004). 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 exploitation of sandeels for levels of depletion ranging from 0 to 50%. This depletion range was selected as it enables us to simulate the impacts of moving towards 0% depletion, but also the impacts of exceeding the current level of sandeel depletion which is around 20% based on the modelled biomass of sandeel in 2020 compared to biomass of sandeels when not fished.

Simulations were generated for sandeels, following previously published methods (Eddy and others, 2015), by projecting the model forward while exposing sandeels to incremental increases in fishing mortality. Simulations were run for 100 years to allow the model to reach equilibrium. The fishing mortalities of all other exploited species were held constant at their 2020 levels (leading to Caveat 1, as set out below). The level of depletion for sandeels was calculated by comparing the biomass at each stage of exploitation to the biomass of sandeels during a simulation where there was no exploitation (for example, a depletion value of 50% means the biomass at that point is half of unfished biomass).

While fishing mortality was used to drive the depletion of sandeels 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 sandeel stock declines”. Sandeel depletion could occur in response to multiple drivers of mortality, such as climate change or changes in food availability.

Scenarios were simulated for the prohibition of sandeel fishing in:

1) the North Sea (ICES Subarea 4).
2) for UK waters of the North Sea.

To simulate the impact of full North Sea prohibition, simulations were generated where sandeel fishing mortality (based on 2020 landings) was removed from the system. To simulate the impact of prohibition in UK waters, the ecosystem was simulated under scenarios of reduced fishing mortality based on the average (58%), upper (73%), and lower (38%) estimated proportions of landings coming from UK waters (as shown in Figure 3).

Outputs have been provided to show the predicted impact of sandeel depletion on 4 commercial stocks and 8 biomass guilds. The commercial stocks include cod, saithe, haddock, and whiting.

The biomass guilds include baleen whales (predominantly minke whales), toothed whales (harbour porpoise, white-beaked dolphin, and Atlantic white-sided dolphin), seals (grey seals and harbour seals), seabirds (including fulmar, gannet, shag, kittiwake, herring gull, great black backed gull, lesser black backed gull, guillemot, razorbill, puffin, and great skua), demersal fish, pelagic fish, benthos (such as crabs and *Nephrops*), and zooplankton.

The impacts of sandeel depletion on the biomass of these groups have been presented as relative change (%), where 100% is equivalent to the group biomass when sandeels are not being exploited (0% depletion).

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 131 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.

Results and discussion

The results from EwE illustrate the ecosystem's response to the depletion of sandeels and prohibition of fishing for sandeels in the North Sea and UK part of the North Sea. An overview of how to interpret the outputs from Ecosim is illustrated in Figure 5, while the results are presented in Figure 6. Table 3 provides a summary of the benefits and risks associated with prohibiting sandeel fishing. The results in Table 3 are based on the average relative biomass change from the model set. Annex 2 sets out the upper and lower estimates of relative biomass change from the model set.

Figure 5: Guide to interpreting the outputs from Ecopath with Ecosim (EwE) and impacts of reducing sandeel depletion by prohibiting sandeel fishing in UK waters of the North Sea

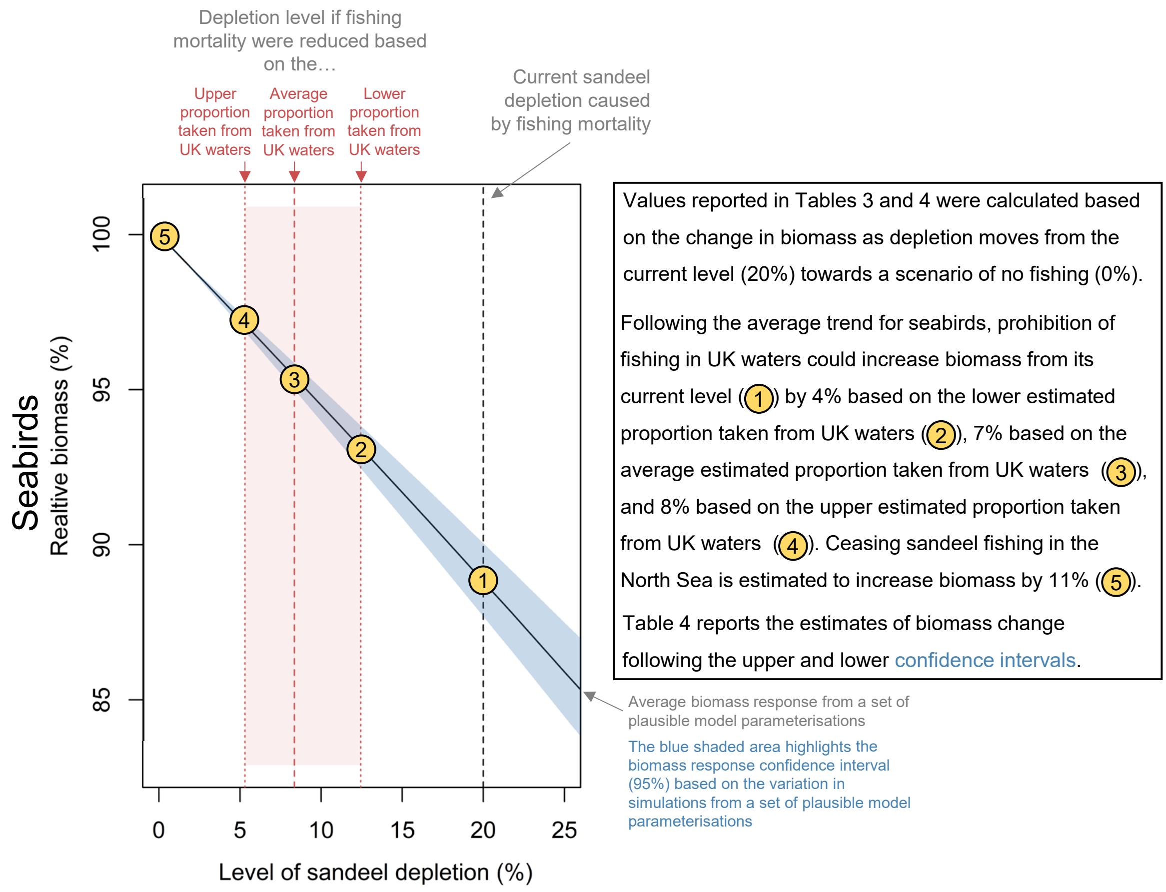

Figure 5 provides a guide to interpreting the results presented in Figure 6. The guide shows how the biomass of seabirds changes (declines) as the proportion of sandeels depleted increases. Following the trend, we can see where the x-axis intersects with the trend and infer from the y-axis what the biomass of seabirds may be at alternate levels of sandeel depletion compared to a scenario with no depletion.

For example, the current sandeel depletion is 20%. At 20% depletion, seabird biomass is estimated to be roughly 11% below where it could be if sandeel depletion was zero.

We can then explore the impacts of alternate management strategies that reduce sandeel depletion and estimate what we would expect the benefits or impacts to be. Prohibiting sandeel fishing in UK waters may reduce sandeel exploitation to somewhere between 5% and 13%, which is estimated to lead to increase in seabird biomass between 4% and 8%.

Figure 5: Impacts of sandeel depletion on the relative biomass of commercial stocks and trophic guilds in the North Sea (represented as the change in biomass compared to a scenario with no sandeel exploitation). The black dashed line highlights the current level of depletion based on fishing mortality from 2020. The red shaded area represents how the level of depletion might reduce if landings from UK waters were prohibited. 3 scenarios are presented for UK reductions based on the average (58%, middle red line), lower (38%, right red line), and upper (73%, left red line) proportion of landings taken from UK waters between 2003 and 2020.

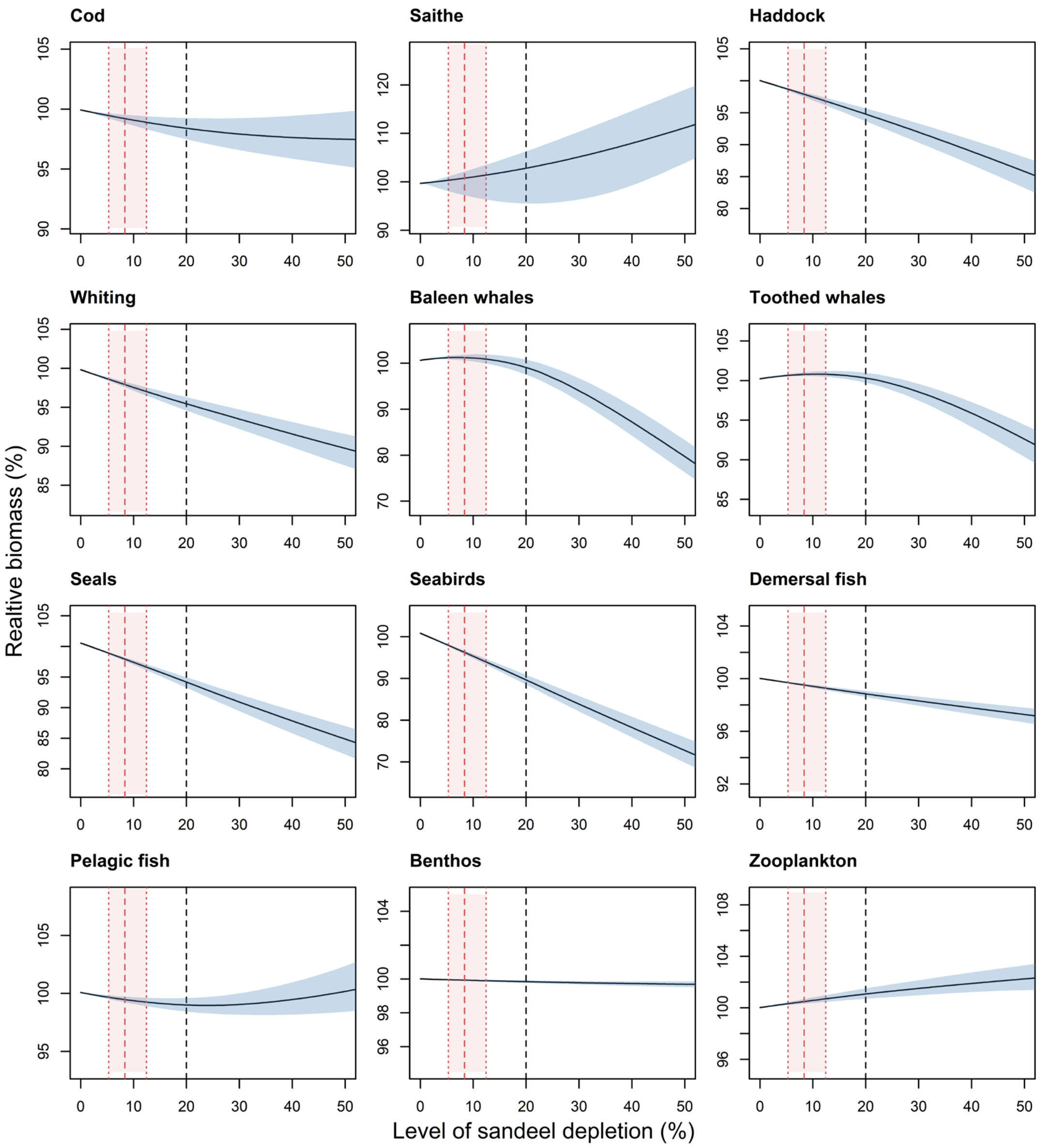

Figure 6 shows simulations of functional group responses to changes in sandeel depletion. Haddock, whiting, baleen whales, toothed whales, seals, seabirds, and demersal fish all show declining biomass trends in response to sandeel depletion. Cod, pelagic fish, benthos and zooplankton all show limited responses to changes in sandeel depletion, whereas saithe biomass simulations increase with increasing sandeel depletion.

Results were generated using an Ecopath with Ecosim (EwE) food web model of the North Sea. 2 scenarios are presented:

1) The biomass response to prohibition of industrial sandeel fisheries in the North Sea.
2) The biomass response to prohibition of industrial fisheries in the UK waters of the North Sea.

Prohibition in UK waters was calculated based on the average proportion of landings taken from the UKs EEZ between 2003 and 2020 (58%). 95% confidence intervals are given for scenario 2 based on upper (73%) and lower (38%) proportions of landings taken from the UKs EEZ between 2003 and 2020. Annex 2 provides upper and lower uncertainty bounds for these estimates based on model parameter uncertainty.

Table 3: Summary of the average risks and benefits of full prohibition of industrial sandeel fishing (based on 2020 landings) on the biomass of commercial stocks and functional groups in the North Sea (ICES Subarea 4).

Commercial stocks and biomass guilds	Biomass response to prohibition in the North Sea	Biomass response to prohibition in UK waters of North Sea	95 % Confidence intervals for biomass response to prohibition in UK waters of North Sea
Seabirds	+11%	+7%	(+4%, +8%)
Seals	+6%	+4%	(+2%, +5%)
Baleen whales	+1%	+2%	(+2%, +2%)
Toothed whales	0%	0%	(0%, 0%)
Whiting	+5%	+2%	(+1%, +3%)
Haddock	+5%	+3%	(+2%, +4%)
Cod	+2%	+1%	(0%, +1%)
Saithe	-3%	-2%	(-1%, -2%)
Demersal fish	+1%	+1%	(0%, +1%)

Commercial stocks and biomass guilds	Biomass response to prohibition in the North Sea	Biomass response to prohibition in UK waters of North Sea	95 % Confidence intervals for biomass response to prohibition in UK waters of North Sea
Pelagic fish	+1%	0%	(0%, +1%)
Benthos	0%	0%	(0%, 0%)
Zooplankton	-1%	-1%	(0%, -1%)

Simulations of cod biomass showed a limited response to the depletion of sandeels. As an opportunistic predator, cod was able to compensate for the reduction of sandeels by increasing the proportion of other prey (for example, Norway pout and herring) in its diet. Uncertainty analyses suggested cod could either increase or decrease by a small margin if sandeels were depleted. Increases were linked to the increased availability of other prey (such as herring) and reduced direct predation pressure from the declining seal population.

Slight decreases were linked to simulations where the availability of other prey did not increase. Simulations suggest that prohibiting sandeel fishing in UK waters would have little to no impact on the total biomass of cod (maximum increase of 2%)

Simulations of saithe biomass increased with the depletion of sandeels. This modelled increase was linked to the greater availability of herring, which increased following a reduction in the predation mortality exerted by the decreasing baleen whale population. Reducing the current level of sandeel exploitation was predicted to have limited impact on the biomass of saithe as sandeels constitute only a small proportion of their modelled consumption.

The simulated biomasses of haddock and whiting declined with the increased depletion of sandeels. Sandeels are core components of the diets of these commercial species: around a quarter of their dietary consumption within the model is made up of sandeels. As sandeels declined, the proportion of Norway Pout and sprat in the diets of whiting and haddock increased which compensated in part for the reduced availability of sandeels. Prohibiting sandeel fishing in UK waters led to small increases in the simulated biomass of whiting (2%) and haddock (3%).

Increasing sandeel depletion led to declines in the biomasses of marine mammals and seabirds. Sandeels constitute a large portion of diets of these groups. This can be shown in Figure 3, for example, sandeels make up 50% of the diet of baleen whales, 27% of the diet of toothed whales, 30% of the diet of Seals and 29% of the diet of seabirds: 29%. Diet preferences increased for other prey items, such as herring, Norway pout, and squid and cuttlefish, however shifting preferences were unable to counteract the negative impacts of sandeel depletion on group consumption and production. Prohibiting sandeel fishing in UK waters had limited impacts on the biomasses of toothed whales and baleen whales as their consumption in the model was compensated by increased consumption of other prey (such as whiting and mackerel). Prohibiting sandeel fishing in UK waters led to larger increases in the simulated biomass of seabirds (7%) and seals (4%).

As an amalgamated group, the biomass of demersal fish, which includes all demersal functional groups in the model (withholding sandeels), declined slightly with increasing sandeel depletion. This muted response reflects the amalgamation of multiple functional groups (such as rays, flatfish, gurnards, gadoids, and monkfish) with often conflicting responses to sandeel depletion. For example, rays and gurnards declined with increasing sandeel depletion due to reduced food availability, whereas plaice and several other flatfish groups increased following a reduction in predation mortality. Prohibiting sandeel fishing in UK waters led to only a 1% increase in the overall biomass of the demersal fish community.

The uncertainty ranges associated with pelagic fish (including mackerel, herring, horse mackerel, blue whiting, whiting, and Norway pout) simulations suggest that sandeel depletion could have either a negligible or positive impact on the overall biomass of the pelagic community. Like demersal fish, functional groups within the pelagic fish community showed conflicting responses to sandeel depletion. Most pelagic fish, including herring and sprat increased in response to reduced predation pressure from higher trophic predators such as baleen whales and whiting.

Mackerel was predicted to decline with sandeel depletion due to reduced food availability. Prohibiting sandeel fishing in UK waters led to only a maximum increase of 1% in the overall biomass of the pelagic fish community.

Benthos biomass simulations showed a negligible response to changes in sandeel depletion or the prohibition of sandeel fishing in UK waters. Zooplankton showed a negligible to increasing biomass trend when taking into consideration model uncertainty. Zooplankton projections were driven by changes in the pelagic fish community and varying top-down predation pressure.

Ensemble modelling

Overview

Numerical models are an attempt to simplify a complex system and to capture some key aspects of their function. They are not attempts to perfectly mirror a system and in any given model there will be parts of the system that are better represented than others. In addition, there are empirical studies that can be used as evidence to what is going on.

The ensemble model of Spence and others (2018) synthesises multiple sources of information, be that empirical studies or modelling studies, to give a single estimate of the true quantity of interest, with rigours quantification of uncertainty. It describes the aspects of the modelling that is missing, known as discrepancies.

In this report we used the ensemble model to look at 2 effects of sandeel fishing:

1. We investigated the effects on 9 commercial stocks, using ICES stock assessments and 4 multispecies models, including EwE.
2. We used EwE to quantify its predictions of the effects on birds and marine mammals using empirical evidence.

Methodology

4 multispecies models were used to examine the effect of fishing on the sandeel fishery: LeMans (Thorpe and others, 2015), mizer (Blanchard and others, 2014) and FishSUMs (Speirs and others, 2016), along with the ICES stock-assessments (ICES 2021a,b). Each of the models were simulated up until 2019 using historic fishing pressure and then projected with a fixed fishing pressure up until 2100. The fishing pressure of the other 8species was fixed to its value in 2019, whereas we varied the pressure on sandeels in the whole of the North Sea.

The EwE model described above was combined with the empirical study of Waggitt and others, 2020 to look at the effect of sandeel fishing pressure on seabirds and mammals. Historical fishing was simulated up until 2019 from which 2 scenarios were projected into the future: current fishing and no fishing in the whole of the North Sea.

Results and discussion

Figure 6: The distribution of the SSB of 9 species in the North Sea for various fishing mortality levels on sandeels. The solid black line is the median estimate, and the dashed lines show the 90% credible interval. The vertical red line shows the fishing pressure on sandeels in 2019.

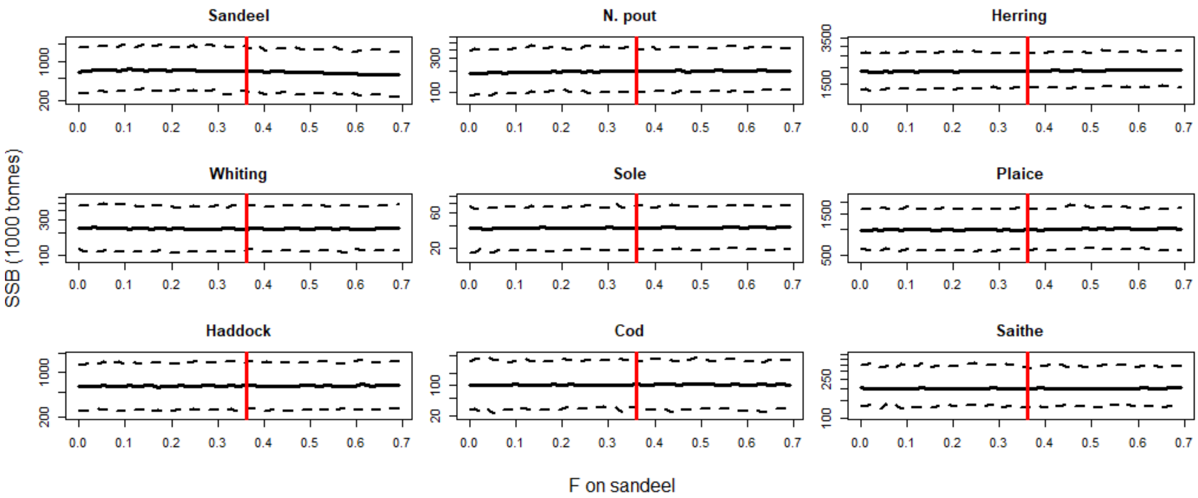

Figure 7 shows the distributions of spawning stock biomasses for 9 species of fish in the North Sea (sandeel, Norway pout, herring, whiting, sole, plaice, haddock, cod, and saithe) and how they are simulated to change under various levels of fishing mortality using the ensemble approach. Simulations show limited changes in the biomass of these species under various fishing mortality levels.

The 4 multispecies models combined with the single-species assessments show uncertainty regarding what will happen to the commercial stocks under altered sandeel fishing pressure. Figure 7 shows the median and 90% credible interval or the commercial stocks under various fishing mortality values. This could suggest that fishing doesn’t have a large effect on the biomass of sandeels, which could either be linked to the model’s capacity to simulate sandeel dynamics or it could be due to the overriding effect of recruitment variability on stock size.

In summary, simulations suggest that altered sandeels fishing pressure may have a limited impact on commercial stocks, such that, based on the ensemble, stocks may be equally likely to experience positive or negative effects.

EwE estimated a similar absolute marine mammal biomass to the empirical study of Waggitt and others, 2020, however EwE does not simulate the same dynamics as the empirical study. The ensemble model therefore attributes high uncertainty to marine mammal simulations, with increasing uncertainty further into the simulated period (Figure 8). Using the models presented in this study, additional work is needed to better understand the effects of sandeel fishing pressure on marine mammals.

Figure 7: The EwE (in red), empirical study (in blue) and ensemble model (in black) for marine mammals (top) and birds (bottom) under current fishing (2019) from 2020. The translucent blue and black parts are the 90% credible intervals for the empirical s and ensemble model.

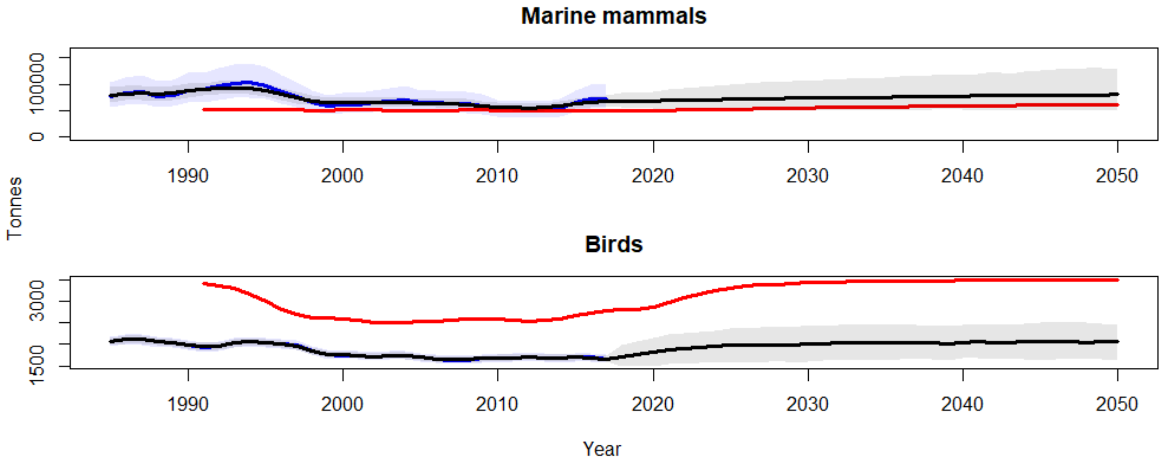

Figure 8 shows ensemble model simulations for mammals and seabirds in comparison to simulations from an empirical study and Ecopath with Ecosim (EwE). For marine mammals, the trends between the empirical study and EwE are dissimilar, leading to large uncertainty in the ensemble simulation.

For seabirds, both the EwE model and empirical study simulate similar trends for seabirds from 1990 to 2020 (decrease from 1990 to around 2000, followed by a period of stability and slight increase in recent years). The ensemble projection is attributed with less uncertainty and suggests that under the current fishing (2019) seabird biomass will increase over time.

EwE estimated a higher absolute seabird biomass than the empirical study, however both produced comparable relative trends (Figure 8). The discrepancy in the ensemble model is predictable and therefore the uncertainty in the ensemble model grows slowly and is constant by 2050. EwE recreates the dynamics of the empirical study and therefore the EwE seabird projections can be trusted with a higher degree of certainty.

Scenarios of current fishing and no fishing on sandeels both led to more seabirds than in 2020, with an increase of 12% with current fishing (90% credible interval -16% to +48%) and 20% with no fishing (90% credible interval -10% to +63%). It is more likely that no fishing will lead to a larger increase in seabirds than under current fishing, but the biomass of seabirds will have increased in both scenarios, reaching the new biomass within 10 to 15 years.

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 importance of sandeels, which is an important consideration in food web dynamics and how we choose to manage food web impacts (informing how we deliver D4 under the Marine Strategy Regulations).

Caveat 1

The model simulates the depletion of sandeels in isolation. It does not simulate an increase in fishing effort. This means that indirect impacts or benefits which would likely change with sandeel exploitation (such as bycatch and habitat impacts) are not included in the impact analyses.

Caveat 2

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.
2. forage fish and predators compete at different life stages (such as juvenile predator and adult forage fish).

The use of a model ensemble (with different structures) accounts for size-structured interactions.

Caveat 3

The models used in this study do not account for the spatial distribution of sandeels. 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 fishing 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 sandeel biomass on predator condition and reproduction.

Caveat 4

Models simulate into the future based on current environmental conditions and an understanding of past ecosystem dynamics. Simulations presented here do not consider how environmental variation may impact the expected benefits of reduced fishing mortality, however recent ensemble modelling work produced by Natural England accounted for climate uncertainty (IPCC best and worst-case scenarios) when simulating alternate sandeel fishing strategies.

While simulations suggest that sandeels may decline under climate change scenarios, removing fishing pressure increased stock resilience and dampened the rate at which sandeel biomass declined under unfavourable temperatures.

Risks of displacement

Displacement into EU waters of the North Sea

Any spatial measure for the management of sandeel has the potential to cause displacement of fishing effort into areas outside of the spatial management measure area. A prohibition of sandeel fishing in UK waters is likely to lead to the displacement of effort into other areas of the North Sea outside of the UK EEZ as fisheries seek to maintain landings.

It is difficult to make a detailed prediction of displacement effects as the choice of where to fish is subject to multiple influences. Management, regulation, and availability of quota are primary factors influencing these effects. In the case of the industrial sandeel fishery, 3 sandeel stock management units overlap with the UK EEZ; Sandeel Area 4 which lies 100% within the UK EEZ, Sandeel Area 3r which overlaps with the Norwegian EEZ, and Sandeel Area 1r which overlaps with EU waters.

With access to opportunities in the Norwegian sector limited, it would be anticipated that Danish sandeel fishing effort would increase on suitable habitats in the EU waters of SA1r of the North Sea following any closure of the fishery in UK waters as vessels seek to compensate for any reduction in landings from UK waters.

- as 100% of Sandeel Area 4 is within the UK EEZ, a closure of the fishery within UK waters would prevent all landings from this stock management unit Effort would be displaced into other sandeel areas (provided there was unused quota) or onto alternative species (see below)

- Sandeel Area 3r overlaps with the Norwegian EEZ, where a majority of the fishery occurs. A closure of the fishery within the UK component of this area would not be anticipated to result in any significant displacement of fishing effort either into other areas within the management area, into other management areas, or onto other species
- Sandeel Area 1r is shared with the EU. An estimated 84% of landings within this stock management unit are estimated to come from within the UK EEZ (STECF data, 2014 to 2019) and the western edge of Dogger Bank is one of the most important grounds for the Danish sandeel fleet. A closure of the fishery covering UK waters would be expected to displace significant effort into the EU portion of this management unit, particularly onto banks already known to deliver high catch per unit effort (CPUE) such as the EU portion of Dogger Bank. Effort may also increase on other currently unfished or lightly fished locations as the fleet seeks to maintain landings from this stock management unit

Experience with partial stock closures where effort is simply displaced into open areas suggest that the anticipated benefits to stocks and predators may not materialise. Whilst the northeast UK closed area covers habitat which accounted for approximately 50% of the catch for Sandeel Area 4, the stock assessment and reference points are based on the entire stock including those sandeels distributed in the closed areas. As a result, the advised Total Allowable Catch (TAC) is disproportionately large relative to the available area open to the fishery.

ICES (2021) warn that taking the full catch from the banks in the open areas may therefore increase the risk of local depletion because, whilst there is exchange of sandeels between the closed and open banks in Sandeel Area 4, restocking distant depleted banks in the open area sourced exclusively from the closed area may take years (ICES, 2021).

Jensen and others (2011) found evidence of spatial differences in mortality at the scale of grounds more than 28km apart. The risk of localised depletion is increased when effort is displaced from large sandbanks with a high sandeel abundance and CPUE to smaller sandbanks with lower abundance.

Whilst sandeel are largely sedentary and remain associated with specific individual sandbanks, their larvae are capable of dispersing more widely as they are transported by currents for up to 10 weeks: larval mixing among grounds less than 67km apart has been suggested to be common, whereas the probability of mixing is very low among grounds more than 200km apart (Wright and others, 2019).

Localised depletion on banks where the fishery remains open has the potential to disrupt larval dispersal to connected sandbanks and could affect the local abundance and availability of sandeels in habitats within any closed area (potentially more of an issue for SA1 as opposed to SA4).

Therefore, closures at the sub-stock level would be best considered if implemented alongside proportionate reductions in TAC.

Displacement into other ICES management areas

Displacement into other Sandeel Areas will be dependent upon the availability of TAC for other units. Sandeel areas are managed independently and not adjusted to compensate for closures in other areas. Therefore, the potential for displacement into other areas is limited.

Displacement onto other species

In addition to displacement of effort to other sandeel banks there is also the potential for the displacement effort onto other forage fish stocks and or other ecoregions within UK or EU waters. Several fish species have been identified as other current or potential targets for industrial fisheries. These species include Norway pout, blue whiting, European sprat, Atlantic herring, horse mackerel, boarfish, sardine, and greater silver smelt.

In some cases, these stocks may have ecological traits which make them particularly susceptible to exploitation, such as boarfish which live to approximately 30 years of age (White and others, 2010; Hüssy and others, 2012). Other stocks of forage fish may not have well-established management areas, and no associated TAC (such as sprat in the Celtic Sea and West of Scotland). Those species with an established TAC may see increased uptake of the quota to compensate for losses induced by prohibition of sandeel activity in UK waters.

Additionally, whilst the food webs of the North Sea are amongst the best studied in the world, much less is known about the role of forage fish in the wider Celtic Seas ecoregion (ICES 2021). Therefore, mitigation of potential displacement, would best be considered as part of any spatial measures for sandeel. Such an approach would need to include areas outside the North Sea, and other forage fish species.

An ecosystem-based approach to the management of forage fish would be better able to prevent or mitigate the unintended consequences of managing stocks without accounting for links to other species and environmental variation.

We are currently witnessing progress towards an operational ecosystem approach through ICES, UK policy, and foreign policy (see Annex 1), however, regulatory barriers and inertia within fisheries management continues to limit and undermine meaningful progress and requisite international collaboration (Patrick and Link, 2015; Prellezo and others, 2015; Bastardie and others, 2021).

Summary of ecosystem risks

Table 4: Ecosystem risks associated with the displacement of fishing activity following a full prohibition of industrial Sandeel fishing in the UK waters of the North Sea.

Impact type	Risk number	Impact	Summary of ecosystem impact
Risk	R2	Effort displaced onto other industrial species and data limited stocks	Displacement may lead to the increased harvest and quota fulfilment of other stocks of forage fish which may not have well-established assessment methods, management areas, and no associated TAC.
Risk	R3	Effort concentrated in smaller area	Increased risk of localised depletion and reduced availability of sandeels in areas where effort in concentrated.
Risk	R4	Effort displaced to previously unfished areas	Effort may increase in currently unfished and lightly fished locations as the fleet seeks to maintain landings from this stock management unit. This may lead to new localised negative ecosystem impacts.

Impact type	Risk number	Impact	Summary of ecosystem impact
Risk	R5	Negative impacts to larval dispersal into closed area	Displacement to adjacent areas (less than 200km away) and localised depletion therein could reduce larval dispersal into closed areas.

Influence of environmental variation and risk to realising potential benefits

Due to the importance of sandeels as one of the main links between primary producers and higher trophic levels in the North Sea, recruitment to these stocks is well-studied (Arnott and Ruxton, 2002; van Deurs and others, 2009; Eigaard and others, 2014; Lindegren and others, 2018; Henriksen and others, 2018).

In the southwestern part of the North Sea (which corresponds to sandeel management area 1r), sandeel shows signs of being influenced negatively by temperature, with the change in abundance of age 1 sandeels being significantly related to bottom temperature at the beginning of the overwintering period (Henriksen and others, 2021a).

Higher bottom temperatures lead to significant declines in the abundance of age-1 sandeel as warming of bottom waters may trigger the emergence of sandeels from their winter dormancy (Henriksen and others, 2021b).

There is limited evidence of direct physiological effects on temperature rises on sandeels (Buckley and others, 1984; Pitois and others, 2012). Instead, in years with high spring temperatures, sandeels emerge to feed earlier which means their periods of dormancy are shorter and their active periods are prolonged. This increases the risk of predation mortality (MacDonald and others, 2018) and impacts feeding opportunities and energy reserves (MacDonald and others, 2019).

The abundance of sandeels main prey, calanoid copepods (*Calanus finmarchicus* and *Calanus helgolandicus*), influences sandeel survivability and growth rates (Arnott and Ruxton, 2002; Lindegren and others, 2018).

Temperature variation can disrupt this important link by influencing the development timing of sandeels and copepods which can lead to a high degree of mismatch in the synchrony of sandeel hatch dates and the availability of copepod prey (Régnier and others, 2019). Changes in the timing of sandeel emergence could have ecosystem wide consequences affecting plankton communities and predators. This negative trend is seen more strongly in the southern North Sea as average temperatures are greater. Ocean warming in the coming decade may therefore threaten the viability of sandeel populations in the North Sea and particularly in the southern North Sea.

A full prohibition of sandeel fishing from UK waters has the potential to benefit dependent predators and ecosystem resilience, however the strong influence of environmental variability could negate or dampen any expected benefits. For example, following fears that industrial fishing may have been impacting top predators, a precautionary approach was adopted and in 2000 the sandeel fishery off southeast Scotland was closed.

While sandeel biomass initially rebounded following the implementation of the closed area, sandeel biomass subsequently declined following a period of poor environmental conditions (Greenstreet and others, 2010).

Numbers of guillemots, razorbills, puffins, and kittiwakes all appeared to increase with closure of the fishery, but then subsequently dropped as local sandeel abundance declined. Since this study, sandeel numbers in the area have fluctuated, with large increases and decreases in sandeel biomass linked to variability in recruitment.

Modelling results from a previous study suggest that, while fishing has been responsible for sandeel declines and historic low abundances, a complete recovery of the sandeels to the highly productive levels of the early 1980s might only be possible through changes in the surrounding ecosystem, involving lower temperatures and improved feeding conditions (Lindegren and others, 2018).

Even with a full prohibition of sandeel fishing in UK waters, sandeel biomass and recruitment will fluctuate, meaning sandeels are unlikely to be sustained at levels where they alone are sufficient to support the dietary needs and reproductive performance of predators.

However, such a management measure would likely reduce the cumulative impacts of fishing and environmental variation on sandeel biomass and ensure that industrial fishing is not directly responsible for sandeel or predator population collapses.

Summary of ecosystem risks

Ecosystem pressures external to those inflicted by industrial fisheries could prevent the realisation of all the benefits that might be expected to occur following the prohibition of sandeel fishing in the UK waters of the North Sea. While not all benefits may be realised, it is expected that prohibiting fishing will dampen any negative impacts by removing an additional source of mortality. Key risks are presented in Table 5.

Table 5: Environmental variation, climate change, and the risk it poses to realising potential ecosystem benefits following a full prohibition of industrial Sandeel fishing in the UK waters of the North Sea.

Impact type	Risk number	Impact	Summary of ecosystem impact
Risk	R6	Negative impacts of environmental variation on sandeel abundance	Changes in abundance of age-1 sandeel are significantly linked to increasing bottom temperature at the beginning of the overwintering period (impacting emergence from winter dormancy). Sandeel recruitment is influenced by the availability of prey (calanoid copepods). Changes in temperature are increasing the probability of phenological mismatch between predator and prey. This is expected to lead to a decline in sandeel recruitment. Sandeel populations in the southern North Sea may be particularly at risk due to greater average temperatures.

Ecosystem approach

The ecosystem approach, as defined in the UK Fisheries Act:

(a) ensures that the collective pressure of human activities is kept within levels compatible with the achievement of good environmental status, (b) does not compromise the capacity of marine ecosystems to respond to human-induced changes.

(b) To progress towards an ecosystem approach for fisheries there are additional measures which should be considered alongside the proposed management action of a full prohibition of sandeel fishing from UK waters.

These additional measures may help to reduce risks and increase the likelihood of realising ecosystem benefits.

Biomass and fishing reference points

Better accounting for annual fluxes in productivity (for example, driven by environment) and predator needs when setting reference points, TAC, and quota provides a step towards an ecosystem approach that may be readily applied in the short-term. Recent advances have seen the use of ecosystem-based reference points within the traditional single-species stock assessment and management frameworks across the North Atlantic (Bentley and others, 2021; Chagaris and others, 2020; Howell and others, 2021).

ICES are beginning to identify stocks which may benefit from the estimation of ecosystem-based reference points (F_{eco}). Ecosystem reference points provide an appropriate and meaningful step towards an ecosystem approach for internationally shared forage fish stocks and should be considered as the UK further develops forage fish management strategies.

TAC accounting for partial closures

If advice on catch levels within sandeel management areas fail to take account of zones that are closed by law to sandeel fishing, fishing effort may be consequently concentrated into a smaller area which could encourage vessels to ‘fish the line’ and lead to overfishing and localised depletion of sandeels. This has been the case for the advised TAC in sandeel management area 4 (SA 4), where advisory catch limits have been routinely set based on the entire stock, including the proportion within the closed area off east Scotland and Northeast England. ICES are aware of this issue but takes no account of areas closures when advising on TACs.

In the past, ICES have caveated their advice for sandeels in SA 4 by acknowledging the closed area and advising that full TAC is not taken as it could increase the risk of local depletion (ICES 2017 and 2018), however it would be preferable if appropriate adjustments were made when setting catch limits so that the existence of closed areas are explicitly considered in the advice.

Failing to adjust TAC means there may be little overall impact on removals from the stock if effort simply shifts. This may reduce the ecosystem benefits and potentially cause additional problems if the abundance in the remaining open area falls below levels critical for successful predator foraging.

TAC adjustments considering ecosystem information

Setting TAC below headline advice could help to support ecosystem resilience and progress towards an ecosystem approach and Good Environmental Status (GES). Decisions should reflect trade-offs between fisheries and biodiversity objectives, and whether a given TAC may increase or decrease the likelihood of achieving marine policy objectives. Such considerations may be particularly important for forage fish due to their keystone role in the ecosystem.

The European Commission recently proposed a TAC below headline ICES' advice for Baltic Sea sprat (20% reduction), Gulf of Bothnia herring (28%), and Riga Herring (4%) due to their poor status and recognition of their ecosystem role as prey for higher trophic level predators.

Data collection and scientific surveys

Traditionally, most information regarding the abundance of sandeels has originated from scientific monitoring of the fishery itself (Wright, 1996; Furness, 2002). Full prohibition of sandeel fisheries from UK waters of the North Sea will disrupt the source of such data making monitoring the effectiveness of the closure difficult.

If a full prohibition of sandeel fishing is implemented in UK waters of the North Sea then a viable alternative will be needed to monitor sandeels, likely beyond the scope of monitoring for commercial fisheries to capture the links between sandeels and food web dynamics and identify progress towards GES. Future monitoring efforts focussed on ecosystem resilience should seek to use non-invasive sampling methods (for example, acoustic surveys).

Overview of risk of impact

Risks which have been highlighted throughout this evidence report have been summarised below in 3 sections. Each section identifies a different risk theme:

1) Risks associated with extraneous factors.
2) Risks associated with the full prohibition of sandeel fishing in UK waters of the North Sea.
3) Risks associated with evidence uncertainty.

Risks have not been ranked as comparability across themes is limited in terms of knowledge of severity and capacity to mitigate.

Qualitative scores have been assigned for the following risk components:

- confidence: Scores rank from 1 to 4 (with 1 being the lowest confidence and 4 being the highest) with the following rationale: 1) expert opinion through communication, 2) expert opinion from published work, 3) observed experimentally, and 4) observed in nature
- likelihood of risk and severity: scores scale from 1 to 5 with the following rationale: 1) highly unlikely, 2) unlikely, 3) possible, 4) likely, and 5) highly likely. Severity is also included in the description as either not harmful, slightly harmful, harmful, or extremely harmful
- spatial scale of the risk is characterised as either 1) local, 2) sandeel management area, or 3) regional

Risks associated with the full prohibition of sandeel fishing in UK waters of the North Sea

Risk 1: Effort displaced onto other industrial species and data limited stocks

Confidence

Type: 1 (expert opinion through communication)

Full prohibition may force complete uptake for other industrial species or displace effort onto data limited species. Examples were communicated where fishers targeting sandeels in the North Sea shifted their focus to sprat in the English Channel (a data limited stock) following action upon ICESs advice of 0 TAC for sandeel in certain sandeel management areas for 2022.

Likelihood of risk and severity

Type: 3 (possible)

It is possible that, in response to reduced harvest opportunities for sandeels, vessels shift focus to other species which may be data poor.

Severity: This risk has the potential to be harmful if data limited stocks are overexploited.

Spatial scale

Type: 1 to 3 (impact at either local, sandeel management area, or regional scale)

The spatial scale of this risk would be influenced by:

1) the capacity of vessels to diversify and move to alternate fishing grounds.

2) the distribution of the target species.

Risk 2: Sandeel fishing effort concentrated in smaller area

Confidence

Type: 4 (observed in nature)

Following the establishment of a closed area in sandeel management area 4 in 2000, fishing for sandeels was displaced to the area outside of the closure however TAC was not adjusted to reflect the proportion of the stock protected by the closed area. There may be little overall impact on removals from the stock if effort simply shifts. This may reduce the ecosystem benefits and lead to issues if the abundance in the remaining open area falls below levels critical for successful predator foraging

Likelihood of risk and severity

Type: 4 (likely)

It is likely that sandeel fishing effort will be displaced into EU waters of the sandeel management areas. If TAC is not revised to account for areas closures (as we have witnessed previously) then overall removals may remain the same and the impact merely shifts.

Severity: This risk has the potential to be harmful for sandeel populations and dependent predators if concentrated effort leads to localised depletion.

Spatial scale

Type: 1 to 2 (impact at either local, or sandeel management area scale)

Sandeel fishing effort may be concentrated at the edge of the closed area as has been observed with the Dogger Bank closure, with impacts residing within sandeel management areas. Sandeel areas are managed independently and not adjusted to compensate for closures in other areas. Therefore, the potential for displacement into other areas is limited.

Risk 3: Effort displaced to previously unfished areas

Confidence

Type: 1 (expert opinion through communication)

Effort may increase in other currently unfished and lightly fished locations as the fleet seeks to maintain landings.

Likelihood of risk and severity

Type: 2 to 3 (unlikely to possible)

It is possible that, in response to reduced harvest opportunities for sandeels, vessels move to areas which are currently unfished, however this assumes (for the sandeel fishery) that areas exist that are unfished, which is unlikely.

Severity: This risk has the potential to be extremely harmful if previously undisturbed habitats are subjected to the impacts of fishing effort (such as habitat degradation).

Spatial scale

Type: 1 to 3 (impact at either local, sandeel management area, or regional scale)

A closure of the fishery covering UK waters would be expected to displace significant effort into the EU portion of said management unit, however vessels may move to other ICES areas and species to maintain landings.

Risk 4: Impacts to larval dispersal into closed area

Confidence

Type: 4 (observed in nature)

Larval mixing among grounds less than 67km apart has been suggested to be common, whereas the probability of mixing is very low among grounds more than 200km apart.

Likelihood of risk and severity

Type: 3 (possible)

It is possible that any transport of larvae arriving from EU waters will see numbers decline if stock levels in the EU were depressed through fishing. There is also the possibility that the area outside of the UK EEZ may benefit if larval transport from the closed area increased.

Severity: This risk has the potential to be slightly harmful if the dispersal of larvae into closed areas is reduced, however there is substantial evidence to suggest that sandeel mixing is limited and is primarily driven by oceanographic processes.

Spatial scale

Type: 2 (Sandeel management area scale)

SA4 is within the UK EEZ therefore impacts to larval dispersal from localised depletion is unlikely. The SA1 population is distributed within and outside the UK EEZ and may therefore be at greater risk if the stock is depleted in adjacent waters.

Risks associated with extraneous factors

Risk 5: Risk to realising benefits. Negative impacts of environmental variation on sandeel abundance

Confidence

Type: 4 (observed in nature)

Data collected from the closed area off Scotland's east coast suggests that closing offshore areas may not be sufficient to guarantee the long-term prospects of predators. Even with fishery closures, sandeels and seabird numbers declined following a period of poor environmental conditions and the absence of sustained recruitment. Environmental variation has been linked to emergence from winter dormancy, increasing predation mortality and the synchrony of sandeel development and food availability.

Likelihood of risk and severity

Type: 5 (highly likely)

Environmental variation is a fundamental driver of sandeel recruitment, with conditions likely to worsen under climate change. Future variation (for example, increased bottom temperature) is highly likely to lead to declines in sandeel biomass with subsequent negative impacts for dependent predators (such as kittiwakes). Food availability is very likely to impact the future production of sandeels.

Severity: This risk has the potential to be extremely harmful if sandeel populations are unable to adapt to changing environmental conditions.

Spatial scale

Type: 3 (regional scale)

Environmental variation is diffuse and will impact sandeel populations across the North Sea. Populations in the southern North Sea may be more susceptible to negative impacts due to the greater temperature rises in this area.

Risks associated with evidence uncertainty

Risk 6: Sandeel reducing available prey for other commercial species

Confidence

Type: 1 (expert opinion through communication)

Increased forage fish may not necessarily lead to benefits for piscivorous fish if early life stages of predator fish compete with forage fish for limited zooplankton resources. This link has been identified between cod and herring but, to the best of our knowledge, not between sandeels and other commercially important fish.

Likelihood of risk and severity

Type: 3 (possible)

It is possible that sandeels could compete with other commercial species for limited prey resources, however more work is needed to fully understand the ecosystem role of sandeels.

Severity: it is possible that, if sandeels do compete with early stages of their predators for limited zooplankton resources, it could be slightly harmful, for example negative relationships have been found between Atlantic herring and young cod. A similar link has yet to be identified between sandeel and their predators.

Spatial scale

Type: 1 (local scale)

We would expect impacts to occur at a local scale due to the spatial extent of sandeels and observed relationship between sandeel abundance and commercial fish condition which appears to be restricted to a local scale.

Risk 7: Modelling caveats introduce uncertainty into simulations of reduced sandeel fishing

Confidence

Type: 4 (observed in nature)

The ecosystem models used in this evidence report are associated with data uncertainty and several caveats that may lead to the over- or underestimation of ecosystem benefits and risks.

Likelihood of risk and severity

Type: 5 (highly likely)

It is highly likely that model simulations fail to capture many of the nuances associated with the full prohibition of sandeel fishing from UK waters.

Severity: this risk is not harmful, but it is important to acknowledge that models are not infallible, and that any management action should follow a precautionary approach and establish a monitoring programme to assess the impact of said management action.

Spatial scale

Type: 1 to 3 (impact at either local, sandeel management area, or regional scale)

The models used in this report cover the extent of the North Sea (ICES area IV) and thus provide a generalised estimation of ecosystem risks and benefits. From field studies, many of the changes observed in predator production following changes in sandeel biomass have been observed at a local level. The models are therefore restricted in their capacity to capture impacts at a local or sandeel management area level.

References

- Arnott, S.A. and Ruxton, G.D., 2002. Sandeel recruitment in the North Sea: demographic, climatic and trophic effects. Marine Ecology Progress Series, 238, pages 199 to 210.
- Bentley, J.W., Lundy, M.G., Howell, D., Beggs, S.E., Bundy, A., De Castro, F., Fox, C.J., Heymans, J.J., Lynam, C.P., Pedreschi, D. and Schuchert, P., Serpetti, N., Woodlock, J., Reid, D.G. 2021. Refining fisheries advice with stock-specific ecosystem information. Frontiers in Marine Science, 8, p.602072. doi: 10.3389/fmars.2021.602072
- Blanchard, J.L., Andersen, K.H., Scott, F., Hintzen, N.T., Piet, G. and Jennings, S., 2014. Evaluating targets and trade-offs among fisheries and conservation objectives using a multispecies size spectrum model. Journal of Applied Ecology, 51(3), pages 612 to 622.
- Boulcott, P. and Wright, P.J., 2011. Variation in fecundity in the lesser sandeel: implications for regional management. Journal of the Marine Biological Association of the United Kingdom, 91(6), pages 1273 to 1280.
- Buckley, L.J., Turner, S.I., Halavik, T.A., Smigielski, A.S., Drew, S.M. and Laurence, G.C., 1984. Effects of temperature and food availability on growth, survival, and RNA-DNA ratio of larval sand lance(Ammodytes americanus). Marine ecology progress series. Oldendorf, 15(1), pages 91 to 97.
- Campanella, F. and van der Kooij, J. (2021). Spawning and nursery grounds of forage fish in Welsh and surroundings waters. Cefas Project Report for RSPB, 65 page
- Carroll, M.J., Bolton, M., Owen, E., Anderson, G.Q., Mackley, E.K., Dunn, E.K. and Furness, R.W., 2017. Kittiwake breeding success in the southern North Sea correlates with prior sandeel fishing mortality. Aquatic Conservation: Marine and Freshwater Ecosystems, 27(6), pages 1164 to 1175.
- Chagaris, D., Drew, K., Schueller, A., Cieri, M., Brito, J. and Buchheister, A., 2020. Ecological reference points for Atlantic menhaden established using an ecosystem model of intermediate complexity. Frontiers in Marine Science, 7, p.606417.
- Christensen, V. and Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecological modelling, 172(2-4), pages 109 to 139.
- Cook, A.S., Dadam, D., Mitchell, I., Ross-Smith, V.H. and Robinson, R.A., 2014. Indicators of seabird reproductive performance demonstrate the impact of commercial fisheries on seabird populations in the North Sea. Ecological indicators, 38, pages 1 to 11.
- Daunt, F., Wanless, S., Greenstreet, S.P., Jensen, H., Hamer, K.C. and 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(3), pages 362 to 381.
- Dickey-Collas, M., Engelhard, G.H., Rindorf, A., Raab, K., Smout, S., Aarts, G., van Deurs, M., Brunel, T., Hoff, A., Lauerburg, R.A. and Garthe, S., 2014. Ecosystem-based management objectives for the North Sea: riding the forage fish rollercoaster. ICES Journal of Marine Science, 71(1), pages 128 to 142.

- Dunn, E. 2021. Revive our Seas: The case for stronger regulation of sandeel fisheries in UK waters. RSPB
- Eddy, T.D., Coll, M., Fulton, E.A. and Lotze, H.K., 2015. Trade-offs between invertebrate fisheries catches and ecosystem impacts in coastal New Zealand. ICES Journal of Marine Science, 72
- Eigaard, O.R., van Deurs, M., Behrens, J.W., Bekkevold, D., Brander, K., Plambech, M., Plet-Hansen, K.S. and Mosegaard, H., 2014. Prey or predator—expanding the food web role of sandeel Ammodytes marinus. Marine Ecology Progress Series, 516, page 267-273. (5), pages 1380 to 1388.
- Engelhard, G.H., Blanchard, J.L., Pinnegar, J.K., van der Kooij, J., Bell, E.D., Mackinson, S. and Righton, D.A., 2013. Body condition of predatory fishes linked to the availability of sandeels. Marine biology, 160(2), pages 299 to 308.
- Engelhard, G.H., Peck, M.A., Rindorf, A., C. Smout, S., van Deurs, M., Raab, K., Andersen, K.H., Garthe, S., Lauerburg, R.A., Scott, F. and Brunel, T., 2014. Forage fish, their fisheries, and their predators: who drives whom?. ICES Journal of Marine Science, 71(1), pages 90 to 104.
- Fisheries Act 2020. Available at: https://www.legislation.gov.uk/ukpga/2020/22/contents/enacted (Accessed: 23 October 2022).
- Frederiksen, M., Wright, P.J., Harris, M.P., Mavor, R.A., Heubeck, M. and Wanless, S., 2005. Regional patterns of kittiwake Rissa tridactyla breeding success are related to variability in sandeel recruitment. Marine Ecology Progress Series, 300, pages 201 to 211.
- Frederiksen, M. and Wanless, S. 2006. Assessment of the effects of the Firth of Forth sand eel fishery closure on breeding seabirds. PROTECT Work Package 5/Case Study 2.
- Frederiksen, M., Jensen, H., Daunt, F., Mavor, R.A. and Wanless, S., 2008. Differential effects of a local industrial sand lance fishery on seabird breeding performance. Ecological Applications, 18(3), pages 701 to 710.
- Frederiksen, M., Wanless, S., Harris, M.P., Rothery, P. and Wilson, L.J., 2004. The role of industrial fisheries and oceanographic change in the decline of North Sea black-legged kittiwakes. Journal of Applied Ecology, 41(6), pages 1129 to 1139.
- Furness, R.W., 2007. Responses of seabirds to depletion of food fish stocks. Journal of Ornithology, 148(2), pages 247 to 252.
- Furness, R.W., MacArthur, D., Trinder, M. and MacArthur K. 2013. Evidence review to support the identification of potential conservation measures for selected species of seabirds. MacArthur Green, Glasgow.
- Greenstreet, S., Fraser, H., Amrstrong, E., Gibb, I. 2010. Monitoring the Consequences of the Northwestern North Sea Sandeel Fishery Closure. Scottish Marine and Freshwater Science Vol 1 No 6. Edinburgh: Scottish Government, page 31.
- Greenstreet, S.P., Armstrong, E., Mosegaard, H., Jensen, H., Gibb, I.M., Fraser, H.M., Scott, B.E., Holland, G.J. and Sharples, J., 2006. Variation in the abundance of sandeels Ammodytes marinus off southeast Scotland: an

evaluation of area-closure fisheries management and stock abundance assessment methods. ICES Journal of Marine Science, 63(8), pages 1530 to 1550.

- Hammond, P.S., Hall, A.J. and Prime, J.H., 1994. The diet of grey seals around Orkney and other island and mainland sites in north-eastern Scotland. Journal of Applied Ecology, pages 340 to 350.
- Wilson, L.J. and Hammond, P.S., 2016. Harbour seal diet composition and diversity. Marine Scotland Science.
- Henriksen, O., Rindorf, A., Brooks, M.E., Lindegren, M. and van Deurs, M., 2021a. Temperature and body size affect recruitment and survival of sandeel across the North Sea. ICES Journal of Marine
- Henriksen, O., Christensen, A., Jónasdóttir, S., MacKenzie, B.R., Nielsen, K.E., Mosegård, H. and van Deurs, M., 2018. Oceanographic flow regime and fish recruitment: reversed circulation in the North Sea coincides with unusually strong sandeel recruitment. Marine Ecology Progress Series, 607, pages 187 to 205.
- Henriksen, O., Rindorf, A., Mosegaard, H., Payne, M.R. and van Deurs, M., 2021b. Get up early: Revealing behavioral responses of sandeel to ocean warming using commercial catch data. Ecology and Evolution, 11(23), page 16786-16805. Science, 78(4), pages 1409 to 1420.
- Howell, D., Schueller, A.M., Bentley, J.W., Buchheister, A., Chagaris, D., Cieri, M., Drew, K., Lundy, M.G., Pedreschi, D., Reid, D.G. and Townsend, H., 2021. Combining ecosystem and single-species modeling to provide ecosystem-based fisheries management advice within current management systems. Frontiers in Marine Science, 7, p.607831.
- ICES, 2010. Report of the Benchmark Workshop on Sandeel (WKSAN), 6–10 September 2010, Copenhagen, Denmark. ICES CM 2010/ACOM:57. 1 page
- ICES, 2013. Interim Report of the Working Group on Multispecies Assessment Methods (WGSAM): 21-25 October 2013, Stockholm, Sweden.
- ICES. 2017. Sandeel (Ammodytes spage) in divisions 4.a–b, Sandeel Area 4 (northern and central North Sea). In Report of the ICES Advisory Committee, 2017. ICES Advice 2017, san.sa.4,
- ICES. 2018. Sandeel (Ammodytes spage) in divisions 4.a–b, Sandeel Area 4 (northern and central North Sea). In Report of the ICES Advisory Committee, 2018. ICES Advice 2018, san.sa.4,
- ICES. 2022. Sandeel (Ammodytes spage) in divisions 4.b and 4.c, Sandeel Area 1r (central and southern North Sea, Dogger Bank). In Report of the ICES Advisory Committee, 2022. ICES Advice 2022, san.sa.1r, https://doi.org/10.17895/ices.advice.10000.
- Jensen, H. and others, 2011. Inferring the location and scale of mixing between habitat areas of lesser sandeel through information from the fishery ICES Journal of Marine Science, Volume 68, Issue 1, January 2011, pages 43 to 51,
- Kennedy, M.C. and O'Hagan, A., 2001. Bayesian calibration of computer models. Journal of the Royal Statistical Society: Series B (Statistical Methodology), 63(3), pages 425 to 464.

- Lauerburg, R.A.M., Temming, A., Pinnegar, J.K., Kotterba, P., Sell, A.F., Kempf, A. and Floeter, J., 2018. Forage fish control population dynamics of North Sea whiting Merlangius merlangus. Marine Ecology Progress Series, 594, pages 213 to 230.
- Lindegren, M., Van Deurs, M., MacKenzie, B.R., Worsoe Clausen, L., Christensen, A. and Rindorf, A., 2018. Productivity and recovery of forage fish under climate change and fishing: North Sea sandeel as a case study. Fisheries Oceanography, 27(3), pages 212 to 221.
- MacDonald, A., Speirs, D.C., Greenstreet, S.P. and Heath, M.R., 2018. Exploring the influence of food and temperature on North Sea Sandeels using a new dynamic energy budget model. Frontiers in Marine Science, 5, page 339.
- MacDonald, A., Speirs, D.C., Greenstreet, S.P., Boulcott, P. and Heath, M.R., 2019. Trends in sandeel growth and abundance off the east coast of Scotland. Frontiers in Marine Science, 6, page 201.
- Mackinson, S., 2007. Multi-species fisheries management: a comprehensive impact assessment of the sandeel fishery along the English east coast. Cefas report for Defra, Defra, London.
- Mackinson, S. and Daskalov, G., 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterisation. Sci. Ser. Tech Rep., Cefas Lowestoft, 142: 196 page
- MacLeod, C.D., Santos, M.B., Reid, R.J., Scott, B.E. and Pierce, G.J., 2007. Linking sandeel consumption and the likelihood of starvation in harbour porpoises in the Scottish North Sea: could climate change mean more starving porpoises?. Biology letters, 3(2), pages 185 to 188.
- Mahfouz, C., Meziane, T., Henry, F., Abi-Ghanem, C., Spitz, J., Jauniaux, T., Bouveroux, T., Khalaf, G. and Amara, R., 2017. Multi-approach analysis to assess diet of harbour porpoises Phocoena phocoena in the southern North Sea. Marine Ecology Progress Series, 563, pages 249 to 259.
- McGregor, R., Trinder, M. and Goodship, N. 2022. Assessment of compensatory measures for impacts of offshore windfarms on seabirds. A report for Natural England. Natural England Commissioned Reports. Report number NECR431.
- Miles, W.T., Mavor, R., Riddiford, N.J., Harvey, P.V., Riddington, R., Shaw, D.N., Parnaby, D. and Reid, J.M., 2015. Decline in an Atlantic puffin population: evaluation of magnitude and mechanisms. PLoS One, 10(7), p.e0131527.
- Minto, C. and Worm, B., 2012. Interactions between small pelagic fish and young cod across the North Atlantic. Ecology, 93(10), page 2139-2154.
- Mitchell, P.I., Newton, S.F., Ratcliffe, N. and Dunn, T.E., 2004. Seabird populations of Britain and Ireland. T. and AD Poyser, London.
- Phillips, R.A., Caldow, R.W.G. and Furness, R.W., 1996. The influence of food availability on the breeding effort and reproductive success of Arctic Skuas Stercorarius parasiticus. Ibis, 138(3), pages 410 to 419.
- Pinnegar, J.K., Trenkel, V.M., Tidd, A.N., Dawson, W.A. and Du Buit, M.H., 2003. Does diet in Celtic Sea fishes reflect prey availability?. Journal of Fish Biology, 63, pages 197 to 212.

- Pitois, S.G., Lynam, C.P., Jansen, T., Halliday, N. and Edwards, M., 2012. Bottom-up effects of climate on fish populations: data from the Continuous Plankton Recorder. Marine Ecology Progress Series, 456, page 169-186.
- Poloczanska, E.S., Cook, R.M., Ruxton, G.D. and Wright, P.J., 2004. Fishing vs. natural recruitment variation in sandeels as a cause of seabird breeding failure at Shetland: a modelling approach. ICES Journal of Marine Science, 61(5), pages 788 to 797.
- Ransijn, J.M., Booth, C., and Smout, S.C., 2019. A calorific map of harbour porpoise prey in the North Sea. JNCC Report No. 633. JNCC, Peterborough, ISSN 0963 8091.
- Régnier, T., Gibb, F.M. and Wright, P.J., 2019. Understanding temperature effects on recruitment in the context of trophic mismatch. *Scientific reports*, *9*(1), pages 1 to 13.
- Rindorf, A., Wanless, S. and Harris, M.P., 2000. Effects of changes in sandeel availability on the reproductive output of seabirds. Marine Ecology Progress Series, 202, pages 241 to 252.
- Rindorf, A., Jensen, H. and Schrum, C., 2008. Growth, temperature, and density relationships of North Sea cod (Gadus morhua). Canadian Journal of Fisheries and Aquatic Sciences, 65(3), pages 456 to 470.
- Santos, M.B. and Pierce, G.J., 2003. The diet of harbour porpoise (*Phocoena phocoena*) in the northeast Atlantic: A review. Oceanography and Marine Biology, An Annual Review, Volume 41, pages 363 to 369.
- Smout, S., King, R. and Pomeroy, P., 2020. Environment-sensitive mass changes influence breeding frequency in a capital breeding marine top predator. Journal of Animal Ecology, 89(2), pages 384 to 396.
- Speirs, D.C., Greenstreet, S.P. and Heath, M.R., 2016. Modelling the effects of fishing on the North Sea fish community size composition. Ecological Modelling, 321, pages 35 to 45.
- Thompson, P.M., Mcconnell, B.J., Tollit, D.J., Mackay, A., Hunter, C. and Racey, P.A., 1996. Comparative distribution, movements and diet of harbour and grey seals from Moray Firth, NE Scotland. Journal of Applied Ecology, pages 1572 to1584.
- Thorpe, R.B., Le Quesne, W.J., Luxford, F., Collie, J.S. and Jennings, S., 2015. Evaluation and management implications of uncertainty in a multispecies size-structured model of population and community responses to fishing. Methods in Ecology and Evolution, 6(1), pages 49 to 58.
- Trenkel, V.M., Pinnegar, J.K., Dawson, W.A., Du Buit, M.H. and Tidd, A.N., 2005. Spatial and temporal structure of predator–prey relationships in the Celtic Sea fish community. Marine Ecology Progress Series, 299, pages 257 to 268.
- van Deurs, M., van Hal, R., Tomczak, M.T., Jónasdóttir, S.H. and Dolmer, P., 2009. Recruitment of lesser sandeel Ammodytes marinus in relation to density dependence and zooplankton composition. Marine Ecology Progress Series, 381, pages 249 to 258.
- Walters, C. and Kitchell, J.F., 2001. Cultivation/depensation effects on juvenile survival and recruitment: implications for the theory of fishing. Canadian Journal of Fisheries and Aquatic Sciences, 58 (1), pages 39 to 50.

- Wanless, S., Harris, M.P., Redman, P. and Speakman, J.R., 2005. Low energy values of fish as a probable cause of a major seabird breeding failure in the North Sea. Marine Ecology Progress Series, 294, pages 1 to 8.
- Wright P.J. Greenstreet, S.P.R., Tasker, M.L. 1996. Is there a conflict between sandeel fisheries and seabirds? A case history at Shetland, Aquatic Predators and their Prey, 1996Oxford, UKBlackwell Science, pages 154 to165.
- Wright, P.J., Christensen, A., Régnier, T., Rindorf, A. and van Deurs, M., 2019. Integrating the scale of population processes into fisheries management, as illustrated in the sandeel, Ammodytes marinus. ICES Journal of Marine Science, 76(6), pages 1453 to 1463.

Annex 1: UK policy landscape and environmental objectives

The Conservation of Habitat Regulations 2017 ensure that the requirements set out in the EU Birds and Habitats Directives continue to apply following EU exit. Activities considered to be in conflict with the conservation objectives of Natura 2000 sites must be managed to mitigate that conflict. In the case of marine Special Protection Areas (SPAs), identified for seabird foraging areas, pressures must be managed to maintain/recover the condition of the habitat and availability of food resources to ensure the relevant bird species are in favourable condition.

The UK Marine Strategy Regulations 2010 require the UK to take the necessary measures to achieve or maintain Good Environmental Status (GES) through the development of a UK Marine Strategy (UKMS). The UKMS provides the policy framework for delivering marine policy at the UK level and sets out how the vision of clean, healthy, safe, productive and biologically diverse oceans and seas will be achieved.

The target of Good Environmental Status has not been met for seabirds and marine food webs. In the Greater North Sea frequent and widespread breeding failures have been seen in 35% of seabird species, with surface feeding birds being particularly affected, and the target on marine seabird populations has not been met.

The assessment of this target notes that "the reduced availability of small fish, on which the seabirds feed, has been largely responsible for declines in seabird breeding abundance and the frequent, widespread breeding failures in some species" (Cefas 2018)

The UK Environment Act 2021 seeks to halt the decline in species by 2030 and provides the powers for government to set legally binding targets. It also incorporates the concept of biodiversity offsetting into law. The act requires an Environmental Improvement Plan detailing the steps to be taken to improve the natural environment.

The UK's resulting 25 Year Environment Plan calls for fisheries policies which ensure seas return to health and fish stocks replenished and states that ‘An ecosystem approach to fisheries management will account for, and seek to minimise, impacts on non-commercial species and the marine environment generally, including through technical conservation measures.’ (HM Government 2018)

The UK Fisheries Act 2020 introduces a range of new powers to enable the UK administrations to manage fisheries outside of the CFP framework and includes the Ecosystem Objective, requiring that an ecosystem based approach to management is used, along with the Sustainability Objective which requires fisheries to be environmentally, economically and socially sustainable, and the Precautionary Objective (see below) which are particularly relevant to the issue of industrial sandeel fisheries.

The act also includes

- the Scientific Objective, requiring the collection and sharing of data and the use of the best scientific advice when developing management
- the Bycatch Objective, requiring that bycatch is avoided or reduced and all catches accounted for; the Equal Access Objective, ensuring that UK registered vessels have access throughout UK waters
- the National Benefit Objective, requiring that fishing activity by UK registered vessels delivers economic and social benefits to UK communities
- the Climate Change Act which requires that the impact of fishing activity contributing to climate change are reduced and that fisheries are able to adapt to climate change and shifting species distributions

Scotland's Fisheries Management Strategy 2020 to 2030 includes a vision to strengthen the management of sandeel fishing in Scottish waters. Action 11 of the 12 point action plan states: 'We will work with our stakeholders to deliver an ecosystem-based approach to management, including considering additional protections for spawning and juvenile congregation areas and restricting fishing activity or prohibiting fishing for species which are integral components of the marine food web, such as sandeels' (Scottish Government 2020).

Sandeels were also adopted as a Priority Marine Feature by Scottish ministers in 2014 and are a protected feature of 3 MPAs:

1) Mousa to Boddam NC MPA
2) North west Orkney NC MPA
3) Turbot Bank NC MPA

Several MPAs also aim to conserve sandeel habitat to ensure the continued supply of young recruits to other sandeel grounds around Scotland and the rest of the UK.

The Precautionary Objective of the Fisheries Act establishes the need to apply the precautionary approach to fisheries management, which the Fisheries Act defines as "an approach in which the absence of sufficient scientific information is not used to justify postponing or failing to take management measures to conserve target species, associated or dependent species, non-target species or their environment".

In addition, the UK's draft environmental principles policy statement, states that "the precautionary principle is applicable where there is plausible evidence of a risk that a particular policy could cause serious or irreversible damage to the environment, alongside a lack of scientific certainty about the likelihood and severity of this damage”. As such, demands for additional evidence should not be used as grounds to avoid taking difficult management decisions to prevent potential environmental degradation.

Policymakers are required to make a reasonable assessment on the application of the risk whilst ensuring that management interventions are proportionate to the level of risk. It requires that the level of uncertainty determines the acceptable level of risk. As the risk of serious damage increases, the level of certainty required before action is taken reduces. It also requires that there be sufficient evidence that the risk of serious or irreversible damage is plausible and real.

The current advice seeks to provide sufficient evidence regarding the role of sandeel in the North Sea ecosystem and in turn the impact of prohibition of the fishery. The decision as regards how far to go in adopting a precautionary approach will ultimately rest with the appropriate decision makers.

Annex 2: Uncertainty in Ecopath with Ecosim predictions

Summary of uncertainty of risks and benefits of full prohibition of industrial sandeel fishing (based on 2020 landings) on the biomass of commercial stocks and functional groups in the North Sea (ICES Subarea 4). 2 scenarios are presented:

- Table 6 sets out the confidence intervals (5th and 95th percentiles) of the biomass response from commercial stocks and guilds to prohibition of industrial sandeel fisheries in the North Sea
- Table 7 sets out the confidence intervals (5th and 95th percentiles) of the biomass response from commercial stocks and guilds to prohibition of industrial fisheries in the UK waters of the North Sea (based on average, lower, and upper estimates of the proportion of landings from the UK EEZ)

Estimates within these tables take into consideration the uncertainty in biomass trend projections using an ensemble of 130 model parameterisations with adjusted input parameters.

Table 6: Confidence intervals (5th and 95th percentiles) of the biomass response from commercial stocks and guilds to prohibition of industrial sandeel fisheries in the North Sea

Commercial stocks and guilds	Confidence intervals
Seabirds	+10%, +13%
Seals	+5%, +7%
Baleen whales	-1%, +2%
Toothed whales	-1%, 0%
Whiting	+4%, +6%
Haddock	+4%, +7%
Cod	+1%, +3%
Saithe	-6%, +5%

Commercial stocks and guilds	Confidence intervals
Demersal fish	+1%, +1%
Pelagic fish	0%, +2%
Benthos	0%, 0%
Zooplankton	-1%, -1%

Table 7: Confidence intervals (5th and 95th percentiles) of the biomass response from commercial stocks and guilds to prohibition of industrial fisheries in the UK waters of the North Sea (based on average, lower, and upper estimates of the proportion of landings from the UK EEZ).

Commercial stocks and guilds	Lower landings proportion confidence intervals	Average landings proportion confidence intervals	Upper landings proportion confidence intervals
Seabirds	+4%, +5%	+6%, +8%	+7%, +9%
Seals	+2%, +3%	+3%, +4%	+4%, +5%
Baleen whales	+1%, +2%	+1%, +3%	+1%, +3%
Toothed whales	0%, +1%	0%, +1%	0%, +1%
Whiting	+1%, +2%	+2%, +3%	+2%, +4%
Haddock	+2%, +2%	+2%, +4%	+3%, +5%
Cod	0%, +1%	0%, +1%	0%, +2%
Saithe	-2%, +1%	-4%, +2%	-4%, +2%

Commercial stocks and guilds	Lower landings proportion confidence intervals	Average landings proportion confidence intervals	Upper landings proportion confidence intervals
Demersal fish	0%, 0%	0%, +1%	+1%, +1%
Pelagic fish	0%, 0%	0%, +1%	0%, +1%
Benthos	0%, 0%	0%, 0%	0%, 0%
Zooplankton	0%	-1%, 0%	-1%, 0%