Review of Scientific Evidence on the Potential Effects of Sandeel Fisheries Management on the Marine Environment

July 2023

Scottish Government
Riaghaltas na h-Alba

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1 Aim of this Report

This report provides a review of the available scientific evidence on the potential effects of sandeel fisheries management on the marine environment. It includes information on the drivers of sandeel distribution and abundance, the importance of sandeel to other fish species, seabirds and marine mammals, and the potential effects of sandeel fisheries management measures upon these species. The report's focus is not on the provision of advice on whether sandeel fisheries management measures should be put in place.

2 Sandeel

Sandeel are part of the Ammodytidae family, consisting of small eel-like fishes, and represent the most abundant species group in the North Sea (around 15% of the total fish biomass, Sparholt, 1990), playing a key role in North Atlantic marine food webs. This key role is associated with the structure of North-Atlantic food-webs, often described as a having "wasp-waist" structure, where a relatively low diversity of forage i.e., prey fish (including sandeel and clupeids) form the intermediate trophic link between a large diversity at both lower trophic levels (phyto/zooplankton) and higher trophic levels (predatory fish, marine mammals, and seabirds). In accordance, variations in the abundance and availability of sandeel or other forage fish can have important effects on both ends of marine food web (top-down regulation of lower trophic levels and bottom-up effects on marine predators) and disrupt the energy transfer across the whole food-web (Lynam et al. 2017).

Sandeel in the North Atlantic and the North Sea refers to a complex of species of which the most abundant is the lesser sandeel (Ammodytes marinus), which supports the largest single-species fishery in the North Sea. The lesser sandeel is a winter-spawning species which lay eggs on the sand in winter months, with planktonic larvae occupying the water column from hatching in February - April to settlement in May - June. Settlement marks a key transition in the sandeel life cycle, after which they form pelagic feeding schools (targeted by marine predators) during the day, burying into the sand at night. Following the summer feeding season, sandeel remain in the sand day and night for the overwintering period, apart from a short spawning period in December - January, until emergence from the sand the following spring. These aspects of sandeel life cycle, particularly this life-long attachment to a sand bank, are important determinants of their distribution.

2.1 Sandeel distribution and movements

2.1.1 Habitat preference and broad-scale distribution

Sandeel demonstrate high habitat specificity and are highly reliant upon the availability of suitable sandy substrates (Wright et al. 2000, Holland et al. 2005, Tien et al. 2017, Langton et al. 2021). A study by the Scottish Government's Marine

Directorate on sandeel distribution in sediment grab samples collected in the Firth of Forth found that sandeel preferred medium to coarse sand, presumably as this offers greater permeability and thus higher oxygen concentrations, and avoided fine sediment (Holland et al. 2005, **Figure 1**), confirming previous results of an experimental test of sediment preference conducted by the Marine Directorate (Wright et al. 2000). Sandeel were also found to prefer water depths of around 50 m (Wright et al. 2000).

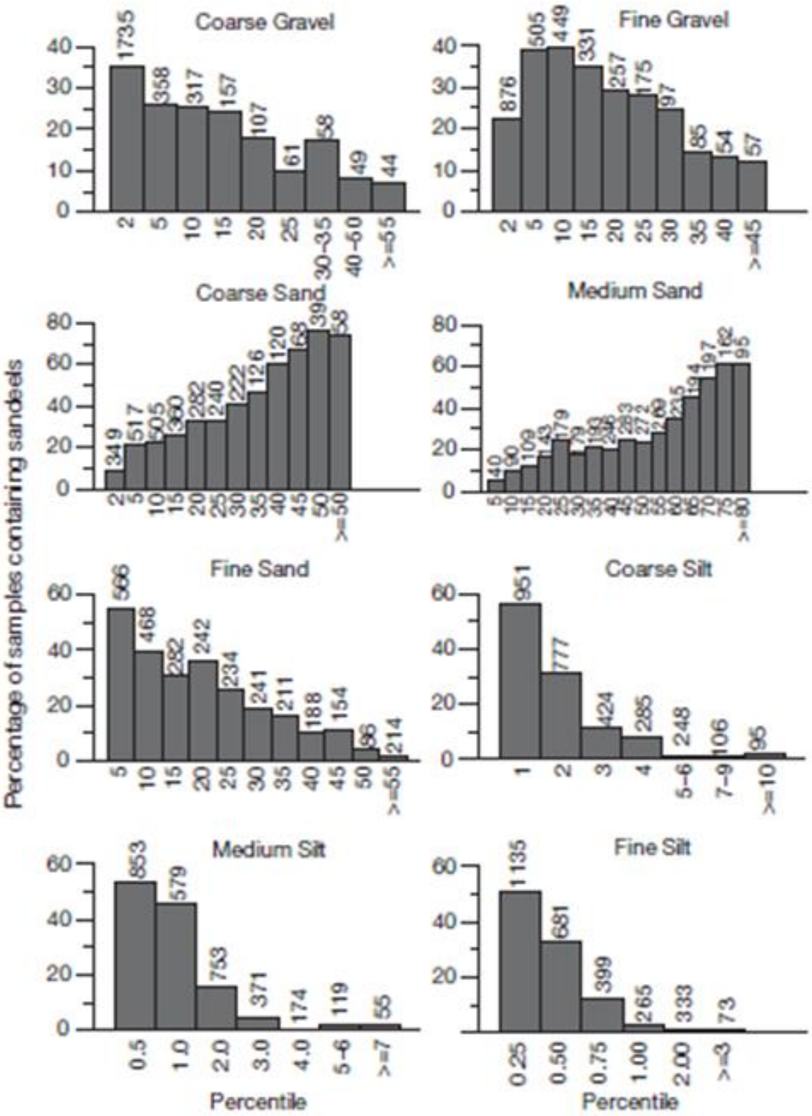


Figure 1: Variation in the percentage of sediment grab samples containing sandeel, with varying proportions of each of the sediment categories (ranging from coarse gravel to fine silt). Histogram bar labels indicate the number of samples.

These sediment preferences, along with other environmental variables, have been used by the Marine Directorate to map sandeel habitat suitability and predict sandeel distributions around Scotland, eastern English waters and the Celtic Seas (Langton et al. 2021). The resultant Species Distribution Models (SDM) highlighted an avoidance of fine sediment, a preference of depths around 40 m and a high patchiness of suitable habitat (Langton et al. 2021). The key output of the model was a prediction of sandeel distribution within and beyond the limits of Scottish waters (**Figure 2**). The model predicts the highest probability of sandeel occurrence on Dogger Bank (North Sea, sandeel management area 1, eastern English waters) and also identifies sandeel grounds in the Firth of Forth (consistent with historic sandeel fishing grounds (Jensen et al. 2011)), the Moray Firth, the east coast of Orkney, east of Dublin, north east coast of Donegal, north and west of Islay, and to the north and west of Lewis. Model predictions were validated against the east coast sandeel dredge survey and both the North Sea and West of Scotland International Bottom Trawl Surveys (Langton et al. 2021).

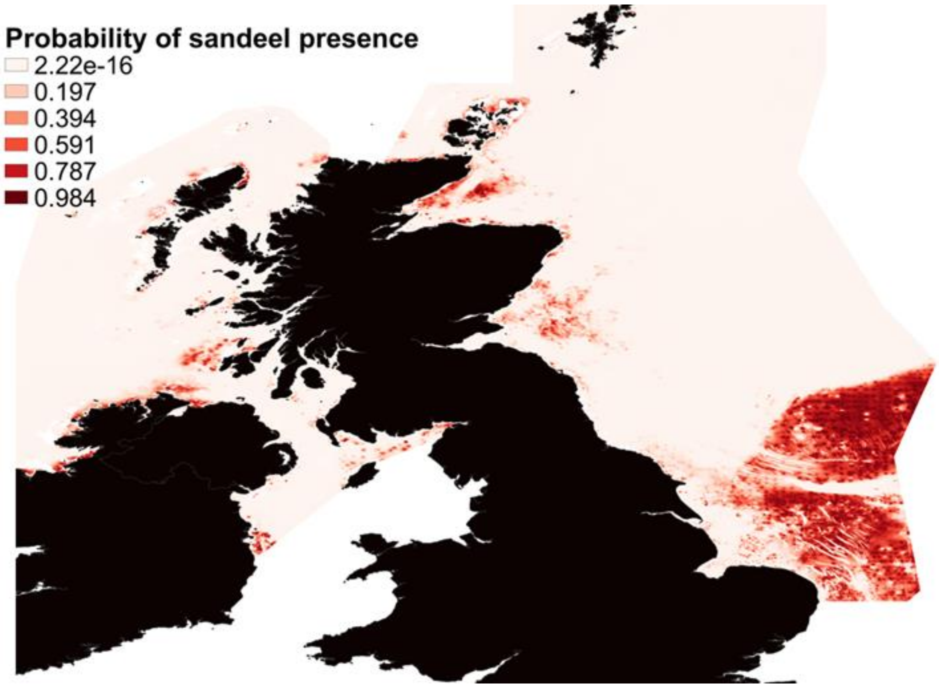


Figure2: Predicted probability of occurrence of sandeel in UK waters. Reproduced from Langton et al. 2021.

The lack of a sandeel assessment on the west coast of Scotland (there are no recent data on sandeel status in this area) and the designation of several Marine Protected Areas (MPAs) in these areas protecting sandeel directly or indirectly (e.g., sandeel reliant predators), resulted in the Marine Directorate conducting a sandeel survey to the west coast of Scotland in 2019. The observed occurrence of sandeel in grab and dredge samples at various sites on the west coast of Scotland was in good agreement with the Langton et al. (2021) predictions (**Figure 3**). The main conclusion of this work is that the Langton et al. (2021) SDM provides a good estimate of sandeel distribution in Scottish waters, however a relatively low threshold of probability of occurrence (in the region of 10%) needs to be adopted to capture suitable sandeel grounds to the west of Scotland.

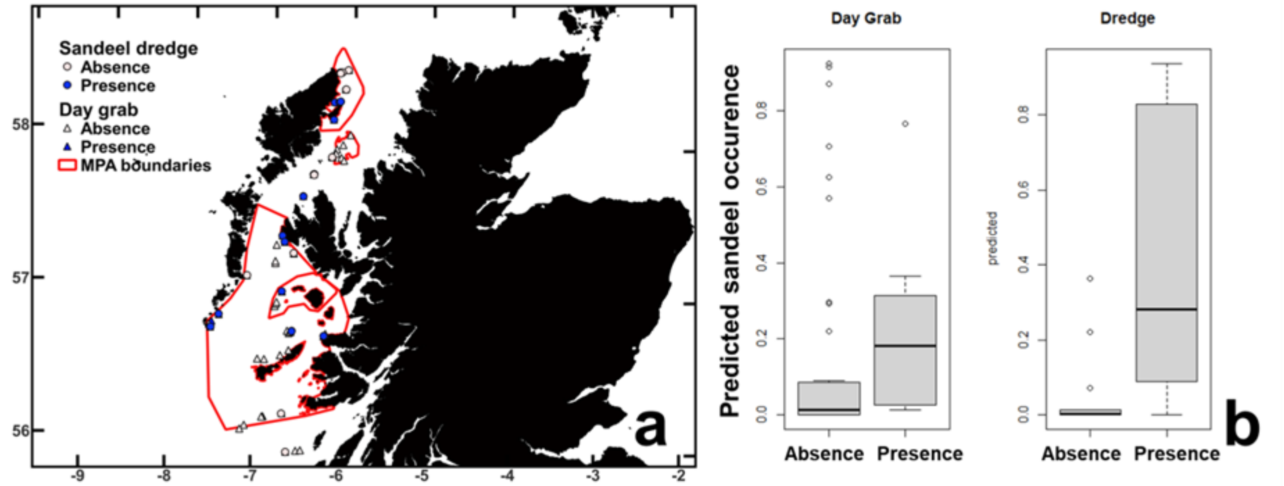


Figure 3: a-Presence/Absence data collected during Marine Directorate survey 1321A on the West coast of Scotland by means of Day Grab and sandeel dredge tows. b-Predicted probability of sandeel occurrence (from Langton et al. 2021) at sites where sandeel were absent or present in the grab and the dredge samples.

A characteristic of the SDM described above is that it was fitted with sandeel occurrence in grab samples. This implies that model predictions are particularly suited for the stages of sandeel life cycle which take place in the substrate (i.e., at night and during the overwintering period), and deviations from these predictions may occur at times when sandeel form pelagic feeding schools during the feeding season (Spring/Summer, i.e., when sandeel are targeted by chick-feeding seabirds). However, since feeding schools remain closely associated with the substrate, the general patterns of distribution remain valid within the limits determined by the daily pattern of sandeel movement.

2.1.2 Sandeel movements and dispersal

2.1.2.1 Daily movements

During the feeding season (spring/summer), sandeel form pelagic feeding schools during daylight hours, and tend to forage in the vicinity of the sandbanks in which they bury at night. However, feeding schools have been found to select a slightly different habitat marked by greater depths, often situated on the edge of sandbanks (van der Kooij et al. 2008, Englehard et al. 2008). These deeper waters to the edge of sandbanks offer different hydrodynamic conditions assumed to favour larger zooplankton abundances targeted by sandeel schools. Separate studies on the Dogger Bank area have reported different extents of diurnal movements in sandeel, varying from 1km to 15 km away from the substrate inhabited at night (van der Kooij et al. 2008, Englehard et al. 2008). However, sediment type is still a key explanatory variable in describing sandeel distribution in the water column, as highlighted in a previous study (van der Kooij et al. 2008) and in ongoing Marine Directorate work within the PrePARED (Predator and Prey Around Renewable Energy Developments) project. In fact, predicted distributions of sandeel occurrence in the sand (Langton et al. 2021) and in the water column (ongoing Marine Directorate work) in the Firth of Forth show substantial overlap (**Figure 4**).

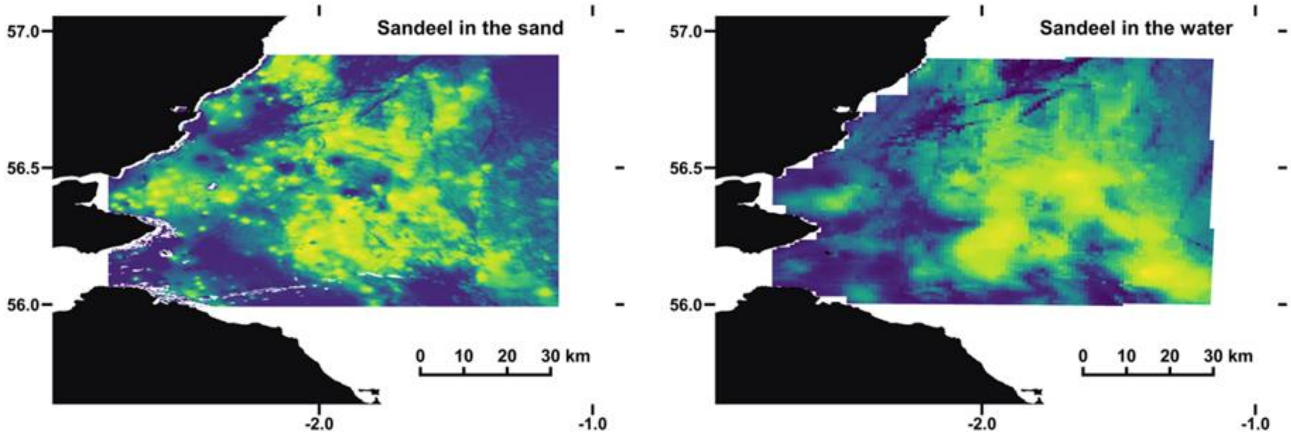


Figure 4: Comparison of sandeel predicted presence in the sand (reproduced from Langton et al. 2021) and in the water column in June (Marine Directorate ongoing work as part of PrePARED). Probability of presence is indicated by a colour ramp from 0 (dark) to 1 (light).

2.1.2.2 Adult movements

After settlement to a particular sandbank (i.e., following the planktonic larval stage), juvenile and subsequent adult sandeel movements have been found to be limited. A study found that the scale of adult mixing was limited to < 30 km (Jensen et al. 2011), and that very little to no exchange was found between sandeel aggregations separated by distances > 28 km, even if these aggregations were connected by continuous stretches of suitable habitat. Early tagging studies revealed that most sandeel were recaptured at sandeel fishing grounds situated within 30 km from release (post marking) locations (Gauld 1990, Wright et al. 2019). Similarly, sandeel captured during the International Bottom Trawl Survey (IBTS) were caught within 30 km of known sandeel fishing grounds (Wright et al. 2019).

The combination of limited adult movements between sandbanks and the patchiness of available suitable habitat indicates that local conditions affecting adult mortality (fishing pressure, food availability and predator abundance) can lead to significant variation in sandeel age and length composition over a relatively fine spatial scale. Local depletion of sandeel aggregations is therefore unlikely to be compensated by the movement of adult sandeel from neighbouring sandbanks, with replenishment of a depleted area more likely dependent of the dispersal of sandeel larvae. As such, recovery may take several years to be achieved.

2.1.2.3 Larval dispersal

Connectivity between sandeel grounds results from the dispersal of sandeel during their planktonic larval stage. While direct tagging studies have been successful in adults, the application of such methods is not possible in larval sandeel due to their small body size. Instead, the investigation of sandeel larval movements relies on two indirect methods: (i) bio-physical modelling of prevailing hydrodynamic conditions to allow the backtracking of larval origins from capture locations (Proctor et al. 1998, Christensen et al. 2008a, b) and (ii) the use of otolith chemistry as natural tags to estimate larval dispersal (Gibb et al. 2017, Wright et al. 2019).

Bio-physical models suggest a high level of regional retention between the current North Sea management areas (these bio-physical model predictions were used to define the management areas) and that larval mixing is common between grounds situated < 67 km apart. However, the probability of mixing between grounds situated > 200 km apart was very low (Proctor et al. 1998, Christensen et al. 2008a, b, Wright et al. 2019). The theoretical predictions from these models, however, require validation from empirical evidence.

Otolith microchemistry studies rely on two key properties of otoliths (the calcified structures of the inner ear), which is that they grow continuously and are not subject to reabsorption. These studies record the chemical signatures of sequential habitats occupied throughout the life of a fish as the otolith continues to grow and differentially incorporate water elemental concentrations. By characterising the chemical signature of the larval region of the otolith, it is possible to infer the location of larval origin (provided the chemical signatures of larval habitats are known and characterised) or identify the number of unique larval sources contributing to different adult sandeel grounds. Using this method, the Marine Directorate studied larval dispersion at the North Sea scale (Wright et al. 2017, 2019) and within Scottish waters (Gibb et al. 2017). The results indicated that while neighbouring sandeel grounds relied on similar larval sources and that local larval mixing was evident, larval mixing across North Sea management areas was very limited (**Figure 5a,** Wright et al. 2017, 2019; SA4 was comprised primarily of natal clusters D and A, SA1r of natal cluster B and SA2r of natal cluster C), suggesting that population dynamics were dependent on local recruitment (larvae produced in the vicinity of the sampling area recruited to the juvenile and adult population). These results agreed with the bio-physical modelling, which indicated that oceanographic processes were the primary influence on the scale of inter-mixing of sandeel. Similarly, support for the bio-physical models is evident at the scale of Scottish waters. Larval mixing was found between grounds in the North Minch (NW Scotland) and near Orkney (**Figure 5b**, Gibb et al. 2017; primarily comprised of natal cluster 1), while sandeel grounds near Shetland and in the Firth of Forth relied on distinct (likely local) larval sources (**Figure 5b**, Gibb et al. 2017; where natal sources were primarily comprised of clusters 2 and 3 respectively).

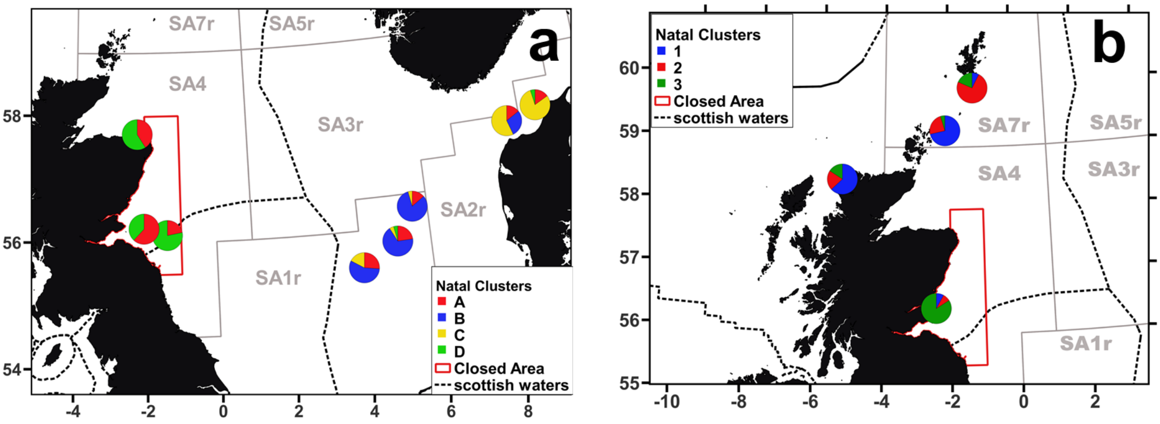


Figure 5: a-Diversity of larval sources contributing to sandeel grounds in the North Sea (from Wright et al. 2017). b-Diversity of larval sources contributing to sandeel grounds within Scottish waters (reproduced from Gibb et al. 2017).

These results indicate that larval dispersal occurs over a limited spatial range, mostly driven by oceanographic processes. Therefore, recovery of a depleted area will depend on the proximity of connected larval sources, the successful settlement of dispersing larvae and their survival to maturity - processes that are likely to take several years. Simulations of recovery after local depletion in an area of 50 km in diameter suggested that replenishment from neighbouring grounds may lead to recovery within 1 - 3 years (Wright et al. 2019), however, direct observation from commercial data revealed that some grounds had not recovered after periods > 8 years (Johannessen & Johnsen, 2015). However, delays in recovery can also result from environmental changes and the unsuccessful settlement and survival of dispersed larvae (Clausen et al. 2018).

2.1.3 Summary of Evidence on sandeel distributions and movements

The Marine Directorate SDM by Langton et al. (2021) provides useful predictions of sandeel distributions within Scottish waters. While it is directly applicable to sandeel distributions at night or during the overwintering period (based on sandeel collected in the sand), sediment preference is also a key variable in the estimation of sandeel distributions in the water column, at a time when chick-provisioning seabirds can rely heavily on this resource. Sandeel movement at the adult stage is limited and connectivity between sandeel grounds results from larval dispersal, mostly driven by oceanographic processes. The degree of connectivity is also limited and little to no exchange of larvae happen between sandeel management areas, and properties of oceanographic currents (e.g., retention in the Firth of Forth) leads to isolation between sandeel grounds situated within Scottish waters. Following local depletion (resulting from exploitation (e.g., fishing) and environmental change), with recovery driven by larval dispersal and oceanographic processes, it may take several years for full recovery to take place, a process that is uncertain as it is likely also affected by environmental conditions (e.g., climate change effects).

2.2 Effects of climate change

Climate change and changes in sea temperature, particularly, have the potential to affect sandeel abundance and their availability to marine predators through a variety of mechanisms. Fish being ectotherms (i.e., cold-blooded organisms), temperature can have a direct impact on sandeel numbers by influencing physiological parameters such as survival, growth, metabolic or maturation rates, and an indirect influence on fecundity through the availability of their resources. Understanding and accounting for these effects it is therefore necessary if the objective is to (i) adapt the management of sandeel stocks to sustain or improve sandeel resilience in a changing climate or (ii) set realistic conservation or management targets accounting for changes in environmental conditions.

2.2.1 Direct temperature effects on physiological rates

Two key characteristics of sandeel biology make them particularly sensitive to a temperature increase during winter: (i) the long overwintering period during which sandeel remain inactive and buried in the sand and (ii) the requirement to build up energy reserves at times when food is abundant due to investment in reproduction at a time of low prey availability (sandeel are capital breeders). As metabolic rate and maintenance costs increase with temperature (VanDeurs et al. 2011), higher winter temperatures are likely to impact the allocation of the limited energy stores to gonad development but will also constrain maintenance (i.e., the energy needed to maintain vital functions) and therefore survival over winter. It was estimated that increasing winter temperatures resulted in a larger threshold size necessary for sandeel to both survive winter and commit to maturation (Van Deurs et al. 2011). In agreement with the increased energy expenditures at warmer temperatures, experimental work by the Marine Directorate has shown that weight loss during the overwintering period increased under warmer temperatures (Wright et al. 2017a). A temperature increase during this period was found to delay ovarian development in sandeel (Wright et al. 2017b), with potential effects on spawning date impacting the early life-history and phenology (timing of key events such as hatching, first feeding and settlement) of the larvae and juveniles produced in these conditions.

Temperature has also been found to affect egg development in sandeel, and experimental work carried out by the Marine Directorate showed that increasing temperature during the incubation period resulted in a shorter egg development period (Régnier et al. 2018, **Figure 6**). However, despite this direct temperature effect on egg development, most of the variation in sandeel hatching date in a subsequent empirical study was found to result from variation in spawning date associated with the intensity of the seasonal decrease in temperature during the overwintering period (Régnier et al. 2019). Strong seasonality and a rapid decrease of temperature during the overwintering period was found to be associated with delayed spawning and hatching dates (Régnier et al. 2019). Spawning date was also found to be influenced by adult size, with earlier oocyte (egg cell) maturation found in larger sandeel (Boulcott et al. 2017). Changes in adult size distributions, resulting from the size selective removal of adults from the population by the fishery, may affect the resilience of exploited sandeel population to climate change by promoting indirect selection for later spawning and hatching dates.

Therefore, warmer seas may impose greater pressure on sandeel, resulting in a decrease in overwinter survival and a delay in maturation which may affect the synchrony between the timing of key life-history events during early stage development in sandeel (hatching, first feeding) and the availability of their food resource in a highly seasonal environment such as the North Sea.

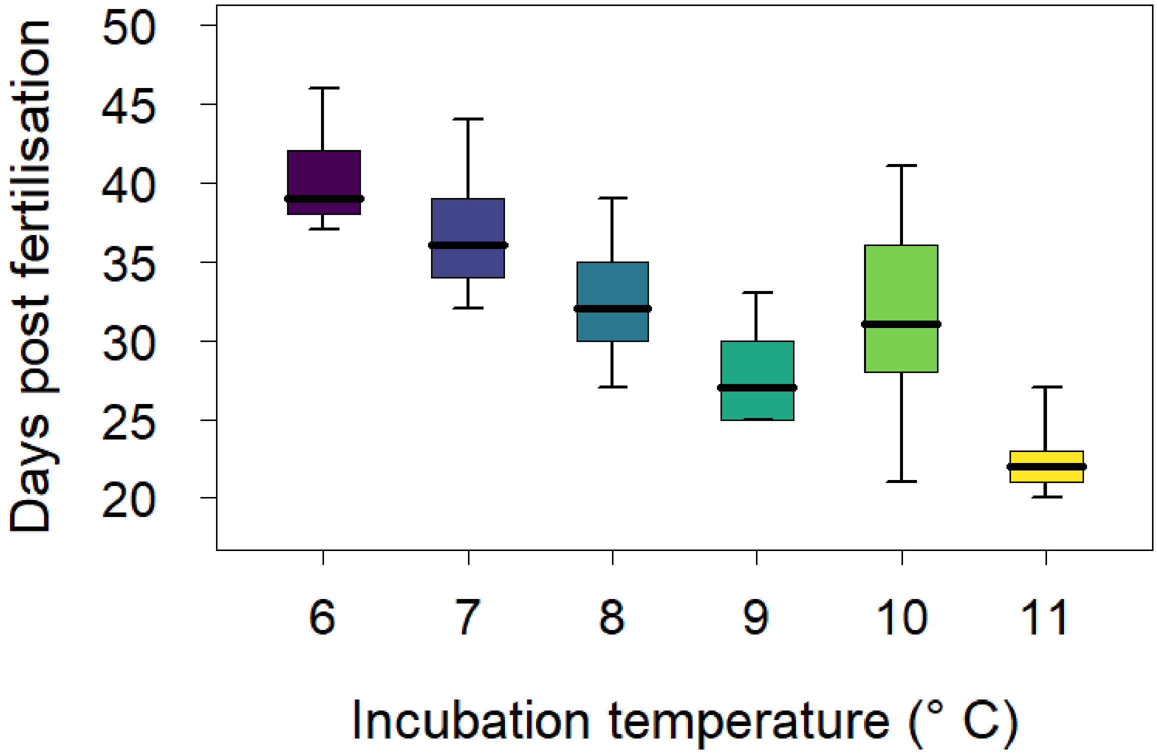


Figure 6: Boxplots of sandeel egg development (in days post fertilisation) at six incubation temperatures. The bold lines represent median hatching days, the edges of the boxes represent 25 and 75% hatching (lower and upper edges respectively) and the lower and upper whiskers represent 5 and 95% hatching respectively. Reproduced from Regnier et al. 2018.

2.2.2 Indirect temperature effects on sandeel abundance

The match-mismatch hypothesis suggests that shifts in the relative seasonal timing of the energy-demanding stage of the predator life cycle (e.g., first feeding in sandeel) and peaks in prey availability (e.g., spring peak in zooplankton abundance) impacts predator abundance (**Figure 7**).

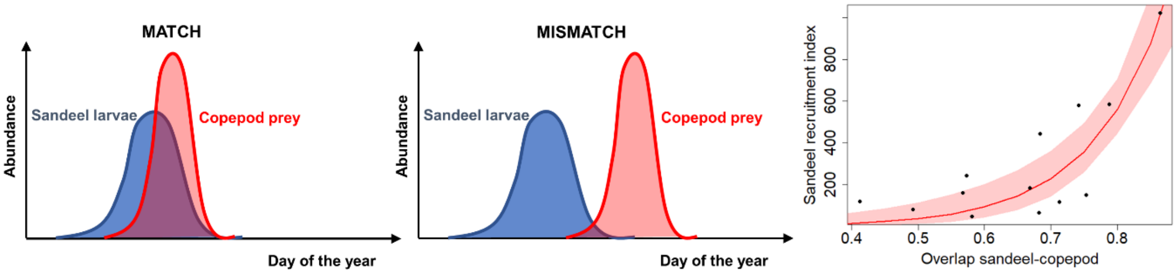


Figure 7: Match-Mismatch hypothesis. A trophic match corresponds to a good overlap between the seasonal timing of the energy-demanding stage in sandeel (in blue) and peak copepod prey availability (in red) while a mismatch corresponds to limited to no overlap. The figure on the right is derived from Régnier et al. 2019 and shows the relationship between sandeel recruitment and the measure of overlap described above.

The Marine Directorate studies found evidence in support of the match-mismatch hypothesis as a key driver of sandeel recruitment (Wright & Bailey 1996, Régnier et al. 2017, 2019). Recruitment in sandeel was related to the degree of overlap between sandeel hatching and peak egg production in their copepod prey (Régnier et al. 2017, 2019). The peak of copepod egg production was also found to depend on temperature. However, while hatching date in sandeel varied with the rate of temperature decrease during the overwintering period, the peak of copepod egg production was found to be associated with February sea temperature (Régnier et al. 2019). The dependence of predator and prey key life stages to temperature over distinct periods of time (autumn-winter in sandeel, late winter in copepod) favours the development of asynchronies. Using climate predictions following medium and high greenhouse gas emission scenarios (IPCC 2007, **Figure 8**), the timing of key life-stages in sandeel and their copepod prey as well as the resulting trophic mismatch were predicted to significantly increase over the next 50 - 80 years (Régnier et al. 2019, **Table 1**).

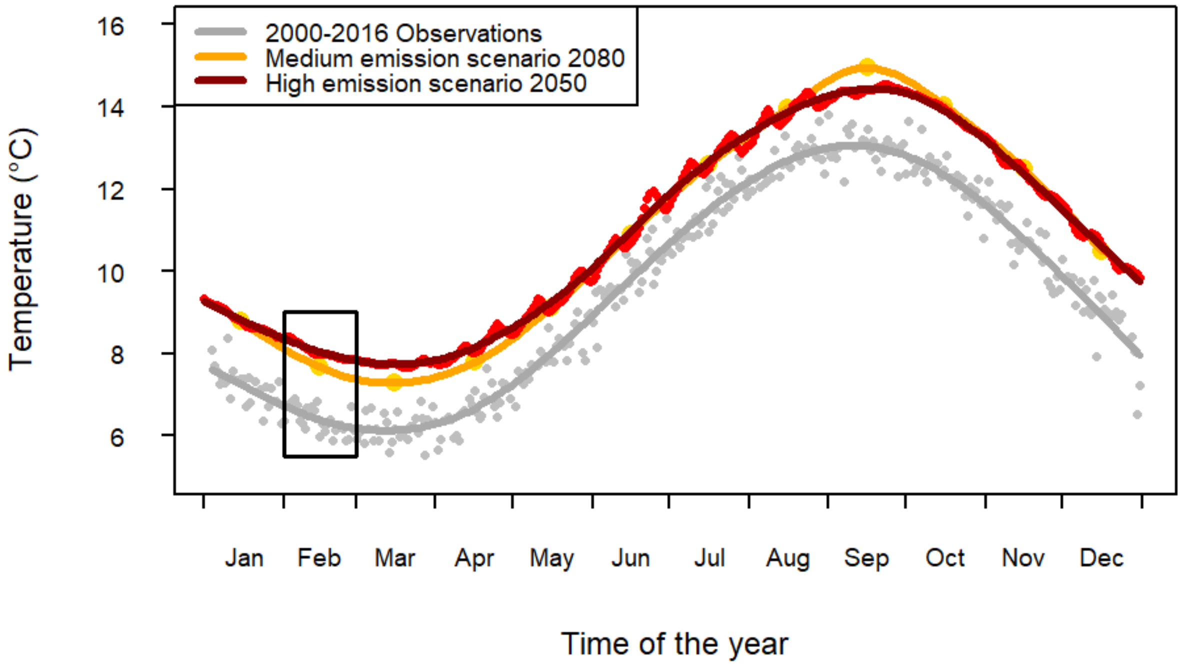


Figure 8: Seasonal variations in seawater temperature near the seabed at the Stonehaven monitoring station, in the recent past and according to two climate change scenarios. Observed temperatures between 2000 and 2016 are indicated in grey, projections using a medium greenhouse gas emissions scenario in orange and high greenhouse gas emissions scenario in red. The difference in February temperatures between the current data and future climate scenarios is highlighted by the black box. Reproduced from Régnier et al. 2019.

Table 1: Comparisons of peak egg production in copepod prey (Calanus helgolandicus, day of the year), sandeel spawning day (day of the year) and embryonic development (in days) and the resulting trophic mismatch (in days) in present temperature conditions or predicted according to modelled future climate projections. Numbers in brackets correspond to 95% CIs. Reproduced from Régnier et al. 2019

Climate change scenario	**C. helgolandicus peak egg production**	**Sandeel spawning**	**Sandeel average incubation duration**	**Mismatch**
Present data (2000-2016)	55.5 (40.4-71.2)	34.6 (17-50.2)	40.6 (37.8-44.4)	19.8 (-9-39.6)
Average GHG emissions 2080	37.3 (24.2-50.3)	28.6 (24.9-32.2)	34.4 (33.1-34.8)	29.3 (14.5-44.1)
High GHG emissions 2050	31.7 (15-48.5)	31.9 (28.9-35)	32.1 (32.1-33)	41.4 (22.2-60.5)

2.2.3 Other Climate Change related effects on sandeel

Climate change is also predicted to affect the marine environment through an increase in ocean acidification resulting from increased CO_2 levels as well as a decrease in dissolved oxygen (See Wright et al. 2020 for a review). While no empirical evidence of the effects of ocean acidification on sandeel is available, effects have been documented in other fish, with potential impacts on metabolic rate (Enzor et al. 2013) and respiratory performance (Couturier et al. 2013) which may ultimately impact survival and abundance. Ocean acidification may also impact sandeel through bottom-up processes as effects have been documented on both phyto and zooplankton communities (Dutkiewicz et al. 2015, Hammill et al. 2018). Oxygen levels are predicted to decrease further with climate change (Townhill et al. 2017) and may impose further restrictions on fish distributions. Sandeel spend a considerable proportion of their life cycle buried in the sediment, in anoxic or near anoxic conditions. Experimental work revealed that decreasing oxygen affected the depth at which sandeel buried in the substrate and that they emerged at very low dissolved oxygen levels (Behrens et al. 2007). A decrease in oxygen levels may therefore indirectly impact sandeel survival and abundance through an increase in sandeel exposure to predators, in addition to potential direct effects on fish physiology. While most studies of the impacts of climate change on sandeel have focussed on temperature, other effects such as ocean acidification and low dissolved oxygen levels are likely to play an important role and their cumulative effects may result significant impacts on sandeel abundance and availability to marine predators.

2.2.4 Summary of Evidence on the effects of climate change on sandeel abundance

Climate change acting through an increase of sea temperature, ocean acidification, a decrease in oxygen levels and their cumulative effects can affect sandeel abundance through direct effects on survival and physiological rates, including phenology (the timing of key life-stages). Direct effects on the phenology of both sandeel and their copepod prey can lead to indirect effects of climate change on sandeel abundance through trophic mismatch. High fishing mortality is often associated with the selective removal of older and larger fish and evidence show that these fish tend to spawn earlier. Limiting or closing the sandeel fishery may therefore improve sandeel resilience to the seasonal variation in prey availability (i.e., no selective removal of early spawners). Similar to the mismatch between sandeel and their copepod prey, the abundance of marine top-predators may be impacted by climate change effects acting on the degree of synchrony between sandeel peak availability and the timing of the energy-demanding stage in marine top-predators (e.g., the chick-provisioning period in seabirds) and a fishery closure may promote the resilience of marine top predators as the resulting marginal increase in fish abundance may compensate for mild asynchronies between sandeel availability and predator demand.

2.3 Management and fishery

2.3.1 Sandeel management

Currently, sandeel fisheries are assessed and managed in the North Sea only. Due to the lack of data and the current absence of a fishery, sandeel on the west coast of Scotland are not assessed. Prior to 1995, sandeel in the North Sea were divided into two large units (Northern and Southern North Sea) and two small units (Shetland and Skagerrak-Kattegat areas) based on observed growth differences between these areas. Following a re-analysis of these apparent growth differences, and the lack of knowledge regarding sandeel movements, a decision to combine the Northern and Southern units as a single stock was made in 1995 (ICES 1995). New evidence suggesting limited sandeel movement and mixing as well as high uncertainty in sandeel assessment led ICES to review the North Sea sandeel stock structure in 2010 (ICES 2010). Seven management areas were proposed on the basis of the extent of larval exchange predicted by a biophysical model (Christensen et al. 2008a, b). The proposed structure was revised again at an ICES benchmark in 2016, to account for revision of the biophysical model and new evidence from otolith microchemistry studies (ICES 2017). At present, for assessment purposes the North Sea stock is divided into seven sub-populations or sandeel areas (SAs) (ICES 2023, **Figure 9**), and analytical stock assessments are currently carried out in SA1r–3r and 4, whereas SA6 is managed under the ICES approach for data-limited stocks. A recent Marine Directorate led review of evidence from biophysical modelling, tagging, otolith microchemistry, and spatial variations in recruitment studies provided support for the current divisions (Wright et al. 2019).

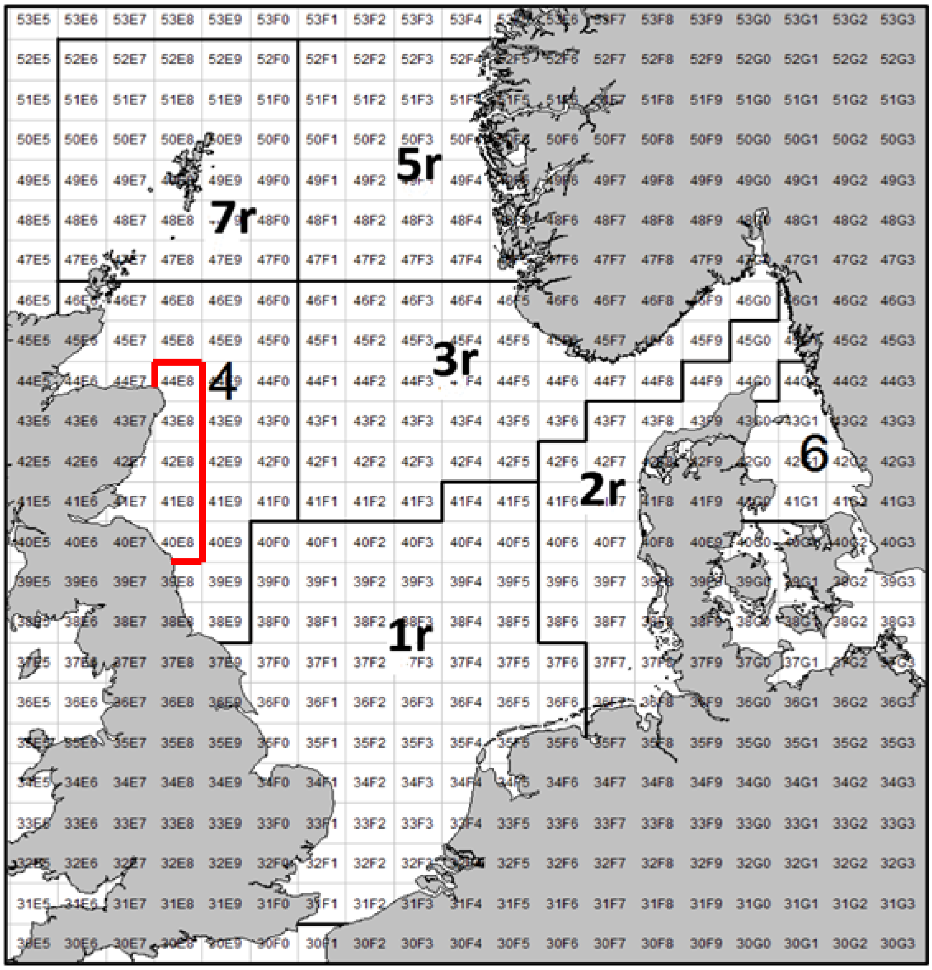


Figure 9: Division of the seven current sandeel management areas in the North Sea, the Scottish closed area within SA4 is indicated in red.

The largest of the sandeel stocks in Scottish waters is SA4, and this is the only one with an active fishery. The expansion of the fishery off the north-east UK coast and evidence of a decline in breeding success of sandeel-reliant seabirds (Rindorf et al. 2000, Daunt et al. 2008) led to the establishment of a precautionary fishing closure within part of SA4 (see **Figure 9**), corresponding to a reproductively isolated sandeel aggregation (Proctor et al. 1998; Wright et al. 1999).

Since 2008, the Marine Directorate has conducted an annual winter dredge survey at grounds off the Firth of Forth and Turbot Bank in SA4. These surveys provide an index of sandeel abundance by age class (i.e., abundance of fish of a given age). The good correlation between the abundances of age classes belonging to the same cohort in consecutive years (e.g., age 0 abundance in year Y and age 1 abundance in year Y+1) of the Marine Directorate survey (ICES 2023) provides confidence in the survey estimates of sandeel abundance indices. This survey is used to fine tune an age- based assessment for the SA4 stock. While most of the stations sampled in the

Marine Directorate survey are within the closed area (i.e., fishing mortality is assumed to be minimum), the combination of a interannual correlation and strong variation in recruitment (**Figure 10**) provides support to the conclusion that variation in sandeel abundance is mostly driven by recruitment in this area (see section 2.2 "**Effects of climate change**").

The analytical assessment in SA4 estimates the numbers for each age class and spawning stock biomass (SSB) using information on maturity and weight for each age class. While the assessment uses commercial catch data, the high variability in fisheries landings and the lack of age-0 (i.e., fish born the year of the survey) sandeel in the commercial catch means that the dredge survey index has a strong influence on the estimate of stock size and recruitment. ICES advises on a total allowable catch (TAC) based on an escapement strategy, whereby a fishery should only be allowed to operate if the stock assessment indicates that the spawning stock will be above a precautionary spawning biomass level (Bpa) the following year. Due to the uncertainty in forecasting future Bpa for short lived species like sandeel, a ceiling to the maximum fishing mortality (Fcap) is also set. Owing to the relatively low productivity of sandeel in SA4 (Boulcott et al. 2007, Boulcott & Wright 2011, Rindorf et al. 2016) this Fcap is much lower than that for other North Sea sandeel stocks.

An important caveat of this method is associated with the fishery closure on the east coast of Scotland as: (i) the representativeness of the recruitment estimated to the whole SA4 can be questioned when most of the stations sampled in the winter dredge survey are located within the closed area, (ii) inversely, commercial data used to estimate the abundance of older age classes originate mostly from the area open to fishing and (iii) the advised TAC for SA4 will be, in practice, harvested from only a fraction of SA4 (in the part open to fishing), raising concerns of local depletion in the part of SA4 open to the commercial fishery (ICES 2023).

2.3.2 2023 assessment of sandeel in SA4

Recruitment in 2014, 2016, 2017, 2019, 2021 and 2022 was above the geometric mean for the period 2012-2021, while the remaining years after 2010 were below (**Figure 10**). Fishing mortality (F) has been low since 2005, apart from 2018 and 2021 (**Figure 10**). The low level of F, together with high recruitment in 2014 and 2019, has resulted in Spawning Stock Biomass (SSB) above the precautionary spawning biomass level (Bpa) between 2016 and 2019 and in 2021. Spawning Stock Biomass (SSB) was between the Limit reference point for spawning stock biomass (Blim) and the precautionary spawning biomass level (Bpa) in 2020 and 2022 (**Figure 10**). As a result of the above average recruitment in 2022, a Total Allowable Catch (TAC) of 35,020 tonnes was advised by ICES for 2023 in SA4.

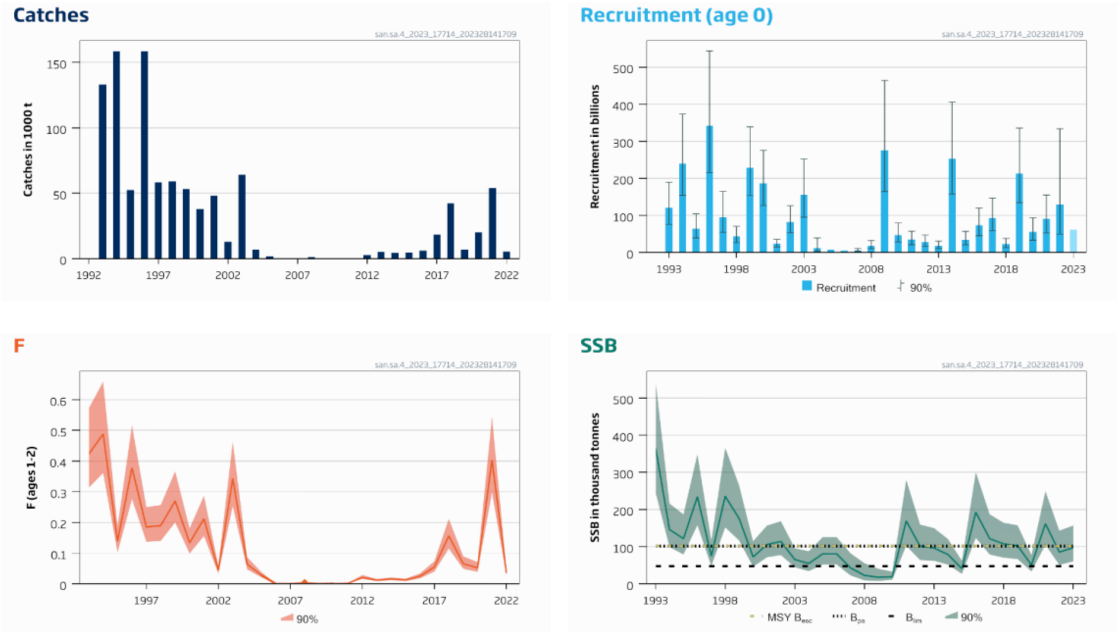


Figure 10: Summary of the stock assessment for SA4 in 2023 with catches, recruitment (2023 value corresponds to the geometric mean for the period 2012-2021), fishing mortality (F) and spawning stock biomass (SSB) in SA4. From ICES advice (2023).

2.3.3 Sandeel fishery

Sandeel is the target of the largest single-species industrial fishery in the North Sea. Sandeel are processed for their oil and fish meal for use in many types of food for human and animal consumption. Denmark, Norway, Sweden, UK, and Germany participate in the sandeel fishery (though no quota has been allocated to UK vessels since 2021), with Denmark being the main contributor to the sandeel landings. The fishery is highly seasonal, taking place mostly in the spring and summer. The sandeel fishery developed during the 1970s, and landings peaked in 1999 at 1.2 million tonnes. There has been a significant reduction in landings since 2003, with average landings of 880,000 tonnes for the period 1994 to 2002 and average landings of 300,000 tonnes for the period 2003 to 2016. The vessel size distribution of the fleet has changed through time, with a clear tendency towards fewer larger vessels (ICES 2007).

Currently fishing takes place in five out of seven management areas (SAs 1r, 2r, 3r, 4 and 6; **Figure 9**). Technical measures for the sandeel fishery include a minimum percentage (95%) of the target species for meshes <16 mm, or a minimum of 90% target species and maximum 5% of the mixture of cod, haddock, and saithe for vessels fishing with meshes of 16-31 mm. Since 2011, the fishery has been regulated by an area-based TAC. From 2005, Danish vessels have not been allowed to fish sandeel before 31 March. The sandeel fishery takes a significant bycatch of small whiting and, to a lesser extent haddock, and this component is explicitly modelled in the assessments for these species.

Figure 11 summarises the distribution of vessels fishing for sandeel in SA4 from 2014 to 2021. The data consist of two-hourly Vessel Monitoring System (VMS) location ‘pings’ from Danish and Swedish vessels, filtered for low speed (moving at ≤ 1 knot) to discount time spent moving between fishing areas or to/from ports. The information is presented as heat maps to avoid inference about specific vessel locations (as these data can be viewed as commercially confidential). Areas where the fleets were targeting Norway pout have not been included. The contouring algorithm used for the heat maps leads to some overlap into the closed area, but no such fishing occurred. Fishing was most widespread in these waters during 2015, but generally focussed on two areas during the years depicted: directly east of Aberdeen (Turbot Bank) and adjacent to the Scottish border with England. The fishing pattern was rather different in 2021, however, with a westward shift of both locations so that fishing was closer to the boundary of the closed area.

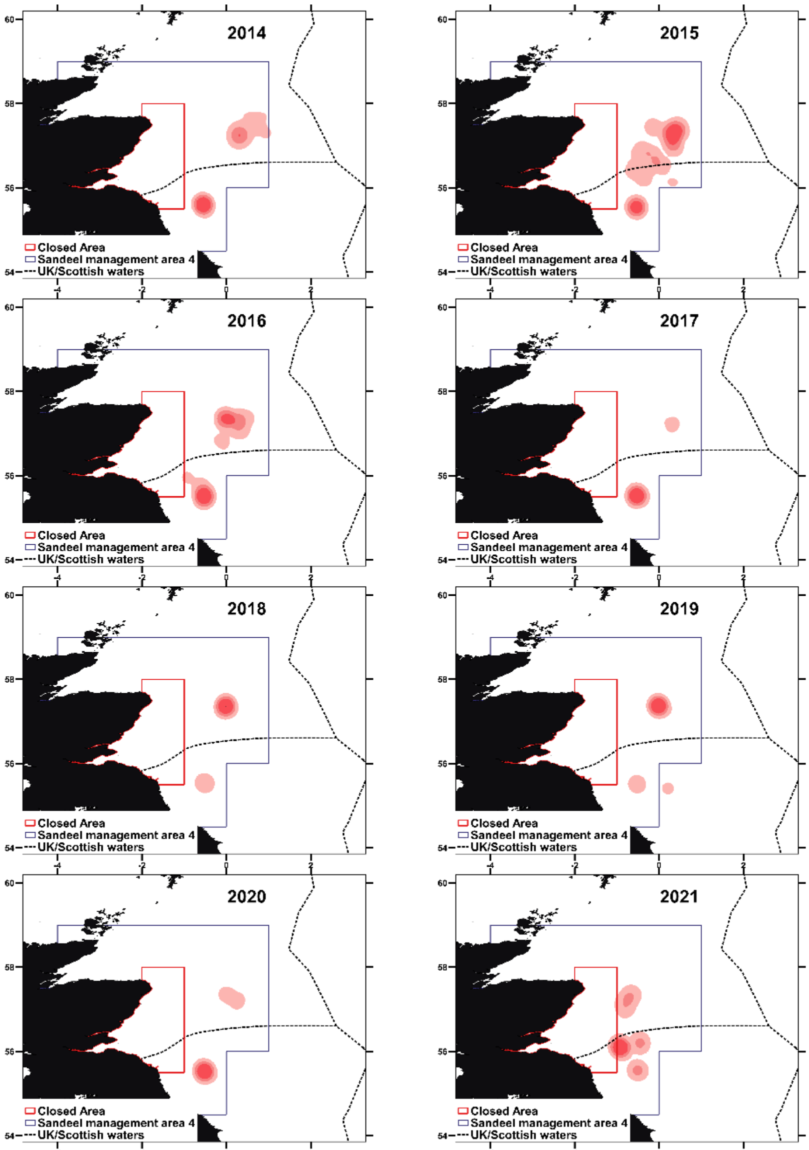


Figure 11: Heatmaps derived from VMS data from vessels fishing for sandeel, from 2014-2021, filtered for low speed. Darker red colours indicate more intensive sandeel fishing.

2.3.4 Spatial measures for sandeel within Scottish waters

2.3.4.1 Sandeel fishery closure

As a precautionary measure to safeguard marine top predators, particularly seabirds at internationally important colonies in and around the Firth of Forth, an area off the east coast of Scotland, from Rattray Head to St Abbs, was closed to industrial fishing for sandeel in 2000. The extent of the area is indicated in **Figure 12** and covers about 27% of SA4 fishing grounds historically targeted by the fishery (Jensen et al. 2011).

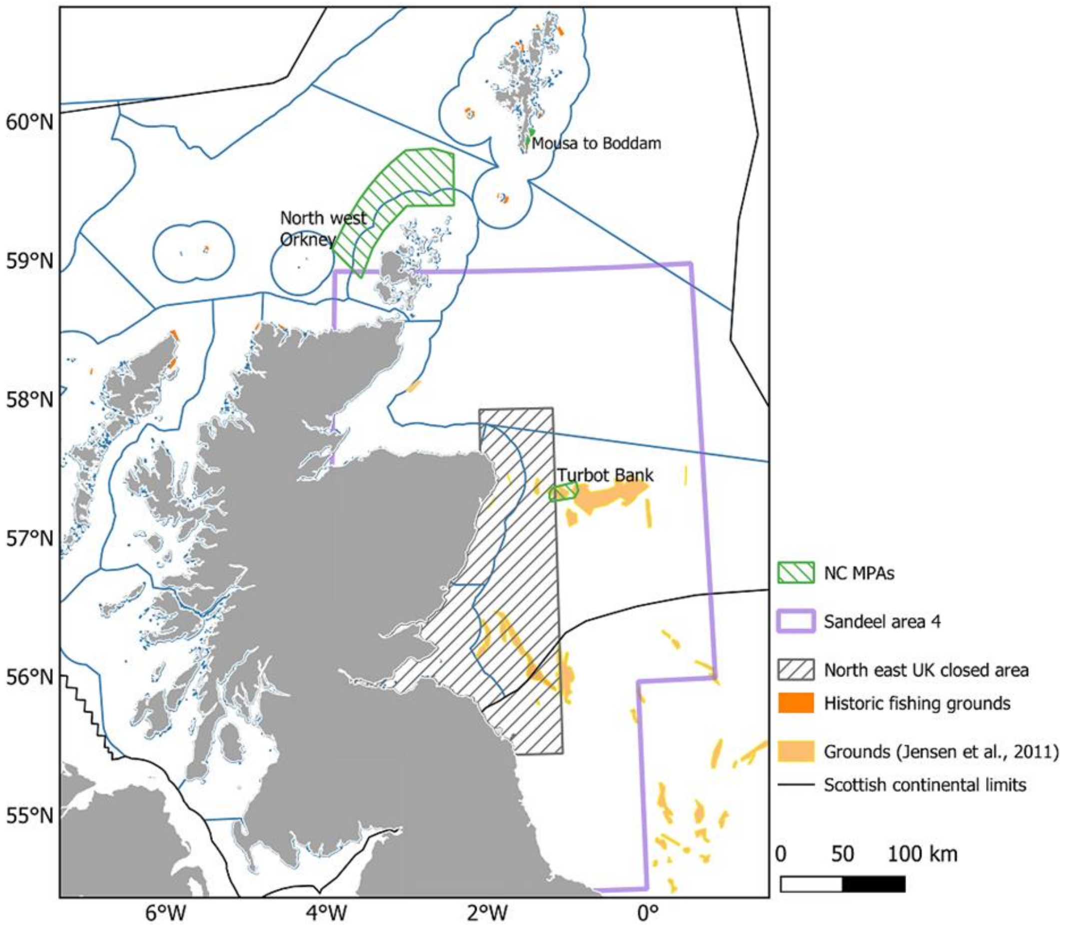


Figure 12: Map of Sandeel Area 4 and the various spatial measures for sandeel within Scottish waters. Blue lines show Scottish Marine and Offshore Regions for context.

Nature Conservation Marine Protected Areas (NC MPAs)

Due to their ecosystem importance, sandeel were made a Scottish priority marine feature and given their limited movements, various Nature Conservation (NC) MPAs have been designated with sandeel as a key conservation target (**Figure 12**). In 2014, following two public consultation exercises, the North West Orkney, the Mousa to Boddam and the Turbot Bank NC MPAs were designated under the Marine (Scotland) Act 2010 and Marine and Coastal Access Act 2009 to protect sandeel. Designations were based primarily on assessment of peer-reviewed scientific evidence, using the process as set out in the Scottish MPA Selection Guidelines. These areas demonstrated a regular presence of sandeel and were particularly important to adult aggregations (Turbot Bank), recruitment (Shetland) and/or larval export (NW Orkney, Turbot Bank), and had geophysical attributes supportive to sandeel populations, based on evidence from historic trawl, dredge and continuous plankton recorder (CPR) surveys, particle size analysis (PSA) and oceanographic modelling.

2.3.4.2 Evidence of an effect of the sandeel fishery closure

Evidence establishing the effect of the fishery closure is limited. The Marine Directorate led studies that compared measures of sandeel abundance before and during the closure (Greenstreet et al. 2006, 2010), relying on sandeel sampled during the summer months using a variety of gears (demersal trawls, pelagic trawls, acoustic surveys, dredges, and grabs). A substantial increase in sandeel biomass was observed in the Firth of Forth in 2000 and 2001 (i.e., the first years following the closure). This increase was found to be associated with high levels of recruitment in 1999 and 2000, combined with the lack of fishing pressure. However, the cause of the 2000 increase in sandeel biomass (high recruitment in 1999 and 2000) is unclear as it preceded any increase in the local spawning stock, so cannot be attributed to the closure. Since 2001, sandeel biomass has declined to reach levels in 2008-2009 that were similar to those observed in 1997 and 1998 when the sandeel fishery in the area was active (**Figure 13,** Greenstreet et al. 2010).

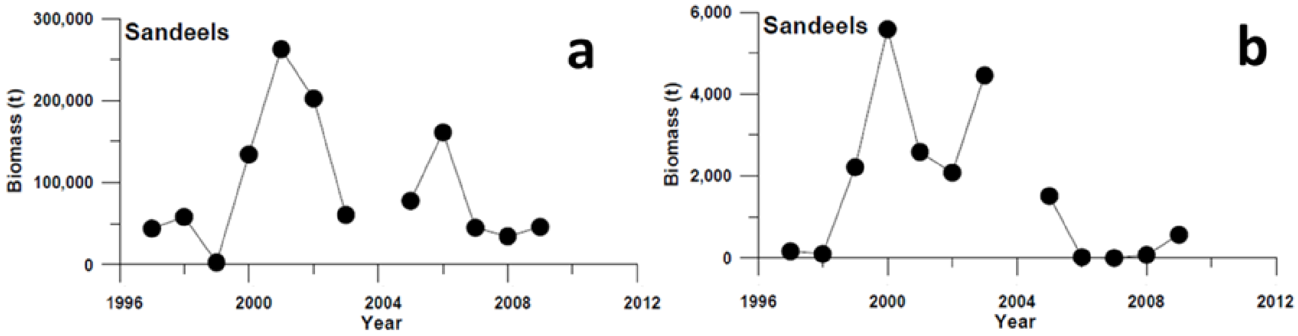


Figure 13: Sandeel abundance estimates in the Firth of Forth from a-fisheries acoustic surveys and b- demersal trawls (from Greenstreet et al. 2010).

Sandeel abundance for each age class estimated from these surveys was then found to be positively related to the breeding success of kittiwake between 1997 and 2003 (Daunt et al. 2008). Together, the sandeel biomass increase in the first years following the fishery closure and the positive relationships between sandeel abundance and kittiwake breeding success were used as evidence to maintain the closure in a review of the effectiveness of the closure (STECF, 2007).

While the trend observed is valid (an overall decrease of sandeel biomass despite the fishery closure), and the estimated sandeel abundance in the water column likely reflects the sandeel available to seabirds at this time of year (as the surveys were designed to coincide with the chick-feeding period), it is important to be aware of the limitations of these studies, particularly due to the timing of the surveys and the gear used. The surveys took place in summer, when some components of the sandeel populations (i.e., particular sizes and age-classes) are in the sand and others are in the water column (some close to the seabed, others closer to the surface). Sandeel activity and location at this time of year depends on size, age (size-assortative schooling), body condition, and local environmental conditions (e.g., water turbidity, local zooplankton abundance, disturbances). The biomass estimated using different gear (targeting sandeel in the water column, near the seabed or in the sand) can therefore be quite different (**Figure 13**). For example, biomass estimated from acoustic surveys in 2005 is the 3rd highest in the time-series but one of the lowest estimated from demersal trawls (**Figure 13**). Due to gear-specific selectivity, a composite abundance index from abundances estimated using different gear is challenging and as a result, abundance for the different age classes estimated from these surveys quite unreliable. Often high age 1 abundances are estimated in years following estimated low recruitments (Greenstreet et al. 2006, Daunt et al. 2008), therefore a poor correlation between the abundances of age classes belonging to the same cohort in consecutive years is often found in these surveys, questioning their reliability.

While sandeel catchability is low with a dredge, surveying sandeel in winter, when all sandeel are in the sand is accepted as the most reliable method to estimate abundance for each age class in sandeel (ICES 2010). Unfortunately, the Scottish dredge survey was discontinued between 2003 and 2008, creating a gap in the time-series in the period following the fishery closure. However, abundance indices from the Marine Directorate winter dredge survey are able to confirm the observations of high sandeel biomass in 2000 and 2001 (**Figure 14a**) resulting from strong recruitment in 1999 and 2000 (**Figure 14b**). Such high sandeel abundances have not been observed in the survey since 2001. The survey also shows that recruitment is highly variable without any trend, and that the strong recruitment observed in 1999 and 2000 has been exceeded in 2009 and 2020, without leading to sandeel abundance estimates greater than the ones observed in 2000-2001. This result indicates that other sources of mortality besides fishing mortality, possibly related to environmental change, played a greater role in shaping sandeel abundance in the area over the period considered.

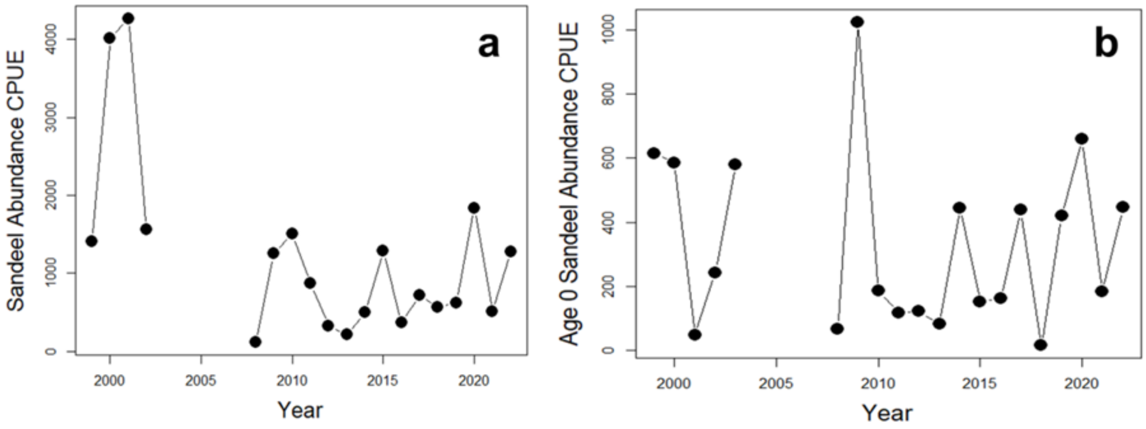


Figure 14: a-Sandeel abundance index (total of age 0, age 1 and age 2 sandeel) and b-Age 0 abundance index (Recruitment) from the Marine Directorate winter dredge survey in the Firth of Forth.

Therefore, predicting the effect of further fishery closures on sandeel abundance and their availability to marine top-predators is difficult, as the effect of the closure could be concealed by other sources of mortality. This could be reflected in the data following 2000, as other factors such as environmental forcing or high natural mortality rates may influence sandeel abundances irrespective of anthropogenic pressures (Poloczanska et al. 2004).

An alternative approach in estimating the future effects of any closure would be to examine mortality indices taken from fished and unfished areas. In the last year, the Marine Directorate winter dredge survey data, as well as the corresponding Danish survey data, have been made available online. These data (compiled between 2009 and 2021) were used to calculate a mortality index for age 1 fish (as age 1 sandeel are the main age class caught by the fishery) by tracking cohorts at stations across the North Sea and comparing spatial variation in the mortality index both within and between sandeel management areas. The results displayed in **Figure 15** show that sites in the Firth of Forth and the closed area within SA4 have the lowest age-1 mortality indices compared to stations outside of the closed area or in other management areas where the fishery operates. It is also evident from **Figure** 15a that age 1 mortality is higher at the north end of the closed area and inshore in the Moray Firth. While this area is not targeted by the sandeel fishery, significant fishing activity does occur (Mapped Outputs - Scottish Marine and Freshwater Science Volume 5 Number 17: ScotMap Inshore Fisheries Mapping in Scotland: Recording Fishermen's use of the Sea - gov.scot (www.gov.scot)) and suitable spawning and nursery grounds of piscivorous fish have been identified in the area (González-Irusta & Wright 2016a, b, 2017), therefore higher mortality in the area may result from both bycatch from other fisheries and higher predation mortality.

While differences in mortality between closed and open areas in the North Sea may appear small in **Figure 15b,** because the mortality index is calculated on log transformed abundance indices, the reduced mortality rate in the closed area of SA4 translates into a larger proportion of age 1 sandeel surviving. However, these results should be treated with caution, as other sources of mortality may have differing impacts in the various management areas. For example, data from the other management area used in the comparison originates from the Danish survey which takes place in winter, but earlier than the Marine Directorate survey. These potential confounding factors are absent from the comparison of mortality indices between the closed and open area within SA4, however the very low sample size in the open area (N=7) is not sufficient to draw definitive conclusions. While these results seem to provide evidence supporting the effect of the fishery closure on age-1 sandeel mortality, translating into increased age 1 abundance, the lack of samples in the part of SA4 currently open to the fishery limit our ability to conclude decisively.

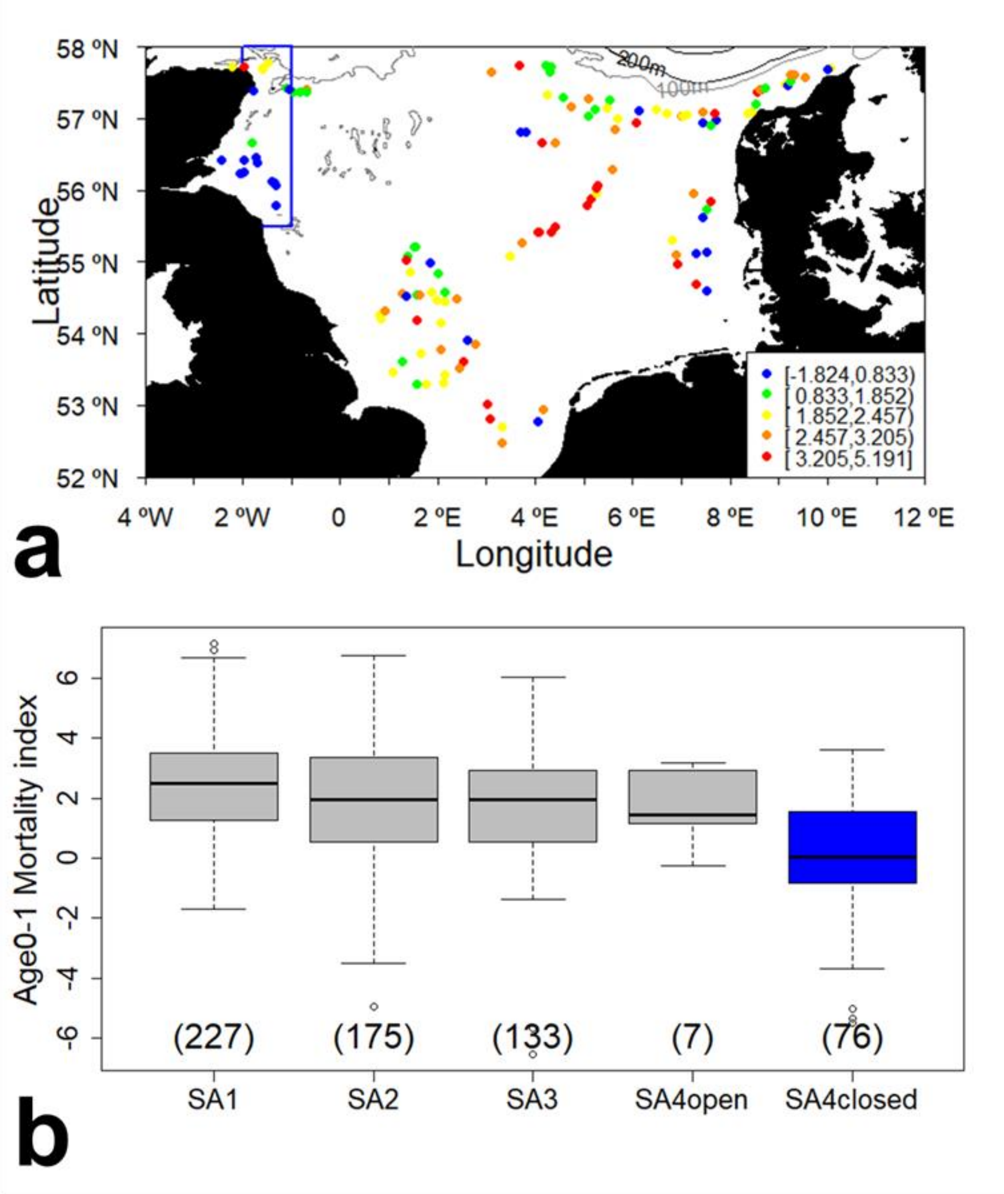


Figure 15: a-Map of stations surveyed by the winter dredge survey (the Marine Directorate and Danish surveys compiled). Colours indicate the average age 0 to 1 mortality index, with blue and red referring to the lowest and highest mortality respectively. The closed area is marked by a blue line. b- A boxplot comparison of the mortality indices between the different sandeel management areas, and the open and closed area (in blue) within SA4. Numbers between brackets correspond to the sample size (number of years and stations) used to produce the figure.

2.3.5 Summary of Evidence on the potential effects of fishery closure on sandeel

Causes of variation in sandeel abundance are numerous and are driven by fishing mortality and (principally) natural mortality, the latter being influenced by factors such as environmental change (temperature effects, regime shifts) and top-down processes (trophic regulation by marine predators). Evidence shows that causes of variation in natural mortality played a more prominent role than fishing mortality in shaping sandeel abundance in Scottish waters and as these causes of variation are rarely accounted for, an effect of fishing pressure on sandeel abundance is seldom observed. However, while results should be considered with caution, age 1 sandeel seem to have a higher survival rate in the current fishery closure.

While the effect of a fishery closure may be difficult to observe in a changing environment, sandeel are likely to benefit from spatial management measures aimed at reducing fishing mortality due to their life-long attachment to particular sand banks and limited dispersal and movements. As represented in **Figure 16,** variations in Spawning Stock Biomass (SSB) are mainly driven by variability in recruitment.

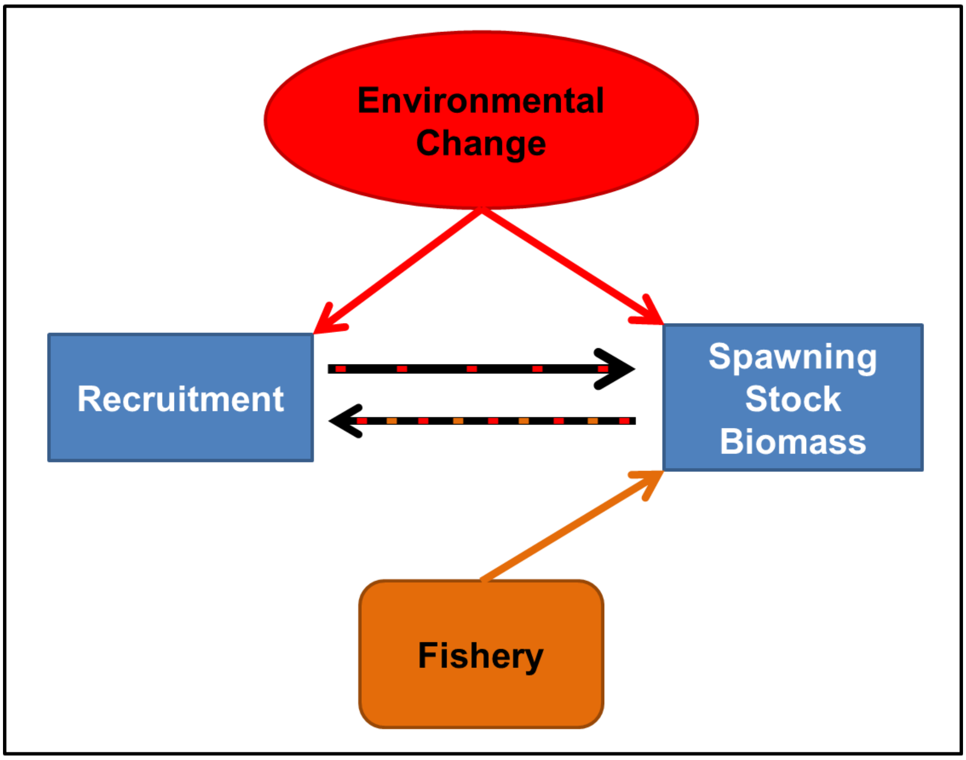


Figure 16: Diagram representing the pressures affecting sandeel biomass.

Here recruitment, to a certain extent, is contingent on the size of the reproductive population (SSB). Environmental change has a multitude of effects (direct and indirect) and can affect SSB through the maturation process (see section 3.2.1 Direct temperature effects on physiological rates); recruitment through the effects on phenology (spawning date, incubation time, hatching date); and trophic mismatch between sandeel hatching and the availability of their copepod prey. The fishery can directly affect SSB through fishing mortality and there is some evidence that it may also indirectly affect recruitment by decreasing SSB (through mortality) or by reducing the abundance of large individuals which have a higher fecundity and may spawn earlier (which in turn may affect trophic mismatch and interact with climate change effects). A fishery closure may therefore promote sandeel resilience to climate change by limiting variation in SSB that might affect recruitment and ensuring that sufficient large, early spawning individuals are present in the population. In accordance, a modelling study found that population collapse was more likely under exploitation (Poloczanska et al. 2004).

3 Fisheries

3.1 Predation on sandeel

Initial analyses of fish stomach contents by ICES (of which the most recent analysis is 1991; ICES 1997) revealed that sandeel constituted up to 20% of age 1 cod diet in July-September and between 5-10% of the diet in other age classes in April to September, when sandeel actively feed. In haddock, sandeel constituted >50% of age 0 fish in April to June and between 40-50% of the diet for all other age classes in July to September. In whiting, sandeel composed around 45% of the diet of all age classes in April to June and decreased to around 20% in July to September. Whiting body condition was also found to be correlated with the amount of sandeel present in their stomachs (Engelhard et al. 2012) and their spatial distribution was found to be influenced by sandeel, with whiting found to aggregate near sandeel-rich areas (Temming et al. 2004, Engelhard et al. 2008).

Following these initial analyses, the ICES Working Group on Multispecies Assessment Methods (WGSAM) recommended the use of natural mortality estimates from the North Sea Stochastic Multispecies Model (SMS) key-run for both southern and northern North Sea sandeel. Multispecies models of fish stocks in the North Sea help determine which species prey on which other species, and how important such predation is for total mortality. Predation mortalities are estimated every three years and are based on recent analytical stock assessment data, available data on predators not included in the SMS (including mammals, birds, and other fish), as well as historical sampling data on stomach contents of predators. Results for northern North Sea sandeel are presented from the most recent SMS key-run from 2020 (ICES, 2021). In **Figure 17**, annual predation mortalities (expressed as M2, the natural logarithm of the ratio of abundance in year t to abundance in year t +1) are shown by age class.

Predation mortality is relatively high for this stock and is considerably higher than fishing mortality in younger ages. Young sandeel are preyed upon particularly by haddock, saithe, and birds, as well as by grey gurnard in recent years. Older ages (>2 years) are preyed upon to a larger extent by grey seal as well as haddock and saithe. In **Figure 18,** the overall biomass of sandeel eaten by predators is illustrated. An increasing proportion of sandeel is taken by grey gurnard and grey seal. While predation by mackerel, saithe, and birds is assumed relatively constant over time, a decreasing proportion of the biomass is taken by cod and horse mackerel due to their decrease in abundance in the North Sea since the 1980s and 1990s respectively.

There were no simulations run to evaluate the impact on other fish species of lowering the fishing mortality of sandeel following a closure. From personal communication with WGSAM experts, it seems the impact for other stocks of lowering fishing mortality (F) of sandeel is likely to be small in the current set up of the SMS key run (ICES, 2021). Whilst predator species may show higher proportions of sandeel in their diets following an increase in sandeel biomass, it should be noted that the SMS key run does not include a feedback loop to directly infer predator abundances. **Figure 19** shows the estimated annual amount of sandeel overall eaten by all predators as compared to other prey species. Northern and Southern sandeel

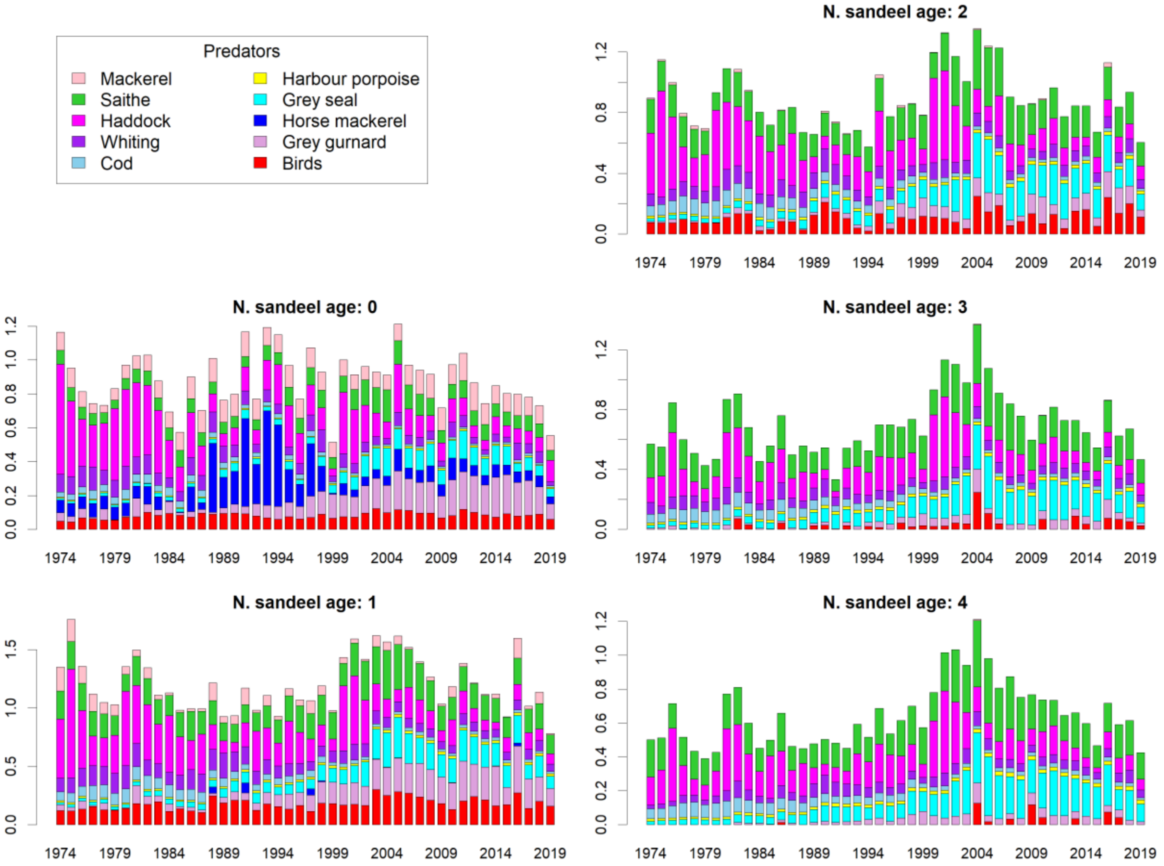


Figure 17: Annual predation mortality (M2, the natural logarithm of the ratio of abundance in year t to abundance in year t +1) on Northern North Sea sandeel for each age class as estimated in WGSAM North Sea SMS key run 2020 (ICES, 2021).

taken together constitute a large proportion of predators' diets in the North Sea. The proportion of northern North Sea sandeel in the diet of predators increased in recent years following a recent increase in SSB of northern North Sea sandeel.

The amount of sandeel consumed by predators will also depend on predator stock abundance and spatial distribution. Northern shelf haddock and North Sea whiting have shown a strong recent increase in stock size (ICES, 2022b), which could lead to increase in predation on sandeel. Spatial distributions for cod, haddock and whiting are illustrated for quarter 1 surveys in **Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, Figure 25**. On the other hand, NE Atlantic mackerel, Northern shelf saithe and grey gurnard have shown a decreasing trend in stock size (ICES 2022b,c).

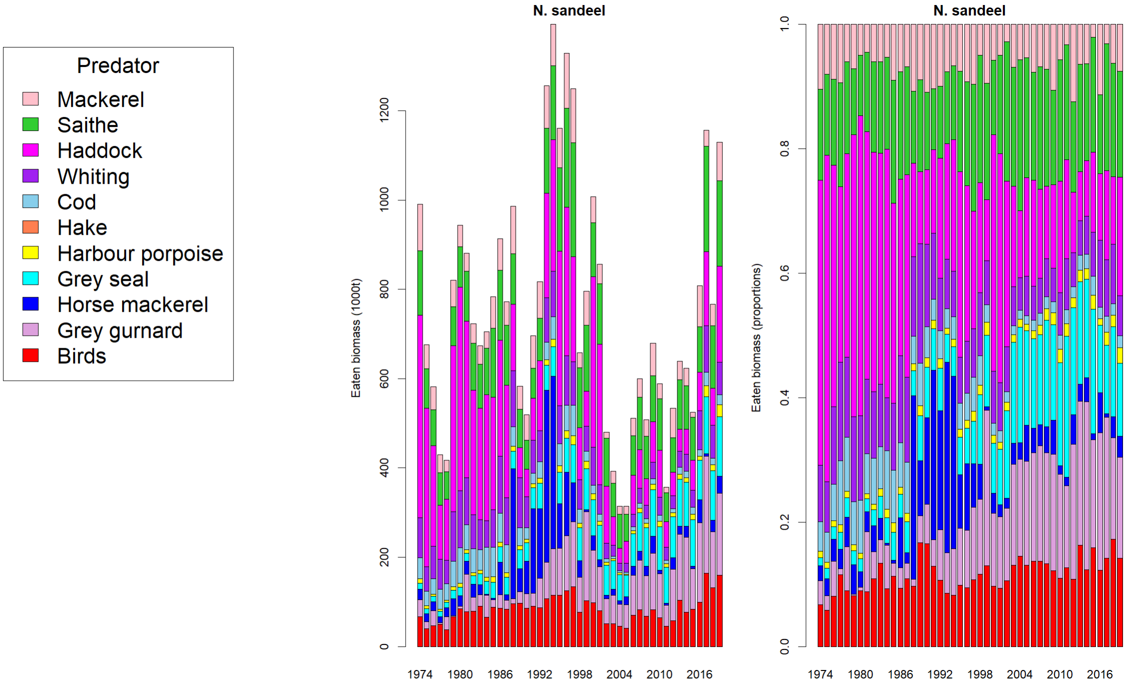


Figure 18: Annual biomass of Northern North Sea sandeel consumed by predators (1000t or proportions) as estimated in WGSAM North Sea SMS key run 2020 (ICES, 2021).

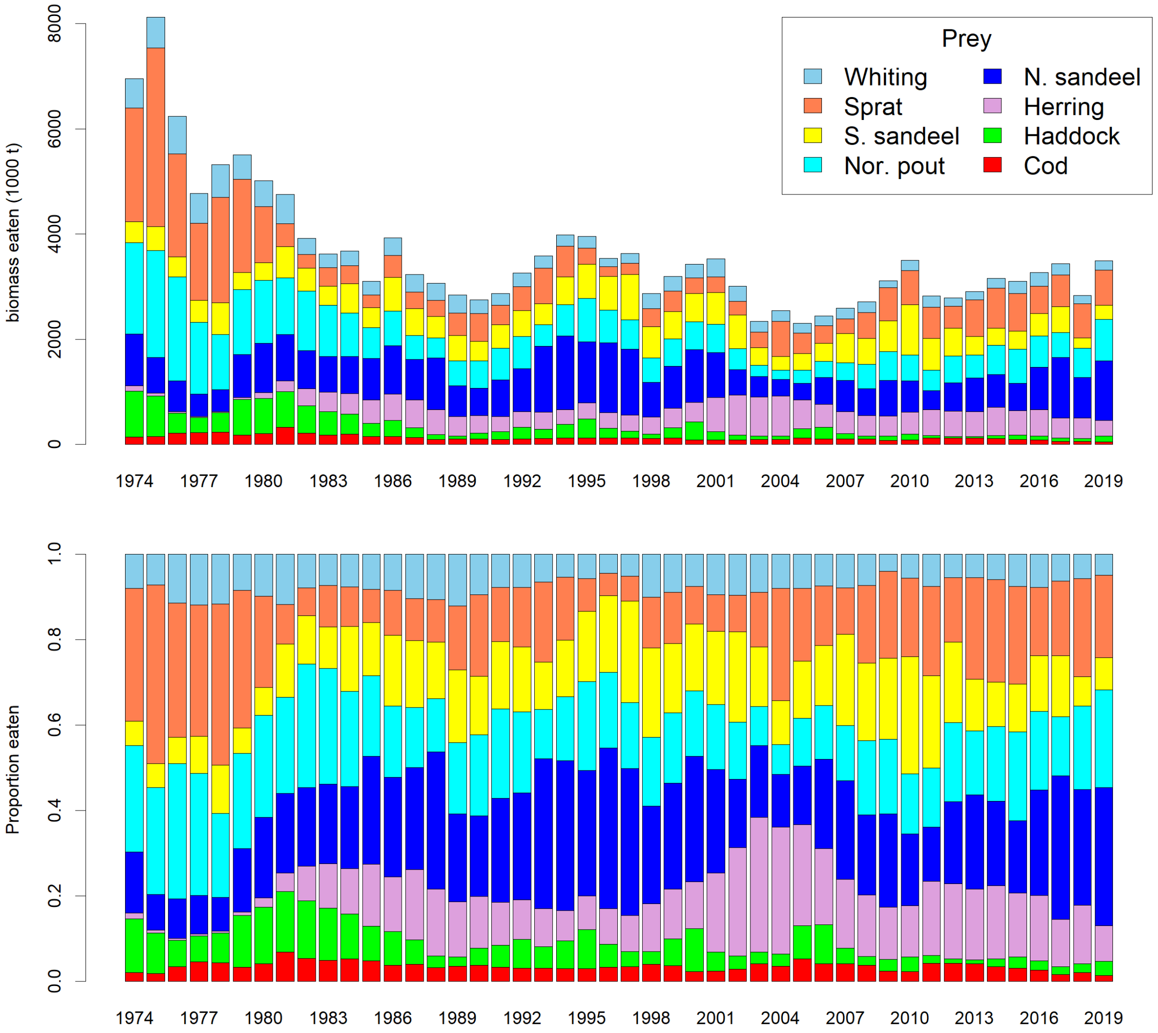


Figure 19: Annual biomass of prey species (northern North Sea sandeel in dark blue) consumed by all predators (1000t or proportions) as estimated in WGSAM North Sea SMS key run 2020 (ICES, 2021).

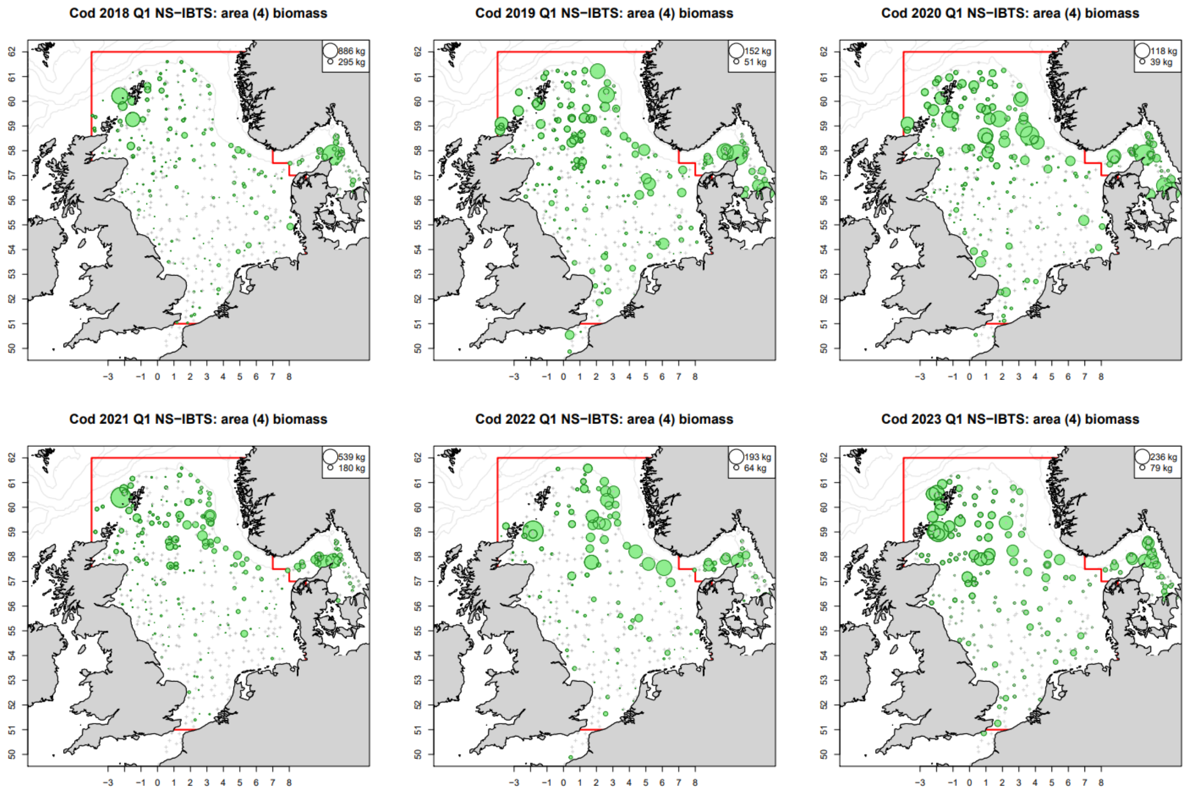
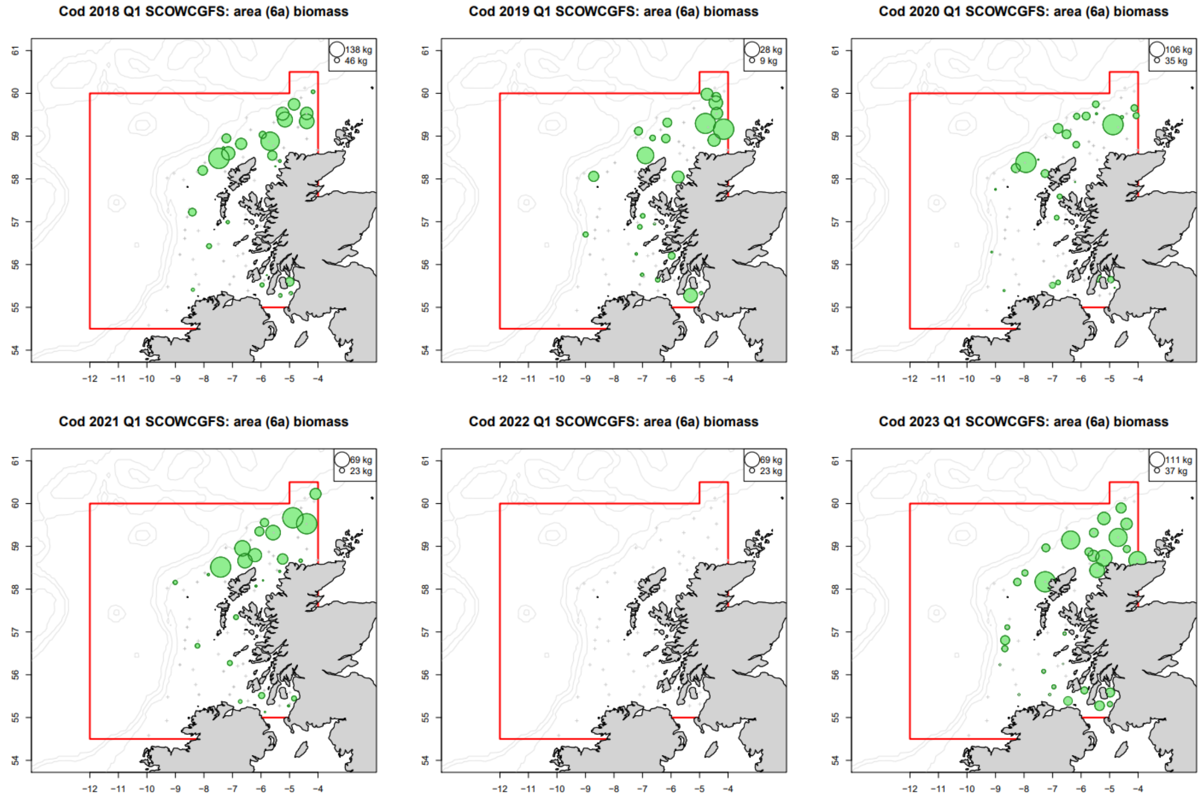


Figure 20: Distribution of cod biomass in the North Sea IBTS Q1 survey 2018-2023. circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.


Cod 2018 Q1 SCOWCGFS: area (6a) biomass

Cod 2019 Q1 SCOWCGFS: area (6a) biomass

Cod 2020 Q1 SCOWCGFS: area (6a) biomass

Cod 2021 Q1 SCOWCGFS: area (6a) biomass

Cod 2022 Q1 SCOWCGFS: area (6a) biomass

Cod 2023 Q1 SCOWCGFS: area (6a) biomass

Figure 21: Distribution of cod biomass in the SCOWCGFS Q1 survey 2018-2023. circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.

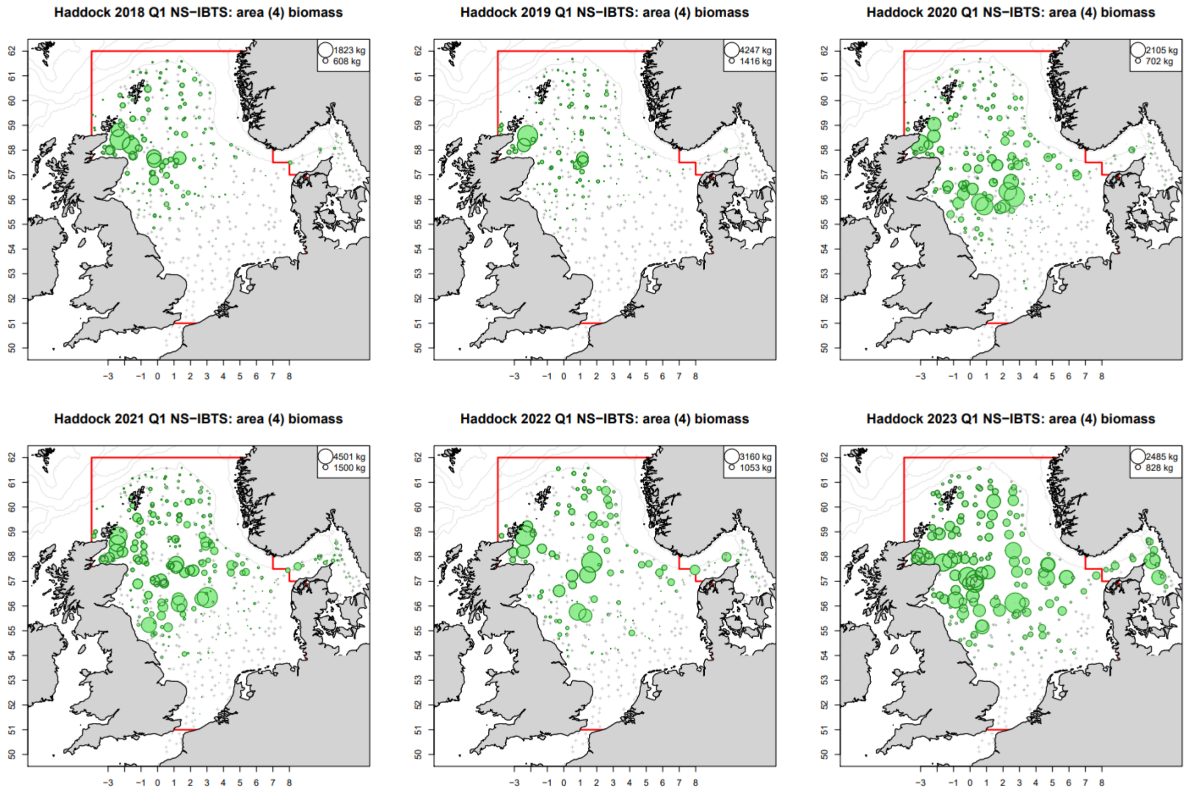


Figure 22: Distribution of haddock biomass in the North Sea IBTS Q1 survey 2018-2023. Circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.

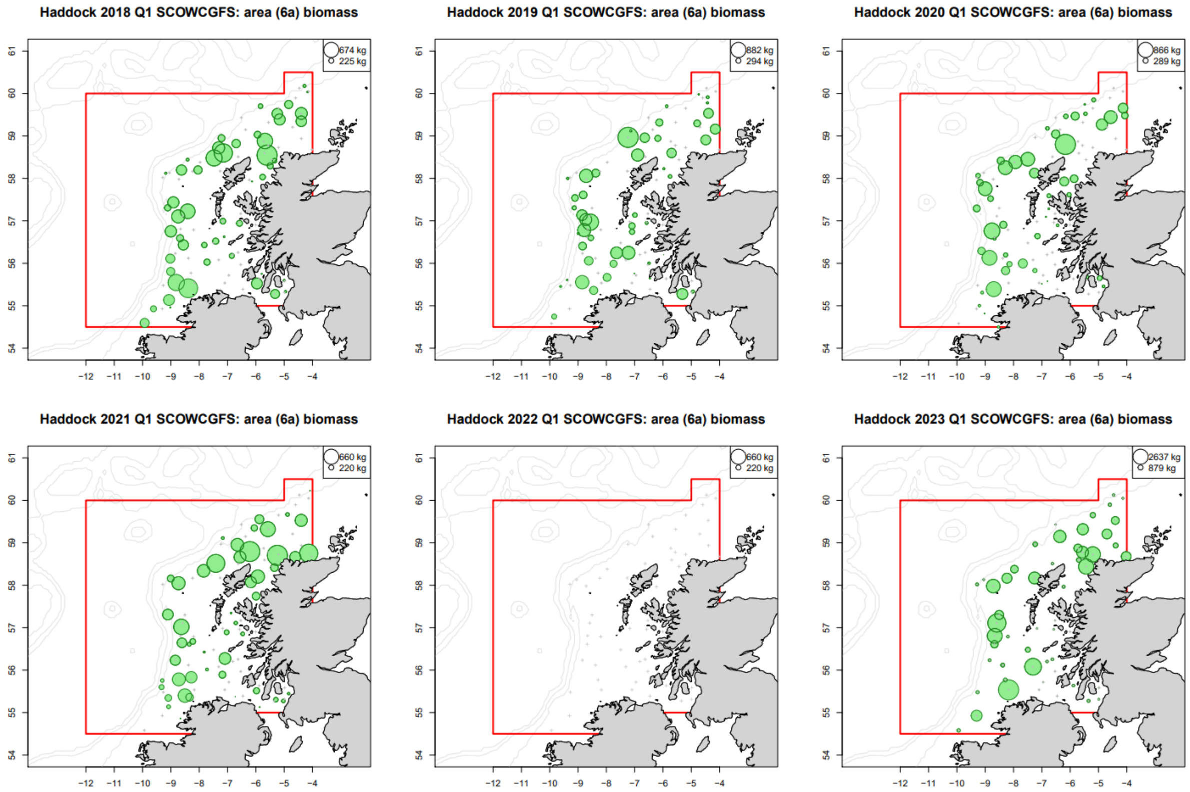


Figure 23: Distribution of haddock biomass in the SCOWCGFS Q1 survey 2018-2023. Circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.

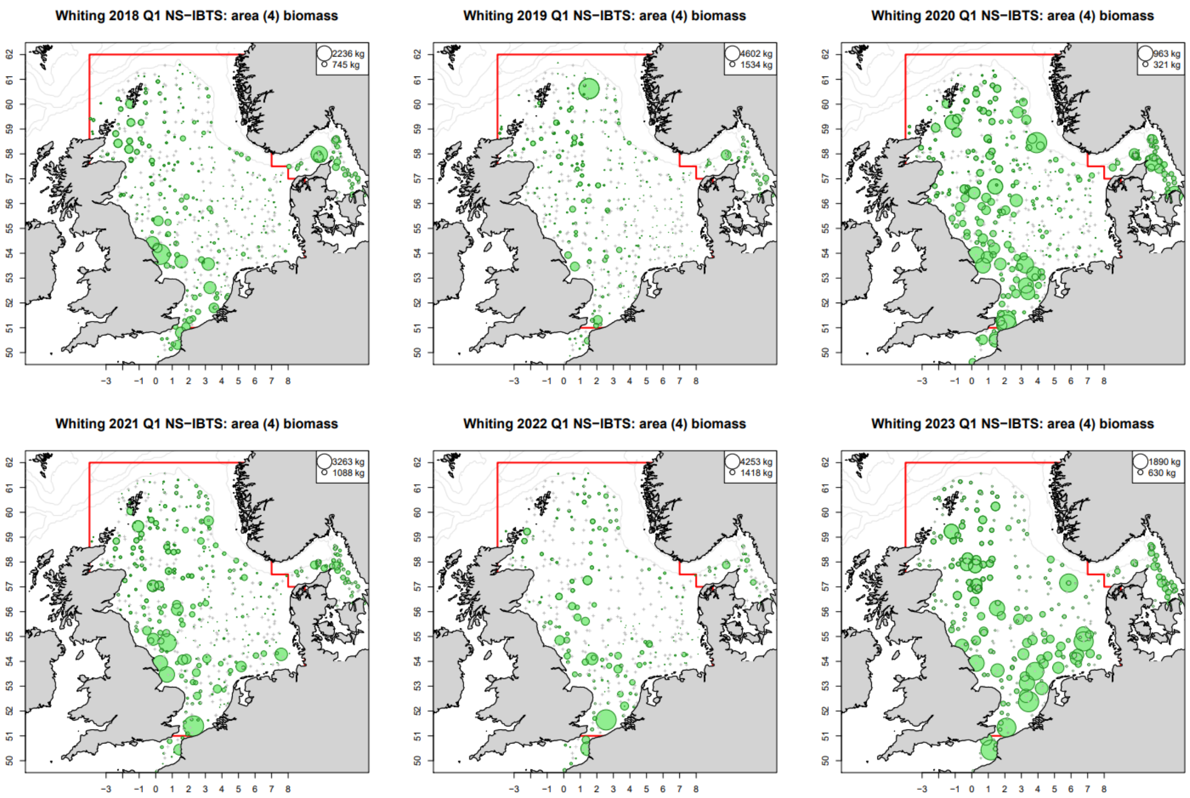


Figure 24: Distribution of whiting biomass in the North Sea IBTS Q1 survey 2018-2023. Circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.

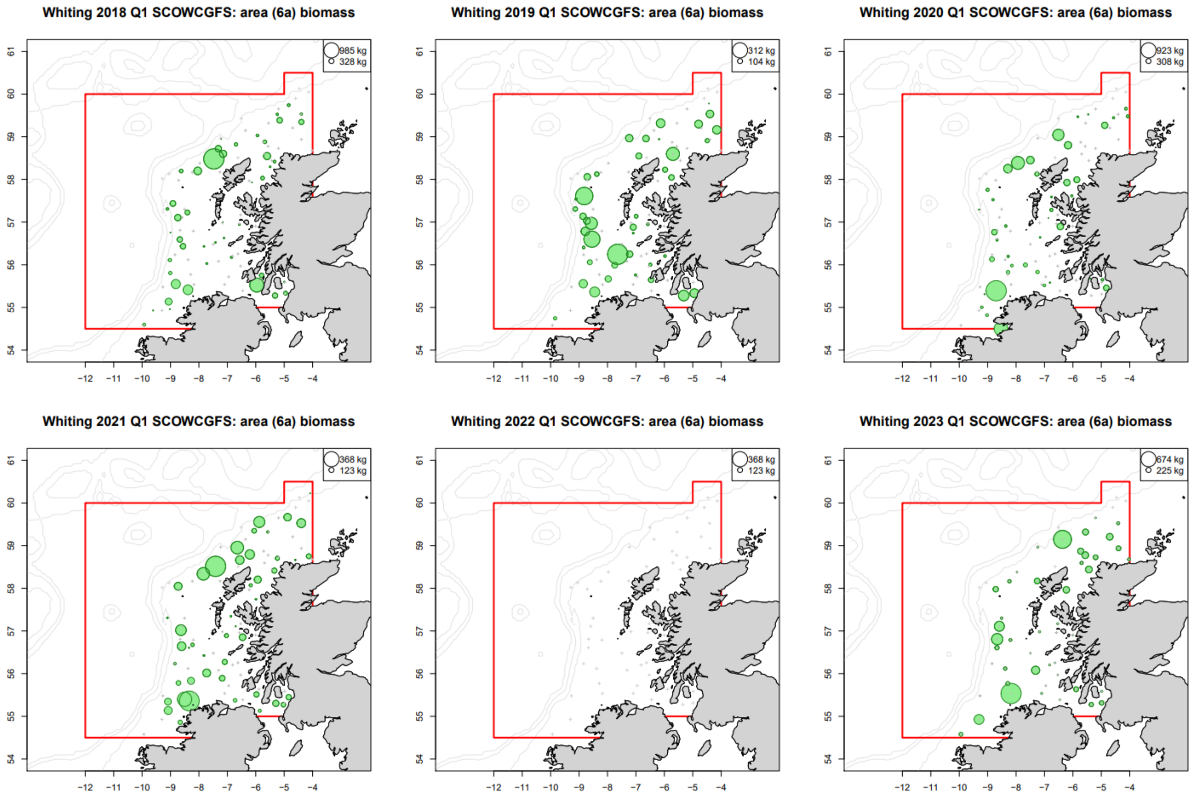


Figure 25: Distribution of whiting biomass in the SCOWCGFS Q1 survey 2018-2023. Circles in the distribution maps are proportional to the square root of the weight of fish caught per hour at each haul location, scaled so the maximum is always the same size as indicated in the legends.

3.1.1 Benefits of a sandeel closure on predatory fish

Predatory fish are often generalist feeders, where the diet typically consists of no more than 20% of any species, as predators switch between prey species based on availability (Engelhard et al. 2014, Trenkel et al. 2005). The importance of sandeel as a food source is more variable for predatory fish than for seabirds and mammals (Engelhard et al. 2014). Some fish species such as whiting, haddock, cod, plaice, lesser weever and grey gurnard have shown higher body condition indices or growth in years of high sandeel abundances (Engelhard et al., 2013; Rindorf et al., 2008). Body condition relates to growth, survival and reproduction and can thereby affect fitness and abundance of predators.

As previously noted, complex environmental interactions, including dynamics in predatory fish populations, competition for food sources, cannibalism and climate change may also affect the abundance of sandeel in the North Sea, making prediction of sandeel stock development following a fishery closure difficult (Arnott & Ruxton 2002, Eigaard et al. 2014, Engelhard et al 2014, Furness 2002, Furness 2003, Henriksen et al. 2021, Frederikson et al. 2007, van Deurs et al 2009).

3.2 Bycatch by sandeel fishery of other species

With the data currently available, it is not possible to comment definitively on the quantity of other fish caught in the fishery directed at sandeel after 2020. Estimates of "industrial bycatch" are included in ICES assessments for haddock and whiting in the North Sea, but these cover fisheries for sandeel, Norway pout and sprat, and it is not possible to distinguish bycatch from these fisheries at present. There is also an "industrial" component to the herring assessments in the North Sea and Skagerrak, but that represents fishing for small herring, rather than specifically sandeel fishery bycatch. So, while it is certainly the case that sandeel fisheries do include some bycatch of other fish, and for whiting in particular this may be considerable, it is not possible to quantify the bycatch component of the sandeel fishery due to a lack of detail in the ICES data collation. However, data are available for the 2017-2020 period to indicate the bycatch of other species in the international fishery directed at sandeel in UK waters. The average bycatch percentage by weight over these years was 0.05%.

3.3 Displacement of fisheries

One common response of a fishery to an area closure is displacement, in which the vessels concerned move to a different area to fish (spatial displacement) or change their fishing gear and methods to focus on different species (species switching). The fishery distribution plots in **Figure 11** show that there remains significant sandeel fishing activity in Scottish waters. The current ICES advice for sandeel indicates that the assessment model doesn't take account of the current Scottish closure, meaning that the available TAC must be taken from a smaller area than intended. This situation would be exacerbated if the closure was extended. However, without a robust model of fleet dynamics (which does not yet exist for these fisheries) or an extensive consultation with the international fishing industry, it is impossible to determine what the response of the fleet would be to an area fisheries closure in Scottish waters.

3.4 Summary of Evidence on Fisheries and Sandeel

The evidence of the effect of a fishery closure on sandeel and related predatory species is currently unclear. As sandeel stock dynamics are driven more by environment and ecosystem effects, rather than by fishing, it is similarly difficult to predict the effect on the sandeel stock of a reduction in fishing mortality. There has been an overall decrease in predation mortality on sandeel from 2005 until 2020. However, a reduction of fishing mortality could promote resilience in local sandeel populations by providing a buffer against an increase in predation mortality as predator stocks increase in abundance (for example recent positive stock trends for whiting and haddock). It is also not possible to comment on the quantity of other fish caught in the fishery directed at sandeel, with the data currently available. Finally, without a robust model of fleet dynamics (which does not yet exist for these fisheries) or an extensive consultation with the international fishing industry, it is impossible to determine what the response of the sandeel-directed fleet would be to an area fisheries closure in Scottish waters.

4 Seabirds

Scotland holds internationally important numbers of breeding seabirds, with 24 species regularly breeding in Scotland (Mitchell et al. 2004). A large proportion of these species include sandeel in their diet during the breeding season. The ability of seabirds to prey on sandeel will depend on both the absolute numbers of sandeel (stock biomass) and the availability of sandeel to seabirds. Seabirds are constrained in both the distance from nest sites that they can forage (when breeding) and the depth in the water column that they can reach, with both foraging range and dive depth varying greatly among species.

4.1 Sandeel stock biomass and availability to seabirds

The estimated sandeel total stock biomass (TSB) in the SA4 region off eastern Scotland, has fluctuated greatly over the last seven decades (ICES 2022, **Figure 26**). Drivers of sandeel stock biomass are discussed in detail in section 2 and include bottom-up processes such as environmental effects on sandeel copepod prey and density dependent regulation, and top-down effects such as natural predation by piscivorous fish, marine mammals and seabirds, as well as fishing.

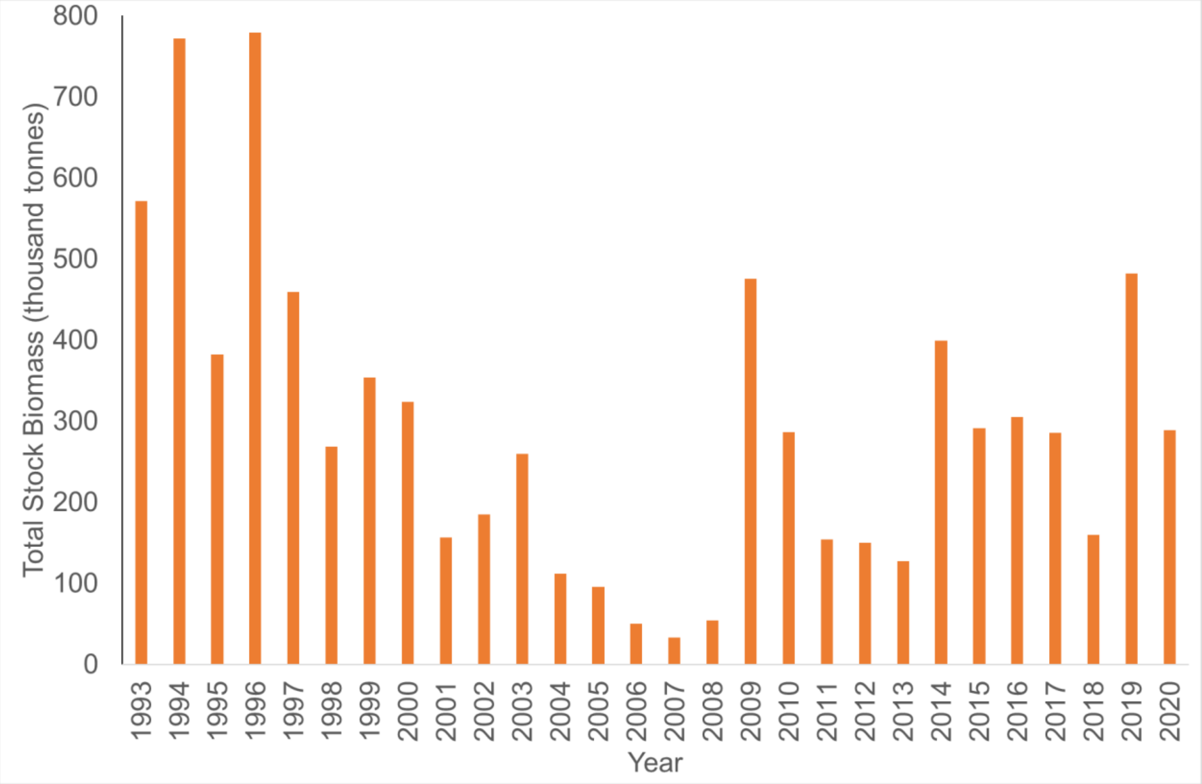


Figure 26: Estimated total stock biomass (TSB), for sandeel fishery area SA4 over the last 29 years. Reproduced from Table 9.5.10 in the Herring Assessment Working Group for the area south of 62°N (HAWG). ICES Scientific Reports 4:16.

4.1.1 Sandeel in the water column and availability to different seabird species

Following the planktonic larval stage, sandeel are only in the water column for a few months of the year. The extent to which seabirds can dive down into the water column to obtain sandeel at different depths varies greatly among species. Surface feeding seabirds, such as terns (Sterna sp) and black-legged kittiwake (Rissa tridactyla, hereafter kittiwake), can only take fish very close to the surface whereas other species such as common guillemot (Uria aalge, hereafter guillemot), razorbill (Alca torda) and Atlantic puffin (Fratercula arctica, hereafter puffin) can dive to considerable depths. Guillemot and European shag (Gulosus aristotelis, hereafter shag) can also extract fish from the sediment on the seafloor and so can feed on sandeel even when they are not in the water column.

The period during which sandeel are in the water column shows inter annual variation. The timing of the sandeel' seasonal return to the sediment is highly important for surface feeding seabirds as an early return to the sediment can result in sandeel no longer being available towards the end of the seabird breeding season.

4.2 Prevalence of Sandeel in Seabird Diet

The extent to which seabirds are dependent on sandeel varies among species. For example, guillemot have been shown to have greater capability to switch to foraging on sprat and small herring when sandeel are unavailable compared to kittiwake (Rindorf et al. 2000). See **Table 2** for a list of seabird species known to prey on sandeel.

During breeding many Scottish seabird populations exploit seasonal peaks in sandeel abundance, feeding on both adult (1+ year group) and juvenile (young-of-the-year; age 0) age classes. For example, on the Isle of May, Firth of Forth, which is one of the best studied seabird colonies in the world, sandeel comprised approximately 75% of the breeding season diet of shag, kittiwake and puffin between 1991 and 2011 (Newell et al. 2013). Sandeel also constituted a substantial proportion of the diet of seabirds breeding on Canna, Western Isles between 1981–2007 (Swann et al. 2008). Over this period sandeel were the greatest component (62%) of regurgitations from young shag and adults feeding chicks, comprised a quarter of young guillemot diet, and occurred in 60% of kittiwake regurgitations, being the commonest fish family in 14 of the 20 years in this latter seabird species' diet (Swann et al. 2008).

Many seabirds in Scotland display seasonal shifts in diet composition from larger adult to smaller juvenile sandeel throughout breeding (Phillips et al. 1999; Lewis et al. 2001; Lewis et al. 2003; Wilson et al. 2004; Howells et al. 2017; Harris et al. 2022), which is consistent with sandeel life history (Winsdale 1974). For example, adult kittiwake generally switch from feeding on older sandeel at the start of breeding (April/May) to juvenile sandeel (for both self-feeding and their young) as the season progresses (Harris & Wanless 1997; Lewis et al. 2001). Similarly, in shag the proportion of adult sandeel decreases and juvenile sandeel increases throughout the breeding season (Howells et al. 2017). Spatial variation in diet composition is also apparent, with the importance of sandeel varying among seabird colonies of the same species, likely linked to local environmental conditions, foraging distributions and prey availability (Bull et al. 2004; Anderson et al. 2014; Wilson et al. 2021).

Due to the challenges of studying seabird diet in the non-breeding season, when birds are at sea and away from their colonies, less is known about the importance of sandeel in seabird diet during this period (Barret et al. 2007). Despite this, the limited information that exists suggests that seabirds forage on a wider variety of prey during the non-breeding season, but still include sandeel to some extent (Blake 1985; Howells et al. 2018). For example, Howells et al. (2018) identified that the frequency of sandeel occurrence in shag diet decreases markedly between the breeding and non-breeding season. Using stomach contents from shot birds, Blake (1985) also identified differences between the breeding and non-breeding seasons, with sandeel dominating between March and August and a changeover occurring in September when clupeid and gadoid remains became increasingly frequent. Thus, while sandeel are preyed upon by Scottish seabirds throughout the year, other prey are also important in the non-breeding season to a varying extent.

While sandeel have traditionally been considered one of the most abundant and energy rich prey for seabirds in Scotland (Dunnet et al., 1990; Hislop, Harris and Smith, 1991; Furness and Tasker, 2000), the availability, size and calorific content of this species has declined in recent decades (Wanless et al., 2004, 2005; Frederiksen et al. 2013; Wanless et al. 2018). As a result, many seabird populations now appear to have a reduced dependency on sandeel, although this can be highly variable among years and colonies (Wanless et al. 2004, 2005; Heubeck 2009, Anderson 2018; Howells et al. 20017, 2018; Wanless et al. 2018). For example, in a comprehensive long-term, community-level analysis of seabird diet on the Isle of May between 1973 and 2015, Wanless et al. (2018) identified reductions in the importance of sandeel in seabird diet, along with a decline in adult (age 1+) relative to juvenile (age 0) sandeel. Further, by combining data on sandeel length and energy density in the diet of seabirds, Wanless et al. (2018) identified overall reductions in average energy values of both adult (c.70% reduction) and juvenile (c.40% reduction) sandeel over the past 4 decades. This reduction was detected in both inshore and offshore foraging seabird species, suggesting a widespread pattern of change. While concurrent, independent time series data on prey abundance at a spatial scale relevant to seabird breeding foraging ranges are lacking, the available fisheries data, collected over a much wider area and coarser resolution, were broadly in line with these observed changes - indicating that sandeel have become significantly shorter in length and lighter than those in central and north-eastern areas (Rindorf et al. 2016; Wanless et al. 2018). Whilst energy density (kJg^{-1}) per gram of sandeel did not decline between 1973-2015 (Wanless et al. 2018), the absolute amount of energy per fish will be lower in smaller fish than larger fish (Booth et al. 2023, Wanless et al. 2004), meaning seabirds need to catch more, smaller sandeel to obtain the same energy to meet their own and their offspring’s energetic requirements (Rindorf et al. 2016). Where such compensation is not possible, seabird chicks of many species, including guillemot, shag, kittiwake, puffin and razorbill, experience net reductions in energy value at the time of chick-rearing because of declines in sandeel length (Burthe et al. 2012). However, some species may be able to maintain their energetic intake for chicks through prey switching (Smout et al. 2013). Indeed, in Shetland, declines in local sandeel biomass resulted in great skua switching from feeding predominantly on sandeel via kleptoparisitism of other seabird species to predating other seabirds (Votier et al. 2007), highlighting the complexities of marine food webs and the challenges of predicting the response of seabirds to changes in sandeel populations.

4.3 Predicted vulnerability of seabirds to declines in sandeel abundance

Due to differences in seabird life-history, ecology and diet, the dependency on and vulnerability to changes in sandeel biomass and availability varies among species (Rindorf et al. 2000; Furness & Tasker 2000). Furness & Tasker (2000) assessed the vulnerability of the North Sea seabird community to reductions in sandeel abundance using an ‘index of vulnerability to reduced food-fish abundance’ based on a suite of species characteristics including: body size, foraging costs and range, diving ability, spare time in daily energy budget and dietary flexibility. Some species, such kittiwake and Arctic skua, are considered highly sensitive to changes in sandeel availability due to factors such as high foraging costs, limited diving ability (i.e., surface feeders) and restricted dietary flexibility. Other species, such as shag and gannet, are considered more resilient to fluctuations in sandeel abundance, due to greater foraging and dietary flexibility, with gannet far ranging and shag able to target prey throughout the water column (**Table 2**).

Table 2: Vulnerability index of breeding success of different seabird species to reduced abundance of food in vicinity of colonies (reproduced from Furness & Tasker, 2000).

Species	**Small Size**	**High cost of foraging per unit of time**	**Constrained to short foraging range**	**Little ability to dive**	**Lack of spare time in daily budget**	**Low ability to switch diet**	**Score**
Arctic tern	4	4	4	3	4	3	22
Roseate tern	4	4	4	3	4	3	22
Little tern	4	4	4	3	4	2	21
Common tern	3	4	4	3	4	2	20
Sandwich tern	3	4	3	3	3	3	19
Black-legged kittiwake	2	2	1	4	4	3	16
Arctic skua	2	2	3	4	1	3	15
Black-headed gull	3	3	3	4	2	0	15
Common gull	2	3	3	4	2	0	14
Black guillemot	2	3	3	1	3	2	14
Great skua	0	3	3	4	1	2	13
Atlantic puffin	2	3	1	2	3	2	13
Razorbill	1	3	2	1	2	3	12
Red-throated diver	0	3	4	0	2	3	12
Lesser black-backed gull	1	2	2	4	1	1	11
Herring gull	1	2	3	4	1	0	11
Greater black-backed gull	0	2	3	4	1	0	10
British storm petrel	4	2	1	3	0	0	10
Leach’s petrel	4	2	1	3	0	0	10
Common guillemot	1	3	1	0	2	2	9
Shag	0	3	3	0	0	2	8
Great cormorant	0	3	4	0	0	0	7

Manx shearwater	2	1	0	2	0	2	7
Northern fulmar	1	0	0	4	2	0	7
Northern gannet	0	2	0	2	1	0	5

Table 3: Index of sensitivity of breeding success to sandeel abundance for seven seabird species. Vulnerability score is from Furness & Tasker (2000), Table 1. Proportion of sandeel in the diet was mean across years for the species listed below, breeding on the Isle of May during 1996-2003. Sensitivity is vulnerability score x proportion of sandeel in diet. Reproduced from Daunt et al. 2008.

Species	Vulnerability Score	Proportion of sandeels in diet	Sensitivity to sandeel abundance
Kittiwake	16	0.87	13.9
Puffin	13	0.81	10.5
Razorbill	12	0.77	9.2
Shag	8	0.96	7.7
Guillemot	9	0.84	7.6
Tern species	21.8	0.34	7.4
Gannet	5	0.42	2.1

Daunt et al. (2008) further added to Furness & Tasker's (2000) vulnerability index by using data on the proportion of sandeel in the diet of species breeding at the Isle of May colony during 1996-2003, to assess the sensitivity of species to sandeel abundance (**Table 3**). This sensitivity score is a measure of both the seabird species' vulnerability to a paucity of sandeel and their reliance on sandeel.

If the predictions of Furness & Tasker (2000) and Daunt et al. (2008) are correct, the seabird species most sensitive to changes in sandeel abundance should have exhibited a decrease in breeding success in response to reduced sandeel size and abundance over recent decades. Kittiwake and puffin would be predicted to have shown the greatest decrease in breeding success over recent decades while guillemot and gannet would be predicted to have not shown the same declines.

4.4 Seabird demography and sandeel abundance, biomass and availability

Understanding the extent to which seabird demography (breeding success, survival, and population size) is determined by sandeel abundance, biomass and availability to seabirds, and hence the potential benefits that a sandeel fishery closure might bring for seabirds, is not straightforward. However, the large changes in sandeel biomass and availability over the last few decades, coupled with intensive monitoring of seabird population size, breeding success and diet, particularly at the Isle of May, enables investigation of any correlation between seabird demography and sandeel biomass.

Furness and Tasker (2000) and Daunt et al. (2008) identified kittiwake as one of the species most sensitive to changes in sandeel biomass. Kittiwake breeding abundance in Scotland has undergone a sustained and significant decline (Harris & Wanless, 1997) with the most recent Seabird Monitoring Programme breeding abundance index, for 2019, being 60% below the 1986 baseline (JNCC, 2021).

4.5 Seabird breeding success and sandeel biomass and abundance

A consistent pattern in the way seabird breeding success changes with forage fish abundance has been reported for many seabird-forage fish interactions around the globe. Known as ‘one-third for birds’, Cury et al (2011) found seabird breeding success to vary little or not at all at intermediate and high forage fish abundance, but once forage fish abundance dropped below a threshold of one-third of maximum biomass, seabird breeding success rapidly declined. This relationship has also been found for seabirds feeding on sandeel, e.g., for breeding success of Arctic skua, great skua and kittiwake on Foula in relation to the Shetland sandeel total stock biomass (Frederiksen et al. 2007; MacArthur Green 2021). A similar relationship has also been found for a proxy of adult survival at the Isle of May for kittiwakes (MacArthur Green, 2021).

Further evidence supporting the role of sandeel abundance in driving kittiwake breeding success at large spatial scales comes from synchronised variation in breeding success among multiple kittiwake colonies. Frederiksen et al. (2005) found that regional variation in prey availability had a stronger effect on kittiwake breeding success than local prey depletion. Olin et al. (2020) found the spatial structure in sandeel populations played a role in driving this synchrony within and among clusters of kittiwake colonies.

As described above (see section Prevalence of Sandeel in Seabird Diet) seabird species which are capable of switching to feed on alternative prey have generally been able to sustain better breeding success than species without the ability to switch. However, in Shetland, alternative prey such as sprat and juvenile herring are scarce (Frederkisen et al. 2007, Hamer et al. 1993; Furness & Tasker 2000). Consequently, when the Shetland sandeel stock collapsed in the 1990s, many seabird species exhibited reduced breeding success e.g., Arctic skua, kittiwake (Davis et al. 2005; Furness 2007; Phillips et al. 1996; Frederkisen et al. 2007) and survival e.g., Arctic skua, great skua, kittiwake (Davis et al. 2005; Oro & Furness 2002; Ratcliffe et al. 2002). Olin et al. (2020) noted the extent to which sandeel populations drive patterns in kittiwake breeding success among colonies is stronger in Shetland and Orkney than further south, due to the absence of alternative prey.

4.6 Influence of sandeel availability on seabird demography

Seabird breeding success is influenced not only by sandeel biomass, abundance, and quality but also by their availability. Assessing sandeel availability to seabirds, especially surface feeders, is difficult as availability varies as sandeel move between the water column and the sediment.

Kittiwakes on the Isle of May had higher breeding success during 1986-1996 when age 0 sandeel made up a higher proportion of chick diet (Harris & Wanless, 1997). During the late 1980s to late 2000s, community level comparisons of seabird breeding on the Isle of May showed a synchronised decline, driven by reduced chick survival rather than failure during egg incubation (Lahoz-Montfort et al. 2013). Concurrent community-level reductions in the importance of sandeel in chick diet suggests dietary changes could have contributed to the synchronised declines (Wanless et al. 2018). Breeding success on the Isle of May in kittiwake, razorbill and guillemot was greater in years when the proportion of sandeel in chick diet was higher (Searle et al. 2023).

Guillemot, kittiwake and shag breeding success was significantly lower when sandeel fisheries catch per unit effort (CPUE) was lower, suggesting more sandeel in the water column can contribute to higher breeding success (Rindorf et al 2000). Whilst this positive relationship was strongest in surface-feeding kittiwake, it was also found for shag and guillemot which are capable of foraging throughout the water column, implying higher foraging efficiency for these two species when sandeel availability in the water column is greater.

As well as sandeel availability in the water column, temporal availability of sandeel also influences seabird breeding success. The peak in sandeel abundance needs to coincide with the seabird breeding season. Breeding success of three seabird species on the Isle of May was greatest when CPUE in June was high and the May/June CPUE ratio (an index of the timing of the onset of sandeel burying behaviour) was low, implying a peak abundance in May is too early to benefit seabird chicks (Rindorf et al 2000).

The extent to which availability of age 0 and age 1+ sandeel influences breeding success varies among seabird species. Kittiwake, guillemot, puffin, and shag breeding success was positively related to sandeel larval biomass in the previous year, implying seabirds were feeding on 1 year old sandeel (Frederiksen et al. 2006). Kittiwake tend to feed on age 1+ sandeel in April and May, shifting to age 0 sandeel in June and July, with highest breeding success occurring when age 0 sandeel appeared early in the season (Lewis et al. 2001).

Thus, not only is total abundance or biomass of sandeel important to seabirds but also the timing of that peak abundance and the extent to which it coincides with key stages of the seabird breeding season (Rindorf et al. 2000).

Kittiwake breeding success was higher when sandeel size was larger (Lewis et al. 2001) but sandeel in seabird diet have been getting smaller over the last 30 years (Wanless et al 2004). Consequently, seabird breeding success has also been impaired by the size and thereby energy value of sandeel as well as their availability.

4.7 Industrial sandeel fisheries and seabird demography

4.7.1 Challenges of establishing a relationship between industrial sandeel fisheries and seabird demography

Obtaining measures of how a sandeel fishery changes the abundance or availability of sandeel to seabirds, and hence seabird demography, is not straightforward.

Figure 27 illustrates the multiple complexity of linking changes to a sandeel fishery to seabird population size.

Only correlative relationships between breeding success and sandeel fishing and/or abundance can be established, meaning confidence in observed results is less than from an experimental manipulation. Also, seabird demography is driven by lag effects and interannual fluctuations that make teasing out effects of a fishery from environmental variation difficult (Searle et al. 2023).

The sandeel fishery is only one driver of sandeel stock biomass, the latter also being determined by top down (natural predation (Furness 2002)) and bottom up (environment and copepod prey abundance (Frederiksen et al. (2004)) regulation. This makes demonstrating a causal relationship between industrial sandeel fishing and seabird demography challenging (Sydeman et al. 2017).

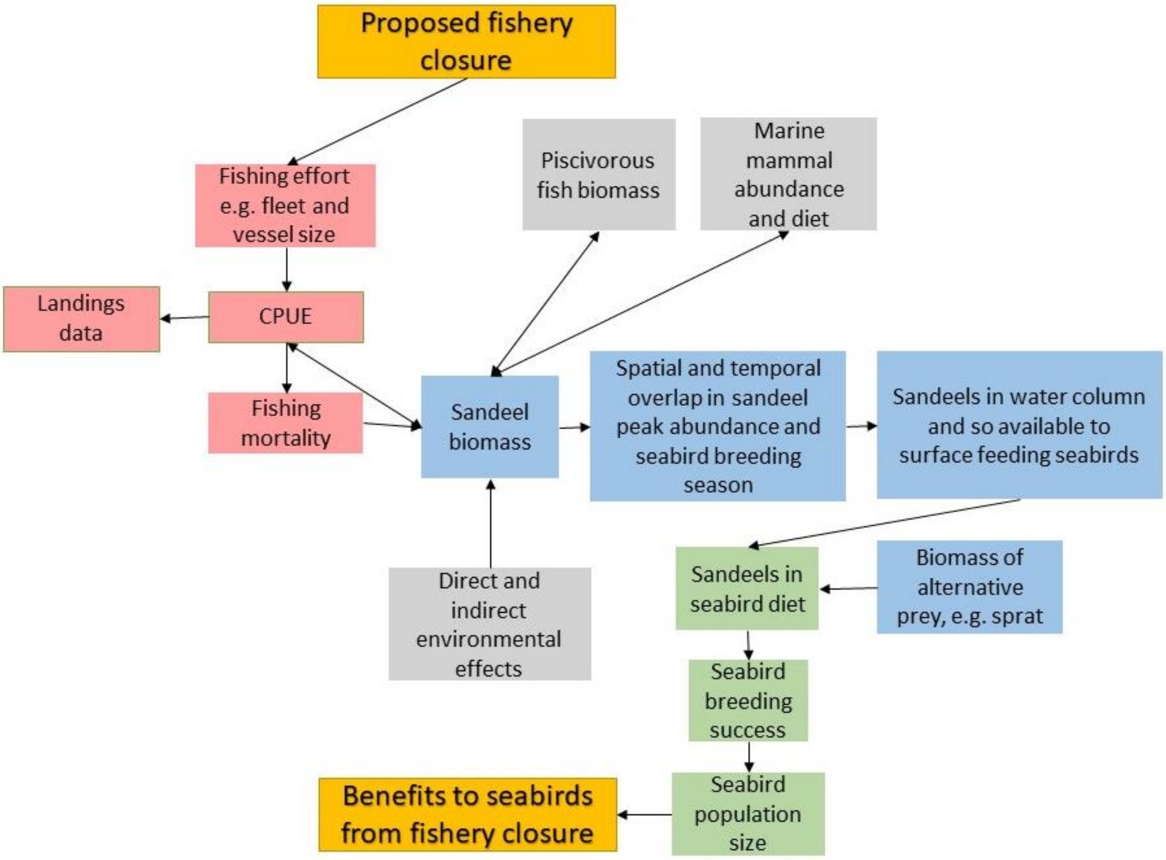


Figure 27: Diagram illustrating the complex relationship between sandeel fisheries measures and seabird breeding success. Drivers of sandeel biomass are indicated in grey (top down predation by fish and marine mammals and bottom up environmental effects). Sandeel fishery information is indicated in red. Sandeel components are indicated in blue and seabirds in green.

4.7.2 Seabird demography and sandeel fisheries

Seabird breeding success has been shown to have a non-linear relationship with forage fish biomass, with breeding success rapidly declining as stocks fall below one third of maximum (Cury et al, 2011). Fisheries targeting fish that are key prey for seabirds have the potential to push stocks below this threshold, causing decreases in breeding success (Sydeman et al 2017; Cury et al 2011).

Fishing effort from the Wee Bankie sandeel fishery was associated with a decreased proportion of sandeel in puffin diet (Searle et al. 2023). Fishing effort was also associated with a decrease in the relative proportion of age 0/age 1+ sandeel in diet of kittiwake, razorbill and puffin (Searle et al. 2023). However, only kittiwake breeding success decreased with fishing effort.

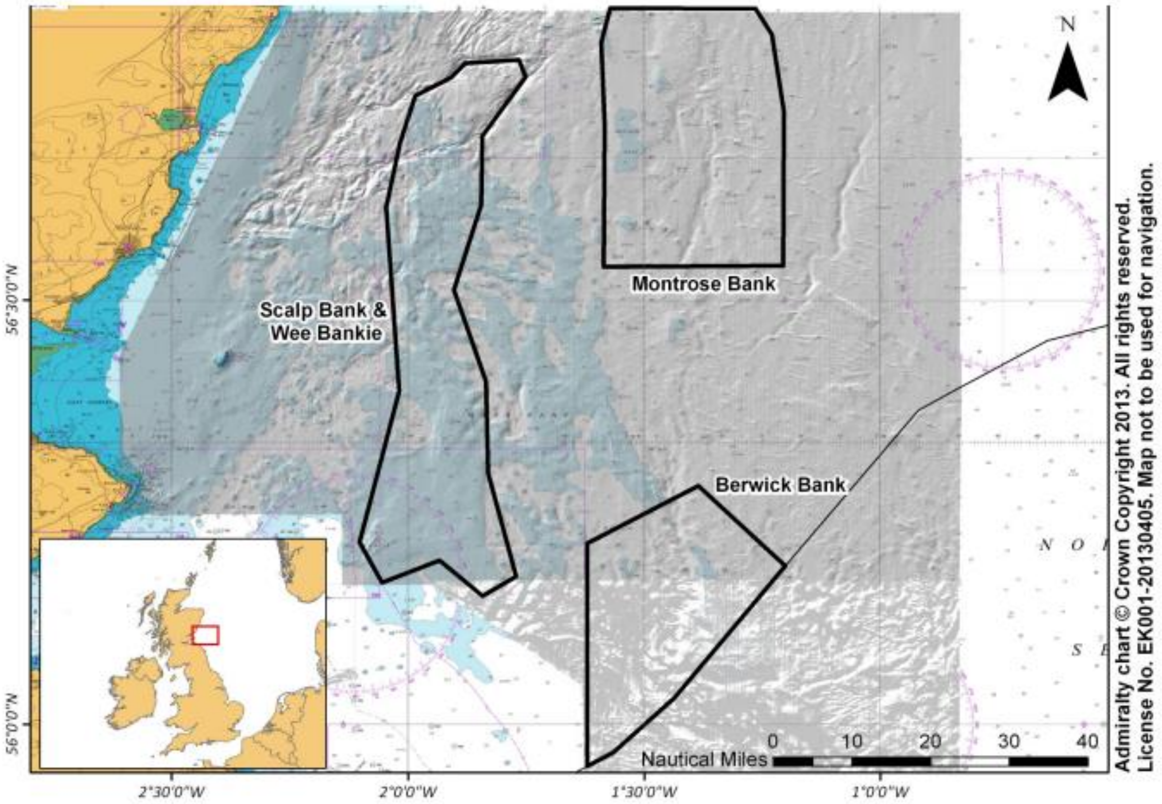


Figure 28: Boundary of the Firth of Forth Banks Complex MPA. Reproduced from JNCC (2023): Firth of Forth Banks Complex MPA: Site Summary Document, [Firth of Forth Banks Complex MPA | JNCC - Adviser to Government on Nature Conservation]()

Kittiwake breeding success at Flamborough & Filey Coast SPA, eastern England, was positively correlated with sandeel spawning stock biomass the preceding winter and negatively related to fishing mortality with a two-year lag (Carroll et al. 2017). GPS tracking indicated kittiwakes and the fishing fleet were both targeting the same grounds on the Dogger Bank (Carroll et al. 2017).

Whilst seabirds generally feed on age 1+ sandeel during the first part of the breeding season and then switch to age 0 sandeel in May, the fishery targets only age 1+ sandeel in May, June and July. So, whilst there was some spatial overlap in foraging areas used by the fishery and seabirds (the extent of overlap varying among species) (Wanless et al. 1998), they were likely to be targeting different age classes (Daunt et al. 2008).

Fishery impacts on sandeel availability are known to be potentially additive to environmental effects (Daunt et al 2008, Rindorf et al 2000). Cook et al (2014), when investigating the use of seabird breeding success as an environmental indicator, found a negative relationship between kittiwake breeding success and sea surface temperature among colonies along the east coast of the UK. When the Wee Bankie sandeel fishery was active, the number of kittiwake colonies failing to achieve predicted breeding success, given the underlying environmental conditions (e.g., sea temperature), increased, particularly in areas close to the Wee Bankie. Once the fishery closed, colonies failing to achieve expected levels of breeding success instead became clustered around Orkney and Shetland, due to reduced sandeel availability and increased great skua predation (Cook et al 2014). This suggests that fishery impacts on kittiwake breeding success were additive to underlying environmental effects.

4.7.3 Benefit of sandeel fishery closures to seabirds

On two separate occasions, industrial sandeel fisheries have been closed due to concerns about their impacts on the breeding success of seabirds (Greenstreet et al. 2006). During the mid to late 1990s, a small sandeel fishery off Shetland was closed following declines in breeding success of seabirds including Arctic tern (Monaghan et al. 1989), great skua (Hamer et al. 1991) and kittiwake (Hamer et al. 1993).

More recently, an industrial sandeel fishery on the Wee Bankie, Scalp Bank and Marr Bank that opened in 1990 was closed in 2000 due to concerns about the fishery impacting breeding success of seabirds nesting around the Firth of Forth, including the Isle of May (Rindorf et al. 2000). Guillemot, razorbill, kittiwake and, to some extent puffin, were known to use the fished area for foraging during the breeding season (Wanless et al. 1998). The evidence for the fishery reducing breeding success, particularly for kittiwake, was so strong that ICES recommended using ‘the criterion of kittiwake breeding success falling below 0.5 fledged chicks per well-built nest for three successive seasons as the threshold to close sandeel fisheries in areas important for foraging by the kittiwake colonies being monitored’ (ICES, 2000).

4.7.4 Wee Bankie sandeel fishery closure and seabird demography

Following closure of the Wee Bankie sandeel fishery in 2000, sandeel abundance initially increased, as did kittiwake breeding success. Consumption rates of age 0 sandeel were higher after the fishery closure, despite the fishery not targeting age 0 sandeel (Daunt et al. 2008). However, no significant relationship between sandeel abundance and breeding success was found in shag, guillemot, razorbill, puffin, common tern or Arctic tern (Daunt et al. 2008; Frederiksen et al. 2008).

The effect of the opening and subsequent closure of the Wee Bankie fishery on kittiwake breeding success can be investigated using a quasi-experimental approach, with a BACI (before-after-control-impacted-design). The Before/After is the period when the Wee Bankie fishery was active (1991-1998) compared with when the fishery was inactive (1999 onwards); the Control/Impacted uses breeding success at colonies where kittiwakes forage in areas that remain subject to industrial sandeel fishing throughout the study period as a control, and colonies foraging within the closed Wee Bankie fishery zone as the treatment (Frederiksen et al. 2008; Searle et al. 2023). Foraging areas used by birds from impacted colonies overlapped, to varying extents, with the grounds used by the fishery (Wanless et al. 2018; Daunt et al. 2008). The BACI analysis showed that for colonies with kittiwake foraging in the impacted area, breeding success was significantly lower when the fishery was active, compared to when the fishery was inactive, while no significant change in breeding success was found at control colonies over the same time period (Frederiksen et al. 2008). Kittiwake breeding success at impacted colonies was also negatively correlated with fishery effort when the fishery was active but not at control colonies (Frederiksen et al. 2008).

Recently, Searle et al. (2023) repeated the analytical design of Frederiksen et al. (2008), examining changes in breeding success and diet of kittiwake, guillemot, razorbill and puffin during 1986-2018 in relation to the opening and closure of the Wee Bankie fishery. All four species showed a decrease in breeding success across the 32 years of the study. Kittiwake showed a decrease in breeding success attributable to the sandeel fishery (from 52% to 23% proportion of nests to young fledged), followed by a smaller increase (10%) when the fishery closed, compared with control colonies . Importantly, closing the fishery did not enable kittiwake breeding success to recover to pre-fishery levels. Puffin, razorbill and guillemot showed no negative effects of the fishery on breeding success, nor any positive effects following closure (Searle et al. 2023).

4.8 Other drivers of seabird demography

Evidence of sandeel biomass, abundance and availability influencing seabird breeding success, and how this changed in the presence and absence of the Wee Bankie sandeel fishery, is presented above. However, seabird breeding success and population size are also driven by other factors. There are numerous other pressures on Scottish seabird populations including Highly Pathogenic Avian Influenza (NatureScot 2022) and climate change (Mitchell et al. 2002). Wind and rain can reduce breeding success in kittiwake (e.g. Christensen-Dalsgaard et al. 2018; Alvestad 2015; Newell et all 2015) although changing environmental conditions are more likely to influence prey quality and availability rather than have substantial direct impacts on seabirds (MacDonald et al. 2015). Despite synchrony in kittiwake breeding success (Olin et al. 2020; Frederiksen et al. 2005), breeding success can vary between colonies in close proximity due to other effects such as human disturbance. For example, two kittiwake colonies in Scotland (Dunbar Coast and the Isle of May) only 40km apart showed very different population trajectories, one increasing by 17% the other showing a moderate decline (Searle et al. 2023). Predation of both chicks and adult seabirds can impact breeding success and population size, e.g., by great skua or white-tailed eagle (Anker-Nilssen et al. 2023; Votier et al. 2004). Incidental seabird bycatch in fisheries can also impact seabirds, although this varies by species, fisheries gear and region, with fulmar bycatch in long-line fisheries a particular concern within Scotland (Northridge, Kingston & Coram, 2020).

4.9 Potential benefits to seabirds from sandeel fishery closure

The evidence above shows negative relationship between presence of a sandeel fishery and kittiwake breeding success, but limited evidence of a negative relationship for the other seabird species studied. However, Furness (2002) points out that the period of largest sandeel landings corresponds to the period of maximum seabird population size and breeding success over the last five decades. For example, UK kittiwake breeding numbers increased by 24% during 1969-1988 during which period the North Sea sandeel fishery greatly increased from landing less than 200 thousand tonnes annually to regularly landing around 800 thousand tonnes from 1977 onwards (JNCC 2021; Furness 2002). Despite the fishery removing large numbers of sandeel, seabird populations thrived. Furness (2002) hypothesised that reduced numbers of piscivorous fish had allowed a large increase in the sandeel stock that could sustain both seabirds and a large industrial fishery (Sherman et al, 1981). Furness (2002) proposed that the sandeel stock was regulated by bottom-up processes and so fishing and natural predation served to reduce density dependence in the stock and increased population growth. However, longer term, the stock did not continue to support high numbers of breeding seabirds. Whilst the fishery continued to land similar numbers of sandeel until 2000, kittiwake numbers declined in the UK by 25% between the Seabird Colony Register (1985-88) and

Seabird 2000 (1998-2002) censuses, and subsequently sustained a further 29% decline by 2019 (JNCC 2021). Frederiksen et al. (2007) suggested that mature herring feeding on sandeel could be outcompeting seabirds around Shetland, observing a negative correlation between herring spawning stock biomass and sandeel total stock biomass. It is therefore possible that over this period piscivorous fish stocks have increased to the level that they may be outcompeting seabirds.

4.10 Role of environment

The impacts of industrial sandeel fishing and subsequent benefits following closure of the Wee Bankie fishery to seabirds during the breeding season has been extensively investigated (Daunt et al. 2008, Rindorf et al. 2000, Searle et al. 2023, Frederiksen et al. 2008, Wanless et al. 1998, Frederiksen et al. 2004, Cook et al. 2014, Wanless et al. 2004, Frederiksen et al. 2006, Frederiksen et al. 2005, Wanless et al. 2018). Whilst all studies identified some negative effect of the fishery and/or subsequent benefit following the closure, particularly on kittiwake, effects of the fishery on seabirds were complex and the role of environment on driving sandeel availability was also likely a dominant factor. The effects of the sandeel fishery may be additive on top of wider environmental processes, particularly climate change, that are reducing sandeel availability to seabirds (Rindorf et al. 2000). Therefore, closing the fishery may be beneficial but environmental processes will more strongly determine seabird breeding success (Cook et al. 2014, Daunt et al. 2008).

4.11 Seabird foraging ranges and existing sandeel fishery closed area

During the breeding season, seabirds are constrained to foraging within a certain distance from their breeding site due to the need to return to their nest to incubate eggs, feed chicks, brood young and protect eggs and chicks from predation. For seabirds to achieve improved breeding success from an increase in sandeel biomass from a fishery closure, the sandeel need to be within foraging range of colonies, in the water column (i.e., not buried in the sediment) and peak age 0 and age 1+ availability needs to coincide with the key phases of the breeding season.

Kittiwake have a mean foraging range of 55km and a mean maximum foraging range of 156km (Woodward et al. 2019). For many seabird colonies along the east coast of Scotland, this means that a typical foraging range would not regularly include foraging outside of the existing closed area (**Figure 29**). Whilst kittiwake are capable of flying further to the wider SA4 area, there would need to be considerably improved foraging opportunities above what is available in the existing closed area to make the longer foraging distance worthwhile. There is evidence that kittiwake forage at greater distances from their colonies when breeding success is low, suggesting birds will travel further when prey is not available locally (Hamer et al. 1993; Wanless et al. 1992). Unless sandeel metapopulation dynamics mean a wider sandeel closure would significantly change sandeel availability within the existing closed area,

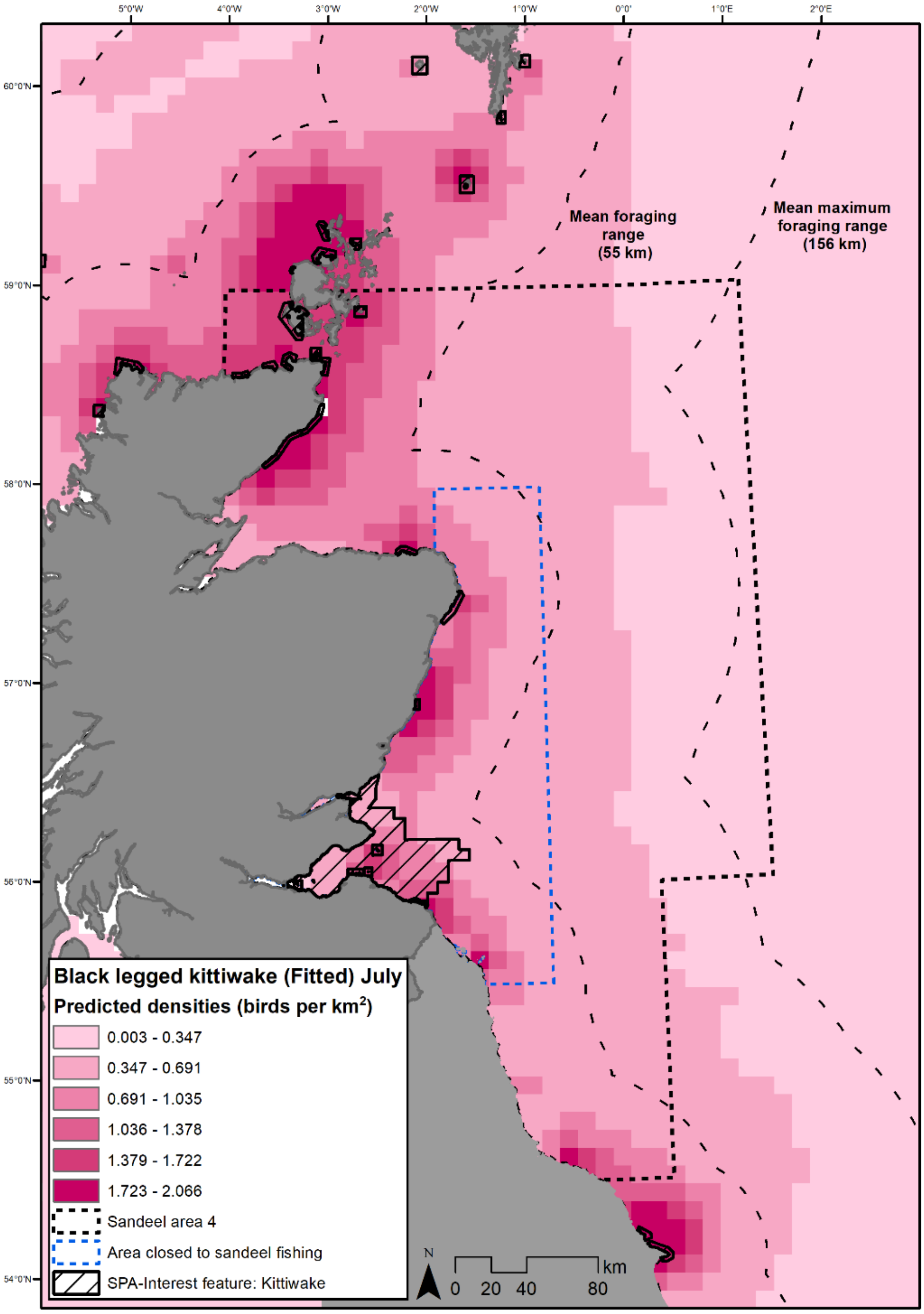


Figure 29: Kittiwake predicted densities in July (reproduced from Waggitt et al. 2019), overlaid with the existing closed area and SA4. Special Protection Areas (SPA) with kittiwake as an interest feature are marked on the map with buffers around each at 55km (mean foraging range) and 156km (mean maximum foraging

range) from Woodward et al. 2019. © Crown copyright and database rights Ordnance Survey 100024655

improved sandeel availability may generally be of limited benefit to kittiwake breeding success (see sections 3.1.2.2 and 3.1.2.3).

Some other seabirds have greater foraging ranges and could benefit from increases in sandeel availability, e.g., gannet with a mean foraging range of 120km, though this species is considered to have a low sensitivity to changes in sandeel availability. However, most species either have a similar mean foraging range to kittiwake, e.g., 61km and 62km for razorbill and puffin respectively, or they have a smaller mean foraging range than kittiwakes (Woodward et al. 2019). This means that for colonies within the existing area closed to sandeel fishing, with the exception of gannet, benefits of extending the closure will only be seen if either seabirds increase their mean foraging ranges and/or the closure changes availability of sandeel within the inshore existing closed area.

For species with colonies outside of the existing closed area, e.g., Orkney, Shetland, Caithness and Moray coast, benefits from a wider closure would be within their typical foraging ranges (**Figure** 29). However, as discussed above, these areas are not currently targeted by the sandeel fishery and benefits of a closure may be minimal.

While seabirds are not constrained to feeding around their colonies or provisioning offspring during the non-breeding period, the winter months are energetically challenging for many seabirds due to more inclement weather, limited daylight and reduced prey availability (Daunt et al. 2014). For example, winter sandeel spawning may provide an important prey resource prior to breeding allowing individuals to attain breeding condition. In addition, for species which can extract sandeel from the seabed, sandeel may provide an important prey throughout the non-breeding period, albeit at lower numbers/frequency compared to breeding (Howells et al. 2018). Thus, while the limited available evidence on seabird diet in the non-breeding period suggests that sandeel are less important relative to breeding, maintenance of sandeel stocks may confer some benefits to and resilience in seabird populations.

4.12 Variation in response to a sandeel fishery closure across seabird species

The extent to which seabirds might benefit from a wider sandeel fishery closure will vary among species. Benefits from increased sandeel abundance would be most likely to be seen in species that are most sensitive to changes in abundance, e.g., kittiwake and least in those species that can dive (guillemot, razorbill, puffin), switch to alternative prey (guillemot, gannet, great skua) or forage over a wider area (gannet) (Furness & Tasker, 2000).

Some seabird species have increased the proportion of clupeids (mostly sprat but some herring) in their diet in response to decreased sandeel availability (Wanless et al. 2018). Chick diet of kittiwake, guillemot, razorbill and puffin is almost entirely sandeel or sprat. This diet switch has helped buffer some species, e.g., guillemot, from decreases in sandeel abundance, compared with kittiwake. However, if sprat abundance also declines, these seabird species could see large reductions in breeding success.

Both Daunt et al. (2008) and Searle et al. (2023) did not detect any increase in breeding success following the Wee Bankie sandeel closure for any species other than kittiwake. Daunt et al. (2008) concluded this was because some species feed close inshore in unfished areas (terns, shag) or can dive in the water column (guillemot, razorbill and puffin) and so are less affected by a decrease in absolute abundance of sandeel than surface feeders. However, identifying or quantifying benefits of a sandeel fishery closure to seabirds, particularly with ongoing environmental change, is challenging (Rindorf et al. 2000, Searle et al. 2023, Daunt et al. 2008, Furness et al. 2007).

Seabird demography is also driven by variables besides prey availability, but increased prey availability might reduce the impact of other drivers, such as predation. Anker Nilssen et al. (2023) found that kittiwake breeding success and population size declined at a colony subject to white-tailed eagle predation, but that good foraging conditions for kittiwake slowed the rate of decline.

Whilst seabirds may not exhibit increases in breeding success because of the closure of Scottish waters to industrial sandeel fishing, there may be ecological benefits to seabirds which are more difficult to measure and quantify. For example, as described above, the larger sandeel stock will comprise a greater range of ages and sizes, which might increase the duration of sandeel availability to seabirds, fecundity, or population resilience to changing environmental conditions. This could in turn result in less extreme fluctuations in seabird breeding success and ensure greater resilience in kittiwake populations.

4.13 Summary of Evidence on Seabirds and Sandeel

Scotland supports internationally important populations of breeding seabirds, with 24 species regularly breeding in Scotland. Breeding seabirds are constrained in the distances from the nest site that they can forage, potentially limiting access to available sandeel and other prey resources. A large proportion of seabird species in Scotland include sandeel in their diet during the breeding season, though this dependence varies across species with gannet identified as having low sensitivity to sandeel abundance and kittiwake high sensitivity.

Kittiwake tend to feed on age 1+ sandeel in April and May, shifting to age 0 sandeel in June and July, with highest breeding success occurring when age 0 sandeel appeared early in the season. To be of most benefit to seabirds, the peak in sandeel abundance needs to coincide with the seabird chick rearing phase of the seabird breeding season. However, the timing of sandeel availability and absolute abundance shows inter-annual variation, which can result in a mismatch between peak sandeel availability and seabird chick rearing and negative effects on seabird productivity. Some seabird species are more able to switch prey species than others, for example guillemot switch prey species more easily than kittiwake, which may help mitigate some of the negative effects of reduced or mismatched sandeel availability.

Seabird breeding success has been shown to have a non-linear relationship with forage fish biomass, with breeding success rapidly declining as stocks fall below one third of maximum. Positive relationships between seabird breeding success and changes in forage fish abundance have been described for a range of seabird species.

Prey availability, rather than abundance or biomass, plays a key role in the breeding success of some seabirds. Prey need to be within foraging distance of seabird colonies, they need to be within the water column, and they need to be within dive depth (which varies considerably among seabird species). Similarly, prey of the right age or size class must be available at the right time of year for provisioning to chicks.

Establishing a relationship between industrial sandeel fisheries and seabird demography is extremely challenging. Only correlative relationships can be established meaning confidence in results can be low, and lag effects between seabird demography and environmental conditions increases complexity and uncertainty. Fishing mortality is only one factor influencing sandeel stock biomass, with natural predation by other fish, marine mammals, and seabirds, copepod prey abundance, and wider environmental conditions key factors.

On two occasions sandeel fisheries have been closed due to concerns about their impacts on the breeding success of seabirds: the small sandeel fishery off Shetland in the 1990s and the Wee Bankie, Scalp Bank and Marr Bank fishery in 2000. Searle et al. (2023) examined changes in breeding success and diet of kittiwake, guillemot, razorbill, and puffin during 1986-2018 in relation to the opening and closure of the Wee Bankie fishery. Kittiwake showed a significant decrease in breeding success attributable to the sandeel fishery (from 52% to 23% proportion of nests to young fledged), followed by a non-significant increase (10%) when the fishery closed, compared with control colonies. A key finding was that closing the fishery did not enable kittiwake breeding success to recover to pre-fishery levels, perhaps suggesting that wider environmental drivers were the dominant factors. Puffin, razorbill, and guillemot showed no negative effects of the fishery on breeding success, nor any positive effects following closure.

Over recent decades, the availability, size, and calorific content of sandeel has declined and some seabirds appear to have reduced their dependency on sandeel. Compensating for these reductions by increasing the number of prey items may be possible for some seabird species or populations. Therefore, whilst closing a sandeel fishery may be beneficial, wider environmental conditions are likely to determine seabird breeding success more strongly.

The positive benefits to seabird productivity and populations of a sandeel fishery closure are difficult to quantify because of the complex relationships between prey and seabird demography, ongoing climate-mediated changes in sandeel population (including from climate change) and the numerous other pressures that seabirds face. There is also considerable variation across seabird species in their dependence upon sandeel and their ability to switch to alternative prey. However, despite these uncertainties, maximising abundance and availability of sandeel stocks as prey for seabirds in Scotland remains a key mechanism by which resilience in seabird populations might be achieved.

5 Marine Mammals

5.1 Diet

Sandeel are a key prey species for marine mammals in Scottish waters, comprising a large proportion of the diet of seals and some cetaceans (Pierce et al., 2004, Santos et al., 2004, Wilson & Hammond, 2019). However, the importance of sandeel to marine mammal diet varies considerably with species and season.

5.1.1 Seals

Grey seals (Halichoerus grypus) and harbour seals (Phoca vitulina) are largely sympatric within the UK, occupying similar ecological niches with some degree of regional spatial partitioning. This is marked by a notable overlap in diet throughout the UK populations where sandeel and large gadids are proportionally the most represented prey groups by weight, in both species (Brown et al., 2001; Hall et al., 1998; Pierce and Santos, 2003; Sharples et al. 2009; Tollit & Thompson, 1996; Wilson and Hammond, 2019). While assessing the UK populations as a whole reveals these striking overlaps in diet, it is important to note that there is considerable regional and seasonal variation both in species specific diet structure and regionally specific overlaps.

Scat analysis studies have concluded that sandeel dominate the diet of grey seals in all regions during autumn and winter except for the Inner Hebrides where gadids predominated (Wilson & Hammond, 2019). However, this dominance shifts to gadids and other benthic species during the spring and summer in Orkney and Shetland, and drops from 22.2% to 8% of the diet of grey seals in the inner Hebrides (**Table** 4). For harbour seals, sandeel were also dominant but with regional variation. In the Moray Firth, sandeel were dominant in harbour seal scats across all seasons. However, the data suggested that sandeel became less important in more southerly regions with flatfish and gadids predominating in south-east Scotland, the southern North Sea and the Inner Hebrides. In addition, harbour seals from the Outer Hebrides and Shetland preferred pelagic species with sandeel only representing 13.1% and 23.7% of the diet in these regions during the spring and summer months (**Table 4**). This prevalence does increase during autumn and winter in Shetland where sandeel become the preferred prey of harbour seals, representing 31.5% of their diet (Wilson & Hammond 2019).

Table 4: Summary comparison table of harbour seal (Pv) and grey seal (Hg) diets adapted from Wilson and Hammond (2019). Trend is the population trajectory of seals in each region since 2000 (SCOS 2020): ↗ = population increasing, -- = population stable and ↘ = population declining. SS = spring/summer; AW = autumn/winter. Species evenness: H = high (PIE > 0.75), M = moderate (PIE = 0.3-0.75) and L = low (PIE < 0.3). Diet composition: prey groups are listed in order of dominance and include those that together comprise at least two-thirds of the diet, by weight. Strongly dominant prey groups (in bold) are defined as top ranked prey groups contributing > 45% to the diet and a greater % than the sum of prey groups ranked 2, 3 and 4. All instances of sandeels are highlighted in red, with instances of strong dominance of sandeels additionally emboldened and underlined for clarity. Blank cells indicate absence of data.

Region	Trend		Species evenness				Diet Composition			
	Pv	Hg	SS		AW		SS		AW	
			Pv	Hg	Pv	Hg	Pv	Hg	Pv	Hg
Southern North Sea	↗	↗	H>L		H>L		Sandy benthic Flatfish	**Sandeel**	Flatfish Gadid Sandy Benthic	Sandeel Scorpion fish
SE Scotland	↘	↗	M>L		M>L		Sandeel Flatfish	**Sandeel**	**Flatfish** Gadid	Sandeel Gadid
Moray Firth	--	↗	L=L		L=L		**Sandeel**	**Sandeel**	**Sandeel**	**Sandeel**
Orkney	↘	--	L<M		M=M		Sandeel Gadid	Gadid Sandeel Trisopterus	Gadid Pelagic	Sandeel Gadid
Shetland	↘	--	M<H		M=M		Pelagic Gadid Sandeel	Gadid Scorpion Fish	Sandeel Gadid Pelagic	Sandeel Gadid Sandy benthic
Outer Hebrides	↘	--	M		M		Trisopterus Pelagic Gadid Scorpion fish			Sandeel Gadid

Inner Hebrides	**--**	**--**	H=H	H=H	**Gadid** Pelagic	Gadid Sandy Benthic	Gadid Pelagic Sandy benthic	Gadid Sandeel Sandy Benthic

Wilson & Hammond (2019) suggested that the decline in harbour seal abundance in the North Sea may be linked to a reduction in sandeel stocks. Specifically, there appears to be a correlation between regional declines of sandeel stocks (northern and eastern Scotland) and the declining populations of harbour seals in eastern Scotland and Orkney, where sandeel dominate the diet of harbour seals. This relationship with sandeel stock levels was supported by findings that the diet of harbour seals appeared more diverse in areas where harbour seals are not in decline (West of Scotland). If sandeel are in short supply, it has been proposed that grey seals may out compete harbour seals thereby contributing to their decline given grey seal preference for sandeel in these regions (Wilson & Hammond 2019).

While the data collected by Wilson and Hammond (2019) provided a broad spatial resolution encompassing all seal management areas to varying degrees these data are up to 15 years old and may not reflect any changes in prey selection which have occurred since dramatic changes in seal population size and distributions have progressed (SCOS, 2021). However, there is currently no reason to believe that sandeels no longer form an important part of seal and porpoise diet.

5.1.2 Cetacean diet

Harbour porpoises (Phocoena phocoena) in Scottish waters have been found to feed predominately on whiting and sandeel (Santos & Pierce, 2003, Santos et al. 2004) with sandeel being particularly important during the spring and summer (**Table 5**; Santos et al., 2004). More recent diet data for harbour porpoise in the northern North Sea are unavailable. However, studies on stranded harbour porpoise in the southern North Sea (Leopold, 2015; Lambert, 2020) found gobies, gadids, clupeids and sandeel to be the main diet components.

Table 5: The main diet composition of harbour porpoises in different regions of the North Sea, adapted from Ransijn et al. 2019. Calculated according to the estimated proportion (by reconstructed biomass) that each prey contributed to the diet. The sample size of each study is reported as n. Numbers are not always reported to species level, in such instances, values are reported by species group. Grey highlighted numbers represent prey groups and species that contributed more than 5% of the total prey weight.

Species Group and species	Dutch North Sea				Scottish North Sea	
	1989-1995[1] n=62	2003-2010[2] n=76	2003-2013[3] n=229	2006-2014[4] n=826	1992-1996[1] n=72	1992-2003[5] n=188
Gobies	6.4%	36.6%	22.1%	20.5%		
Gadidae	85.9%			36.5%	54.2%	
whiting	78.4%	25.4%	42.3%		43.6%	53%
haddock						5.6%
saithe						
pollock						
Atlantic cod	3.3%	5.2%	4.4%			3.8%
Clupeidae	1.9%			10.9%		
Atlantic herring		5.9%	4.6%		3%	1.3%
European sprat		4.1%	5.8%			
Sandeels	**2.8%**		**11.1%**	**18.1%**	**41.1%**	**25.6%**
Lesser sandeel		**13.2%**				

[1](Santos 1998) [2](Jansen 2013) [3](Leopold et al. 2011) [4](Leopold 2015) [5](Santos et al. 2004)

A diet study on stomach contents of ten stranded minke whales (Balaenoptera acutorostrata) in Scotland showed that sandeel were the most important prey species and contributed two-thirds of the individual diet, by weight diet (Pierce et al., 2004). These findings have been supported by other studies in the wider North Sea region. For example, Olsen and Holst (2001) found sandeel to comprise 86.7% of the weight of the prey species found in the stomach contents of minke whales caught by Norwegian whalers in 1999. Windsland et al. (2007) further found that sandeel dominated the diet of minke whales caught in the North Sea, however the proportion of sandeel dominance appeared to change between years, with one year showing a complete absence of sandeel in favour of a dominance of mackerel. Further, the importance of sandeel appeared to diminish through the sampling years, which was suggested to be linked to the poorer availability of sandeels in contemporary years (Windsland et al. 2007).

Sandeel were present in a diet study of a small number of white beaked dolphins (Lagenorhynchus albirostris**)** (Santos et al., 1994) but gadids are thought to be the predominant prey items in the North Sea (Canning et al., 2008, Jansen et al., 2010). Sandeel are not thought to be a major component of the diet of bottlenose dolphins (Tursiops truncatus) (Santos et al., 2001).

Ultimately, cetacean diet studies focussing on Scottish territorial waters are limited both spatially and temporally, with the bulk of work focussing on opportunistic data from dead stranded animals and bycaught animals. This type of study has an inherent bias given stranded animals tend to skew towards specific demographics and can be biased towards animals that die closer to the coast. Basing diet information on animals in poor condition (evidenced by them dying), and individuals which focus more on prey species that bring them closer to the coast provides a biased interpretation of what the relative importance of prey species to the entire population is. This bias is supported in that diet studies have often identified a significant difference in diet composition between individuals with different causes of death and between stranded and live individuals (e.g. Santos et al 2004). It must also be noted that none of the studies focussed on Scottish waters above contain data more recent than 2014, with the most recent published data for porpoises being 20 years old. This highlights the need for more contemporary data to make reasonable inferences on the current importance of sandeel to cetaceans, and how potential fishery closures and fluctuations in sandeel availability may impact cetacean populations.

5.2 Distribution/overlap with sandeel

Scotland holds internationally important numbers of marine mammals with 17 different species regularly occurring in Scottish waters (Hague et al. 2020). These species can occur throughout the marine ecosystem, from shallow coastal waters to the deeper waters beyond the shelf edge. Several species include a seasonally dependant component of sandeel in their diet. Marine mammals are capable divers, with many species foraging on benthic and demersal prey species, thus able to target sandeel occupying different regions of the water column. Furthermore, while seals are constrained to haul out sites to varying degrees throughout the year, cetaceans are relatively free-ranging, able to follow migrating and shifting food stocks.

Only marine mammal species for which sandeel are known to form part of their diet are considered here; grey seal, harbour seal, harbour porpoise, minke whale and white-beaked dolphin. Specific information on the diet composition and importance of sandeel prey for these species is summarised above. The reference source used to identify spatial overlap of sandeel with marine mammal species is the probability of sandeel occurrence data from Langton et al. 2021. Any temporal variation in the predicted overlap (i.e., seasonal movements, breeding seasons etc.) are discussed for each species.

5.2.1 Grey seal

Grey seals occur around the entire Scottish coastline and are known to undertake long foraging trips to areas further offshore (**Figure 30**). In Scottish waters, grey seal at sea distribution is predominantly driven by the proximity to suitable haulout sites, with density scaling inversely with increasing distance from haulouts (Jones et al. 2015; Carter et al. 2020). However, grey seals often undertake foraging trips of hundreds of kilometres (e.g., Thompson et al. 1996). Further to haulout affinity, grey seal distribution has been statistically correlated with several other environmental covariates, however these vary regionally both in importance and in direction. For example, grey seal density in all regions apart from the Western Isles has been shown to be driven, to varying degrees, by sediment type, with most regions showing higher affinities for coarser sand and rocky sediments than finer sands and silt based substrates. This also mimics reported habitat preferences of sandeels in these regions (Holland et al. 2005). Contrastingly around the Western Isles, grey seals appear to be driven by a-biotic oceanographic processes such as sea-surface temperature, stratification and proximity to the shelf edge (Carter et al 2020). Additionally, the at-sea distribution of grey seals suggests particularly high use of offshore sandbanks in some areas (Carter et al. 2020; Jones et al. 2020).

The foraging ranges of grey seals vary greatly depending on the time of year. Individuals may remain close to haulouts during the breeding season (October-December), and as they are capital breeders (animals that use energy stores built up before reproduction to breed), the females do not forage during the lactation period.

Areas of high at-sea usage predicted by Carter et al. (2020) for grey seals include Orkney, areas of the east coast (particularly those around the Firth of Forth and Firth of Tay), and those along the shelf edge to the west of the Western Isles. The outer sandbanks in the Firth of Tay and the Moray Firth also appear to be favoured foraging grounds. Based on the probability of sandeel occurrence predicted by Langton et al. (2021), there will be significant spatial overlap in the waters around Orkney, the east coast, the Inner Moray Firth and the Inner Hebrides (particularly the waters north west of Islay).

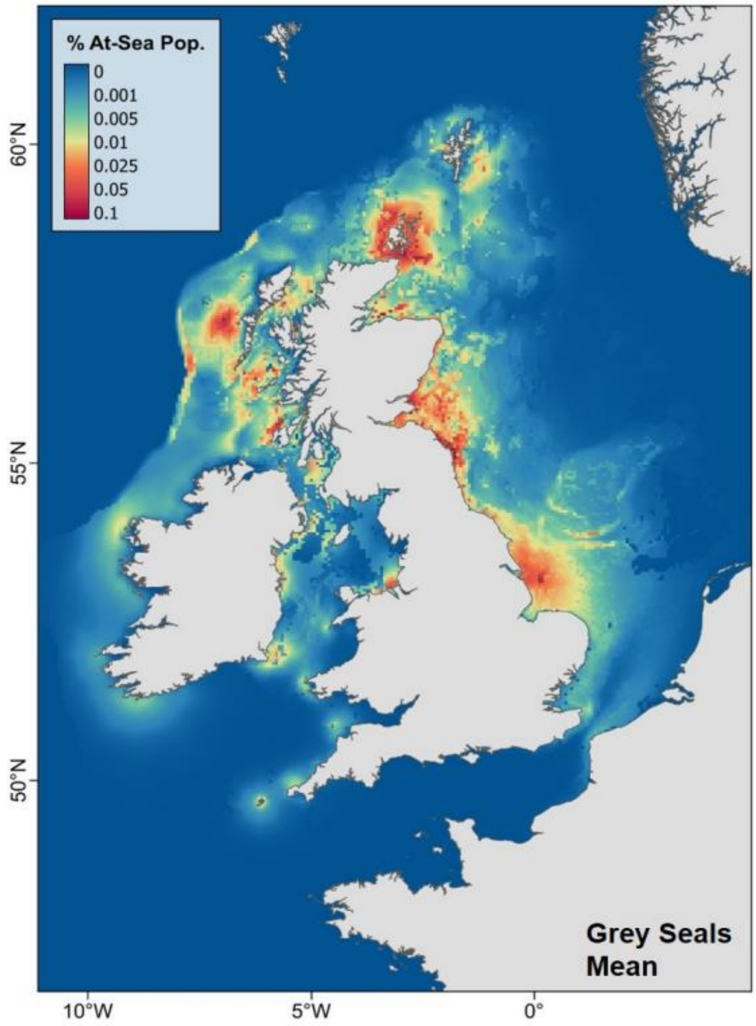


Figure 30: Predicted at-sea densities of grey seal in the UK (Carter et al. 2020)

5.2.2 Harbour seal

Harbour seals usually remain closer to coastline than grey seals (Jones et al. 2015), typically undertaking foraging trips of up to 50km from their haulout sites (**Figure 31**; Thompson et al. 1996; Thompson and Miller 1990). However, foraging range can vary regionally and individuals from some populations are known to make longer trips offshore (Cunningham et al. 2008; Sharples et al. 2012). Harbour seals are occasional income breeders (i.e., females will sometimes continue to forage during lactation), undertaking sporadic foraging trips throughout the lactation period. This means that throughout their breeding season (June-July) harbour seals will still be predating sandeel.

The areas of overlap between sandeel and harbour seal populations in Scottish waters are primarily off the west coast. Harbour seal populations on the east and north coasts of Scotland have experienced severe declines in the last few decades. The highest predicted at-sea densities (and therefore, number of foraging individuals) of harbour seals occur throughout the Inner Hebrides, Orkney, Shetland

and the Inner Moray Firth (Carter et al. 2020). The areas of high probability of sandeel occurrence from Langton et al. 2021 that are therefore most relevant to harbour seal are the waters of the Sea of the Hebrides, the Western Isles and Orkney.

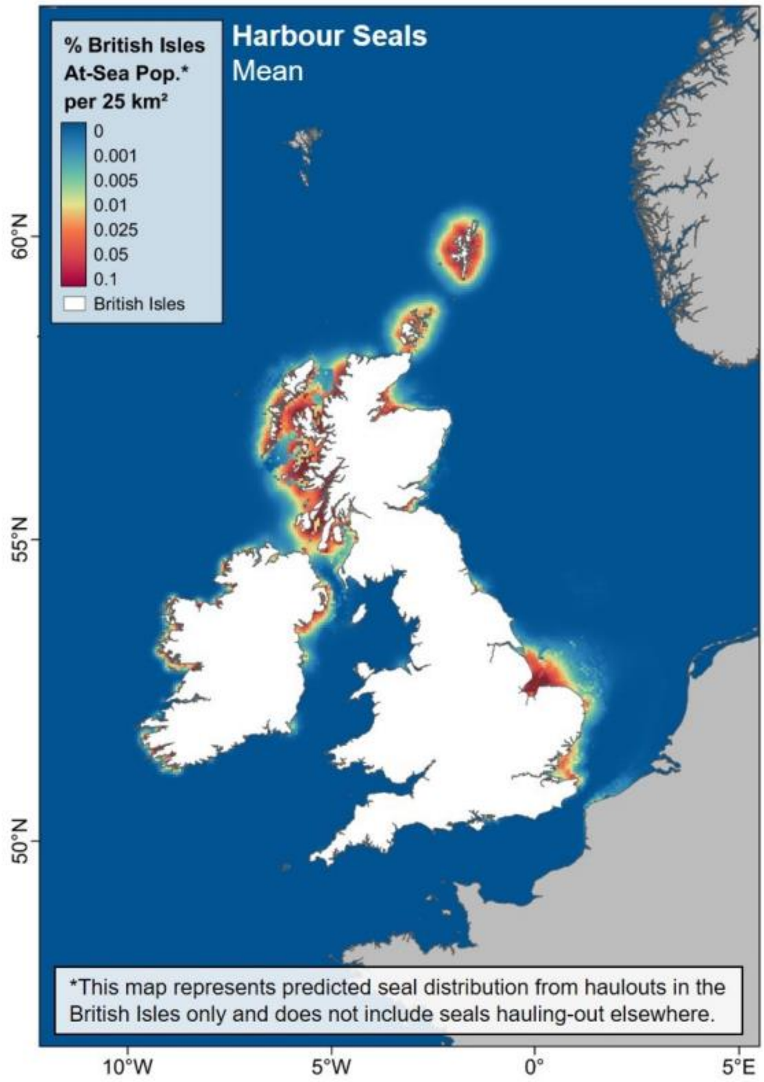


Figure 31: Predicted at-sea densities of harbour seal in the UK (Carter et al. 2020)

5.2.3 Harbour porpoise

Harbour porpoises are resident and abundant year-round in all regions of Scottish waters (**Figure 32**; Hague et al. 2020). Predictive habitat modelling based on data collected on the west coast shows a distinctly inshore distribution, with a preference for areas within 15km of the shore and depths between 50-150m (Booth et al. 2013; Marubini et al. 2009). Harbour porpoise distribution is also thought to vary with season in some areas across the UK, with animals predicted to move into the innermost North Sea during winter months from offshore areas (**Figure 32** and **Figure 33;** Waggitt et al. 2020).

The highest observed densities of harbour porpoise in Scotland are generally in the North Sea (Lacey et al. 2021), where porpoises seem to prefer similar depth ranges as on the west, as well as sandy habitats that are typically favoured by sandeels, such as the gravelly sand seabed area of Smith Bank in the middle of the Moray Firth (Brookes et al., 2013, Williamson et al. 2016). It should be noted that the Inner Hebrides and Minches SAC on the west coast is designated for harbour porpoise, which coincides with areas identified as high probability of sandeel occurrence by Langton et al 2021. In terms of spatial overlap, the areas of high probability of sandeel occurrence that coincide with areas of high area usage by porpoise are the east coast, particularly the offshore regions adjacent to the Firths of Forth and Tay such as Scalp Bank, the waters to the north east of Islay. However, sandeel spatial overlap with porpoises should be expected in any areas of shallow, coastal water and for most areas of the North Sea wherever sandeel are present. Additionally, for most coastal areas in Scotland, harbour porpoise abundance may increase during the summer months which is coincident with the seasonal increase in sandeel in the water column suggesting a possible link with seasonal movement of porpoises and availability of sandeel.

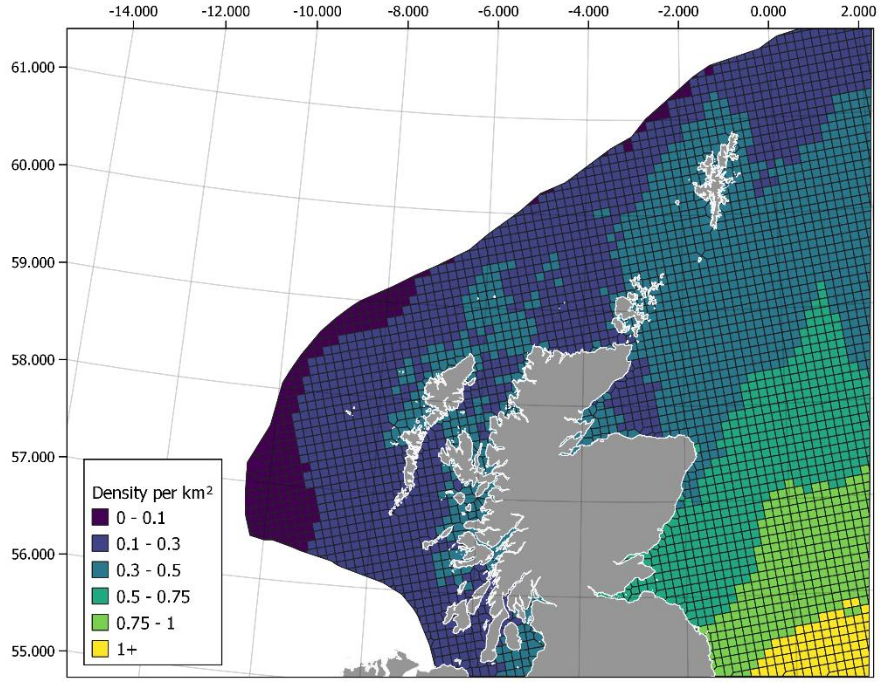
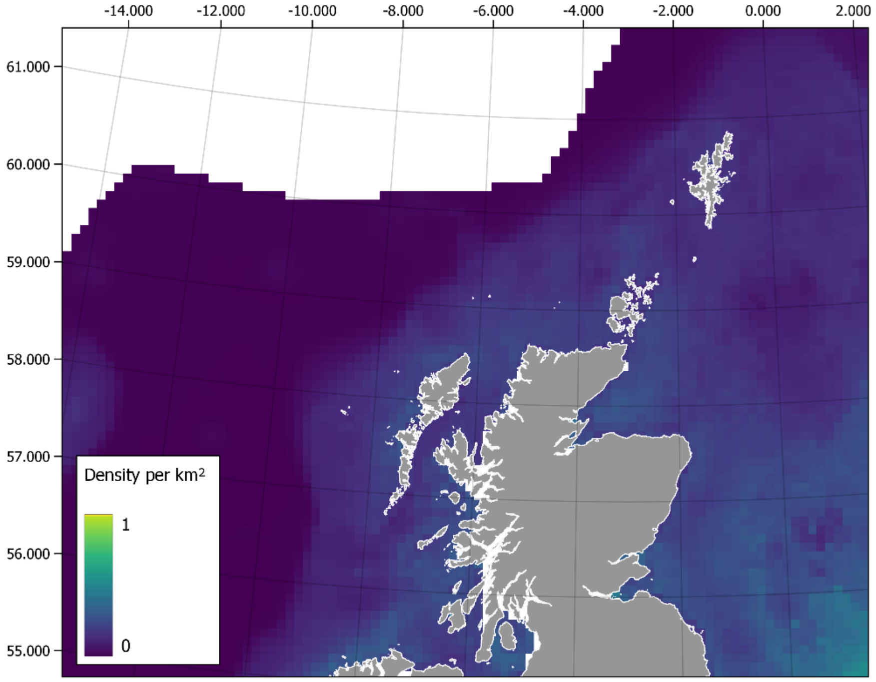


Figure 32: Predicted surface of estimated density for harbour porpoise in Scottish waters in 2016. Density surface downloaded from (https://scans3.wp.st-andrews.ac.uk/files/2022/08/SCANS-III-model-based-estimates-shapefiles.zip) and reproduced using density bins following Lacey et al. (2021).


-14.000
-12.000
-10.000
-8.000
-6.000
-4.000
-2.000
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Density per km²
1
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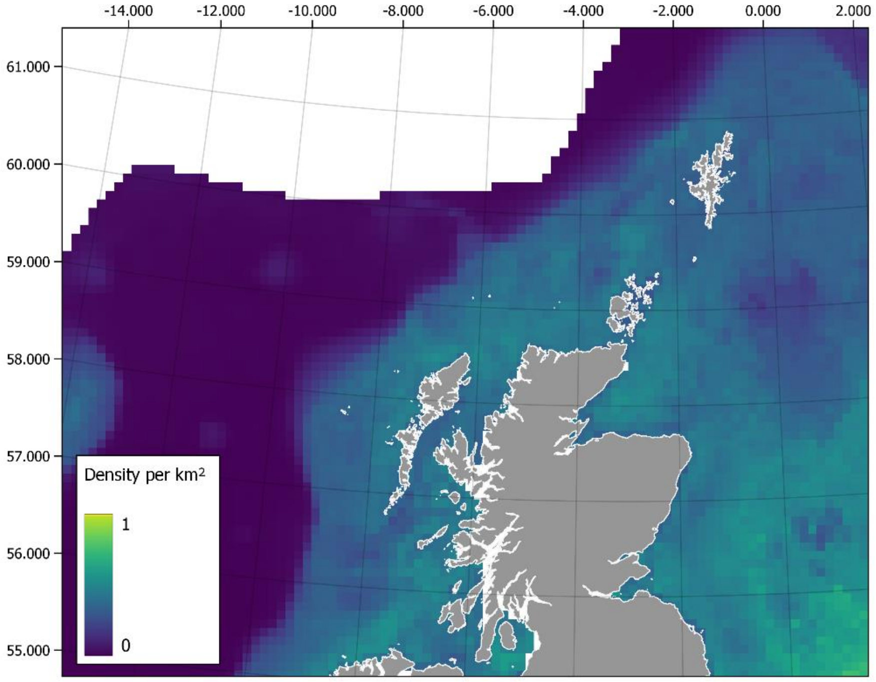
-14.000
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58.000
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56.000
55.000
Density per km²
1
0

Figure 33: Predicted densities (animals per km^2) of harbour porpoise in (above) January and (below) July in the North-East Atlantic (reproduced using density estimates from Waggitt et al. 2020).

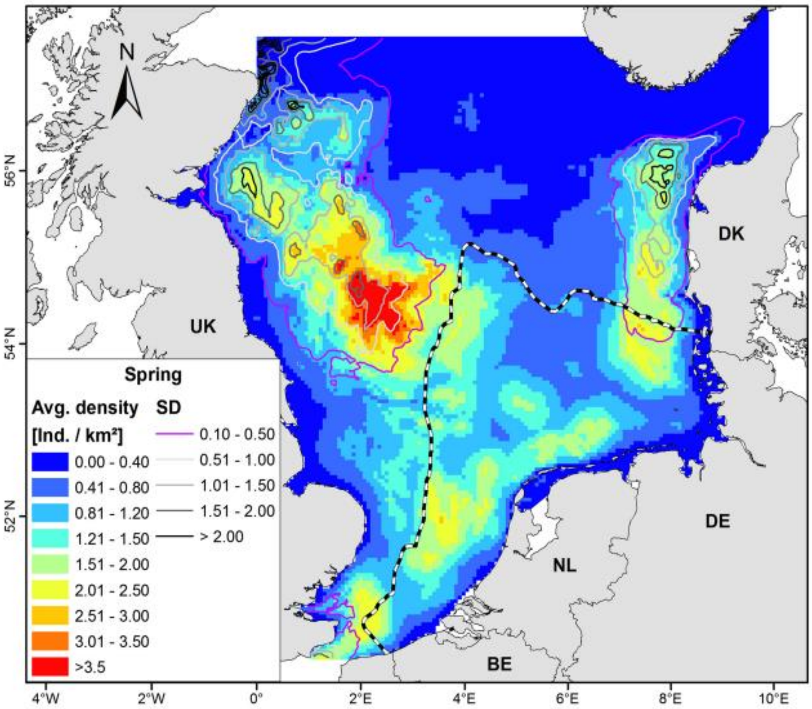


Figure 34: Predicted harbour porpoise densities in the North Sea in spring (March – May; Gilles et al. 2016)

5.2.4 Minke whale

Minke whale distribution in Scottish waters is not well understood. Different studies, using different survey methods, suggest different high usage areas. In some areas there appears to be year-round occurrence, whereas for most areas minke whales are present only in the summer months (**Figure 35** and **Figure 36;** Hague et al. 2020). Minke whale occurrence is associated with sea surface temperatures and chlorophyll concentrations (**Figure 37**; Paxton et al. 2014). As such, temporal and spatial variations in minke whale distribution are to be expected both within and between years.

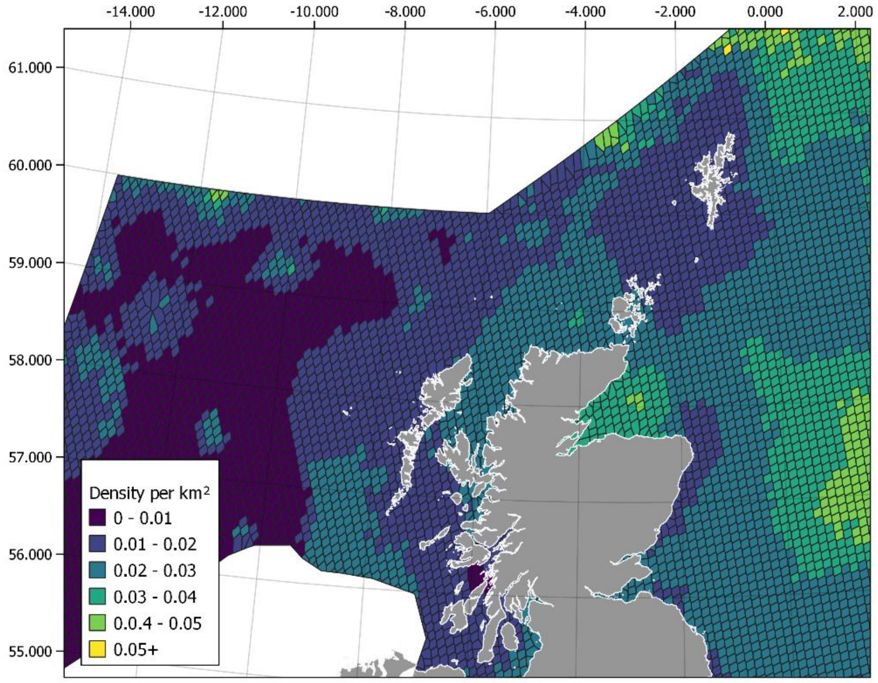


Figure 35: Predicted surface of estimated density for minke whale in Scottish waters in 2016. Density surface downloaded from (https://scans3.wp.st-andrews.ac.uk/files/2022/08/SCANS-III-model-based-estimates-shapefiles.zip) and reproduced using density bins following Lacey et al. (2021).

In summer, high use minke whale areas appear to be the Moray Firth, the waters north of Shetland and the entire west coast of Scotland. This is spatially coincident with identified sandeel hotspots in Scottish waters (Langton et al. 2021) and may reflect movement of minke whales targeting sandeel as they become more abundant in the water column during the summer months. This relationship would be particularly important for filter and lunge feeders such as minke whales given their foraging behaviour predominantly and generally targets small actively swimming (nektonic) species. As density of a pelagic prey species increases it would follow that density of filter and lunge feeding species would also increase. The Minches, the Sea of the Hebrides and off the west coast of the Western Isles are also known to experience seasonally varying hotspots of minke whales (**Figure 36**). While the identified hotspots are not coincident with relatively high sandeel abundances on the west coast (Langton et al. 2021) this may indicate variation in diet between spatially discrete populations of Minke whales; a pattern seen in other, more studied marine mammals, as described above.

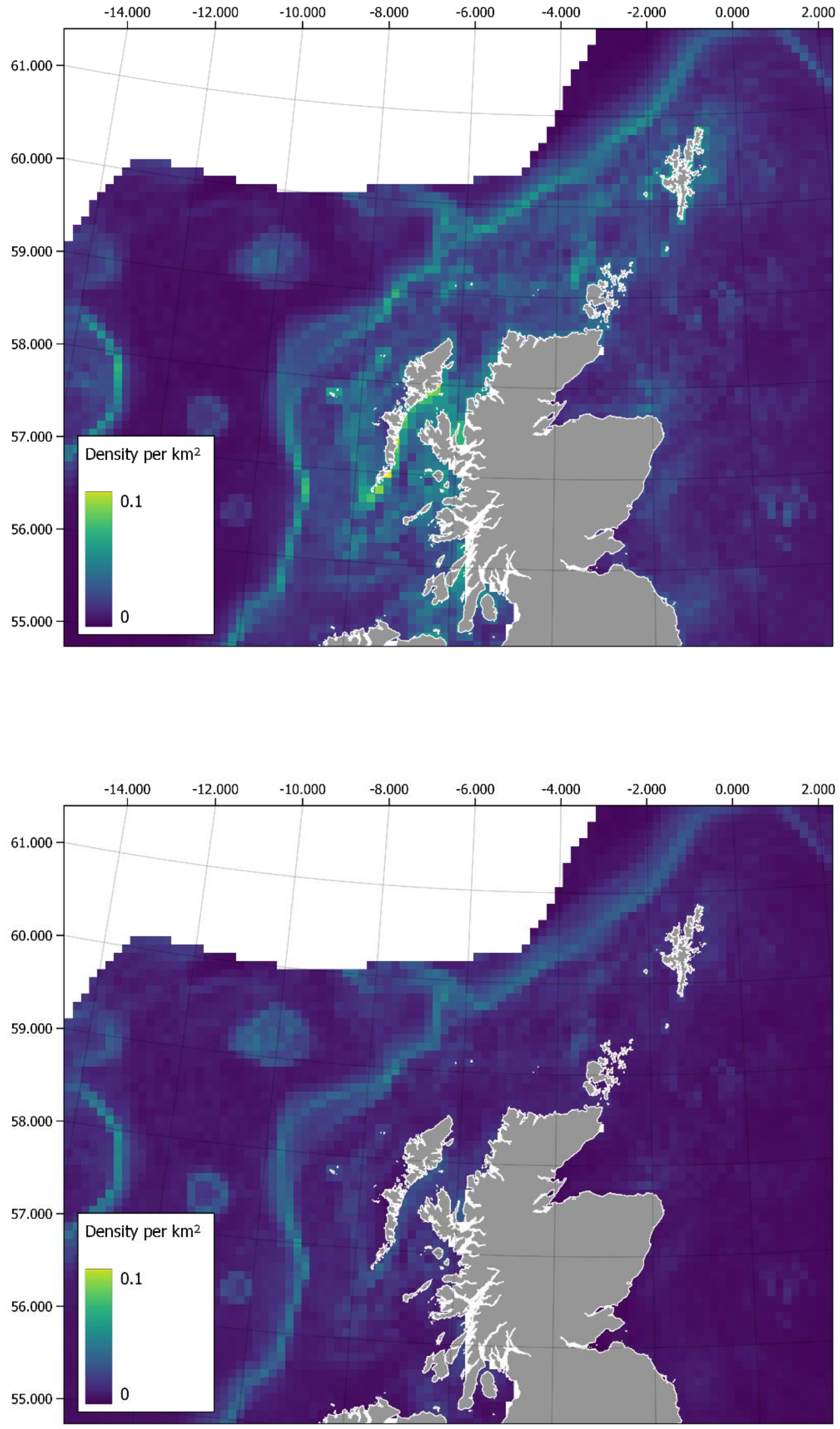
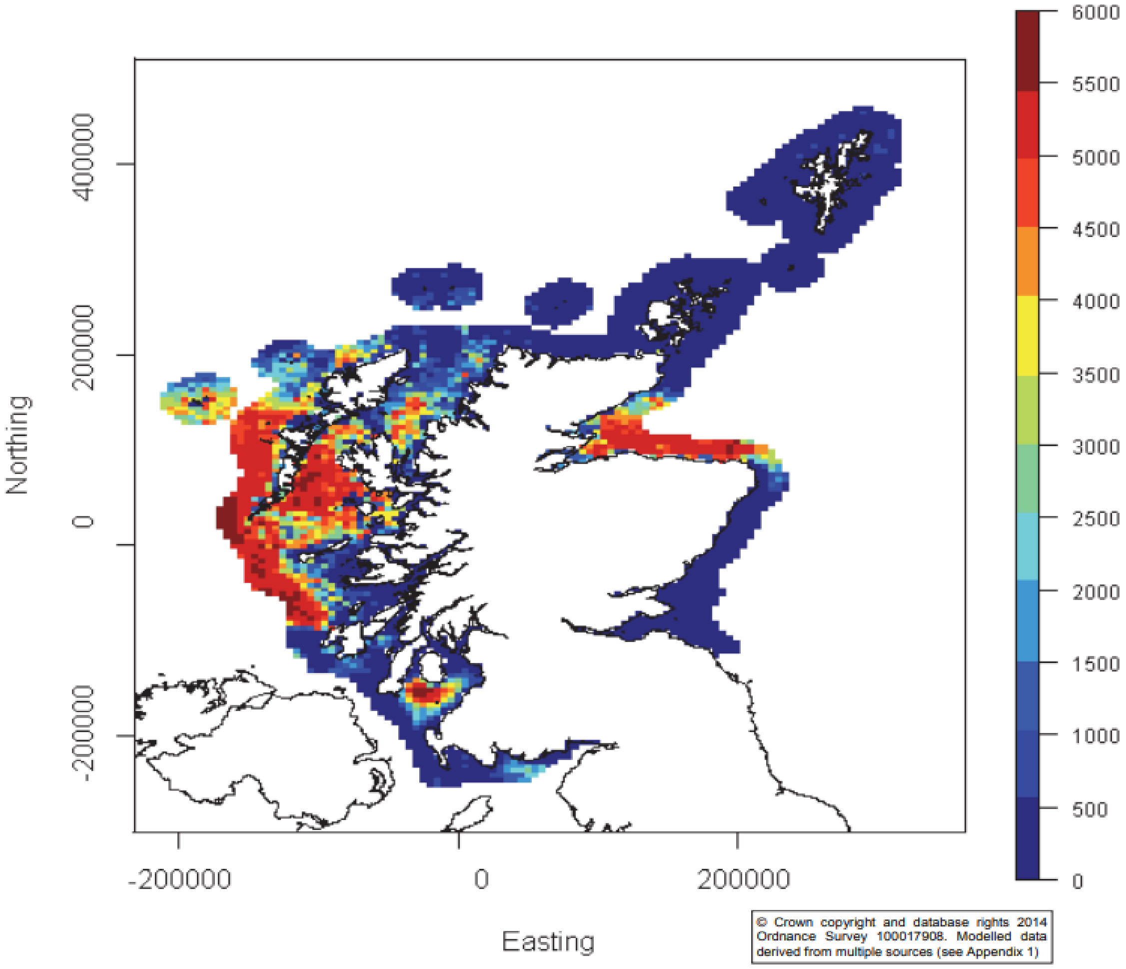


Figure 36: Predicted densities (animals per km^2) of minke whale in (above) January and (below) July in the North-East Atlantic (reproduced using density estimates from Waggitt et al. 2020).



© Crown copyright and database rights 2014 Ordnance Survey 100017908. Modelled data derived from multiple sources (see Appendix 1)

Figure 37: Index of predicted minke whale persistence-certainty (summer only) between 2001 – 2012 (Paxton et al. 2014)

5.2.5 White-beaked dolphin

White-beaked dolphins are present in Scottish waters year-round, with a wide distribution that favours both offshore and nearshore areas depending on the region (**Figure 38**). The presence of white-beaked dolphins has been found to be influenced by slope angle, with individuals appearing to favour areas of slope (Canning et al. 2008) and sections of coast adjacent to deeper water (Weir et al. 2007). The abundance of this species in nearshore waters appears to vary seasonally (Weir et al. 2007), with numbers increasing in the summer months as more individuals move into the area from offshore (Waggitt et al. 2020).

White-beaked dolphins appear to be present in reasonably high numbers in all regions of Scotland except the south west and south east of Scotland (**Figure 38** and **Figure 39**; Lacey et al. 2021). Distribution of white-beaked dolphin appears to change seasonally, with an apparent shift eastwards between winter and summer months, with densities in the North Sea peaking in June and July (**Figure 39**). The main areas of white-beaked dolphin overlap with high probability of sandeel occurrence is the offshore waters of the east coast, concurrent with increased sandeel availability in the water column during summer months where seasonal white-beaked dolphin density is also highest.

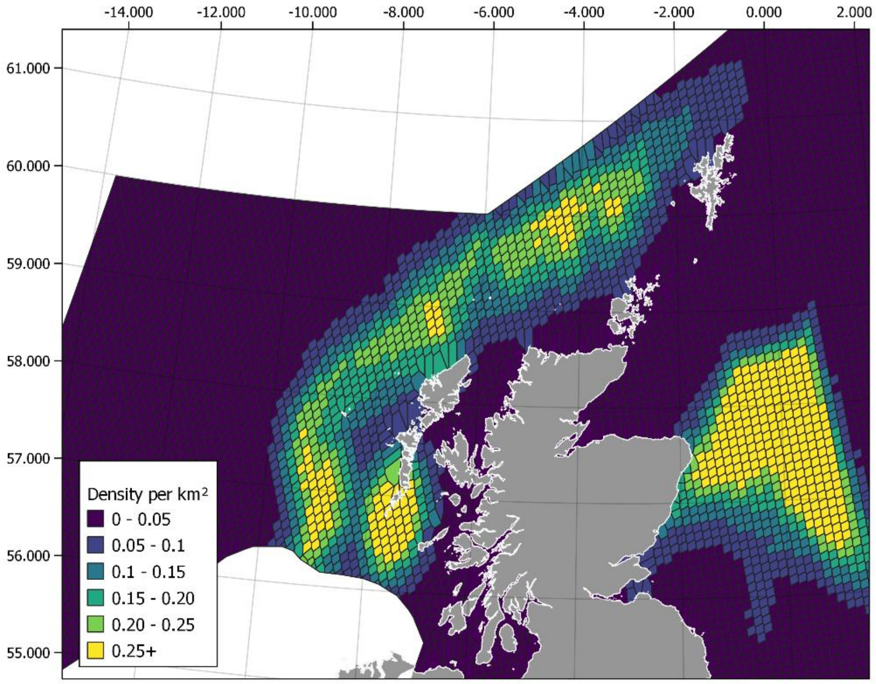


Figure 38: Predicted surface of estimated density for white-beaked dolphin in Scottish waters in 2016. Density surface downloaded from (https://scans3.wp.st-andrews.ac.uk/files/2022/08/SCANS-III-model-based-estimates-shapefiles.zip) and reproduced using density bins following Lacey et al. (2021).

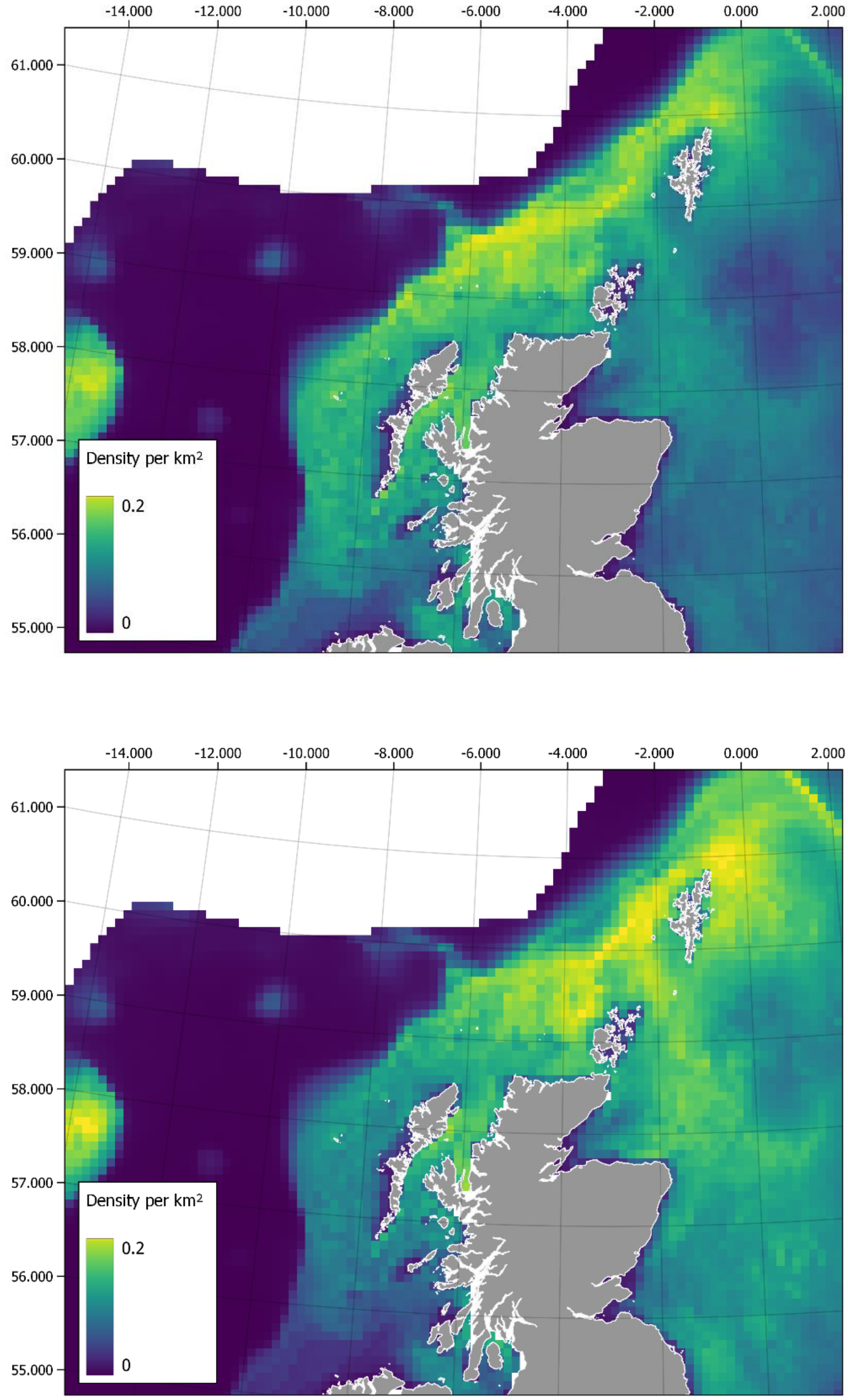


Figure 39: Predicted densities (animals per km^2) of white-beaked dolphin in (above) January and (below) July in the North-East Atlantic (reproduced using density estimates from Waggitt et al. 2020).

5.3 Vulnerability of marine mammals to declines in sandeel abundance

Sandeel are an abundant, but declining food source in much of the distributional ranges of the marine mammal species described above. However, the reliance on sandeel and subsequent susceptibility to fluctuations in sandeel abundance and distribution differ among marine mammal species, owing to variations in their ecological niches and dietary plasticity. Furthermore, the varying vulnerability of marine mammals to declines in sandeel abundance is a complex and stochastic interaction between prey distributions, diet, predator and prey demography, and predator foraging distributions and behaviour (Wilson & Hammond, 2019) so predictions are subject to considerable uncertainty.

Sandeel are a high-quality, lipid-rich prey source (Macleod et al., 2007) and improved body condition in marine mammals is linked to the proportion of sandeel in their diet. For example, Leopold et al. (2015) found a correlation between harbour porpoises in better body condition and higher amounts of fatty fish in their diet. Links between consumption of sandeel and health status of porpoises also suggested that a decrease in sandeel availability could have negative effects on porpoise populations (MacLeod et al. 2007). The predicted consumption of sandeel is high in porpoise diets, despite an abundance of other available prey species. Further, consumption of sandeel is significantly greater than all other prey types even when abundances are roughly equal (Ransijn et al. 2021). Multi-species functional responses have been published, describing the relationship between harbour porpoise and their prey species in the North Sea. These have indicated that when energy rich prey-species (i.e., sandeel) are scarce, porpoises must increase the total biomass consumed to avoid shortfalls in energy intake (Ransijn.et al. 2021) and by extension, poor body condition. As a result, minor differences in overall biomass and energetic intake were predicted between 2011 and 2022 (a period of pronounced sandeel decline in abundance across their range). Porpoise may subsequently travel greater distances or shift their ranges in search of a higher biomass of prey or increased densities of other high energy prey, partially explaining the southward distributional shifts of porpoise in the North Sea between 1994 and 2005 when sandeel in the SA4 region also showed pronounced declines (**Figure 10**, section 3.3.2; Hammond et al. 2005; Mahfouz et al., 2017).

Declines in sandeel stocks could have implications on inter-specific competition between marine mammal species in situations where sandeel are the primary food source. If sandeel are scarce, the considerable overlap in diet between grey and harbour seals (Wilson and Hammond, 2019) could result in exploitative competition which could impact one or both species. With harbour seals noted to be in significant decline in certain regions of Scotland, a depletion in sandeel stocks could be a factor in the further decline of harbour seals as indicated by the continuing decline in areas where seals show high preference for sandeels and little plasticity in diet (Wilson and Hammond 2019). The compounded effects could hasten the decline in certain populations, rendering conservation effort increasingly challenging (Hanson et al. 2015).

5.4 Summary of Evidence on Marine Mammals and Sandeel

As noted in section 3, identifying an effect of the sandeel fishery or a reduction in fishing pressure is difficult as it involves complex interactions between multiple drivers of both sandeel and predator dynamics. Further, data on the effects of sandeel abundance on marine mammal population sizes, foraging ecology and distribution are limited, with few studies able to garner sufficient statistical power to identify significant relationships. However, it seems a reasonable assumption that any increase in sandeel abundance that might result from a reduction in fisheries pressure might be beneficial to several populations of marine mammals given their dependence on sandeel as a prey source.

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Riaghaltas na h-Alba

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The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-83521-125-0 (web only)

Published by The Scottish Government, July 2023

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS1325402 (07/23)