Nordic Council
of Ministers

Improving nature management and marine protection in Skagerrak

Knowledge synthesis for conservation planning, ecosystem-based fisheries management and expanding offshore wind farms

Contents

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Executive summary

Skagerrak serves as a crucial maritime gateway linking the North Sea with the Baltic Sea. The region is characterized by a unique seascape with a deep channel known as the Norwegian Trench, which extends from the Norwegian Sea to the inner reaches of Skagerrak. The Norwegian and Swedish coasts of Skagerrak are characterized by a narrow rocky plateau that descends via steep slopes into the trench, whereas the southern Danish side features shallow sandy slopes with sporadic rocky habitat. Strong currents transport water to Skagerrak from both the northern and southern North Sea, where upwelling brings deep, cold, and nutrient-rich water to the surface, whereas less saline surface water flows from the Baltic Sea. This mixture of diverse habitats and water bodies creates a unique and exceptional ecosystem with a high biodiversity, where the access to deeper and colder water may represent a climate refuge from marine heat waves in coastal and shallow areas. While rich in habitats and species, their status is in many cases poor. Being one of the most intensively trawled areas in the world, there is scope for improvement in the management of Skagerrak's biodiversity and fisheries resources, to restore the services provided and the ecological resilience of this precious ecosystem.

By reviewing the available scientific literature (**Chapter 1**), we show that a majority of species have populations inhabiting the Skagerrak that are genetically and/or morphologically distinct from surrounding populations in the North Sea, Kattegat, and Baltic Sea. Additionally, many species also have several distinct populations within the Skagerrak. Despite this, functional connectivity across Skagerrak is high in most species, meaning individuals from several populations may coexist in certain areas during parts of the year, especially in highly mobile taxa such as many fish species. Management needs to consider that different populations may coexist at certain times in a given area. This is especially relevant in fisheries management, when different stocks coexist, and where genetic mixed-stock analysis should be implemented to disentangle and estimate the proportions of the different stocks.

A policy brief on population connectivity in Skagerrak is available here:

→ www.norden.org/en/publication/spatial-population-structure-and-connectivity-among-marine-populations-skagerrak

We identified a range of commercially valuable fish species that currently lack advice or full analytical stock assessments, or where the stock units are poorly defined, and the current advice therefore applies to an area far beyond the reach of Skagerrak (**Chapter 2**). Not all of these are of commercial interest, and fisheries advice is thus not relevant for all. However, monitoring trends in abundance can also support red list status assessment and biodiversity monitoring. The analyses highlight the remarkable diversity of fish in the Skagerrak, documenting 236 unique species or species groups across two surveys over almost 40 years. This extensive inventory underscores the ecological richness of the region and establishes a foundational dataset for understanding the area's biological complexity. Declines in certain species emphasise the impacts of high fishing pressure and/or environmental changes, signalling the need for targeted management actions. However, summarizing complex temporal patterns into single metrics poses additional challenges. While this study estimates relative abundance indices, reducing these temporal patterns to a single value may obscure year-to-year variability or mask historical baselines critical for understanding long-term trends. Given that many species in this study are deep-water and long-lived, alternative metrics, such as ratios of recent to historical averages or time series analyses over longer periods, could provide more robust insights into population changes.

A policy brief on fish species with management shortcomings in Skagerrak is available here:

→ www.norden.org/en/publication/fish-stocks-skagerrak-management-shortcomings

Marine protected areas (MPAs) are tools for biodiversity conservation in a wide sense including protection of ecosystem functions and services. Preliminary analyses suggest that marine protection in Skagerrak is weak overall, especially considering regulation of mobile bottom-contacting fishing gear (**Chapter 3**). Nature protection in the Skagerrak consists of MPAs ratified under the OSPAR agreement (EU and non-EU members), the Natura 2000 network of MPAs (EU member states) and national parks. Partially protected areas (PPAs) in the form of small-scale spatial protection of European lobster through gear restrictions are implemented widely in Norway and Sweden. Protected areas in Skagerrak are largely restricted to shallow coastal habitats (0-200 m), meaning that important deep-water habitat types are poorly protected. One notable exception is the Bratten MPA with fully protected no-take zones (Sweden). The deepest parts of the Skagerrak are situated in the Norwegian Trench, which is home to vulnerable marine ecosystems, and constitute the most important carbon sink in the greater North Sea region. Current protection of this area is weak and in urgent need of attention. Establishment of a coherent network of MPAs in the Skagerrak will require international coordination, where marine spatial planning should consider the benefits of protection to biodiversity, fisheries and climate change adaptation and mitigation.

A policy brief on marine protection in Skagerrak is available here:

→ www.norden.org/en/publication/protecting-skagerrak-biodiversity-food-and-climate

The push for diversification of renewable energy sources is expanding offshore wind farms, impacting marine ecosystems. Understanding these impacts is key to balancing wind energy benefits with biodiversity risks. We reviewed 129 publications on offshore wind farm ecological impacts, mainly in the northeast Atlantic (**Chapter 4**). The most reported consequence of wind farm installations is the introduction of new underwater habitats, but the effects reported were diverse and evenly distributed between negative and positive impacts. Consistent negative impacts were however reported for some species of seabirds and cetaceans during both operational and installation phases. Only a third of potential ecosystem interactions were studied. Least studied were impacts from cable installation, maintenance, and decommissioning. To complement our review of offshore wind farms' environmental impacts, we conducted a parallel systematic review on their socio-economic impacts on Scandinavian coastal communities. While some evidence exists from other regions, focusing mainly on business development and national industrial policy, empirical research in this area is lagging behind, hindering evidence-based decision-making for planners, managers, and policymakers.

From a Skagerrak perspective, Norway, Sweden and Denmark should consider the possibility of developing a unified local management plan to underpin a sustainable utilization of Skagerrak's seascape and ecosystem services, and to preserve and restore Skagerrak's rich and productive habitats. Skagerrak holds potential for demonstrating the benefits of integrating nature conservation and fisheries management. However, the Nordic countries cannot decide on fisheries management in Skagerrak, which except for the Norwegian EEZ, is an EU concern. Instead, we recommend forming a regional advisory committee for ecosystem-based management tasked with (1) supporting the International Council for the Exploration of the Sea (ICES) in developing the best possible quantitative stock assessments based on biologically representative stock unit definitions, (2) mapping essential habitats and their status, (3) mitigating bycatch of nontarget species, (4) advising on how to best implement a holistic ecosystem-based approach to fisheries management and nature conservation in Skagerrak, and (5) advising on a holistic integrated network of effective MPAs and OECMs across Skagerrak based on connectivity, representativity and integration with fisheries management. This advisory committee consisting of scientists should target managers in Norway and EU and could be formed, e.g. in association with ICES and the existing working group for Nordic fisheries (AG-Fisk).

Chapter 1. Population structure and connectivity among marine populations in the Skagerrak

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Summary

Most species in the Skagerrak have populations that are genetically distinct from populations in the surrounding North Sea, Kattegat, and Baltic Sea. A considerable number of these species also have multiple distinct populations within the Skagerrak, particularly along the coast and inside fjords. Highly mobile fish species, such as cod, herring and bluefin tuna, have multiple distinct populations that temporarily coexist in the Skagerrak during specific parts of the year, or during certain parts of their life cycle. Overall, the Skagerrak is well connected with adjacent seas through passive dispersal of eggs and larvae and active migration of adults. The persistence of distinct local populations despite the large potential for connectivity calls for population-specific conservation and management of marine biodiversity in the Skagerrak. Management, while maintaining an overall ecosystem approach, needs to be species- and population-specific to avoid neglecting or overexploiting vulnerable local populations.

Background

Biodiversity loss is an ongoing crisis that negatively impacts both global and local ecosystems (Cardinale et al., 2012). The currently elevated extinction rate for wild species is often referred to as "the sixth mass extinction" (Cowie et al., 2022) and is caused by various anthropogenic pressures, such as climate change, habitat fragmentation, and overexploitation of wild populations (Pievani 2014). The loss of species is likely preceded by losses of intraspecific diversity (Ceballos et al., 2017), and it has consequently been argued that the population, rather than the species, is the relevant unit for conservation (Allendorf et al., 2022). The UN CBD Kunming Montreal Biodiversity Framework specifically states maintenance of genetic biodiversity as equally important to species and ecosystem diversity. Failure to correctly identify genetic population structure and connectivity in the marine environment can result in the isolation and disappearance of vulnerable and threatened local populations, as well as the overharvesting of depleted fish stocks (Bekkevold et al., 2023). We here summarise biological knowledge on connectivity and population structure in marine species in the Skagerrak – a marginal sea in the northeast Atlantic. The results are of fundamental relevance for both local and regional management, especially in assigning management units, and designing MPA networks. Due to the extensive research performed in this area, we also discuss how conclusions from the Skagerrak may be transferable to other geographic areas.

Definitions

Population structure is the tendency of species to separate into more or less distinct spawning groups or populations. Such populations will independently evolve and maintain genetic differences and adaptations, unless there is genetic connectivity between them.

Connectivity is the passive or active dispersal of individuals – eggs, larvae, spores, seeds, swimming adults, etc. – from one location or population to another. If some individuals reproduce in the new location, this leads to genetic connectivity (gene flow), important for evolution and local adaptation. If the dispersal affects numbers and biomass in the receiving population there is demographic connectivity, important for ecological interactions and fisheries management.

Methods

We performed a systematic literature search for studies on connectivity and population structure in the Skagerrak on the Web of Science database on the 3rd of May 2023. The full list of publications was screened according to a set of five exclusion criteria. Publications were excluded if they A) had a non-marine context; B) were not in the Skagerrak; C) did not investigate connectivity of any marine species; D) were a review, meta-analysis, short-format, or non-peer-reviewed article; or E) were inaccessible.

The systematic literature search yielded a list of 413 unique scientific publications. Out of these, 113 (27 %) were eligible for review. Most excluded publications were so based on thematic irrelevance, i.e., not explicitly assessing connectivity in marine species (exclusion criterion C; 58 %). We supplemented the list of 113 publications by manually adding 59 relevant publications that the authors were aware of, or that were cited in reviewed publications. Thus, after screening, a total of 172 scientific publications, assessing population structure and connectivity in 48 marine species, both within the Skagerrak and in relation to the adjacent North Sea, Kattegat and Baltic Sea and published between 1990 and 2023 were included in the review.

Publications were divided amongst the authors, who extracted information on the study design and methodology, and summarised the relevant results. Population structure was assessed primarily using molecular genetic tools, but also with morphometry and chemical isotope analyses. Connectivity was assessed either by studies of tagged individuals or by oceanographic modelling of propagule dispersal. The scientific literature was strongly dominated by fish species, particularly cod and herring.

Key findings

The Skagerrak harbours distinct populations for the majority of species. For these species, there are clear genetic and/or morphological differences between Skagerrak populations and populations in at least one of the adjacent seas (Figure 1.1). In some of those species, including herring, lumpfish, cod, plaice, sea trout, harbour porpoise, bladderwrack and toothed wrack, the Skagerrak populations are divergent from populations in both the North Sea and the Kattegat. Several species share a genetic barrier on the south-western tip of Norway, between the Skagerrak and the North Sea, and also in the south, between the Skagerrak and Kattegat. For a few species no population structure was detected in the North Sea-Skagerrak-Kattegat area: three-spined stickleback, European flounder, brown crab, Norway lobster, and green sea urchin.

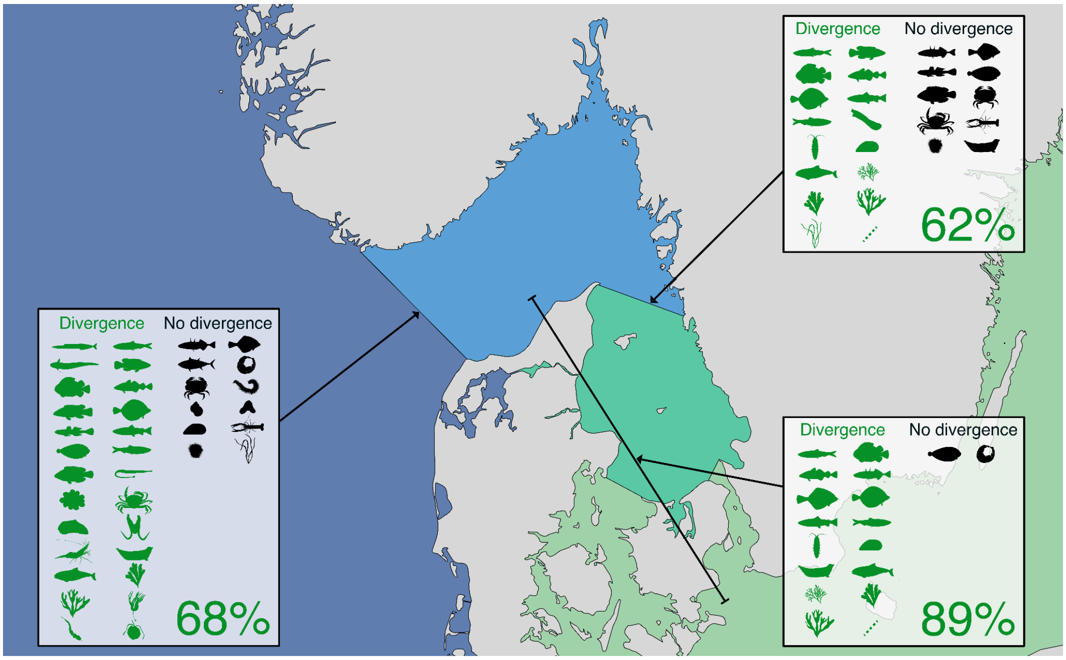


Figure 1.1. Population structure between the Skagerrak and the adjacent North Sea, Kattegat, and Baltic Sea. The boxes show the species for which population structure between two areas has been assessed, and the percentage of these species for which population structure was found (in green).

More than half of the assessed species also have multiple distinct populations within the Skagerrak (Figure 1.2A). Population structure is most common among coastal sites (Figure 1.2B), and between coastal and offshore populations (Figure 1.2C). Population structure is rare in offshore areas, and has only been described for lumpfish, Atlantic bluefin tuna, the cold-water coral *Lophelia pertusa* and the phytoplankton *Skeletonema marinoi* (Figure 1.2D).

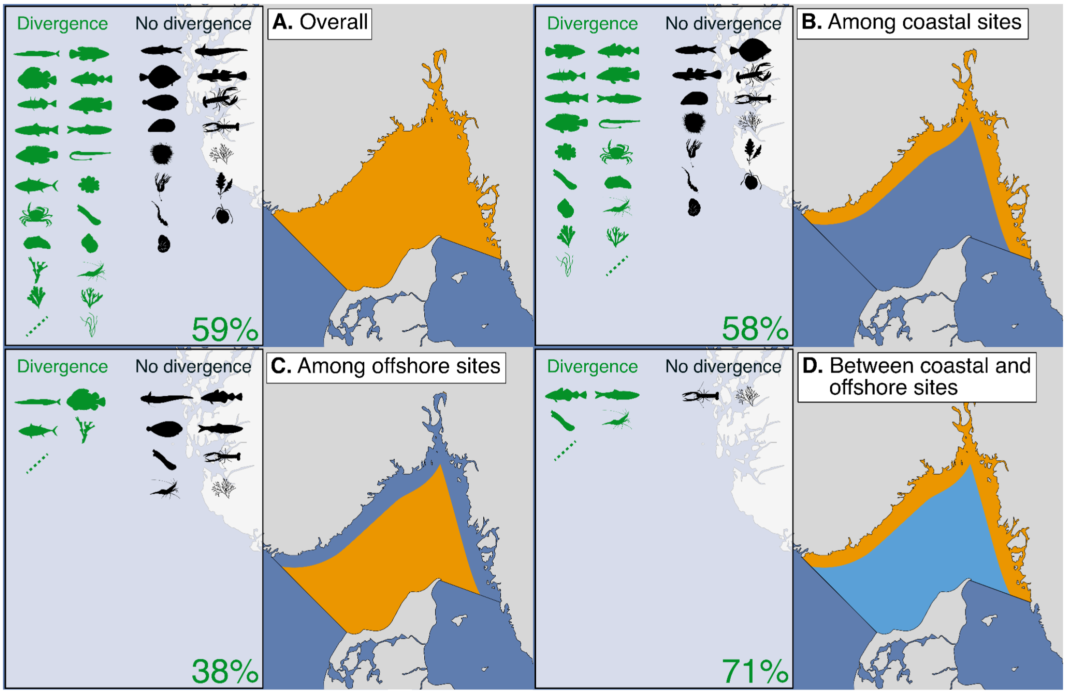


Figure 1.2. Population structure within the Skagerrak for species assessed in the scientific literature. Subplots show whether any population structure has been found A) broadly within the Skagerrak, B) among coastal sites, C) between coastal and offshore sites or, D) among offshore sites. The boxes show which species have been assessed, and the percentage of these species for which population structure has been found (in green).

Skagerrak populations generally have the potential to disperse to the adjacent North Sea, Kattegat, and Baltic Sea. Dispersal of organisms, i.e. connectivity, into the Skagerrak from adjacent seas is high in most assessed species (Figure 1.3A), whereas connectivity out of the Skagerrak is high to the North Sea for all assessed species, but slightly lower southward into the Kattegat and the Baltic Sea (Figure 1.3B). Dispersal distances within the Skagerrak are highly species-specific and may range from a few to hundreds of kilometres, meaning that management needs to be species-specific.

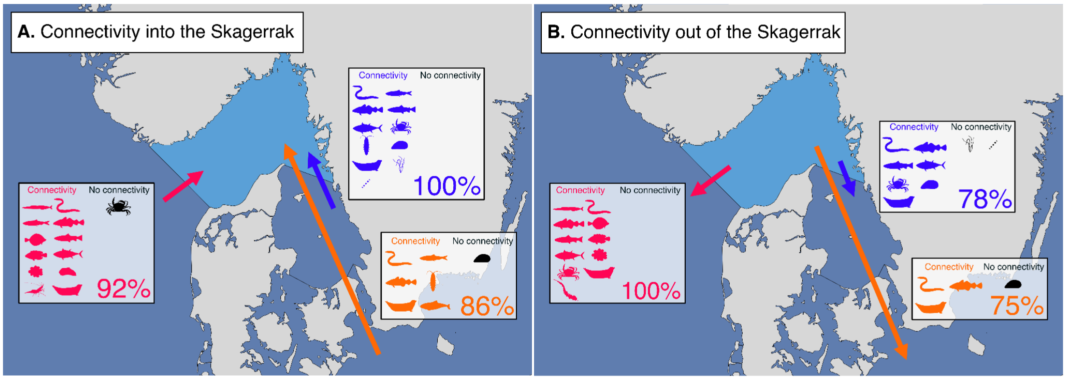


Figure 1.3. Connectivity of Skagerrak species with the adjacent North Sea (pink), Kattegat (blue), and Baltic Sea (orange). The figure summarises connectivity A) into, and B) out of the Skagerrak, assessed either by tagging or oceanographic modelling. The boxes show which species have been assessed, and the proportion of these species for which high connectivity has been found (in colour).

Population structure and connectivity are receiving increasingly more attention within both research and management. Currently, approximately ten scientific publications covering the Skagerak are published every year on these topics (Figure 1.4A). The reviewed scientific literature covers 48 Skagerrak species. However, the literature is dominated by studies on fish species (63% of studies), especially cod and herring (Figure 1.4B).

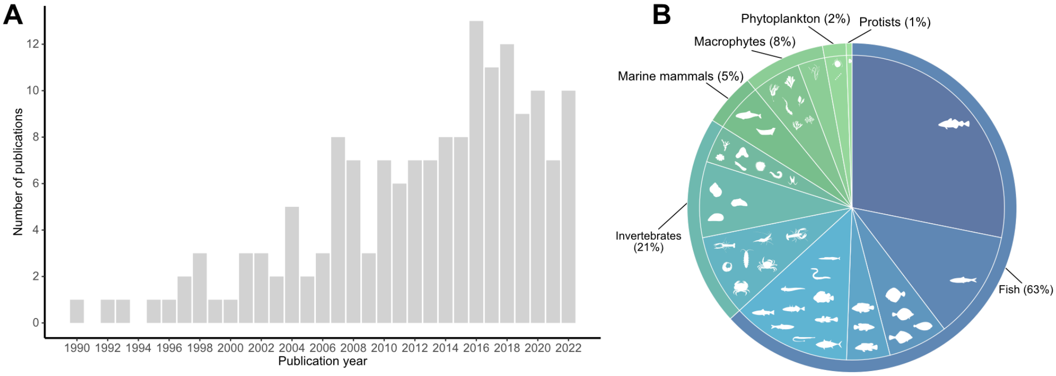


Figure 1.4. Summary of the relative numbers of studies per A) year, and B) taxon (outer pie chart) and species or species group (inner pie chart). The figures are based on the 172 studies that were eligible for review.

Perspectives and conclusion

By reviewing the available scientific literature, we show that a majority of species have populations inhabiting the Skagerrak that are genetically and/or morphologically distinct from surrounding populations in the North Sea, Kattegat, and Baltic Sea. Additionally, many species also have several distinct populations within the Skagerrak. Despite this, functional connectivity on the large scale is high in most species, meaning individuals from several populations may coexist in certain areas during parts of the year, especially in highly mobile taxa such as the more mobile fish species. Working according to this connectivity "rule book" is likely essential to achieving sustainable management of intraspecific biodiversity in the Skagerrak. However, with these findings come considerable challenges. The high contemporary connectivity with adjacent seas on the large scale supports the notion of the Skagerrak as a transition zone between the North Sea and the Baltic Sea. Multiple species have populations dispersing in and out of the Skagerrak at different times. Management of marine populations in the area, thus, cannot view the Skagerrak as an entirely isolated system, but needs to take large-scale connectivity into consideration. As shown herein, however, the Skagerrak itself is not homogeneous. Most species have multiple differentiated populations, particularly along the coast, which are unique to the Skagerrak. Management of such species should be on a much finer geographic scale than the entire Skagerrak to preserve unique populations – often on the scale of 10s of kilometres, or of individual fjords. The Skagerrak is, thus, more than just a transition zone – it is also a unique marginal sea requiring special attention from management, to preserve both coastal and offshore populations.

For many of the fish species, particularly those displaying larger movement, there is also temporal variability in population assemblages. The sympatry of multiple populations within a species in a given area poses a significant challenge for spatial methods used to delineate management units. Management of these species should establish practices suitable for mixed-stock management. For instance, in mixed-stock fisheries, the relative proportions in catches over time should be monitored, for instance using population genetic tools, with management decisions taken expediently according to the relative population sizes. Management, thus, needs to be both temporal and spatial. Adding to this point, the fields of connectivity and population structure are growing, gaining more research attention and more utility in legislation. With this development, we are gaining increasingly detailed knowledge, as well as improved taxonomic and geographic representation at both large and small scales. Consequently, management strategies need to be both spatiotemporally sensitive, and flexible enough to adapt to new scientific findings. For instance, management programs for monitoring genetic diversity (e.g., Mastretta-Yanes et al., 2024), and real-time genetic monitoring of fisheries catches (e.g., Dahle et al., 2018) have been suggested to improve management practices, by enabling agile management in response to updated information on intraspecific diversity and connectivity. Incorporating these monitoring tools in management would also aid in the estimation of population sizes, fundamental to analyses of demographic connectivity, which are lacking in this region.

Conservation management efforts have the highest probability of success when they are supported by scientific information on e.g. vulnerability, diversity, location, and connectivity of ecotypes, populations and species (van Oppen & Coleman, 2022). The finding of differentiated populations despite high functional connectivity, although counterintuitive, is not specific to the Skagerrak. Differentiated but sympatric populations are found in marine species in many other regions around the world, running the same risks of mismanagement unless accounted for (e.g., Le Moan et al., 2016; Moore et al., 2021; Diaz-Arce et al., 2024). Therefore, we believe that the patterns inferred here, as well as our recommendations for management, are likely to be more broadly applicable also to other marine systems. In this review, we have described overarching patterns of connectivity and population structure in a marginal sea, enabling marine wildlife management to better account for, conserve, and restore biodiversity – on all levels.

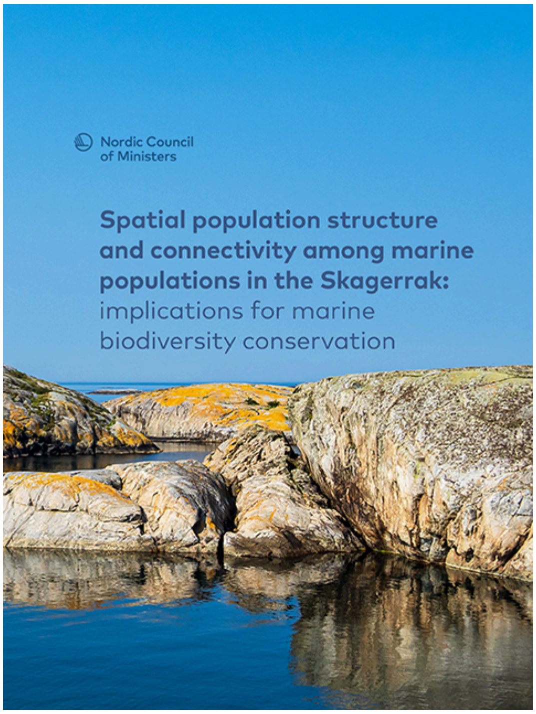
Policy brief on spatial population structure and connectivity among marine populations in the Skagerrak

As part of the SAMSKAG project a policy brief was produced in which the concept of population connectivity was explained and the main findings also presented herein were summarised (André et al., 2024). The following recommendations for management were listed:

- Management of marine biodiversity in the Skagerrak needs to be based on knowledge about species population structure and connectivity.
- Management should be fine-scaled enough to capture population structure within the Skagerrak, often on the scale of 10s of km, especially along the coast and within fjords.
- Fisheries management, MPA design and marine spatial planning need to consider both coastal and offshore marine areas.
- Management needs to consider that different populations may coexist at certain times in a given area. This is especially relevant in fisheries management, when different stocks coexist, and where genetic mixed-stock

analysis should be implemented to disentangle and estimate the proportions of the different stocks.

- More information on population structure and connectivity is needed, both for sessile and mobile species.
- Adaptive strategies that incorporate both spatial and temporal management are more likely to succeed in creating a robust and future-proof biodiversity management in the Skagerrak.



Find the policy brief here: www.norden.org/en/publication/spatial-population-structure-and-connectivity-among-marine-populations-skagerrak

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Chapter 2. An evaluation of fish stocks lacking quantitative assessments in Skagerrak

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Summary

The Skagerrak region, a basin connecting the North Sea and Kattegat, is a diverse and unique marine ecosystem characterized by a rich assemblage of fish species. Despite its ecological and commercial importance, many species in this area remain unassessed and understudied. This report evaluates the trends of fish species in the region that lack quantitative assessments. Using decades of commercial landings and scientific survey data, the study makes an inventory of observed species, highlights significant knowledge and data gaps, particularly for deep-water species in underrepresented habitats like the Norwegian Trench, and analyze trends in landings and abundance indices. Of the 92 species analyzed, 45 exhibited reliable abundance trends, with a mix of population increases and declines. While species like ling and anglerfish show signs of recovery, others, such as pollack and Atlantic wolffish show declining abundance trends, calling for further investigations. The report also underscores the growing economic role of cephalopods in fisheries, despite their unregulated and poorly understood stock status. Recommendations emphasize the need for enhanced monitoring, region-specific management strategies, and international collaboration to ensure sustainable use and conservation of Skagerrak's fish resources. By integrating fishery-dependent and -independent data sources and refining spatiotemporal modeling methodologies, this study and its findings provide a critical foundation for addressing the challenges of data-limited fisheries and achieving sustainable management goals in the Skagerrak.

Background

The Skagerrak basin, located between the North Sea and Kattegat on the European continental shelf, serves as a gateway for water exchange with the Baltic Sea, shaping the oceanographic processes in this region (Bendtsen et al., 2009). This location creates a unique combination of habitats, water masses, and depth gradients, establishing the region as a biodiversity hotspot. However, its ecological complexity, combined with governance challenges stemming from its location between three nations - Denmark, Norway, and Sweden - hinders effective resource management and conservation. While Denmark and Sweden are part of the European Union (EU) and governed by the Common Fisheries Policy (CFP), Norway operates outside the EU framework, adding complexity to coordination efforts.

In the relatively well-studied Skagerrak region, a diverse fleet of fisheries operate (Hornborg et al., 2020). Yet, most studies have focused on its shallow waters, leaving the deeper areas, such as the Norwegian Trench understudied. This gap is partly attributed to the design of the International Bottom Trawl Survey (IBTS), which only monitors depths up to 200 meters (few observations between 200 and 300m), leaving critical habitats in the deeper regions poorly represented. This local limitation reflects a broader global scenario, where most deep-water stocks are considered data-limited, lacking data to conduct a quantitative assessment and to estimate reference points, such as the maximum sustainable yield (MSY; Costello et al., 2012). Therefore, unassessed but harvested stocks are often associated with low biomass and unsustainable fishing pressure, as highlighted in previous studies (Costello et al., 2012; Hilborn et al., 2020).

The International Council for the Exploration of the Sea (ICES) is an intergovernmental marine science organization that primarily provides advice on fish stocks in the Northeast Atlantic. In its most recent annual advice, ICES evaluated 185 fish stocks in this region, encompassing over 60 species (López and Perry, 2022). Although the Northeast Atlantic is one of the best-studied marine regions, nearly 50% of its fish stocks remain without quantitative assessments, due to data limitation (ICES, 2024). This issue is particularly pronounced for non-target species or those inhabiting deeper habitats that are challenging to monitor, such as the Norwegian Tench in Skagerrak. Effective monitoring and science-based management are crucial for achieving the United Nations Sustainable Development Goal 14 (SDG 14; "Conserve and sustainably use the oceans, seas, and marine resources"), which aims for sustainable oceans by 2030.

In this study, more than 50 fish species in Skagerrak that lack quantitative stock assessments and management frameworks were identified. For each species, trends in commercial landings (if available) by Denmark, Norway, and Sweden, and fishery-independent catch rates were examined based on a novel combination of two scientific surveys. These findings provide a foundation for developing stock assessment models, improving red list status assessments, and prioritizing future monitoring and management efforts to ensure the sustainable exploitation and conservation of this exceptional and diverse marine ecosystem. Our research further underscores the need for collaborative, region-specific management approaches to safeguard the biodiversity and fisheries of the Skagerrak.

Scientific surveys

Two demersal scientific surveys provide comprehensive coverage of the Skagerrak area: the North Sea International Bottom Trawl Survey (NS-IBTS) and the Norwegian Shrimp Survey (NOSS). The NS-IBTS is one of the oldest surveys in the Northeast Atlantic that has operated in the first quarter (Q1) of the year since 1967. Initially designed to monitor juvenile herring abundance, its scope later expanded to include recruitment indices for many gadoid species. Since 1986, the sampling has employed standardized methods, including the use of the GOV bottom trawl as the main fishing gear, as well as protocol for identifications and records of species. The survey spans over a wide area of the North Sea, including the Skagerrak, at depths of 10–300 meters. The NOSS, established in 1984, focuses on providing a fishery-independent abundance index for northern shrimp (*Pandalus borealis*) in the deeper areas of the Skagerrak and North Sea. Since 2006, the survey employs a standardized design using a Campelen 1800 bottom trawl with rockhopper gear and operating in the first quarter. The survey covers the deeper areas of the Norwegian trench, with depths ranging from 111 to 552 meters. Although the NS-IBTS also conducts surveys in the third quarter (Q3), these data are excluded from this study to mitigate the effect of seasonal changes in species distribution and focus on the overlapping season between the two surveys.

Selection of species

From a total of 236 taxonomic entities recorded in the NS-IBTS Q1 and NOSS surveys between 1986 and 2023, 126 species of bony fish (Actinopterygii) and cartilaginous fish belonging to the class Holocephali were selected as a starting point for identifying fish species in the Skagerrak relevant for the analysis. Other Chondrichthyes species (*Elasmobranchii*), although present in the area, were excluded due to species identification challenges. These species will be investigated in a future study. Other species not identified to the species level were also removed to avoid conflating trends for species with potentially different abundance and distribution patterns for different species, leaving 111 species. Further filtering excluded species not classified as demersal, bathy-demersal, or benthopelagic based on FishBase (Froese and Pauly, 2024), as the survey gear is unlikely to adequately capture pelagic species (Berg et al., 2024). Nevertheless, bathypelagic species, such as roundnose grenadier (*Coryphaenoides rupestris*) and pearlsides (*Maurolicus muelleri*), were included as little is known about many of these species and the majority of Skagerrak consist of suitable deep-water habitat for these species. This process resulted in a final list of 92 species. From these 92 species, only 10 had quantitative stock assessments and advice by ICES (i.e. ICES stock category 1 or 2) that included Skagerrak (ICES area 3a or 3a.20; Supplementary Table S1). The remaining 82 species, caught in one or both surveys from 1986-2023, lack specific quantitative stock assessments and associated advice, or are not assessed and considered as any stock in ICES, making this species list the focus of this analysis (Supplementary Table S2). Note, that a data-limited stock assessment (i.e. ICES stock category 3-6) was found for 12 out of these 82 species (Supplementary Table S2).

Estimating relative abundance of fish species in Skagerrak

The survey data was cleaned and processed according to ICES (2023) guidelines. Duplicate haul IDs and entries with missing values were removed. Only valid hauls with complete species records from 1986–2023 in Q1 and the North Sea and Skagerrak were retained. Categories with less than 2 hauls with positive observations were excluded. The final dataset categorized gear as either one of the two bottom trawl gear types, GOV and Campelen. To combine the two surveys, species were grouped according to their morphological features and association with the seabed (on the seabed vs. above the seabed). Gear efficiency estimation was restricted to 2006–2023, within specific geographical and depth ranges. The temporal and spatial trends in abundance of the species were explored by means of spatiotemporal modelling, fitting Generalised additive models (GAMs) to survey catch rates for each species following the procedure described in Berg et al. (2014). Based on the converged models for each species, the abundance in a fine spatial grid for the Skagerrak area was predicted using fine-scale depth information from bathymetric maps (Pante et al. 2023). For more details on the methodology and spatiotemporal models, please refer to Supplementary Section 2. The models converged for 62 species. However, 17 out of these 62 species showed large uncertainty (coefficient of variation (CV) > 150%) or sparse data scattered over many years. The results for these species were deemed unreliable and excluded from further analysis, leaving 45 species with reliable abundance indices. The resulting abundance indices and spatial distribution and uncertainty for all 45 species are shown in Supplementary Figures S2-S10. Figure 2.1 shows the estimated temporal abundance trends for four example species: Ling (*Molva molva*), Atlantic wolffish (*Anarhichas lupus*), Rabbit fish (*Chimaera monstrosa*), and Greater weever (*Trachinus draco*), while Figure 2.2 shows the spatial patterns and associated uncertainty for these four species.

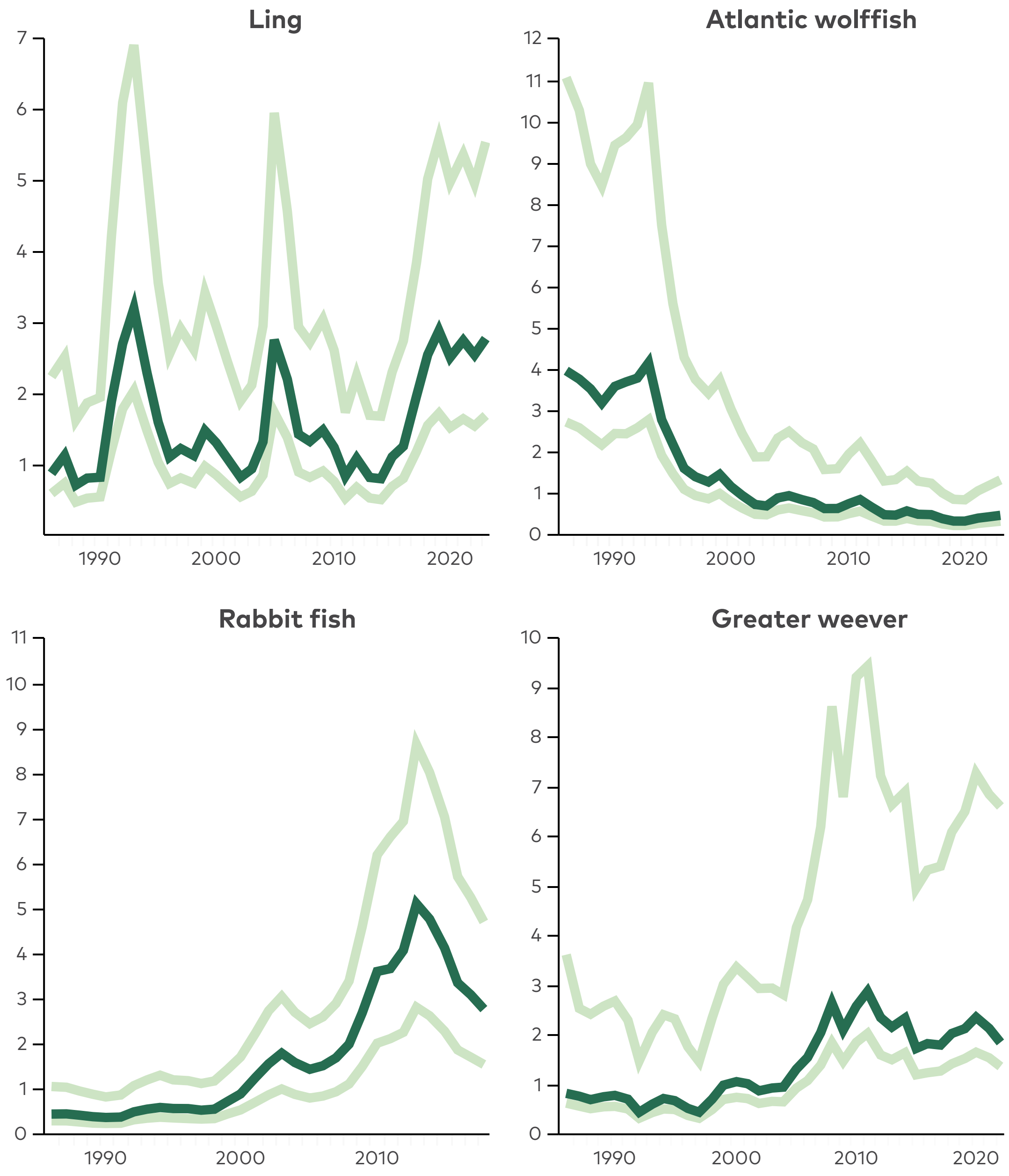


Figure 2.1. Relative abundance index (standardized to mean 1) over time for 4 example species: Ling (Molva molva), Atlantic wolffish (*Anarhichas lupus*), Rabbit fish (*Chimaera monstrosa*), and Greater weever (*Trachinus draco*). The shaded polygon indicates the 95% confidence intervals for the relative abundance index. Some years during the earlier part of the time series have no information, as e.g. for 1989, 1993, and 2002-2003 for Rabbit fish.

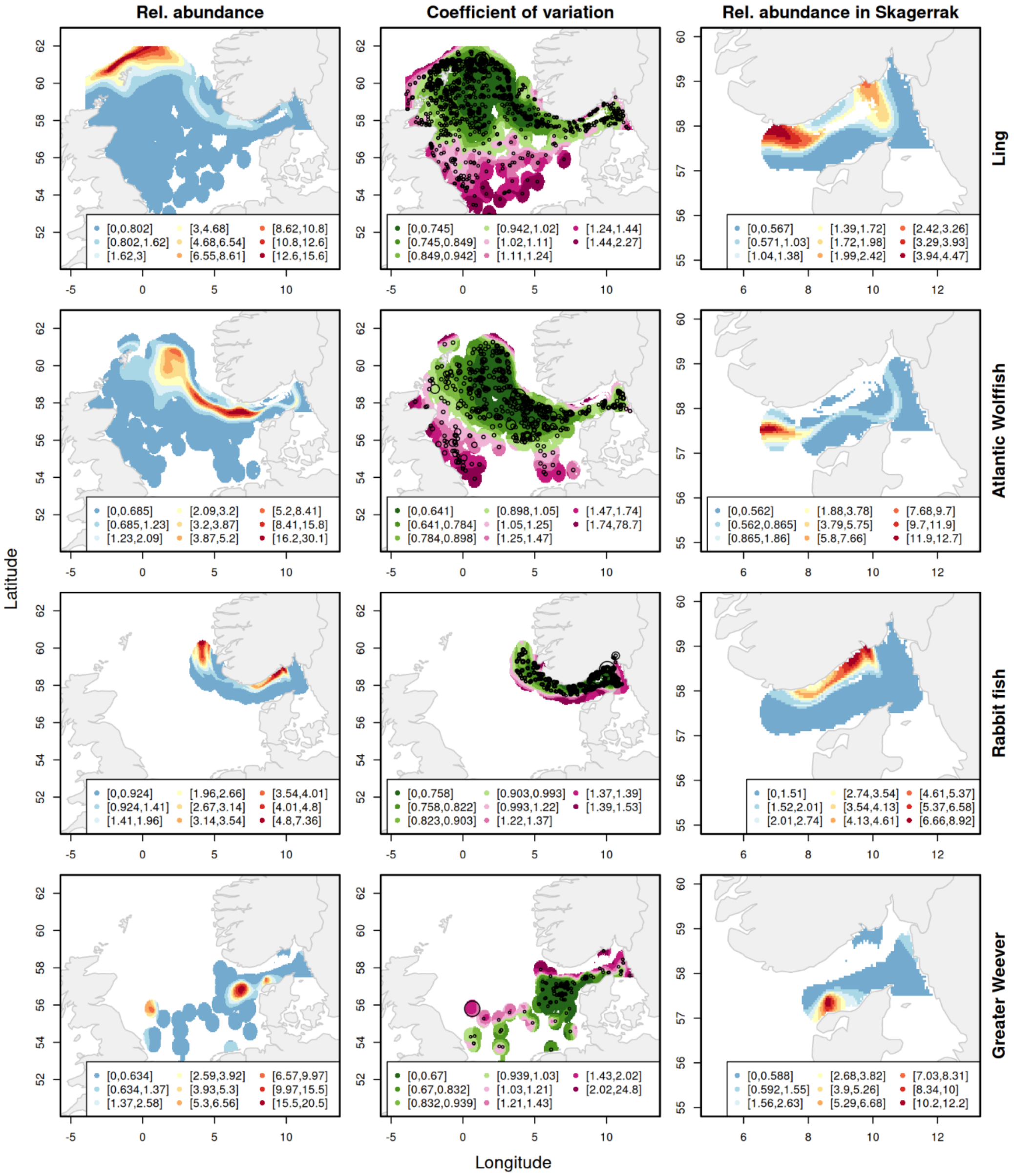


Figure 2.2. Average relative abundance and associated uncertainty (coefficient of variation) for the whole modelling area (North Sea and Skagerrak) over 2013-2022 (first and second column) and average relative abundance in Skagerrak over 2013-2022 (third column) for 4 example species: Ling (*Molva molva*), Atlantic wolffish (*Anarhichas lupus*), Rabbit fish (*Chimaera monstrosa*), and Greater weever (*Trachinus draco*) (rows). The corresponding maps for the other species are shown in Supplementary Figures S5-S10.

Commercial landings from Skagerrak

Not all of the 82 data-poor species (Supplementary Table S2) were caught in commercial landings, alternatively they weren caught but are not identified to species level. Norwegian, Swedish, and Danish experts together identified 19 species belonging to 12 different families for which reliable landings information is available on species level from all three countries. The absolute landings reveal significant variability over time, with Denmark consistently dominating the total landings In Skagerrak (Figure 2.3A). Swedish and Norwegian contributions remain smaller but show slight variations across the years. Landings declined sharply from the early 1990s to the mid-1990s, followed by a period of stability and occasional peaks, such as a notable increase around 2005. Since 2007, total landings have been at lower and stable levels around 3000 tonnes. The relative proportions of landings highlight Denmark's dominant role, with its contributions consistently accounting for 70% to nearly 100% of the total in most years (Figure 2.3B). Sweden and Norway have smaller shares, rarely exceeding 25% combined, though Norway's relative contribution increased slightly after 2007. It should be noted that numbers from official landing statistics, such as those used here, may deviate from actual catches that include discards, particularly back in time.

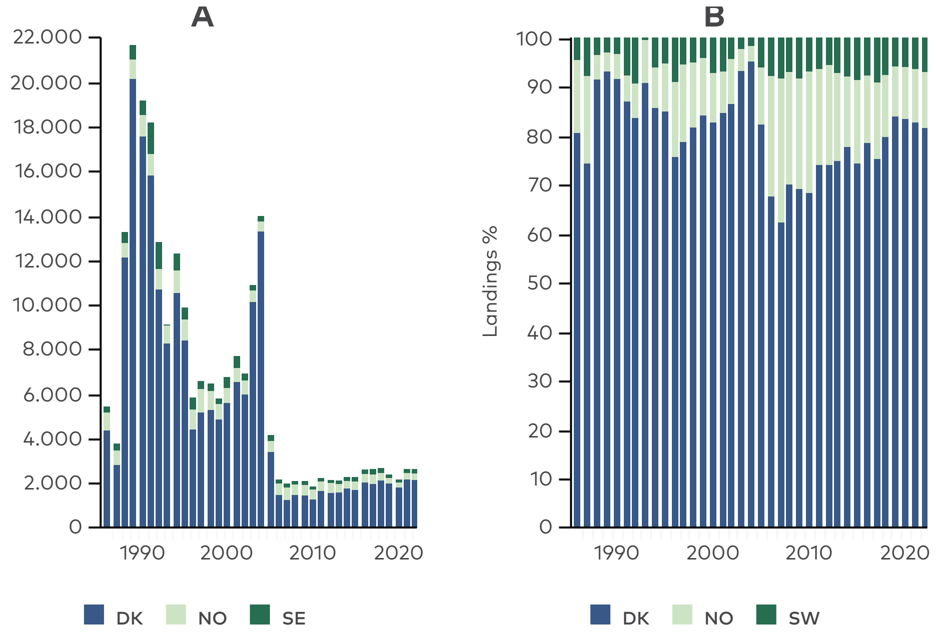
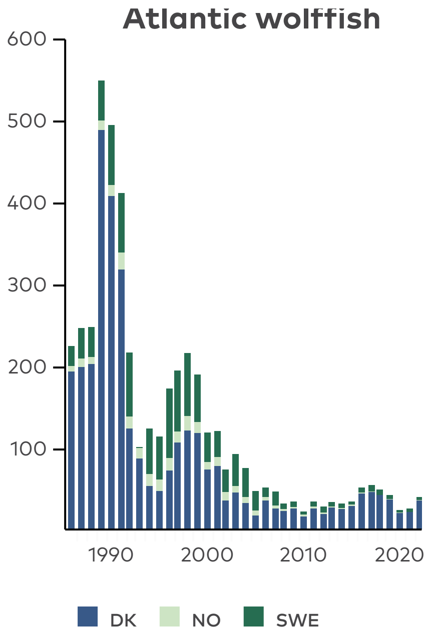
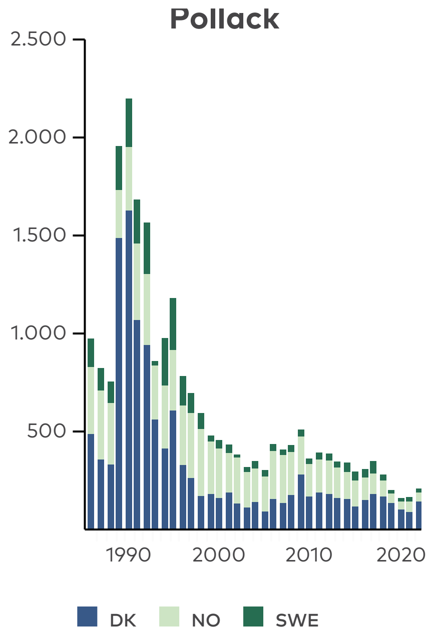
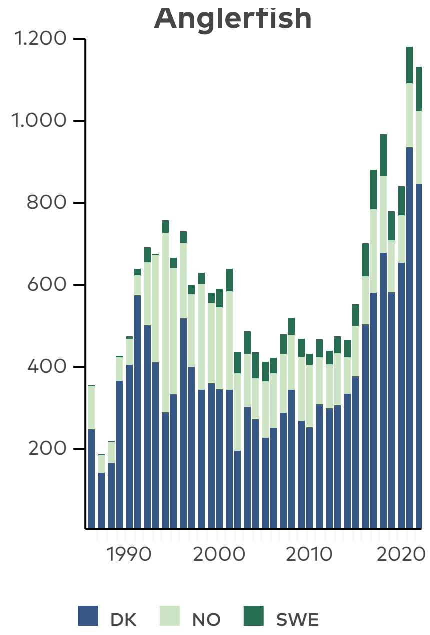


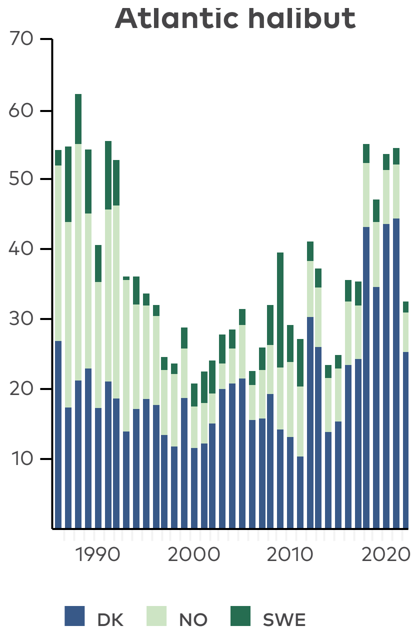
Figure 2.3. Annual landings (in tonnes) from Skagerrak for species in Table 2 by country. A) Absolute landings across species, B) Proportion of annual landings by country in percentage.

Landings by year for six selected example species are presented in Figure 2.4. A general decline in landings is evident for several species, such as Atlantic wolffish (*Anarhichas lupus*) or pollack (*Pollachius pollachius)*. Conversely, certain species exhibit stable or increasing trends. For example, anglerfish (*Lophius piscatorius)* shows increasing landings, particularly in Denmark, after the 2000s, while Atlantic halibut (*Hippoglossus hippoglossus)* shows fluctuations but no clear directional trend. Temporal shifts in landings are apparent for species such as whiting (*Merlangius merlangus)* and roundnose grenadier (*Coryphaenoides rupestris*), which experienced high landings in the 1990s but saw a sharp decline thereafter, particularly in Denmark.


Atlantic wolffish


Pollack


Anglerfish


Atlantic halibut

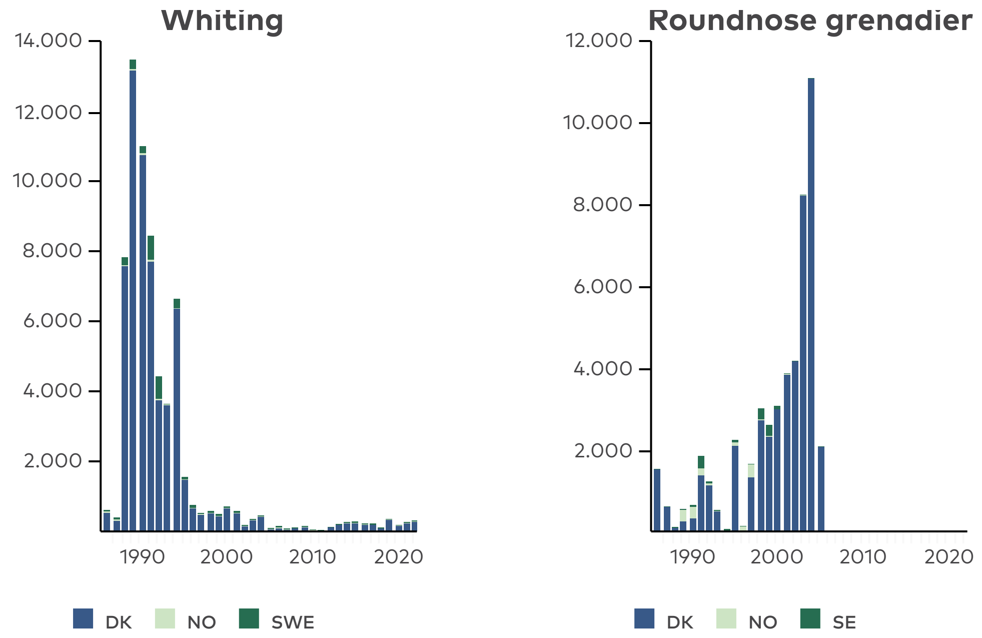


Figure 2.4. Absolute annual landings (in tonnes) by country for six example species: Atlantic wolffish (*Anarhichas lupus*), pollack (*Pollachius pollachius*), anglerfish (*Lophius piscatorius*), Atlantic halibut (*Hippoglossus hippoglossus*), whiting (*Merlangius merlangus*), and roundnose grenadier (*Coryphaenoides rupestris*).

Trend in landings and abundances

The trend in landings and relative abundance indices was estimated as the Pearson correlation coefficients over the period 2013 to 2022. Note that some species that show positive trends in the last decade, had considerably larger landings and/or relative abundance indices before 2013, such as Norway redfish (*Sebastes viviparus*). The estimated trends in landings and/or relative abundance over the last 10 years (2013-2022) for the 45 species are summarized in Table 2.1. Not all 45 species are of commercial interest, and therefore developing fisheries advice may not be so relevant for all, unless they appear in large numbers as bycatch. However, the predictions of changes in abundance over time can help red list status assessment and biodiversity conservation/restoration efforts. According to FishBase, 32 out of the 45 species in Table 2.1 are (or have been) of commercial interest somewhere within its distribution range.

Common name	Latin name	Trend in surveys	Trend in landings	Commercial interest	Coefficient of variation (CV)
Hooknose	*Agonus cataphractus*	-0.84		-	0.25
Atlantic Wolffish	*Anarhichas lupus*	-0.65	0.02	+	0.49
Greater Argentine	*Argentina sphyraena*	0.31		+	0.45
Scaldfish	*Arnoglossus laterna*	0.24		-	1.1
Tusk	*Brosme brosme*	-0.23	-0.0036	+	0.92
Solenette	*Buglossidium luteum*	-0.45		-	1
Common Dragonet*	*Callionymus lyra*	-0.22		-	0.39
Spotted Dragonet*	*Callionymus maculatus*	-0.39		(-)	0.3
Reticulated Dragonet*	*Callionymus reticulatus*	-0.38		+	0.74
Tub Gurnard*	*Chelidonichthys lucerna*	0.88		+	0.68
Rabbit fish	*Chimaera monstrosa*	0.41	0.015	+	0.21
Five-bearded Rockling*	*Ciliata mustela*	0.39		+	1.1
Roundnose Grenadier	*Coryphaenoides rupestris*	-0.25	0.57	+	0.49
Lumpsucker	*Cyclopterus lumpus*	-0.18	-0.22	+	0.29
Four-bearded Rockling*	*Enchelyopus cimbrius*	-0.9		+	0.17
Grey Gurnard*	*Eutrigla gurnardus*	-0.25	-0.094	+	0.26
Blackbelly Rosefish	*Helicolenus dactylopterus*	0.89		+	1.1
American Plaice	*Hippoglossoides platessoides*	-0.68	-0.1	+	0.17
Atlantic Halibut	*Hippoglossus hippoglossus*	0.77	0.7	+	0.27
Great Sand Eel	*Hyperoplus lanceolatus*	-0.55		+	0.89
Fries's Goby	*Lesueurigobius friesii*	0.84		-	0.75
Common Dab	*Limanda limanda*	-0.48	-0.73	+	0.18
Common Seasnail	*Liparis liparis*	-0.86		-	1.3
Anglerfish	*Lophius piscatorius*	0.48	0.91	+	0.25
Snake Blenny	*Lumpenus lampretaeformis*	-0.072		-	0.49
Slender Eelpout*	*Lycodes gracilis*	-0.77		-	0.23

Vahl's Eelpout*	*Lycodes vahlii*	-0.4		(-)	0.4
Pearlsides	*Maurolicus muelleri*	-0.1		+	0.53
Whiting	*Merlangius merlangus*	0.76	0.24	+	0.2
Lemon Sole	*Microstomus kitt*	-0.12	-0.062	+	0.11
Blue Ling	*Molva dypterygia*	0.73	0.8	+	0.36
Ling	*Molva molva*	0.91	0.9	+	0.32
Shorthorn Sculpin	*Myoxocephalus scorpius*	0.64		+	0.59
Greater Forkbeard	*Phycis blennoides*	-0.065	0.93	+	0.29
European Flounder	*Platichthys flesus*	-0.38	0.35	+	0.5
Pollack	*Pollachius pollachius*	-0.4	-0.91	+	0.55
Norway Goby*	*Pomatoschistus norvegicus*	0.8		-	1.2
Brill	*Scophthalmus rhombus*	-0.94	-0.28	+	0.28
Norway Redfish	*Sebastes viviparus*	0.82		+	0.5
Nilsson's Pipefish	*Syngnathus rostellatus*	-0.3		-	0.81
Greater Weever	*Trachinus draco*	0.071		+	0.7
Pouting*	*Trisopterus luscus*	-0.64		+	1.5
Poor Cod*	*Trisopterus minutus*	0.45		+	0.41
Norwegian Topknot	*Zeugopterus norvegicus*	0.23		-	0.89
John Dory	*Zeus faber*	0.26	0.79	+	0.61

Table 2.1. Estimated recent trends in surveys and landings for 45 species ordered by Latin name. Landing trends are given only for those species that are confidently separated by species in the landing statistics. The +/- sign indicates whether the species is of any commercial interest based on FishBase (Froese and Pauly, 2024). A negative sign in brackets, (-), indicates that species has only been reported to be relevant for subsistence fisheries. The *symbol behind the species name indicates that this species may occasionally be mistaken for another species even in scientific surveys. It is important to note that the trends presented here are based on the most recent ten-year period, and for many species landings and/or abundance were considerably larger before 2013. Hence, even though the numbers have been much higher in the past, there might still be a positive trend in recent times (see Supplementary Figures S2-S4 for the full time-series for all species).

For 19 species, both trends (survey and landings) are available, and the results can be presented graphically by contrasting the trend in the two time-series (Figure 2.5). The comparison of 10-year trends in survey and landings data for these 19 fish species provides an indication of the correlation of the trends in both data sources. For most species, the trends in survey-based abundance estimates and commercial landings are consistent, i.e. increasing, decreasing or flat trend in both data sources. For instance, species such as greater forkbeard (*Phycis blennoides*), anglerfish (*Lophius piscatorius*), ling (*Molva molva*), blue ling (*Molva dypterygia*), and whiting (*Merlangius merlangus*) show positive trends in both survey and landings data, suggesting population growth or recovery over the past decade. If these species are recovering from low numbers, careful regulation and monitoring may however still be needed to safeguard recovering populations. It is important to note that the trends presented here are based on the most recent ten-year period, and for many species landings and/or abundance were considerably larger before 2013, and for the deep-sea species (i.e. blue ling) estimating abundance before the introduction of the NOSS survey is not possible.

For other species, the trends between surveys and landings diverge. For example, roundnose grenadier and John Dory exhibit positive trends in landings while survey data suggest declines. These discrepancies may sometimes stem from differences in survey and fisheries coverage, but can also be the result of an increase in selective fishing activities that target these species, indicating population declines as a result of a higher fishing pressure. Such mismatches in trends emphasize the need to integrate multiple data sources to better understand and manage species with complex population dynamics and sparse data. Conversely, pollack, and common dab show consistent declines in both survey and landings data, which warrants further investigations. In case of substantial discards these should also be considered. For example, for common dab, discards are estimated by ICES to be up to 10 times higher than the landings.

Interestingly, no species is in the yellow quadrant, i.e. displaying positive trends in survey data but negative trends in landings, suggesting that an increase in abundance is always accompanied by an increase in catches. This underlines the importance of developing cross-national recovery plans for stocks that are increasing from very low numbers, to allow them to fully recover.

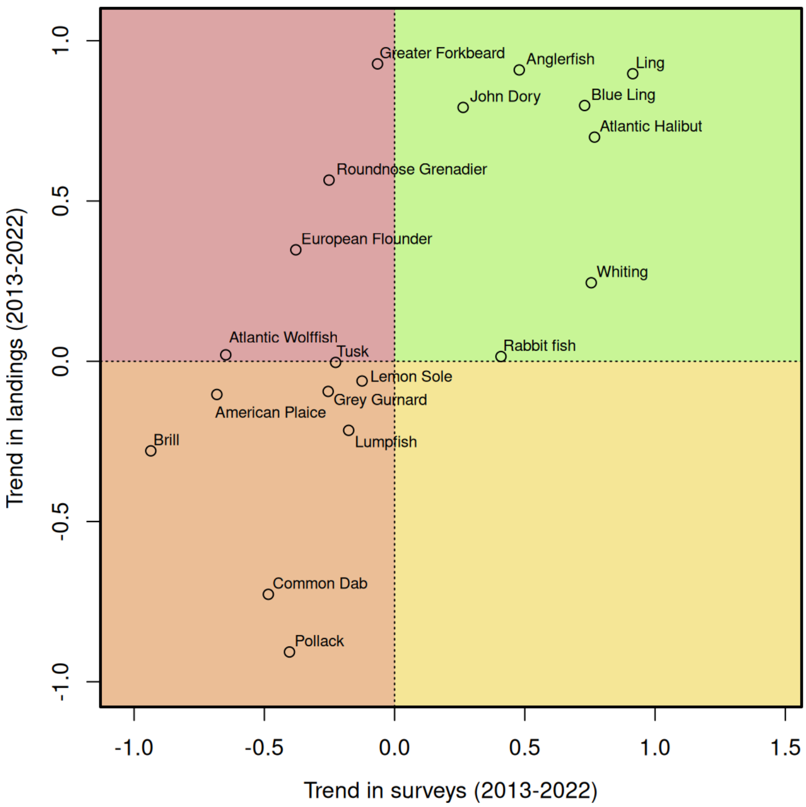


Figure 2.5. Trend in the survey and landings time series in the last 10 years (2013 – 2022) for the 19 species with sufficient information. Note, that discard information was not included in this analysis but might constitute a substantial part of the total removals for some species, such as common dab.

Figure 2.6 presents the 10-year survey trends for all 45 fish species, including species for which no reliable commercial landings data are available. The figure illustrates a full range of abundance changes based on survey data from 1 to 1. The x-axis represents the trend in survey data, with values greater than zero indicating increasing trends and values less than zero indicating declining trends. The y-axis lists the species, sorted by their trend values from most positive to most negative. At the top of the plot, species such as ling (*Molva molva*), blackbelly rosefish (*Helicolenus dactylopterus*), and tub gurnard (*Chelidonichthys lucerna*) exhibit strongly positive trends in the last 10 years, suggestive of populations that thrive under the current environmental regime or where changes in the fisheries have resulted in reduced fishing mortality. However, since the trends presented here are based on the most recent 10-year period, absolute abundances may still be low compared to periods before 2013 (i.e. whiting (*Merlangius merlangus*) and Norway redfish (*Sebastes viviparus*)), and/or reference levels. An increase from very low abundance calls for conservation measures until the stock is fully recovered. In contrast, several species at the bottom of the graph, including brill, four-bearded rockling (*Enchelyopus cimbrius*), and common sea snail (*Liparis liparis*), show strongly negative trends, highlighting significant declines in abundance over the last decade. These downward trends may reflect heightened vulnerability to environmental changes, overfishing, or other anthropogenic pressures. Steep declines are concerning and emphasize the need for targeted conservation measures to mitigate further population losses. However, not all species displaying steep declines are of commercial interest (i.e. common sea snail) and these are therefore more likely to be affected mainly by other factors besides fishing (unless they are common bycatch species). Most species fall between these two extremes, with trends closer to zero and not significantly different from zero, indicating relatively stable populations or minor fluctuations over the survey period. Species like roundnose grenadier, greater forkbeard, and anglerfish exhibit moderate trends, either slightly positive or slightly negative. However, despite roundnose grenadier exhibiting merely a weak negative trend, it appears to be already at a historic low level – a finding that is also supported by the landings (Figure 2.4).

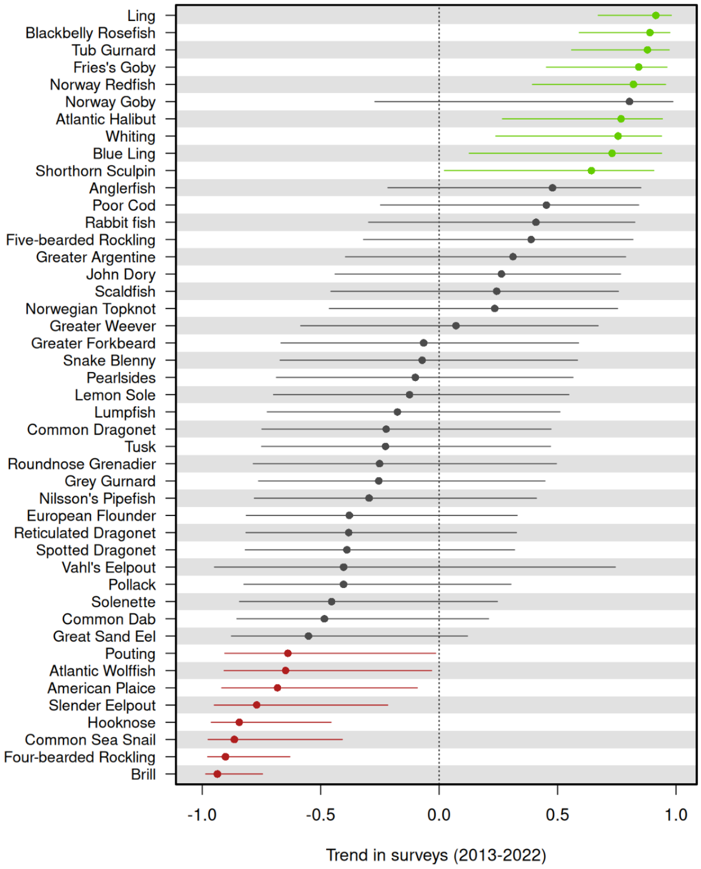


Figure 2.6. Trend in the surveys between 2013 and 2022 as Pearson correlation coefficient with 95% confidence intervals for all 45 species with sufficient information for spatiotemporal modelling. The color indicates whether the value is significantly different from 0 based on the 95% confidence intervals (green significantly larger than 0, green significantly smaller than 0, and grey not significantly different from 0).

Policy brief on fish stocks in Skagerrak with potential management shortcomings

As part of the SAMSKAG project, a policy brief was produced in which ten commercial fish species from the present study were selected for a closer examination (van Deurs et al., 2024). Additionally, one shark species was included, as well as skates and rays as a species group. This selection represents a range of potential management shortcomings from the perspective of Skagerrak. The selected species focus on high-value species with no stock assessment and therefore no biological advice (e.g., Atlantic halibut, Atlantic wolffish, and lumpsucker), and data-poor species for which biological advice is produced by ICES, but for which essentially very little about the stock status is known. The latter may be somewhat safeguarded by the precautionary approach, but this leaves little room for developing sustainable targeted fisheries, and bycatch overfishing occasionally occurs despite these measures. Moreover, stocks that are assumed to be distributed across vast areas extending far beyond the borders of Skagerrak (i.e., geographically wide stock units) were included. If Skagerrak is home to sub-populations or if distinct genetic gradients (as a function of distance) are present due to local homing behaviour or site fidelity, geographically wide stock units can lead to local depletion and loss of genetic diversity (e.g. Berkeley et al., 2004; Ciannelli et al., 2013).

For stocks that have recently moved from data-poor categories that utilize the precautionary approach to full analytical stock assessments and biological advice, a thorough understanding of the sub-stock structure, connectivity, and gene flow becomes pivotal (see also chapter 3 and the associated policy brief, André et al., 2024), particularly in light of potentially developing target fisheries for these stocks

In the policy brief, abundance trends, landing statistics, and international red list status (IUCN) as well as the national red list status ratings from Denmark, Norway, and Sweden, respectively, are described and contrasted. Overall, the results presented in the policy brief are consistent over a wide range of assumptions regarding gear efficiencies of the two surveys and model assumptions. However, note that the trend in the relative abundance index presented in the policy brief differs for three species from the here presented values that are based on an updated approach: The abundance trends for Atlantic wolffish *(Anarhichas lupus*), lumpsucker *(Cyclopterus lumpus*), and greater forkbeard *(Phycis blennoides)* were indicated as positive in the policy brief, whereas the updated analysis now suggests negative trends. These differences reflect advancements in our understanding and improvements in the estimation of gear coefficients between the two surveys, rather than contradictions in the underlying data. The NOSS operates in deeper areas, including depths of up to 600 m in the Norwegian Trench, while the NS-IBTS conducts only limited hauls below 200 m. The improved estimation of gear efficiency involves grouping species with similar habitats and body shapes, while focusing the analysis on a more geographically and depth-restricted area that is well-sampled by both surveys. This refined approach, to the best of our knowledge, represents the most reliable method currently available for estimating gear coefficients across surveys, offering greater consistency and precision compared to earlier methodologies that utilized the entire geographical extent of each survey and estimated effects for individual species.

Find the policy brief here:
www.norden.org/en/publication/fish-stocks-skagerrak-management-shortcomings

Other unassessed marine groups: Cephalopods

Cephalopods, including squids, cuttlefish, and octopuses, are gaining increasing prominence in fisheries across the Northeast Atlantic (Hunsicker et al., 2010). Over recent decades, landings of cephalopods in this region have been steadily increasing (van der Kooij et al., 2016) as also indicated by a notable increase of Danish landings in Skagerrak over time (Figure 2.7A). However, these landings exhibit high interannual variability, reflecting the dynamic nature of cephalopod populations. Importantly, the species composition within the landings is not specified; the majority are categorized under the general group "Cephalopoda". The lack of species-level identification in the landings underscores a critical knowledge gap. Cephalopods in the region are not subject to formal stock assessments, and their stock status remains unknown (ICES, 2023).

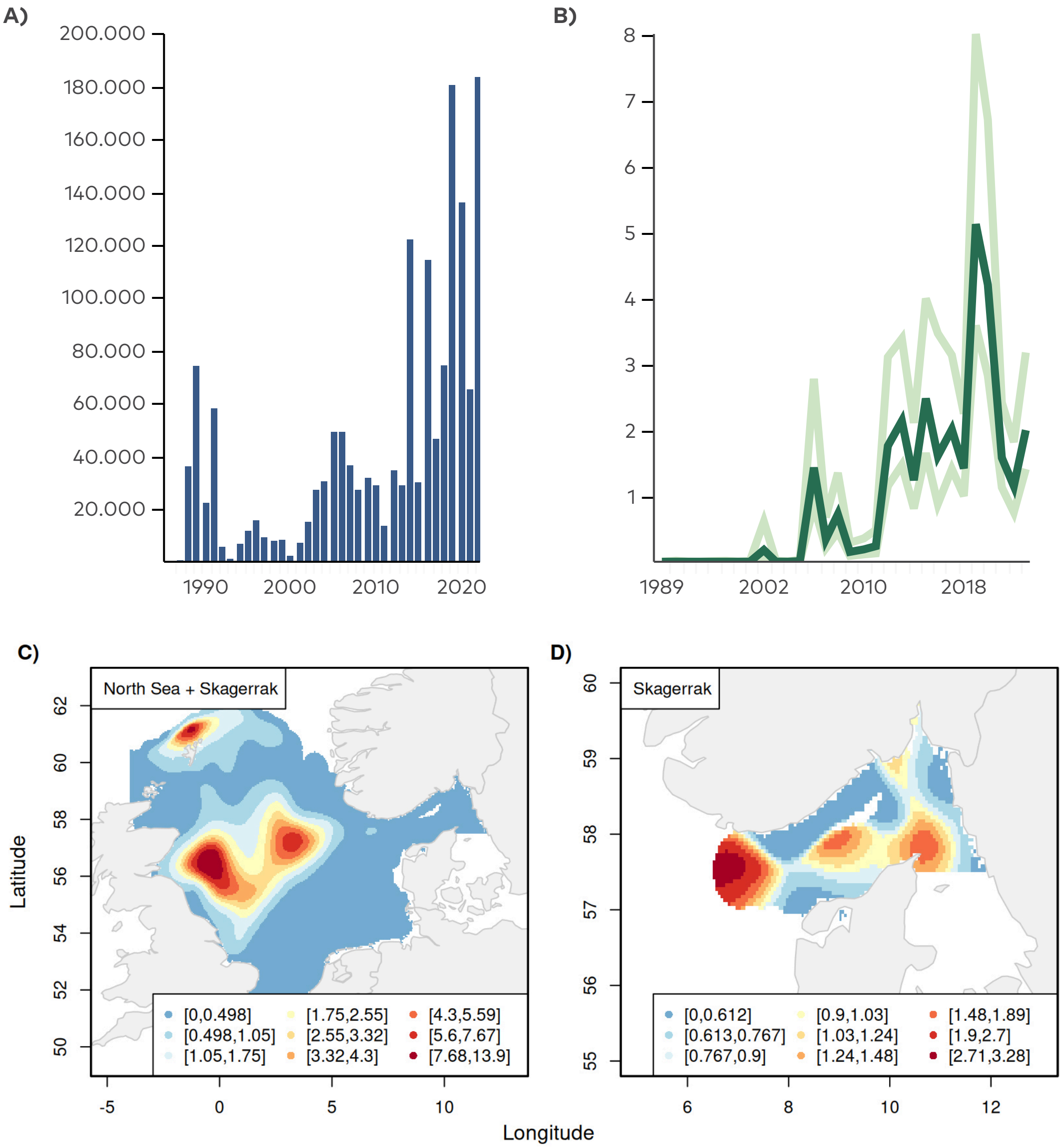


Figure 2.7. Summary plots for Cephalopods: Danish landings (in kg) from 1987 to 2023 of cephalopods in Skagerrak (A). Relative abundance of all cephalopods observations in Skagerrak in two surveys from 1986 to 2023 (B). Abundance of overall cephalopod abundance in two surveys from 1986 to 2023 in the North Sea and Skagerrak (C) and rescaled to Skagerrak only (D).

Despite this limitation, valuable insights are also gained from scientific surveys conducted in Skagerrak. Twenty-nine Aphia IDs belonging to the class Cephalopoda were observed in the two surveys with very differing taxonomic resolution, assigned to the overall class, families, genus or species (Supplementary Table S5). As a starting point, all cephalopod observations were aggregated into a single group and fitted a spatiotemporal model to the combined data from the two surveys. The estimated relative abundance index confirms the trend in the landings with an increasing trend since 2010 (Figure 2.7B). Not only does the overall trend of the abundance index align with the cephalopod landings, but also the pronounced peak in 2020 and 2021. The relative abundance index increased by 189 % from 2018 to 2019 and shows a similarly drastic decrease from 2020 to 2021. The distribution maps reveal that the main hotspot of the recorded cephalopods observations in the surveys is located in the northern and central North Sea (Figure 2.7C). Rescaling the abundance to the Skagerrak area reveals that within Skagerrak, the highest abundance of cephalopods is found in the west with less pronounced hotspots close to the deepest part of the trench in the central Skagerrak region and around Skagen. Available information from NOSS does not allow a spatiotemporal analysis of cephalopods on a finer taxonomic level than the overall class level as cephalopods have only been identified to finer taxonomic levels in recent years. Nevertheless, available information from NS-IBTS allows to investigate the spatiotemporal patterns of two cephalopods families, a family of octopuses (*Eleodonidae*) and pencil squids (*Loliginidae*), and four genuses, shortfin squids (*Illex*), squids of the genus *Loligo*, a genus of bobtail squids (*Sepiola*), and Lesser flying squid (*Todaropsis eblanae*). The estimated abundance indices for these groups show highly variable and uncertain patterns (Supplementary Figure S13).

Cephalopods are characterized by rapid growth, short lifespans (often less than one year), and highly variable population dynamics (Cady, 1983). Unlike many fish stocks, their abundance can fluctuate dramatically from year to year due to environmental conditions, such as temperature and food availability (Oesterwind et al., 2022). This inherent variability and short-lived life-history, makes traditional fish stock assessment models and fisheries management approaches, which often rely on multi-year stock assessments and fixed quotas, less suited to managing cephalopod populations effectively. Management procedures need to account for these short-term fluctuations to avoid overexploitation during low-abundance periods while allowing sustainable harvesting during high-abundance years. The current lack of targeted management for cephalopods in many parts of the Northeast Atlantic is a growing concern and in Europe, specifically, cephalopod fishing is not covered by the CFP, although many coastal small-scale fisheries for cephalopods are managed nationally or regionally (Arkhipkin et al., 2021). Furthermore, the limited priority assigned to these fisheries in Europe, combined with the difficulties of applying classic assessment methods and the data-poor nature for these stocks, presents a set of interrelated challenges (Boyle and Rodhouse, 2005). In most cases, cephalopod fisheries are unregulated, with no specific catch limits or effort controls. However, several countries, including Argentina, Australia, Canada, Chile, the

Falkland Islands, Japan, Mexico, New Zealand, Peru, Russia, and South Africa, routinely assess and manage their cephalopod fisheries (Arkhipkin et al., 2015). These examples demonstrate that management and assessment of cephalopod stocks are achievable, providing valuable insights and practices that could improve the development of targeted strategies in regions where such measures are lacking, such as Skagerrak.

If landings continue to increase and fishing pressure intensifies, the need for tailored management approaches becomes more urgent. Flexible, adaptive management frameworks that can respond quickly to changes in abundance are likely necessary to ensure the long-term sustainability of cephalopod stocks. Such frameworks could include real-time monitoring of stock status, dynamic catch limits tied to environmental indicators, and precautionary measures during recruitment failures. Moreover, the ecological role of cephalopods in marine ecosystems adds another layer of complexity to their management. Due to their voracious prey consumption and high production rate, cephalopods pose an important link in marine food webs (de la Chesnais et al., 2019) and changes in their abundance can have cascading effects on other species. Effective management must therefore consider not only the sustainability of cephalopod stocks but also their broader ecological impacts. Together, these findings suggest a need for greater attention to cephalopods in the North Sea and Skagerrak, both in terms of monitoring and species-specific assessments. Improved data collection and analysis could provide critical information to support sustainable management of these increasingly significant marine resources.

Strengths and limitations

This study focused on the unique ecosystem of the Skagerrak, providing a region-specific examination of species dynamics that are often overlooked in geographically broader studies. By narrowing the scope to this specific area, the study captures fine-scale patterns and processes that might otherwise be missed in large-scale analyses and lead to undesired management outcomes (Cadrin 2020). This localized approach highlights the distinct ecological characteristics and challenges of managing the Skagerrak ecosystem, offering insights tailored to its particular environmental and biological context.

Furthermore, the study highlights the remarkable biodiversity of the Skagerrak, documenting 236 unique species across two surveys over almost 40 years. This extensive inventory underscores the ecological richness of the region and establishes a foundational dataset for understanding the area's biological complexity. While these findings confirm Skagerrak's status as a highly diverse region and stress the need for its protection, they also reveal a critical gap in knowledge, as many species remain without quantitative assessments in the region (Östman et al. 2016; Hornborg et al. 2020).

Integrating data from two surveys using different gear types posed a methodological challenge, as the reliability of swept area estimates is often questioned (e.g., Berg et al. 2024). This study addresses these limitations by employing a robust approach to estimate gear efficiencies. By focusing on overlapping areas, seasons, and years, and grouping species with similar body shapes and behaviors, the study mitigates potential confounding factors. This innovative methodology enables the reliable combination of datasets to estimate species-specific relative abundance indices, providing crucial information for data-limited species.

Moreover, the study incorporates region-specific landings data from Denmark, Sweden, and Norway, identifying 19 species for which reliable landings information is available. By analyzing trends in these data, the research provides a valuable perspective on the correlation between fishing activities and species abundance. This detailed examination of landings trends contributes to a more nuanced understanding of fisheries in the Skagerrak region, offering insights into sustainable resource management.

The analysis of relative survey and landings trends reveals critical information about the status of species in the Skagerrak. Declines in certain species highlight the potential impacts of high fishing pressure or environmental changes, signaling the need for targeted management actions. Conversely, increasing trends may indicate species recovery and success of certain management measures as well as adaptation to changing conditions, potentially opening opportunities for future fisheries. For example, the potential expansion of suitable habitat for blackbelly rosefish in the North Atlantic has been identified, which may influence their distribution and biomass (Morato et al., 2020). This dual perspective helps identify priorities for conservation and sustainable exploitation.

By assessing the availability and quality of data for species caught by commercial fishing fleets, the study lays a foundation for future stock assessments and management advice, such as the risk-based assessment of Swedish fisheries in the Skagerrak-Kattegat region (Hornborg et al., 2020). The inventory of species and their abundance trends serves as a critical resource not only for fisheries management but also for biodiversity conservation and spatial planning efforts. This work emphasizes the importance of robust data collection and analysis in supporting effective management and ensuring the long-term sustainability of Skagerrak's fisheries and ecosystems.

Despite its strengths, this study has certain limitations that should be acknowledged to guide future research. The use of a 10-year timeframe trend analysis, while valuable, may not align with the generation time of all species, potentially limiting the ecological relevance of the findings. For example, the IUCN Red List criteria consider a period spanning three generations or 10 years, whichever is longer (IUCN, 2001). For species with longer generation times, such as the Atlantic wolffish, this 10-year period may not adequately capture all population dynamics and overlook long-term declines. Aligning future analyses with species-specific generation times, as recommended by Punt et al., (2016), would provide a more ecologically grounded perspective, particularly for species of minor commercial importance that are vital for biodiversity conservation and restoration agendas.

Challenges in estimating trends come about from methodological and survey-related factors. Differences in depth ranges between the NS-IBTS and NOSS surveys result in incomplete coverage of deep-water habitats, such as the Norwegian Trench, which is critical for certain species such as roundnose grenadier and rabbitfish. Ship effects and gear efficiency further complicate trend estimation, highlighting the need for standardization and calibration across surveys. This is also highlighted by the need for gear calibration between the GOV and Campelen trawls used in NS-IBTS and NOSS, respectively. The current study mitigates these discrepancies by grouping species based on habitat and body shape building on the approach described by Walker et al., (2017), yet the approach used here does not account for the length of the fish or ship effects and might introduce uncertainties, especially for species inhabiting multiple or mixed habitats. Future research should prioritize further standardization and calibration across surveys.

Summarizing complex temporal patterns into single metrics poses additional challenges. While this study estimates relative abundance indices, reducing these temporal patterns to a single value (here: Pearson correlation coefficient) may obscure year-to-year variability or mask historical baselines critical for understanding long-term trends. Given that many species in this study are deep-water and long-lived, alternative metrics, such as ratios of recent to historical averages or time series analyses over longer periods, could provide more robust insights into population changes. For example, the sharp decline in pollack landings over the last three decades highlights the need for longer-term perspectives to contextualize recent trends.

Lastly, the exclusion of pelagic species and certain taxonomic groups, such as cephalopods or elasmobranchs which are only identified at coarse taxonomic levels, limits the comprehensiveness of the analysis. Cephalopods, which are increasingly important in fisheries, are not subject to detailed stock assessments due to identification challenges and data scarcity (Arkhipkin et al., 2021). Elasmobranchs show pronounced negative abundance trends on a global scale (Dulvy et al., 2024), and, therefore, need to be identified on a species level and monitored closely. Fundamental shifts in elasmobranch assemblages in the North Sea have been noticed from the historical dominance of larger and commercially valuable species to the current prevalence of smaller and more productive species (Bom et al., 2022; Sguotti et al., 2016). Thus, addressing these gaps will require improved species-level identification in surveys and landings, as well as targeted studies to explore the population dynamics of these overlooked taxa.

Perspectives and conclusion

This study represents a significant step toward addressing the gaps in knowledge about the "forgotten" species of the Skagerrak. By shedding light on the diversity of species in this unique marine area, the availability of data, their trends in abundance, and the uncertainties surrounding these trends, this work contributes to a broader understanding of the ecological and fisheries dynamics in the region. It is a testament to the value of international collaboration in creating an inventory of species and prioritizing stocks that require urgent attention for conservation and management.

The results of this study underline the importance of integrating data from multiple surveys and from commercial landings to provide a more comprehensive and accurate picture of species trends. The methodological advancements highlighted here demonstrate how careful analyses can bring new insights into data-deficient species, emphasizing the need for continued improvements in survey coverage, data collection, and analytical methods. Future efforts should explore additional ways to calculate trends or changes in relative abundance that are less susceptible to outliers, such as approaches that take averages over multiple years. These refinements would make trend estimates more robust and reliable for long-term monitoring and decision-making.

Another key area for future work lies in the integration of uncertainty and other ecological factors, such as changes in spatial distributions, into trend assessments. The latter will become particularly important with accelerating ocean warming, which will have species-specific effects on habitat suitability. This could be achieved through methodologies similar to those used for IUCN Red List ratings, where uncertainty and spatial dynamics are explicitly considered in determining species status. Additionally, investigating trends in abundance for different length or age groups will provide a deeper understanding of population structure and dynamics. This will help identify potential vulnerabilities, such as declines in larger, mature individuals, which are often critical for the sustainability of fish stocks.

Emerging fisheries, such as those targeting cephalopods, present both opportunities and challenges. The short generation times and rapid population dynamics of cephalopods, driven by environmental fluctuations, require adaptive management frameworks that go beyond traditional multi-year stock assessments. Incorporating real-time monitoring and dynamic catch limits tied to environmental indicators can help balance economic interests with ecological sustainability. Moreover, the ecological role of cephalopods as both predators and prey underscores their importance within marine food webs, warranting greater attention in research and management.

A major challenge remains the governance complexities of the region, with the Skagerrak spanning multiple jurisdictions, including Denmark, Norway, and Sweden, each with varying management and data collection frameworks (Ziegler et al., 2016). This geographical and political complexity calls for enhanced international collaboration, harmonization of policies, and the development of region-specific management approaches. The report also emphasizes the need for a unified strategy to address data limitations, particularly for species inhabiting deeper areas of the Norwegian Trench, which are poorly represented in existing surveys.

Overall, this study serves as an important foundation for future research and management initiatives in Skagerrak. By bringing attention to the species that have historically been overlooked, it highlights the need for continued international collaboration, innovative methodologies, and targeted conservation efforts to ensure the sustainable use and protection of these vital resources.

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Chapter 3: The status of marine protection in Skagerrak

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Map in Figure 3.1 and area calculations: Juliette Aminian-Biquet (CCMAR-UAlg, CNRS, INRAE), Inês de Sousa (CCMAR-UAlg).

Summary

Marine protected areas (MPAs) are tools for biodiversity conservation in a wide sense including protection of ecosystem function and species interactions. Skagerrak is a productive ‘miniature deep sea’ or submerged fjord with the Norwegian Trench as a prominent feature. The Skagerrak thus offers diverse habitat and nature types harbouring genetically distinct marine populations (see chapter 1). Nature protection in the Skagerrak consists of MPAs ratified under the OSPAR agreement (EU and non-EU members), the Natura 2000 network of MPAs (EU member states) and national parks. Partially protected areas (PPAs) in the form of small-scale spatial protection of European lobster through gear restrictions are implemented widely in Norway and Sweden. Preliminary analyses suggest that marine protection in Skagerrak is weak overall, especially considering areas with regulation of mobile bottom-contacting fishing gear. Further, protected areas in Skagerrak are largely restricted to shallow coastal areas, meaning that important deep-water habitat types are poorly protected. The deepest parts of the Skagerrak are situated in the Norwegian Trench, which is home to vulnerable marine ecosystems, and constitute the most important carbon sink in the greater North Sea region. Establishment of a coherent network of MPAs in the Skagerrak will require international coordination, where marine spatial planning should consider the benefits of protection to biodiversity, fisheries and climate change adaptation and mitigation.

Marine protected areas in the Skagerrak

Nature protection is integral to curbing biodiversity loss and to increasing ecosystems' resilience to climate change. Recent downscaling of climate projections for the North Sea and Baltic Sea showed that Skagerrak will be subject to profound changes regardless of chosen climate scenario (Ottersen et al., 2025). This, in turn, will impact the ecosystem, its vulnerabilities and ability to provide goods and services. Effective nature protection is deemed necessary to lessen the burden of cumulative anthropogenic pressures. Through the UN CBD Kunming-Montreal Biodiversity Framework the signatory nations have agreed to achieve 30% representative nature protection by 2030 in protected areas or by means of other effective area-based conservation measures (OECMs). Additionally, signatory nations should nominate 30% of degraded ecosystems for restoration (European Commission 2024). The Skagerrak Sea is home to genetically and demographically connected marine populations, vulnerable marine ecosystems and the regions' most important natural storage of organic carbon. Nature protection in the Skagerrak features marine protected areas (MPAs) ratified under the OSPAR agreement (EU and non- EU members), the Natura 2000 network of MPAs (EU member states), and national parks. Additionally, Skagerrak coastal nations have implemented partially protected areas (PPAs) that constitute potential examples of other effective area-based conservation measures (OECMs), such as lobster reserves, regulations for threatened fish populations and coastal trawl limits. In Norwegian Skagerrak, this limit constitutes the coastal zone out to the 60 m depth contour. In Sweden, the trawl limit constitutes the coastal zone out to 3 nm from the baseline. In Denmark, gear restrictions apply to bottom trawling within 3 nm from the low water line (e.g., max. 160 kg trawl door weight, except when targeting sandeel) and several non-trawling areas are specified in fjords and coastal areas (Anon, 2019).

Historically, the productive Skagerrak ecosystem was home to diverse small- and medium-scale fisheries that were important for the regions' food security and generated a multitude of livelihoods in coastal communities. Modern fisheries operations in the Skagerrak are still economically important and are now primarily based on mobile bottom-contacting fisheries of mixed vessel size for northern shrimp, Norway lobster and fish including certain high-value demersal fish species (ICES, 2022). The pelagic fishery is small as quotas have been moved to the North Sea to protect Western Baltic Herring.

Several instruments for marine protection are represented in the Skagerrak. OSPAR marine protected areas are areas ratified under the OSPAR agreement. Natura 2000 marine protected areas are designated under the EU Birds- and Habitats Directives. In addition, there are national parks with marine areas designated under national environment protection legislation (Norway). These areas include fully and partially protected areas designated under the EU common fisheries policy and national fisheries legislation.

Globally, there is high variation in regulations of activities inside MPAs spanning from fully protected no-take zones to multiple-use areas. The regulation level of a MPA is considered as a good indicator of their ability to achieve management goals, e.g. conservation of marine biodiversity (Costa e Horta et al., 2016; Grorud-Colvert et al., 2021; Aminian-Biquet et al., 2024).

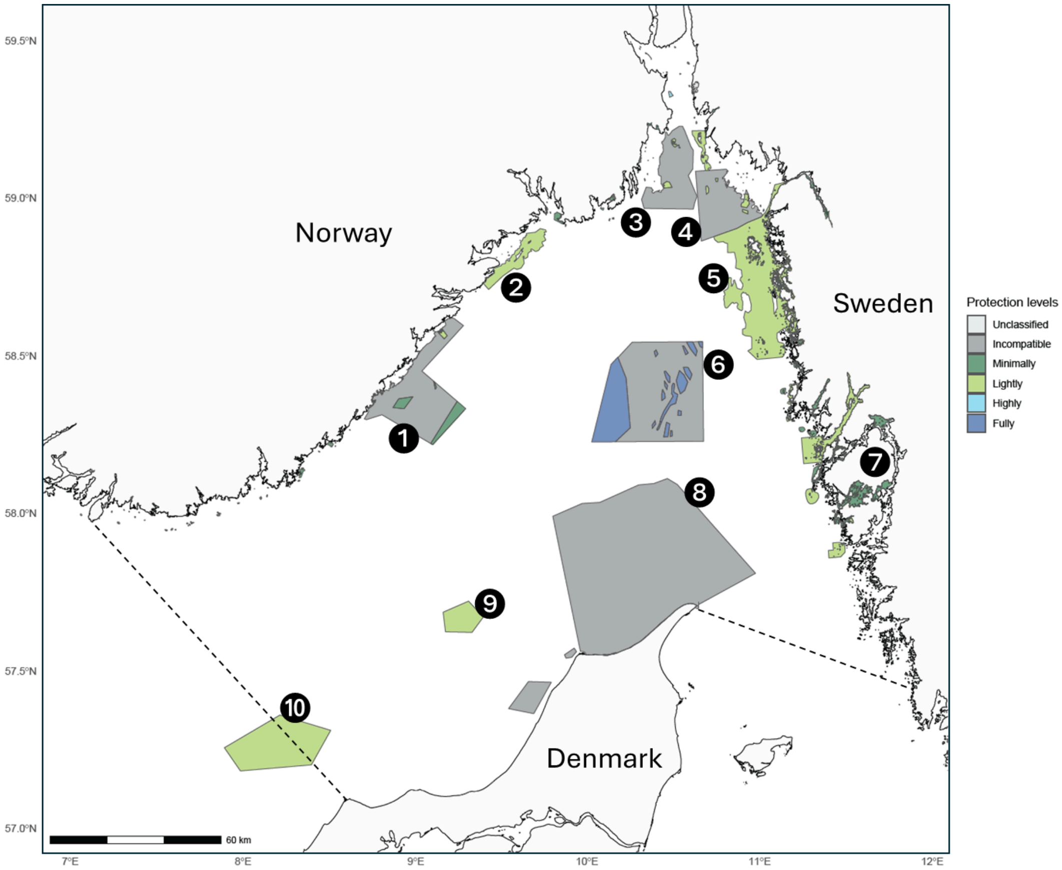


Figure 3.1. Marine nature protection in Skagerrak consists of Ospar- and Natura 2000 MPAs, in addition to national parks designated under national environmental legislation. Preliminary analyses indicate that less than 7 % of Skagerrak's total area (32 231 km^2) has protection instruments compatible with conservation objectives. Dashed lines delimit Skagerrak between the North Sea (left) and Kattegat (right). Examples 1-10: Raet national park (1), Jomfruland national park (2), Færder national park (3), Ytre Hvaler national park (4), Kosterhavet national park (5), Bratten MPA (6), 8-fjordar (7), Skagens Gren and Skagerak (8), Store Rev (9), Gule Rev (10).

Bratten MPA with fully protected no-take zones

The Bratten is a large (1 209 km^2) MPA hosting species and habitats of high conservation value with spectacular bathymetry characterised by steep rock walls, canyons and pockmarks on the slope (100–500 m) towards the Norwegian Trench in the Skagerrak (see Figure 3.1). The exposed rock walls host deep water coral gardens, sponge communities, large predatory fish, and dense sea pen fields in the surrounding soft bottoms (Figure 3.2). Extensive inventories and seabed mapping started in 2003 and since then several reports of biodiversity and habitats have been published. A major challenge for the management and conservation of the area was that Bratten is situated within one of the most important fishing grounds in the Skagerrak for Northern shrimp *Pandalus borealis* and demersal fish, located outside territorial waters in the Swedish EEZ, and intensively fished mainly by bottom trawlers from Sweden and Denmark. In addition, the integration between the EU nature conservation policy and the Common Fisheries Policy (CFP) was poorly developed during the early phases of the process.

The Bratten MPA was designated as a Natura 2000 site (SCI) for reef structures in 2011 and later in 2012 became part of the Convention for the Protection of the Marine Environment of the North-East Atlantic's (OSPAR's) network of MPAs. The development of fisheries regulations was preceded by work in the Interreg project "Hav möter land" (Sea meets Land) 2010 - 2013 lead by the County Administrative Board of Västra Götaland (CAB) in where extensive stakeholder consultations with representatives of the fishing industry, sport fishermen, various national authorities and research institutions from Sweden, Norway and Denmark were held (Länsstyrelsen, 2013). Following recommendations by CAB, the management measures were enforced by the EU commission in 2017 after additional formal EU procedures resulting in a so-called Joint Recommendation by Sweden, Denmark and Germany. The measures include the establishment of no-take zones covering 27% of the area, where all commercial fisheries were prohibited. For control purposes compulsory use of automatic identification system (AIS) for all vessels fishing in the area was implemented. Similarly, conservation measures for recreational fisheries were enforced in 2017 through national legislation by closing several of the zones also to recreational fisheries.

Recent analysis of fishing patterns in the Bratten MPA show that the trawlers ceased to fish in the no-take zones and intensified their efforts in passages between zones and to the north-east within the MPA (Feary et al., in press). There was no significant overall reduction in fishing effort in the MPA, and no indications of displacement to areas outside the Bratten MPA. Rather, the variability in effort within the MPA correlated with the effort and fishing opportunities linked to the variation in availability of northern shrimp between years within the Skagerrak as a whole. As communicated by the active fishermen during the negotiation process for fishing regulations in Bratten, passages mainly in the North to South direction were of great importance to the ongoing fishery in the area as the trawlers follow the slope in that direction, and that hauls continue for long distances through the area. As the most utilized passages identified in the Bratten area were kept open to minimize the conflict between conservation targets and the trawl fishery, it is to these passages the trawlers reallocated, and consequently the effort has increased there. A large zone in the west that was closed had very little effort the years prior to the closure, and no significant shift in effort from that area was expected.

The fishery regulations in the Bratten MPA were negotiated with fishers' organisations from Sweden and Denmark, and authorities considered the arguments from the fishers that it was important to keep passages through the area open. This may explain that effort could be withheld within the MPA, and that compliance with the regulations has been high. In addition, the regulations have been strongly enforced by detailed vessel monitoring covering essentially all vessels operating in the MPA.

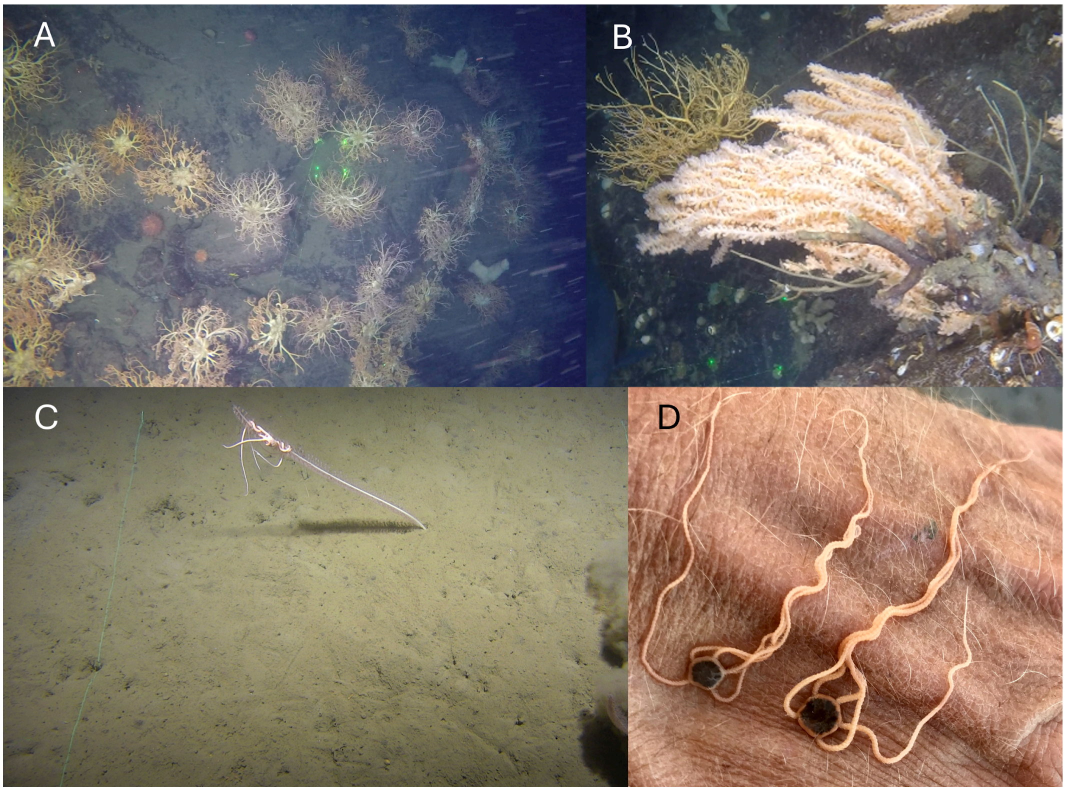


Figure 3.2. The Bratten Natura 2000 area is a rare example of an offshore MPA with fully protected zones. Situated at the easternmost slope of the Norwegian Trench, Bratten is steep and deep (100–500 m) with canyons, pockmarks and outcropping rocks hosting coral gardens and large soft seafloor areas with sea pen fields. A. Basket stars *Gorgonocephalus caputmedusae* on current swept rock, B. Soft coral (*Primnoa resedaeformis*) on steep rock wall, C. Large sea pen *Funiculina quadrangularis* with the associated brittle star *Asteronyx loveni* on muddy seafloor. D. The delicate brittle star *Amphilepis norvegica* dominates the burrowing fauna of the deep muddy seafloor of Skagerrak. All photos: SLU.

Conclusion

Judging from the Bratten case, marine conservation and the innate interplay with fisheries management constitute slow regulatory processes that in many aspects have evolved over the past 20 years. There has been strong improvement of techniques and resources for inventories and mapping, e.g. multibeam bathymetry in high resolution, underwater techniques with remotely operated vehicles (ROV) and towed camera systems, and availability of modern research vessels that can operate in the offshore environment. In parallel, there has been a strong improvement of techniques and resources for mapping of the fisheries over the years. Further, the willingness from the fishing industry to take part in processes has increased, and detailed satellite tracking of fishing vessels combined with logbook information on gear use provide a neutral basis for trade-offs to be made by managers between fishing opportunities and conservation targets. In summary, a solid knowledge basis is necessary for progress, but a strong burden of proof is imposed on environmental management authorities regarding the need for conservation measures. Finally, a strong driver for progress has been obligations under the EU habitats directive.

Raet national park and 'Protect Raet' pilot project

Since 2009, national parks with marine areas under national environment protection legislation have been designated in Norway. Four marine national parks have been implemented along the Norwegian coast of Skagerrak (see area 1-4 in Figure 3.1). Raet national park on the south-eastern Skagerrak coast of Norway was implemented in 2016 and covers 595 km^2 of sea area. The national park (NP) stretches from shallow coastal areas and out to 12 nautical miles with depths down to 500 meters (Figure 3.3). However, except for three trawl free areas and two lobster reserves, covering approximately 10 % of the NP, there are no special management measures directed at fisheries in the NP. In the preliminary evaluation of protection level conducted within the SAMSKAG project, the NP has thus been identified as incompatible with marine protection (Figure 3.1).

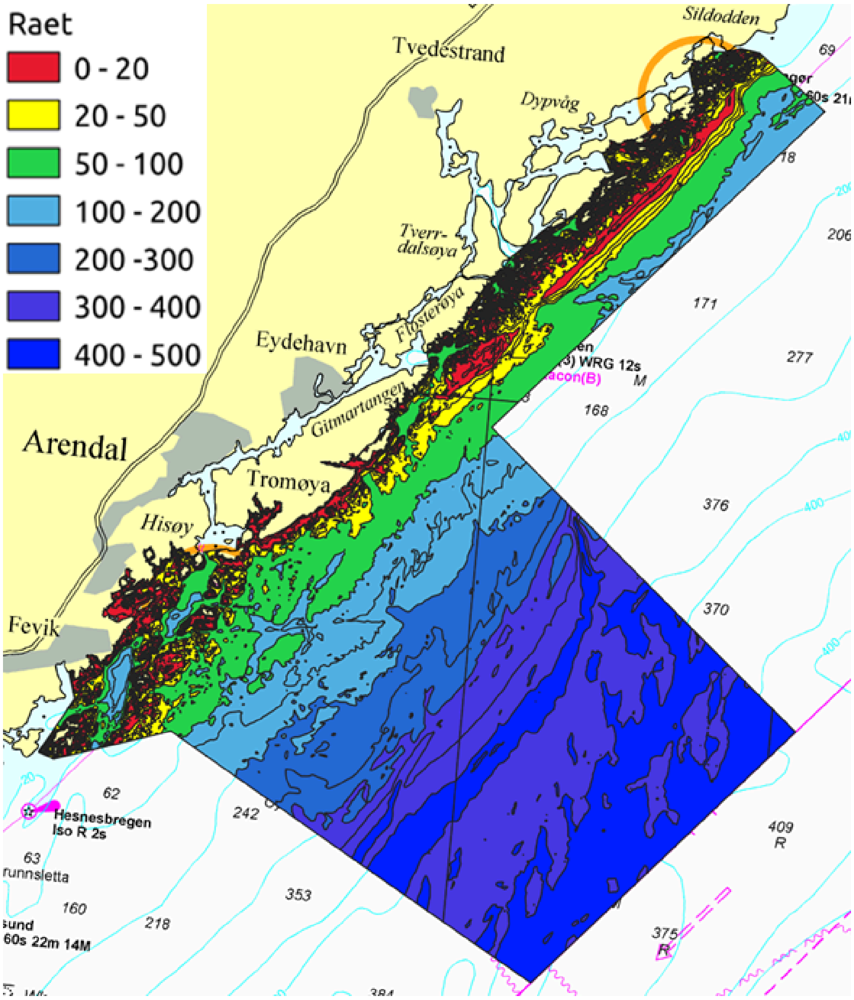


Figure 3.3. Raet national park on the Norwegian south-eastern Skagerrak coast (for an overview map see Figure 3.1). Colours indicate depth in meters.

The local municipalities bordering the national park (Tvedestrand, Arendal and Grimstad) have together with the Agder county municipality initiated a regulatory process to increase the protection level of the NP (the 'Protect Raet' project). The project aims to strike a knowledge-based balance between conservation and use. Therefore, development of a zoning-plan has been suggested with varying degrees of regulations between zones (Kleiven et al., 2024).

This bottom-up approach seeks to include stakeholders throughout the different steps of the process, including a working group consisting of commercial and recreational fishers, environmental NGOs, research institutes and municipal administration. A survey has been conducted through the online spatial planning software SeaSketch to map the different human uses of the NP (Figure 3.4). In addition, before-data on fish communities and ecosystems in both shallow and deeper areas are collected to evaluate future effects of potential management actions.

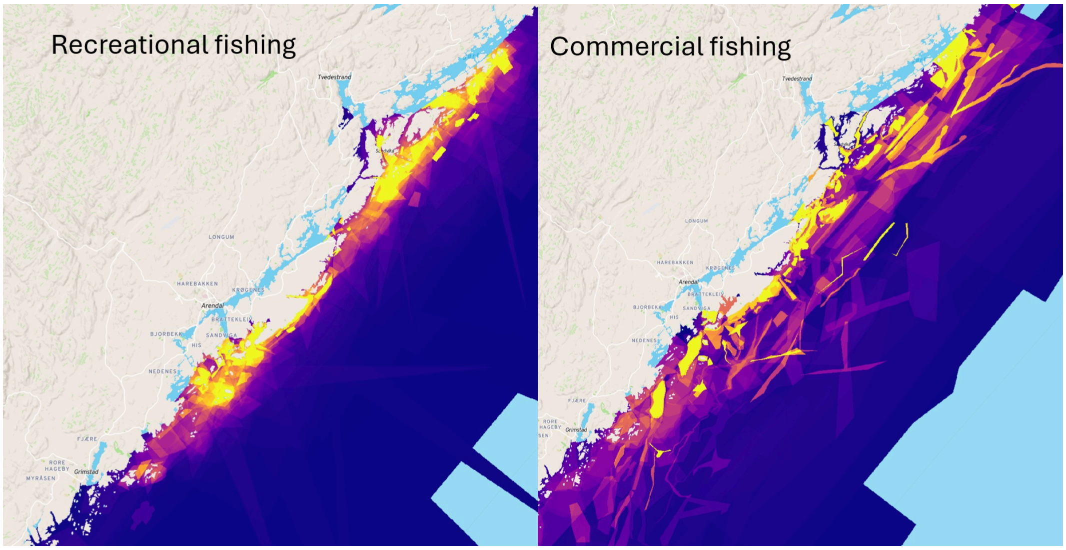
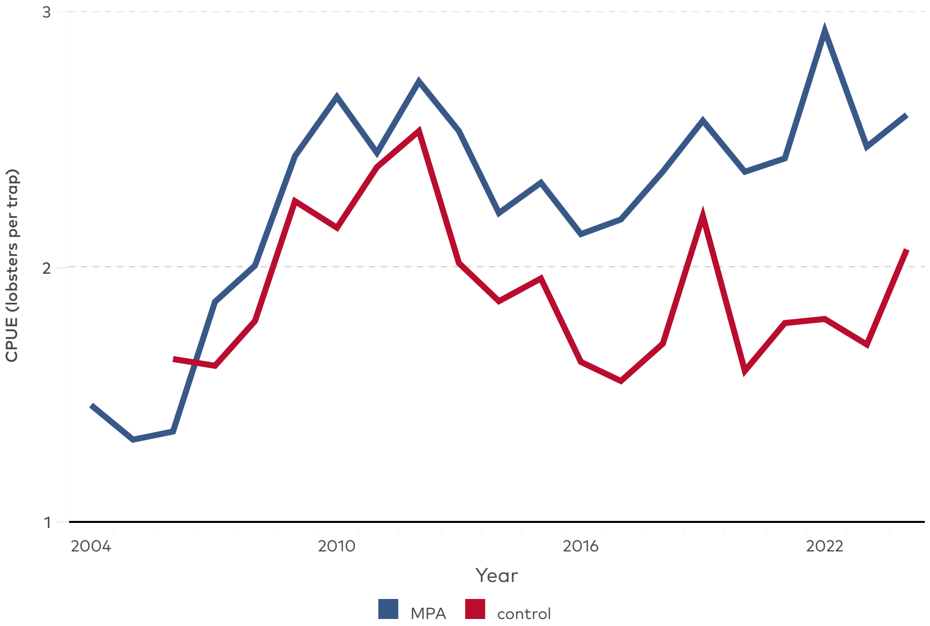
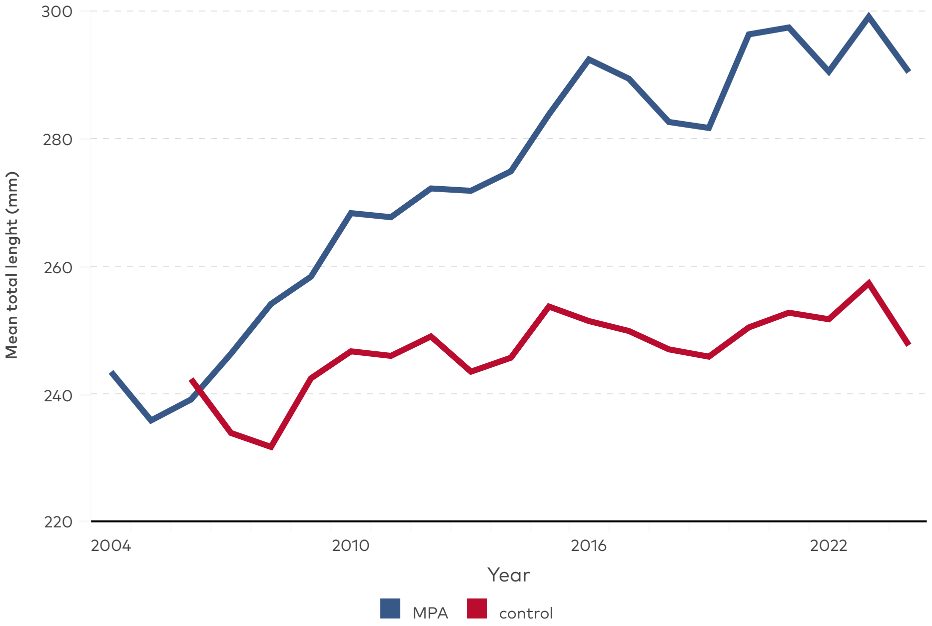


Figure 3.4. Heatmaps from the user survey in Raet national park collected through the online spatial planning software SeaSketch.

Lobster reserves: 'single-species protection' and marine conservation laboratories

Small-scale partially protected areas (PPAs) have been implemented in both Sweden and Norway with the main aim to restore and protect European lobster (*Homarus gammarus*) populations. Within the lobster reserves, passive gear such as gill nets, traps and fyke nets are prohibited. Along the Skagerrak coast in Norway there are to date 28 lobster reserves covering 89 km^2 (mean size 3.2 km^2). Research monitoring from both countries shows positive effects on lobster density, mean size, biomass, reproductive potential and spill-over (Caleb et al., 2016; Bergström et al., 2022; Knutsen et al., 2022; Torgan 2024; Van Hoey et al., 2024). Scientific long-term monitoring of lobster reserves and fished control areas has demonstrated that the lobster fishery has a strong impact on lobster populations and that depleted local populations can be rebuilt if fishing pressure is reduced or eliminated locally (Figure 3.5).


3
2
1
CPUE (lobsters per trap)
2004
2010
2016
2022
Year
MPA
control


300
280
260
240
220
Mean total lenght (mm)
2004
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2016
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MPA
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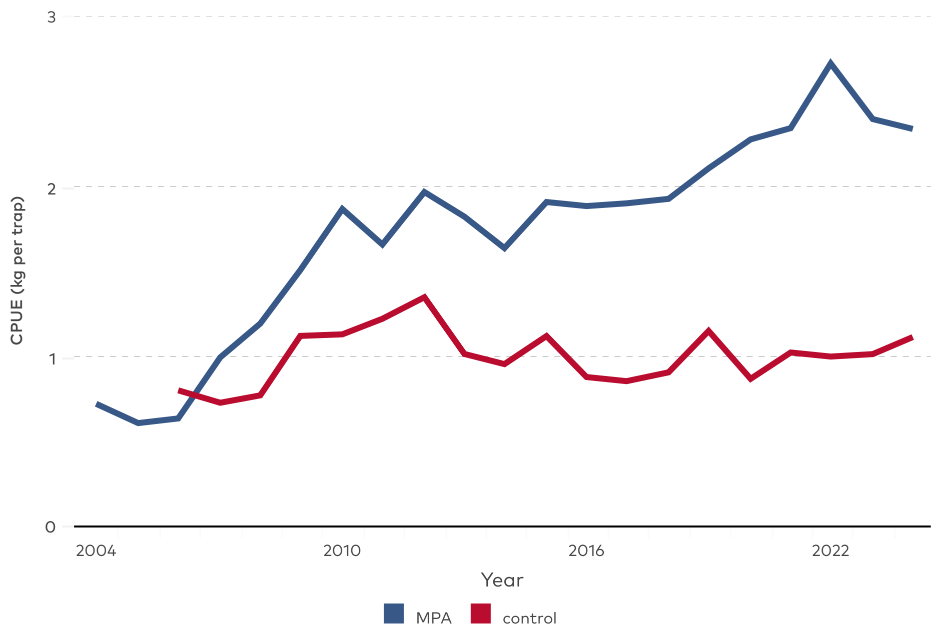

Figure 3.5. Population responses in PPAs protecting European lobster (*H. gammarus*) and fished control areas based on long term monitoring in three lobster reserves in Norwegian Skagerrak. Left panel: catch-per-unit-effort (CPUE, lobster per trap per day^{-1}); middle panel: body size (mean total length in mm); right panel: biomass (kg) per trap. Adapted from Kleiven et al., (2024).

The conservation effects of lobster within lobster reserves are well documented. However, lobster reserves do also have the potential to strengthen the general lobster population and secure improved fisheries management and catches. There are two ways lobster reserves also can contribute to fisheries; 1) Recruitment effect: Larvae have the potential to spread out to surrounding fished areas. In the Kåvra lobster reserve in Sweden, it is estimated that the reproductive potential has increased by a factor between 7 to 9 (Bergström et al., 2022). 2) Spillover effect: Higher densities of lobsters within reserves can lead to increased catches close to reserve borders. For a 5 km^2 lobster reserve in Norway it has been shown that lobster catches increased outside the borders 9 years after implementation (Figure 3.6, van Hoey et al., 2024).

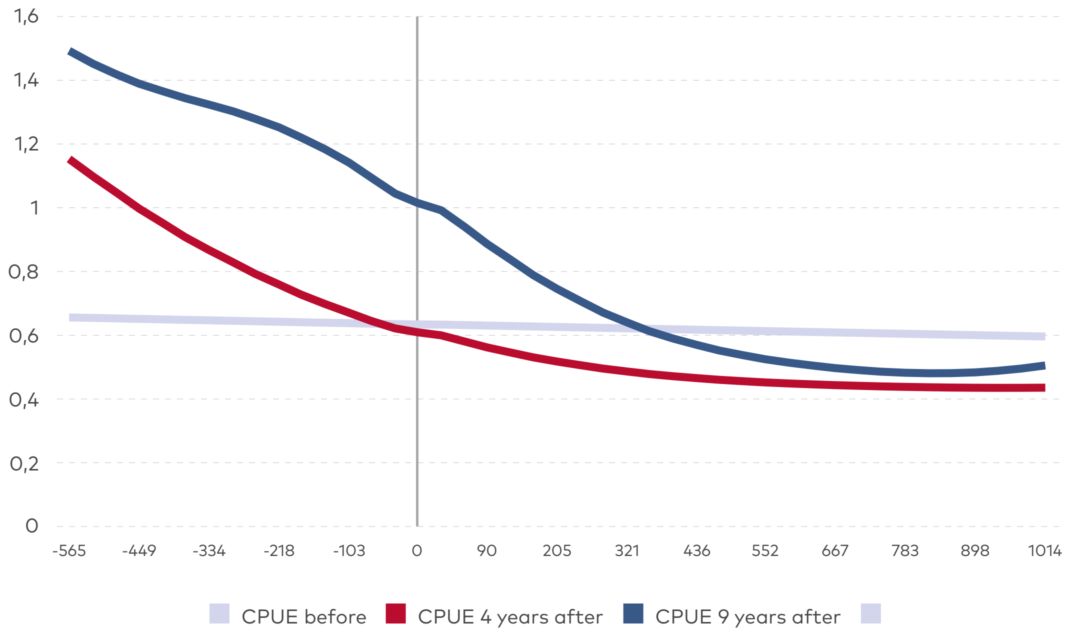

Figure 3.6. Catch-Per-Unit-Effort (CPUE, lobster per trap day^{-1}) response to years of protection (before, 4 and 9 years after implementation) and distance (meters) to MPA border (0). Source: van Hoey et al., 2024.

The monitoring has also shown that brown crab (*Cancer pagurus*) populations decrease in the lobster reserves, most likely due to increased interspecific competition with rebounding lobster. Even though some positive effects have been detected for Atlantic cod (*Gadus morhua*) (Moland et al., 2013; Fernández-Chacón et al., 2015) and wrasses (Halvorsen et al., 2017), the potential wider ecosystem effects of lobster reserves are uncertain and probably negligible due to the limited size of most lobster reserves and continuation of hook and line fishing within the areas (LaScala-Gruenewald et al., 2021; Perry et al., 2025). There is a need for further research on potential ecosystem effects in lobster reserves and their potential to be defined as OECMs. Data on fish communities inside and outside lobster reserves are being collected and will help to answer these questions in the future.

Considerations for holistic marine protection in the Skagerrak

Vulnerable Marine Ecosystems (VMEs) and threatened nature types

The Norwegian Trench and the outer region of the Oslofjord are defined as especially valuable areas (SVO's) due to the richness of ecosystem components meeting the criteria of Ecologically and Biologically Significant marine Areas (EBSA)

(Eriksen et al., 2021; Meld. St. 21). The deeper part of the Norwegian Trench is mainly situated within the Norwegian exclusive economic zone (EEZ). It delivers a series of ecosystem functions in supporting essential ecosystems and key species for Skagerrak, fragile and vulnerable deep-sea life (Álvarez et al. 2019) (see Figure 3.2). When assessed according to the EBSA criteria, it scored medium to high on uniqueness for benthic communities, zooplankton and fish. Zooplankton and fish scored equally high for six of the seven criteria, except naturalness. Based on water exchange with the North Atlantic Ocean and the refuge areas in the stable environments of the deep trench, it is important for phyto- and zooplankton, particularly *Calanus finmarchicus*, which is of key importance in the food web of the Skagerrak and North Sea ecosystem.

'Coral gardens', 'Cold water coral reefs' and 'Sea pen fields' are types of vulnerable marine ecosystems (VMEs) found in the Skagerrak (Buhl-Mortensen et al., 2023). These habitats consist of species that are vulnerable to the impacts of bottom-contacting fishing gear. They provide niches for a number of other species and nursery and feeding areas for demersal fish. The nature type 'Aphotic mud' in the Skagerrak is assessed as Near Threatened (NT) in the Norwegian Red list of Ecosystems (aphotic = beyond the reach of daylight) (Buhl-Mortensen et al., 2018). For aphotic mud, the impact of bottom trawling is also implicated in the assessment. In this case it is based on environmental degradation due to the loss of organisms and functions in the benthic ecosystem.

Burial of organic carbon in deep marine sediments and protection of carbon stocks

Continental margin sediments accumulate organic carbon at scales much larger than vegetated coastal ecosystems because of their larger extent, and because they are accumulation bottoms rather than erosion bottoms. The Norwegian Trench constitutes the major carbon sink in the greater North Sea region (Diesing et al., 2024) (Figure 3.7). Studies are now exploring to what extent management interventions could increase accumulation rates by minimizing anthropogenic disturbance of seafloor sediments through bottom-contacting fisheries. Recent geospatial modeling studies have estimated regional and global aqueous CO_2 emissions resulting from bottom-trawling- induced remineralization of sedimentary organic carbon, with some studies proposing carbon protection zones (CPZs) as an effective climate protection measure (Porz et al., 2023; Zhang et al., 2024).

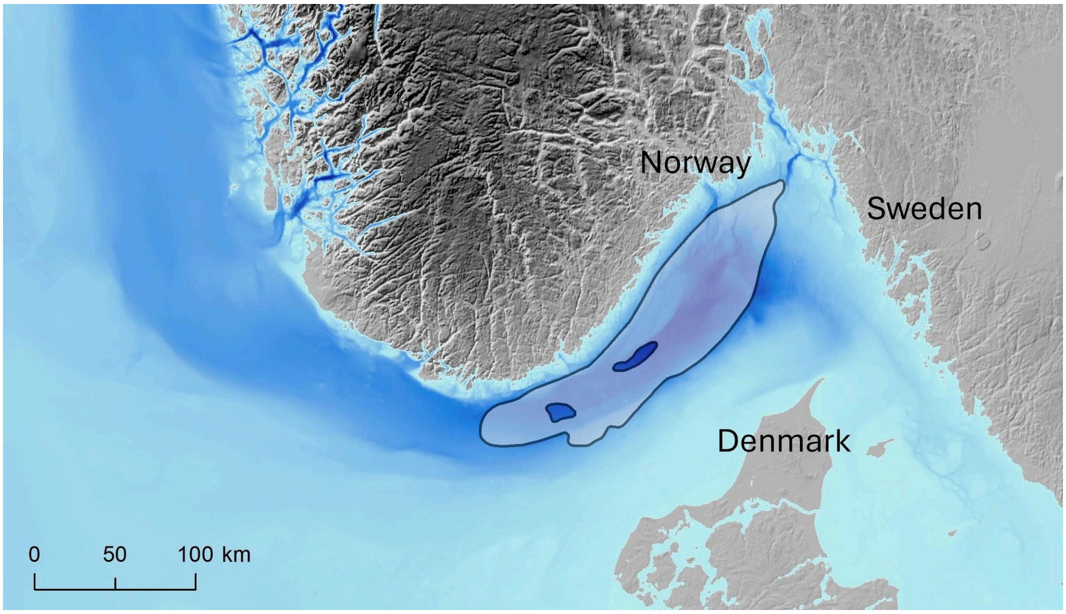

Figure 3.7. The Norwegian Trench is a deep (<700 m) trough carved into the shelf by fluvial erosion and glacial flows. In the eastern part of the Norwegian Trench, between Norway, Sweden, and Denmark (indicated by polygon), a lot of organic carbon are accumulating annually in the seabed sediments. Courtesy of: M. Diesing/Norwegian Geological Survey, redrawn from Diesing et al., (2024).

The 'Skagerrak agreement': reciprocal access to fishing grounds

Based on the principle of upholding traditional fishing rights, Skagerrak is managed according to the 'Skagerrak agreement' between Norway and the European Union on reciprocal access to fishing grounds in the Skagerrak for vessels flying the flags of Denmark, Norway and Sweden. The agreement allows Danish, Swedish and Norwegian vessels to operate within each country's economic zone and territory outside the 4 nautical mile limit. The agreement is a remnant of the time prior to the United Nations Convention on the law of the Sea from 1982, and a continuation of the 1966 agreement securing reciprocal access to Skagerrak (Anon, 2015) (see also Chapter 2). Future marine conservation processes will need to incorporate and take into account the legal implications and precedents that are implicit in this agreement.

How effective are present protection instruments in the Skagerrak?

Preliminary analyses based on regulation-based classification according to the authoritative guidelines of the MPA guide (Grorud-Colvert et al., 2021; Aminian-Biquet et al., 2024) suggest that the present marine protection in the Skagerrak is insufficient in area coverage, ineffective, and unlikely to confer desired outcomes and regional ecosystem benefits. Costa e Horta et al., (2016) developed a regulation-based classification tool for MPAs to predict the MPAs expected conservation outcomes. In collaboration with the EU funded MARHAB project, the SAMSKAG project has developed a preliminary analysis of MPAs in Skagerrak. The analysis showed that the total coverage of these protection instruments is 22 % of Skagerrak's total area. However, less than 7 % of the total area of Skagerrak fall within protection instruments that are likely to confer protection benefits on ecosystems (Figure 3.1). Conversely, a large proportion of the MPAs are found to be incompatible with marine protection. Industrial bottom trawling is found to be incompatible with marine protection (IUCN, 2021; Costa e Horta et al., 2016; Grorud-Colvert et al., 2021), a fishing gear permitted in most MPAs in Skagerrak, and a fishery which is chronic in this ecosystem (see Figure 3.6). This means that the best available scientific knowledge does not support that there are any reasons to expect positive conservation outcomes of these MPAs. Based on their current regulation level, such 'incompatible' MPAs should not be counted in the respective coastal nation's effort to meet the aims laid down in the Kunming-Montreal Biodiversity Framework. Recently, the Danish Biodiversity Council (an independent expert panel) recommended that bottom trawling and other mobile bottom-contacting gear should not be permitted inside marine protected areas (Biodiversitetsrådet, 2024).

Increasing the protection levels of existing instruments will help (see Fig. 3.8B), but marine protection aiming to achieve benefits for biodiversity, fisheries and carbon sequestration would gain from a regional collaborative process where the best available science is incorporated in designing and siting optimal spatial management measures.

Population structure – where species are divided into multiple distinct units or populations – is an evident pattern among organisms within the Skagerrak. Such structure is apparent especially among coastal sites and between coastal and offshore sites. However, population connectivity patterns have yet to be fully utilized in designing coherent networks of marine protection in Skagerrak (see Chapter 1). Mobile bottom-contacting (mainly bottom trawl) fisheries target the Skagerrak basin down to 400–500 meter depth (Figure 3.8A). A holistic MPA network design in Skagerrak should consider patterns in population structure and population connectivity, as well as configuration and representativity of habitats, and prevailing fishing pressure. Some of the most productive sites, which are essential to include in MPA networks to maximise ecosystem benefits, are likely to be heavily targeted by fisheries, thus risking displacement and intensification of fishing effort in adjacent unprotected areas. To keep negative impacts on fisheries to a minimum while maximizing conservation benefits, it is essential to conduct systematic conservation planning, where maps of conservation values, human pressures and socio-economic interests are considered. An effective MPA network in Skagerrak, taking both broad conservation and socio-economic objectives into account, would benefit from an international scientific advisory committee including representatives from Norway, Sweden, Denmark and the EU commission.

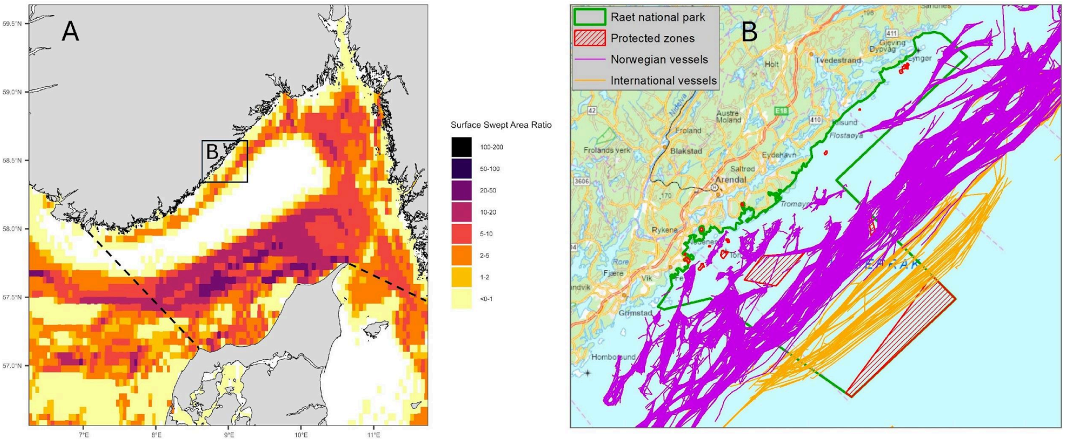

Figure 3.8. Bottom-contacting fishing activity is widespread in Skagerrak. A. Footprint and intensity (yr^{-1}) of bottom trawl fisheries as surface swept area ratio (entire width of ground gear with bottom contact, regardless of penetration depth) from 2018-2022 (ICES 2022). B. Raet national park in Norway and tracking (VMS) of Norwegian (purple) and international bottom trawl vessels (yellow) filtered based on speed (0.8–2.5 knots) within and adjacent to Raet national park from 2019 to August 2024. Dashed lines in A delimit Skagerrak between the North Sea (left) and Kattegat (right). Map in B courtesy of: Norwegian Directorate of Fisheries.

Policy brief on protecting the Skagerrak for biodiversity, food and climate

As part of the SAMSKAG project a policy brief was produced in which the scientific rationale for marine protection was placed in context with the Skagerrak ecosystem and the main findings also presented herein were summarised (Moland et al., 2024). The following recommendations for management were listed.

- Achieving effective marine protection in the Skagerrak depends on sufficient coverage of areas that limit or remove the negative ecosystem effects of fisheries and protect against pressures from other human activities.
- The Skagerrak contains vulnerable marine ecosystems and threatened nature types. To better incorporate protection of biodiversity throughout habitats and nature types, protection must be both horizontally wide and vertically deep and target biodiversity and important ecosystem services.
- MPA network design and marine spatial planning in the Skagerrak need to consider both coastal and offshore marine areas, where representativity, biodiversity, population connectivity and carbon sinks are considered.
- Taking human pressures and socio-economic interests into account, a holistic design of an effective MPA network in Skagerrak will benefit from an international scientific advisory committee.

Nordic Council
of Ministers

Protecting the Skagerrak
for biodiversity, food
and climate

Find the policy brief here:
www.norden.org/en/publication/protecting-skagerrak-biodiversity-food-and-climate

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Chapter 4. The impacts of offshore wind farms on ecosystems

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Summary

The push for diverse energy sources is expanding offshore wind farms, impacting marine ecosystems. Understanding these impacts is key to balancing wind energy benefits with biodiversity risks. This study reviews 129 publications on offshore wind farm ecological impacts, mainly in the northeast Atlantic. The most reported pressure was the introduction of new underwater habitats, but the effects reported were diverse and evenly distributed between negative and positive impacts. Consistent negative impacts were however reported for seabirds and cetaceans during both operational and installation phases. Only a third of potential ecosystem interactions were studied. Least studied were impacts from cable installation, maintenance, and decommissioning. To complement our review of offshore wind farms' environmental impacts, we conducted a parallel systematic review on their socio-economic impacts on Scandinavian coastal communities. While some evidence exists from other regions, focusing mainly on business development and national industrial policy, empirical research in this area is lagging, hindering evidence-based decision-making for planners, managers, and policymakers.

Background: the status of offshore wind farms

Wind energy growth has been rapid, both in terms of technology and real-world generation and capacity, with the EU generating ~272 GW of energy from wind in 2023 (WindEurope, 2024). While this growth has been predominantly brought about by land-based installations, off-shore wind has started to play a role and is expected to contribute to half of new installations by 2030 (GWEC, 2024).

While moving large wind energy installations offshore can reduce their impact on local communities (Ladenburg and Dubgaard, 2009; Staupe-Delgado and Coombes, 2020), their interactions with the environment remain. Such interactions have been studied, case-by-case in various contexts and with specific focus on individual parts of the marine ecosystem, or on certain activities associated with the installation or operation of offshore wind infrastructure. For example, marine mammals displaced by noise (Madsen et al., 2006), changes in fish behaviour in response to foundations (Wahlberg and Westerberg, 2005) and potential collision risks for seabirds (Lieske et al., 2019). However, the ad-hoc nature of the empirical investigations, and how sporadically they are cited, does not provide a clear overview of the various interactions that offshore wind farms have with the marine environment, writ large.

Having a clear understanding of the interactions of offshore wind energy infrastructure with the environment, is critical for planners, consenting managers and policymakers, so that negative impacts can be minimised, while maximising the contributions of offshore wind energy to achieving climate goals.

The aim, therefore, of this chapter is to systematically review and synthesise evidence from primary literature on the various interactions between human activities associated with offshore wind energy production and components of the ecosystem.

Methods

The systematic review was conducted according to the PRISMA approach for Ecology and Evolution (O-Dea et al., 2021). In this framework, biases and subjectivity are minimised by defining research questions, search scope, exclusion parameters, data to be extracted, and analytical methods prior to beginning the work. The review built upon an earlier review by Galparsoro et al. (2022), by utilising the same search terms, but by extending the time series of the data to include the most recent evidence. Furthermore, this review retained only articles that included novel empirical data (excluding theoretical models, mechanistic models and reviews), so that the meta-analyses are undertaken only on observed phenomena, without double counting of observations.

Data extraction included bibliographic information, context specific information about the wind farm, activity information about the operations exerting pressures, taxonomic information about the impacted species, and information about the activity-pressure-ecosystem component-response chain of relationships.

The meta-analyses, considered the quality of the evidence, the direction of interaction (positive, negative, or ambiguous relationships), and the amount of evidence (where individual articles could contribute more than one case), while also measuring the level of agreement/disagreement, in the literature. These different aspects of the evidence were combined to produce an “impact matrix”, whereby categories of human activities associated with wind farm operation are matched with the various ecosystem component categories. For each combination of activity/pressure and ecosystem component where evidence is found, an “impact score” is derived which reflects the direction of the impact and the certainty of these interactions, from the literature.

Key Findings

Literature review

We rejected 43% of records that were included in the previous review by Galparsoro et al. (2022), resulting in 91 articles being retained for the current review. From our update search, we identified 1458 records from multiple databases for the period from the fourth quarter of 2020 (end of previous review) to the first quarter of 2024. Deduplicating records resulted in 1032 unique articles, of which we excluded 947 based on titles and abstracts matching one or more of our pre-determined exclusion criteria. A further 47 articles were excluded after considering the full-texts, which resulted in a combined number of 129 articles being retained for data extraction from the previous review and the update search.

Overview of the evidence

Three quarters of the literature retained came from the North-East Atlantic. The vast majority of the remaining literature was based on experiments, and not of real installations (18% of total), while relatively few articles focussed on offshore wind installations from the Northwest Pacific and Northwest Atlantic (6% and 2%, respectively). Studies from the North-East Atlantic were distributed across the United Kingdom, Germany, Belgium, Denmark, and the Netherlands (Figure 1). There were a significant number of articles investigating cross-border impacts in the North and Baltic Seas, with only one article from each of Ireland and Sweden.

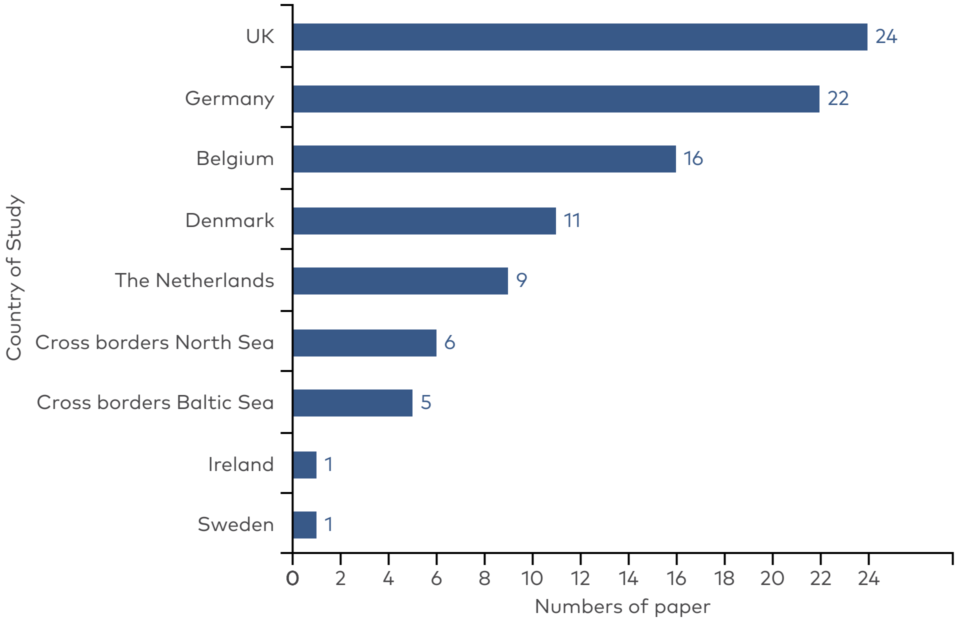


Figure 4.1. Number of articles on the environmental impacts of offshore wind energy infrastructure utilising case studies from the NE Atlantic.

Within these articles, we identified 194 unique cases of relationships between human activities, pressures, and ecosystem components (Figure 4.2). The majority of activities associated with offshore wind farms were documented to create multiple pressures. The presence of foundations had the most diverse set of pressures, including the introduction of novel habitat, which was the most prevalent pressure studied and was most often investigated in relation to impacts on fish and benthos. The pressure of displacement was linked to the broadest set of activities, but the majority of studies considered this in the context of seabirds interacting with above water components. The pressure of Noise was studied in relation to a broad set of ecosystem components, however, nearly half of all investigations into noise were focused on Cetaceans.

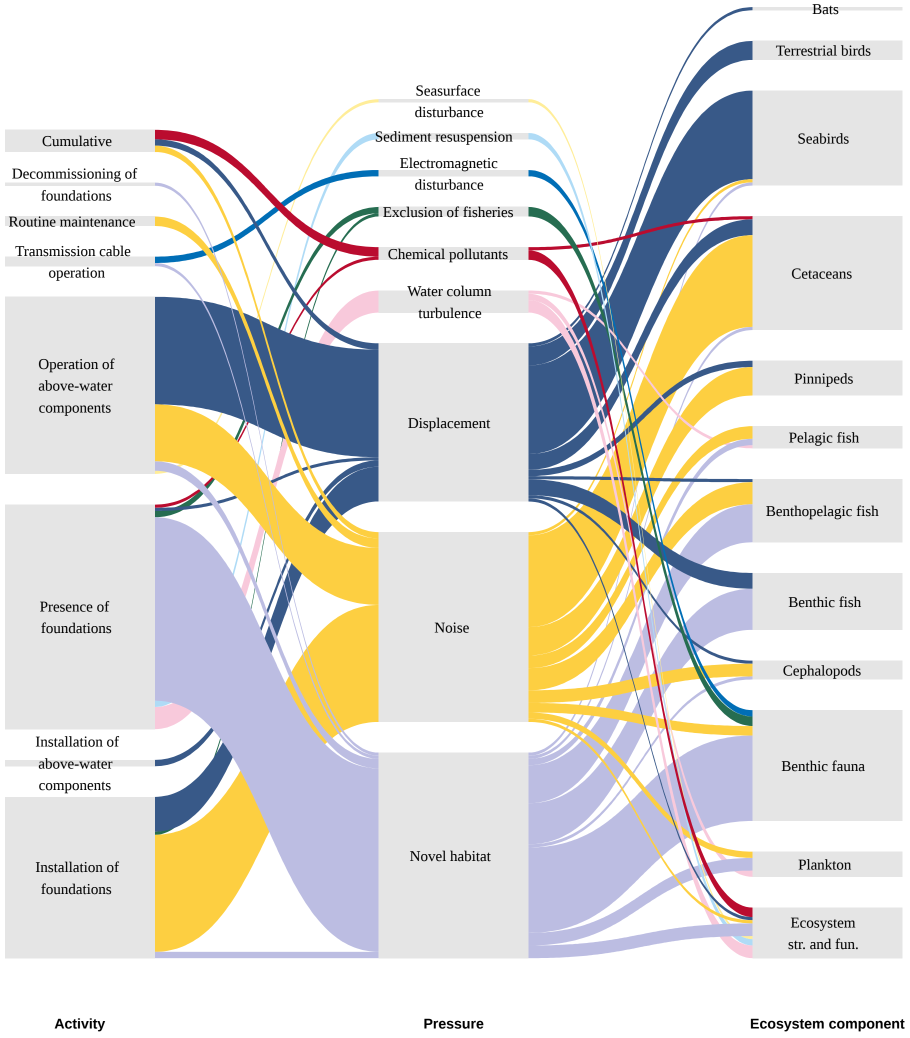


Figure 4.2. Sankey Diagram showing the linkage of activities associated with offshore wind energy infrastructure, the pressures they create, and the ecosystem components impacted by these pressures.

Impacts from the installation of transmission cables, or from decommissioning of above water components were not documented in the literature, indicating potential knowledge gaps.

Twelve different ecosystem components were identified from the literature (Figure 4.3). It is notable that the impact on reptiles as a group was not studied at all, probably due to the geographic bias of both installations and the studies of their impacts to higher latitudes.

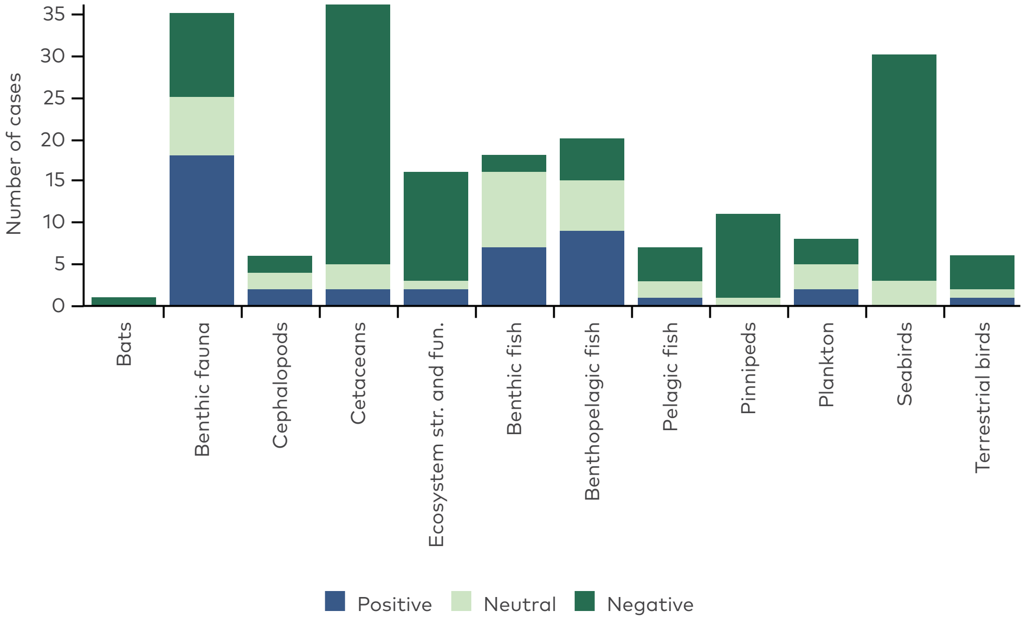
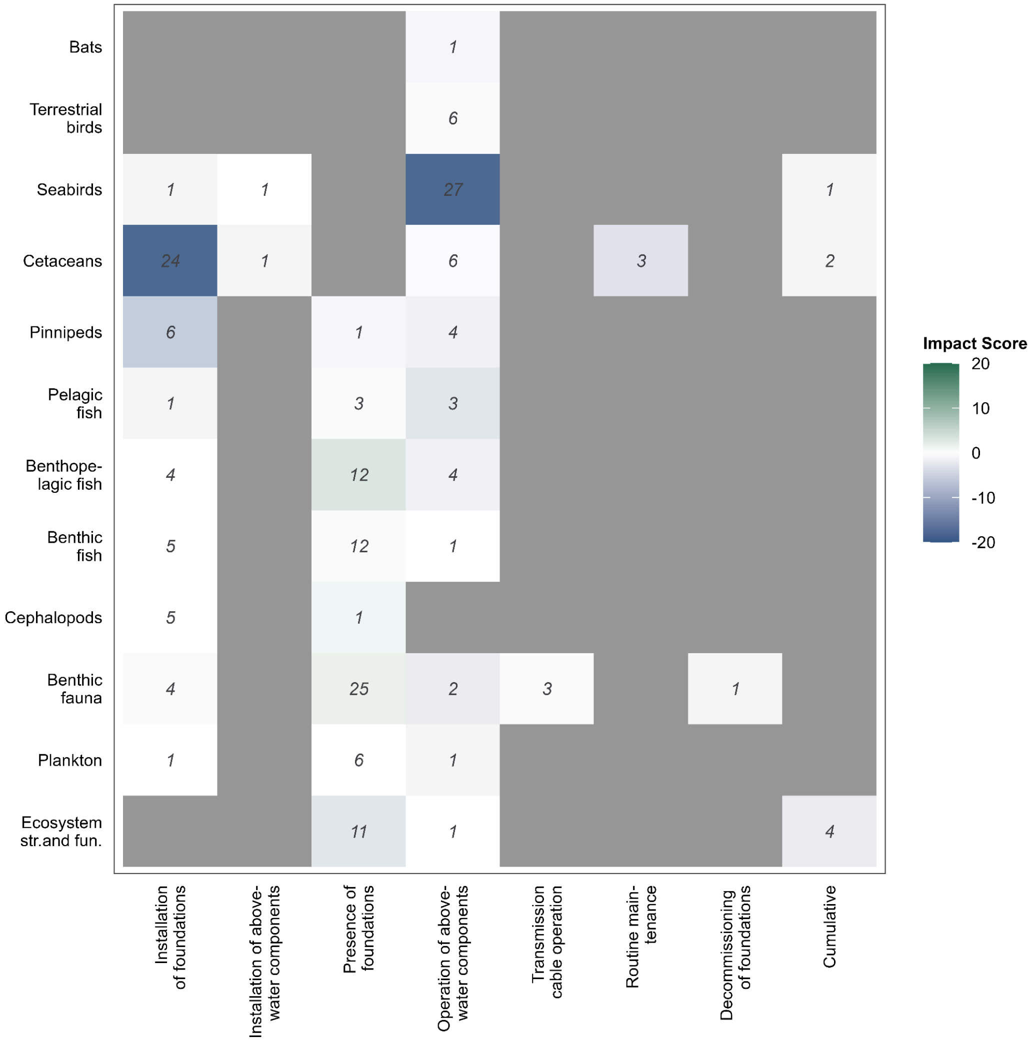


Figure 4.3. Directions of impacts from offshore wind energy related pressures reported for the various ecosystem components across cases.

Meta analyses

Our meta-analyses provide an overview of scientific consensus based only on empirical evidence. Interactions with large (including largely negative) impact scores highlight strong, generalisable relationships, that can be assumed to hold across different contexts. For example, the activity of installing foundations was consistently found to negatively impact cetaceans (Figure 4.4), while the pressure of displacement negatively impacting seabirds was also reported consistently in the literature (Figure 4.5).

Where these impact scores reduce, or become closer to zero, they indicate that the relationship they represent is context dependent. This may be because the score is based on only a few cases of evidence, and thus impacts may vary if studied under different contexts, or because the larger number of cases have a large diversity of outcomes. For example, the pressure of sea-surface disturbance impacting on ecosystem structure and functioning (only an individual case) (Figure 4.5), or the presence of foundations having an ambiguous impact on benthic fish, despite a relatively large number of cases (Figure 4.4).



	Installation of foundations	Installation of above-water components	Presence of foundations	Operation of above-water components	Transmission cable operation	Routine maintenance	Decommissioning of foundations	Cumulative
Bats				1				
Terrestrial birds				6				
Seabirds	1	1		27				1
Cetaceans	24	1		6		3		2
Pinnipeds	6		1	4				
Pelagic fish	1		3	3				
Benthopelagic fish	4		12	4				
Benthic fish	5		12	1				
Cephalopods	5		1					
Benthic fauna	4		25	2	3		1	
Plankton	1		6	1				
Ecosystem str.and fun.			11	1				4

Figure 4.4. Matrix of activity impact scores. Colours represent both the direction of impacts from various activities (x-axis) on ecosystem components (y-axis) as well as the level of certainty in that score (intensity of colour). The numbers in each cell represent the number of cases that contributed to the corresponding interaction.

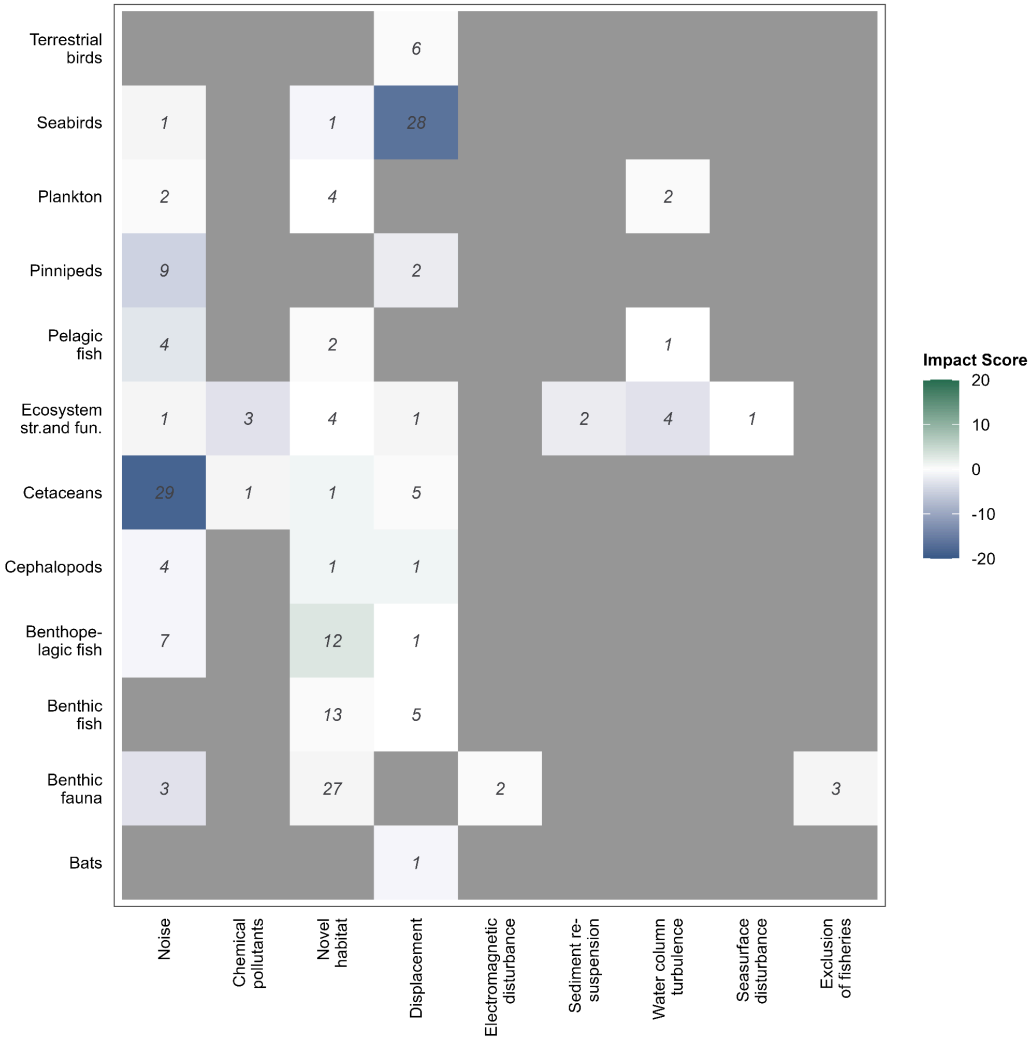


Figure 4.5. Matrix of pressure impact scores. Colours represent both the direction of impacts from various pressures (x-axis) on ecosystem components (y-axis) as well as the level of certainty in that score (intensity of colour). The numbers in each cell represent the number of cases that contributed to the corresponding interaction.

These matrices, therefore, are an up-to-date decision supporting tool for planners, managers and policy makers, where strong impact scores indicate generalised interactions that can be expected across various contexts, where low scores indicate weak evidence that is likely to be context dependent and require project specific consideration, and empty scores that indicate that novel research must be undertaken.

Complimentary review of impacts on coastal communities

To supplement the review of offshore wind farms' impacts on the environment, we undertook a parallel systematic review. Following the same methodology as described above, but with a focus on the question of what socio-economic impacts offshore wind farms have on coastal communities in Scandinavian contexts.

Our literature review covered all published primary literature up to the end of November 2024, catalogued in SCOPUS. Our search returned 107 records. Screening of titles and abstracts excluded 92 records, retaining only 15 for full-text investigation. At the full-text screening stage, a further 14 articles were excluded and only one article was retained. The majority of articles were rejected because they were not attempting to document socio-economic impacts on coastal communities (66) or they were not investigating the impacts from the offshore wind industry (13). Where some articles described good metrics of socio-economic impacts from offshore wind industries, they were primarily focussed on prospective projects or theoretical impacts (8); for example, peoples' willingness to pay to have a theoretical near-shore wind farm installed further offshore. We excluded seven articles as review articles, not contributing novel empirical data, most of which were opinion or perspectives papers.

The retained article (Ladenburg & Dubgaard, 2009), was itself a marginal case for retention, as their empirical evidence was based on a survey of the general populace about the placement of a theoretical wind farm. However, this was retained as the survey took account of respondent's previous exposure to real-world installations, and undertook analyses to investigate how these experiences shaped their perspectives on the presence of offshore wind farms. As only one article was retained, we direct you to read this paper specifically for more information on citizen's willingness to pay for distributing wind farms further offshore, with lower visual impact.

This absence of published empirical research on the impacts of the offshore wind industry on coastal communities, in Scandinavian contexts, is a gap in knowledge that hinders planners', managers', and policy makers' abilities to make evidence-based decisions. While evidence exists from other geographic and cultural contexts (see Serpa et al., 2025), most socio-economic studies remain focussed on business development and national level industrial policy.

Recommendations

Our matrices of impact scores provide a synthesis of empirically based knowledge that can be used to inform decision making in the permitting, planning, and monitoring of offshore wind projects. Decision makers can couple these activity/pressure impacts with local environmental objectives, while considering the trade-offs that offshore wind development can bring to decarbonisation of energy production.

Where our matrices indicate low scores, decision makers can make use of our published database to compare their specific case to the contexts in which impacts have been investigated. In these circumstances, the incongruity in the literature may be overcome by excluding empirical evidence that is clearly derived from different contexts. For example, wind farms installed on offshore sand banks, vs near shore rocky archipelagos.

As offshore wind infrastructure becomes more rapidly deployed, there exists more and novel opportunities to undertake more research and monitoring projects to fill in the large gaps in our knowledge. Offshore wind permitting authorities should engage with research funding bodies (public and private), to couple research and monitoring requirements to appropriate research funding to facilitate this work. Establishing such projects must be done years in advance of project commencement, to ensure that appropriate experimental designs can be implemented (Before-After-Control-Impact, BACI).

Common practice in offshore wind infrastructure deployments include Environmental Impact Assessments. These assessments include pre-surveys, and subsequent follow-up surveys. Access to the findings of such EIA's would greatly improve the knowledge available to meta-analyses, such as those we have undertaken here. Access to the actual survey and monitoring data would enable even richer forms of meta-analyses, opening up much more definite conclusions about magnitudes of impact that are not currently possible. Permitting and monitoring authorities should endeavour to make existing and future EIA reports and data available to relevant research projects to gain insights from these potentially rich sources of knowledge.

Finally, empirical studies of socio-economic impacts on coastal communities need to be undertaken in various Scandinavian contexts, to investigate the costs and benefits, and mechanisms to overcome or maximise them for regional development. Scandinavia provides diverse examples of industry transition (e.g. oil & gas, fisheries, or shipbuilding) towards offshore wind industry.

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Appendix

Appendix for Chapter 2: An evaluation of fish stocks lacking quantitative assessments in Skagerrak

Supplementary Section 1: Species

Table S1: Species with a quantitative stock assessment relevant to the Skagerrak area.

Aphia ID	Species	Family	ICES_ID	ICES_Category	Hauls_NOSS	Hauls_NS-IBTS	Hauls_Total
126417	*Clupea harengus*	Clupeidae	her.27.3a47d,-her.27.20-24	1,1.2	12294	77728	90022
126436	*Gadus morhua*	Gadidae	cod.27.47d20	1	4210	61012	65222
126444	*Trisopterus esmarkii*	Gadidae	nop.27.3a4	1	33687	23780	57467
126437	*Melanogrammus aeglefinus*	Gadidae	had.27.46a20	1	13580	35540	49120
127143	*Pleuronectes platessa*	Pleuronectidae	ple.27.420	1	1237	35372	36609
127136	*Glyptocephalus cynoglossus*	Pleuronectidae	wit.27.3a47d	1	5228	10872	16100
126441	*Pollachius virens*	Gadidae	pok.27.3a46	1	5361	6864	12225
126484	*Merluccius merluccius*	Merlucciidae	hke.27.3a46-8abd	1	3690	7948	11638
127160	*Solea solea*	Soleidae	sol.27.20-24	1	5	3744	3749
127149	*Scophthalmus maximus*	Scophthalmidae	tur.27.3a	2.1	1	424	425

Table S2: Eighty-two species observed in the two surveys in the Skagerrak area. The "x" in column "L" indicates for which species species-specific landings are available. Similarly, the "x" in column "S" indicates for which species, a reliable (CV < 1.5) relative abundance index could be estimated.

Aphia ID	Species	Family	ICES ID	ICES Stock cat	# NOSS	# NS-IBTS	# total	Shape	Habitat	Gear group	L	S
126438	*Merlangius merlangus*	Gadidae	whg.27.3a	3.23	11547	65044	76591	fusiform/-normal	near-bottom	6	x	x
127137	*Hippoglossoides platessoides*	Pleuronectidae			15111	54192	69303	short and/or deep	bottom	4	x	x
127139	*Limanda limanda*	Pleuronectidae	dab.27.3a4	3.22	274	35652	35926	short and/or deep	bottom	4	x	x
150637	*Eutrigla gurnardus*	Triglidae	gug.27.3a47d	3.23	474	18084	18558	elongated	bottom	2	x	x
126450	*Enchelyopus cimbrius*	Lotidae			1722	11352	13074	elongated	bottom	2		x
126446	*Trisopterus minutus*	Gadidae			1523	10476	11999	fusiform/-normal	near-bottom	6		x
127140	*Microstomus kitt*	Pleuronectidae	lem.27.3a47d	3.22	221	9048	9269	short and/or deep	bottom	4	x	x
127312	*Maurolicus muelleri*	Sternoptychidae			6156	2824	8980	elongated	near-bottom	5		x
105824	*Chimaera monstrosa*	Chimaeridae			7278	1224	8502	elongated	bottom	2	x	x
127118	*Lycodes vahlii*	Zoarcidae			0	7792	7792	eel-like	bottom	1		x
127141	*Platichthys flesus*	Pleuronectidae	fle.27.3a4	3.2	4	7676	7680	short and/or deep	bottom	4	x	x
154675	*Lumpenus lampretaeformis*	Stichaeidae			18	6716	6734	eel-like	bottom	1		x
126793	*Callionymus maculatus*	Callionymidae			32	6276	6308	elongated	bottom	2		x
126792	*Callionymus lyra*	Callionymidae			32	6040	6072	elongated	bottom	2		x
126439	*Micromesistius poutassou*	Gadidae			4712	476	5188	elongated	near-bottom	5		
126715	*Argentina silus*	Argentinidae	aru.27.123a4	3.2	4964	156	5120	elongated	near-bottom	5		
127214	*Cyclopterus lumpus*	Cyclopteridae			222	4440	4662	short and/or deep	near-bottom	7	x	x
158960	*Coryphaenoides rupestris*	Macrouridae	rng.27.3a	3.23	3983	20	4003	elongated	near-bottom	5	x	x
274100	*Lycodes gracilis*	Zoarcidae			1526	672	2198	elongated	bottom	2		x
126716	*Argentina sphyraena*	Argentinidae			35	1868	1903	elongated	bottom	2		x
127126	*Arnoglossus laterna*	Bothidae			0	1448	1448	fusiform/-normal	bottom	3		x
127150	*Scophthalmus rhombus*	Scophthalmidae	bll.27.3a47de	3.22	0	1176	1176	short and/or deep	bottom	4	x	x
126440	*Pollachius pollachius*	Gadidae	pol.27.3a4	5.2	79	892	971	fusiform/-normal	near-bottom	6	x	x
127379	*Entelurus aequoreus*	Syngnathidae			7	944	951	eel-like	bottom	1		
127101	*Lycenchelys sarsii*	Zoarcidae			125	752	877	eel-like	bottom	1		
126555	*Lophius piscatorius*	Lophiidae	anf.27.3a46	3.21	184	668	852	short and/or deep	bottom	4	x	x
127153	*Buglossidium luteum*	Soleidae			0	752	752	short and/or deep	bottom	4		x
126461	*Molva molva*	Lotidae			159	412	571	elongated	bottom	2	x	x

127082	*Trachinus draco*	Trachinidae			4	500	504	fusiform/normal	bottom	3		x
127251	*Helicolenus dactylopterus*	Sebastidae			444	56	500	fusiform/normal	bottom	3		x
127190	*Agonus cataphractus*	Agonidae			7	472	479	fusiform/normal	bottom	3		x
126904	*Lesueurigobius friesii*	Gobiidae			0	432	432	fusiform/normal	bottom	3		x
127255	*Sebastes viviparus*	Sebastidae			364	28	392	short and/or deep	bottom	4		x
126758	*Anarhichas lupus*	Anarhichadidae			3	364	367	elongated	bottom	2	x	x
126986	*Mullus surmuletus*	Mullidae	mur.27.3a47d	5	87	244	331	fusiform/normal	bottom	3		
126756	*Hyperoplus lanceolatus*	Ammodytidae			0	324	324	elongated	bottom	2		x
126928	*Pomatoschistus minutus*	Gobiidae			0	288	288	fusiform/normal	bottom	3		
126505	*Gasterosteus aculeatus*	Gasterosteidae			76	180	256	fusiform/normal	near-bottom	6		
127203	*Myoxocephalus scorpius*	Cottidae			3	212	215	fusiform/normal	bottom	3		x
293018	*Zeugopterus norvegicus*	Scophthalmidae			10	160	170	short and/or deep	near-bottom	7		x
127389	*Syngnathus rostellatus*	Syngnathidae			0	160	160	eel-like	bottom	1		x
127138	*Hippoglossus hippoglossus*	Pleuronectidae			35	124	159	fusiform/normal	bottom	3	x	x
127387	*Syngnathus acus*	Syngnathidae			0	124	124	eel-like	bottom	1		
126751	*Ammodytes marinus*	Ammodytidae			8	108	116	elongated	near-bottom	5		
126501	*Phycis blennoides*	Phycidae			90	24	114	fusiform/normal	near-bottom	6	x	x
127427	*Zeus faber*	Zeidae			3	80	83	short and/or deep	near-bottom	7	x	x
127262	*Chelidonichthys lucerna*	Triglidae			0	80	80	elongated	bottom	2		x
126996	*Pholis gunnellus*	Pholidae			0	72	72	eel-like	bottom	1		
127072	*Leptoclinus maculatus*	Stichaeidae			7	64	71	elongated	bottom	2		
126448	*Ciliata mustela*	Lotidae			0	60	60	elongated	bottom	2		x
126281	*Anguilla anguilla*	Anguillidae			5	48	53	eel-like	bottom	1		
126445	*Trisopterus luscus*	Gadidae			0	52	52	fusiform/normal	near-bottom	6		x
127393	*Syngnathus typhle*	Syngnathidae			0	48	48	eel-like	bottom	1		
126795	*Callionymus reticulatus*	Callionymidae			8	28	36	elongated	bottom	2		x
126929	*Pomatoschistus norvegicus*	Gobiidae			32	4	36	fusiform/normal	bottom	3		x
150630	*Echiichthys vipera*	Trachinidae			1	32	33	elongated	bottom	2		
293624	*Liparis liparis*	Liparidae			0	32	32	elongated	bottom	2		x
126752	*Ammodytes tobianus*	Ammodytidae			7	24	31	elongated	bottom	2		
126447	*Brosme brosme*	Lotidae	usk.27.3a45b6a7-912b	3.2	29	0	29	elongated	bottom	2	x	x
127205	*Triglops murrayi*	Cottidae			1	28	29	elongated	bottom	2		

126459	*Molva dypterygia*	Lotidae			23	4	27	elongated	bottom	2	x	x
126975	*Dicentrarchus labrax*	Moronidae			0	20	20	fusiform/-normal	bottom	3		
127146	*Lepidorhombus whiffiagonis*	Scophthalmidae			1	16	17	fusiform/-normal	bottom	3		
126442	*Raniceps raninus*	Gadidae			0	16	16	fusiform/-normal	bottom	3		
127201	*Micrenophrys lilljeborgii*	Cottidae			0	16	16	elongated	bottom	2		
127151	*Zeugopterus punctatus*	Scophthalmidae			1	12	13	short and/or deep	bottom	4		
126878	*Crystallogobius linearis*	Gobiidae			0	12	12	elongated	bottom	2		
126451	*Gaidropsarus argentatus*	Lotidae			9	0	9	elongated	bottom	2		
127071	*Chirolophis ascanii*	Stichaeidae			1	8	9	elongated	near-bottom	5		
127419	*Capros aper*	Caproidae			1	8	9	short and/or deep	bottom	4		
126458	*Gaidropsarus vulgaris*	Lotidae			0	8	8	elongated	bottom	2		
127204	*Taurulus bubalis*	Cottidae			0	8	8	fusiform/-normal	bottom	3		
127220	*Liparis montagui*	Liparidae			0	8	8	elongated	bottom	2		
126892	*Gobius niger*	Gobiidae			0	4	4	fusiform/-normal	bottom	3		
126977	*Chelon labrosus*	Mugilidae			0	4	4	elongated	bottom	2		
127191	*Leptagonus decagonus*	Agonidae			4	0	4	elongated	bottom	2		
127254	*Sebastes mentella*	Sebastidae			3	0	3	fusiform/-normal	near-bottom	6		
126352	*Arctozenus risso*	Paralepididae			1	0	1	elongated	near-bottom	5		
126472	*Macrourus berglax*	Macrouridae			1	0	1	elongated	near-bottom	5		
127193	*Artediellus atlanticus*	Cottidae			1	0	1	elongated	bottom	2		
127235	*Cottunculus microps*	Psychrolutidae			1	0	1	elongated	bottom	2		
127259	*Chelidonichthys cuculus*	Triglidae			1	0	1	fusiform/-normal	bottom	3		

Supplementary Section 2: Methodology

The survey data was cleaned and processed following the guidelines recommended by ICES (2023) procedures. Duplicate haul IDs and entries with missing values in exploratory variables were removed. Only valid hauls (HaulVal = A or V; SpecVal = 1,4,7,10) with complete species records (StdSpecRecCod = 1) were retained. The dataset was restricted to the years 1986–2023 in Q1 and the North Sea (ICES areas 4a, 4b, 4c) and Skagerrak (ICES area 3a.21). Categories with less than 2 hauls with positive observations were excluded to reduce the number of zeros and to help model convergence. For example, if a specific species was only observed in one haul for a specific survey or a specific vessel, then this survey or vessel was removed. The final dataset categorized gear as either GOV (used in NS-IBTS) or ST (Campelen shrimp trawl used in NOSS) to differentiate between the two surveys. This comprehensive data curation ensured that the analysis focused on species most relevant to Skagerrak's demersal ecosystem, providing a robust foundation for examining their trends and management needs.

To combine the two surveys with different gears into a single model, it was necessary to account for potentially different catchability of the two surveys. As the survey catchability likely depends on the body shape of the species, species with similar morphological features were combined similarly to Walker et al. (2014). In addition, species that are associated with the seabed, such as demersal species were differentiated from species that are near or above the surface, such as benthopelagic species. The information for both categories was derived from FishBase (Froese and Pauly, 2024). Furthermore, the estimation of the gear efficiency was restricted to a time period of 2006 to 2023, and the geographical area (ICES rectangles) and depth range (120-180m) with a good overlap and sufficient observations between the two surveys (Figure S1). The spatial-temporal model for the numbers per haul was described by:

$$g(\mu_i) = f_1(time_i) + f_2(lon_i, lat_i) + f_3(time_i, lon_i, lat_i) + \alpha + log(\beta + 5)$$

where:

- $g(\mu_i)$is the link function applied to the expected value of the response variable, here the number of individuals in haul i,
- $f_1(time_i)$is a smooth function of time,
- $f_2(lon_i, lat_i)$is a smooth bivariate function of geographic coordinates (longitude and latitude),
- $f_3(time_i, lon_i, lat_i)$is a tensor product smooth to capture the interaction between time and location,
- αIs the gear effect,
- $log(\beta + 5)$is an offset term accounting for the haul duration (β) of haul i plus 5 minutes according to the recommendation by Berg et al. (2024).

The estimated gear coefficients are based on groups with 3 to 20 species and are overall within a reasonable range but varied widely for 7 groups (range of 0.16-1.82, Table 1). Overall, the catchability is lower for the ST gear in comparison to the GOV gear, with the only exception of elongated species associated with the bottom having a coefficient above 1. These gear coefficients are used for the species-specific models. Supplementary Table S2 shows each species categorized by groups of habitat and body shape.

Table S3: Estimated gear coefficients between the two surveys and gears (GOV and ST) for seven groups based on habitat and body shape. N indicates the number of species included in the group.

Group	Habitat	Body shape	N	Estimate
1	bottom	eel-like	9	0.23
2	bottom	elongated	20	0.16
3	bottom	fusiform / normal	11	0.67
4	bottom	short and / or deep	8	0.45
5	near-bottom	elongated	5	1.82
6	near-bottom	fusiform / normal	6	0.22
7	near-bottom	short and / or deep	3	0.34

The temporal and spatial trends in abundance of the species were explored by means of spatio-temporal modelling, fitting Generalised additive models (GAMs) to a subset of the data representing the realised habitat for each species following the procedure described in Berg et al. (2014). The abundance was represented by the number of individuals N_i referring to the number of individuals in the ith haul. In the next step, the abundance and distribution were estimated for each species without estimating a gear effect but using the estimated gear coefficients as offsets (Table 1). Spatial-temporal GAMs were then used to estimate distribution maps for each species. The model describes the relationship of the numbers per haul for a specific species and external factors by:

$$g(\mu_i) = f_1(time_i) + f_2(lon_i, lat_i) + f_3(time_i, lon_i, lat_i) + f_4(\sqrt(depth_i) + log(\alpha\beta + 5).$$

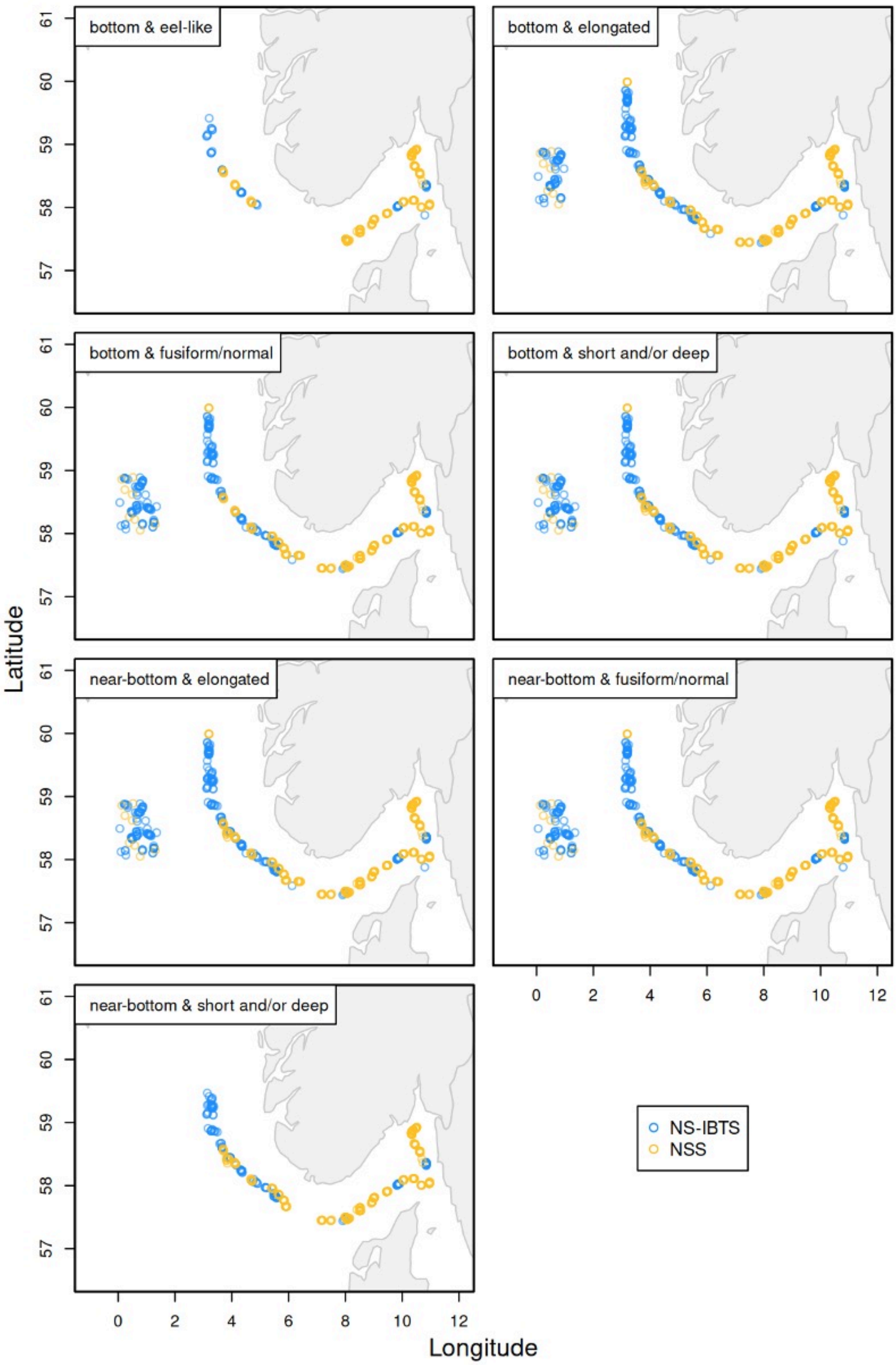
where:

- $g(\mu_i)$is the link function applied to the expected value of the response variable, here the number of individuals in haul i,
- $f_1(time_i)$is a smooth function of time,
- $f_2(lon_i, lat_i)$is a 2-dimensional Duchon spline on the geographic coordinates (longitude and latitude),
- $f_3(time_i, lon_i, lat_i)$is a tensor product smooth to capture the interaction between time and location,
- $f_4(\sqrt(depth_i)$is a smooth function of the square root of depth,
- $log(\alpha\beta + 5)$.is an offset term accounting for the haul duration (β) of haul i plus 5 minutes according to the recommendation by Berg et al. (2024) and the estimated gear effect for that species (α).

The model residuals were assumed to follow a negative binomial distribution, and a log link function was used for the dependent variable. An adequate number of knots was used for each independent term considering the dimensions of the variable. For instance, for f_1 the number of knots were set equal to the number of years of available data, and the knots for f_2 were defined based on the spatial dimensions of the area where the species was observed. If the most complex model did not converge, the model complexity was reduced in 4 steps within an iterative process, including reduction of the number of knots.

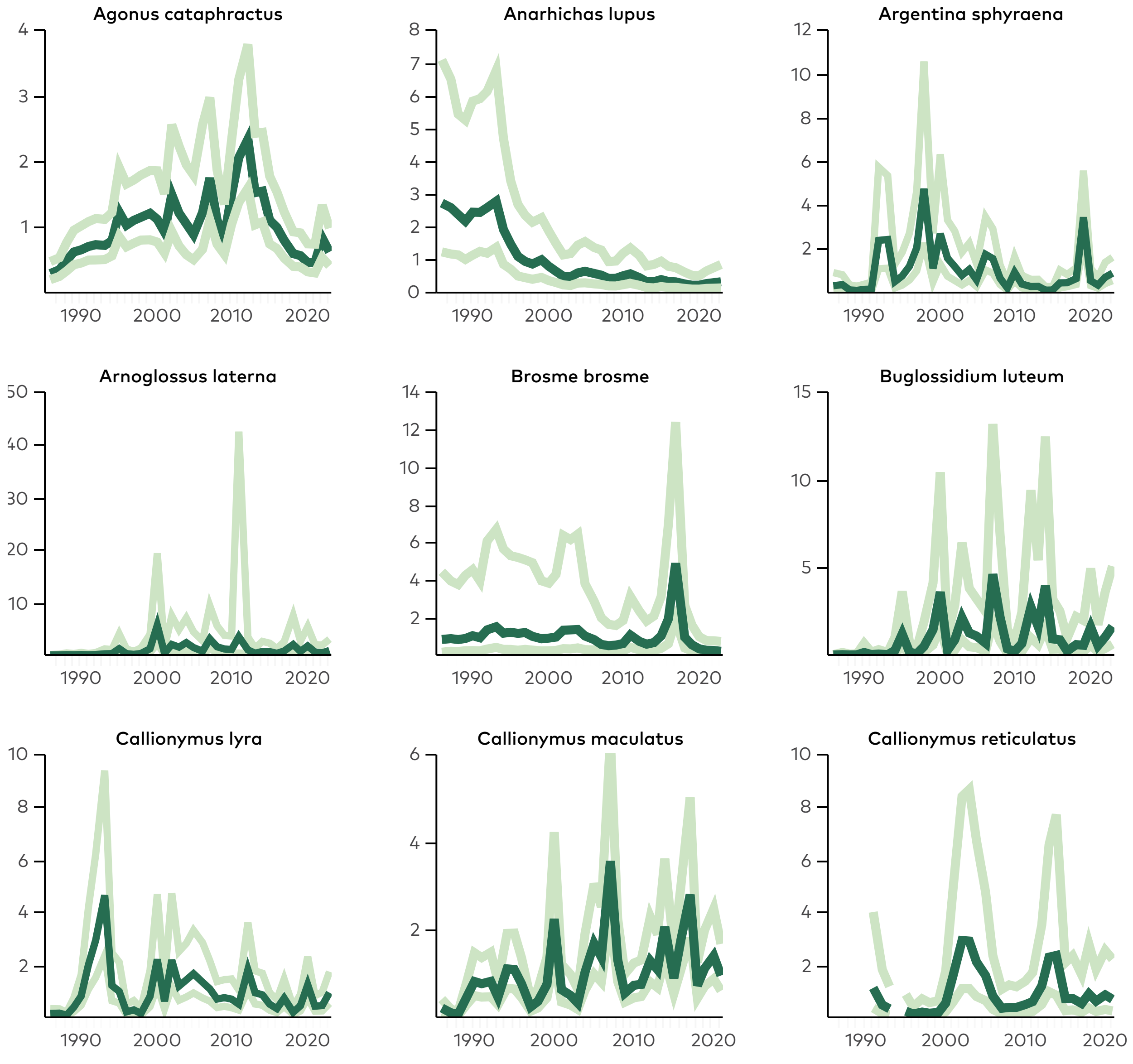
Based on the converged models for each species, the abundance was predicted for a fine spatial grid for the Skagerrak area with depth from bathymetric maps following a similar procedure as described in Berg et al. (2014): (i) dividing the realised habitat into small subareas of approximately equal size; (ii) taking the sum over all predicted abundances using the same reference gear and haul duration as well as the depth and coordinates of the grid cell. The standard deviation, coefficient of variation (CV), and 95% confidence intervals of the abundance indices were estimated based on bootstrapping. Given that n_y denotes the number of hauls each year, a bootstrap data set is created by resampling the data set with replacement, taking n_y hauls for each year from the data. All parameters (incl. smoothing parameters) and the abundance index is re-estimated for each bootstrap data set. The estimation of the standard deviation is based on 1000 bootstrap data sets. For more information about the prediction and bootstrapping procedure, please refer to Berg et al. (2014). The estimated relative abundance with 95% confidence intervals for four example species is shown in Figure 1 (please see Figure S2-4 for all 45 species).

Figure S1: Haul locations for the two surveys used to estimate the gear efficiency coefficients.



Supplementary Section 3: Spatiotemporal abundance trends for 45 species

Figure S2. Relative abundance for species 1-15 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).



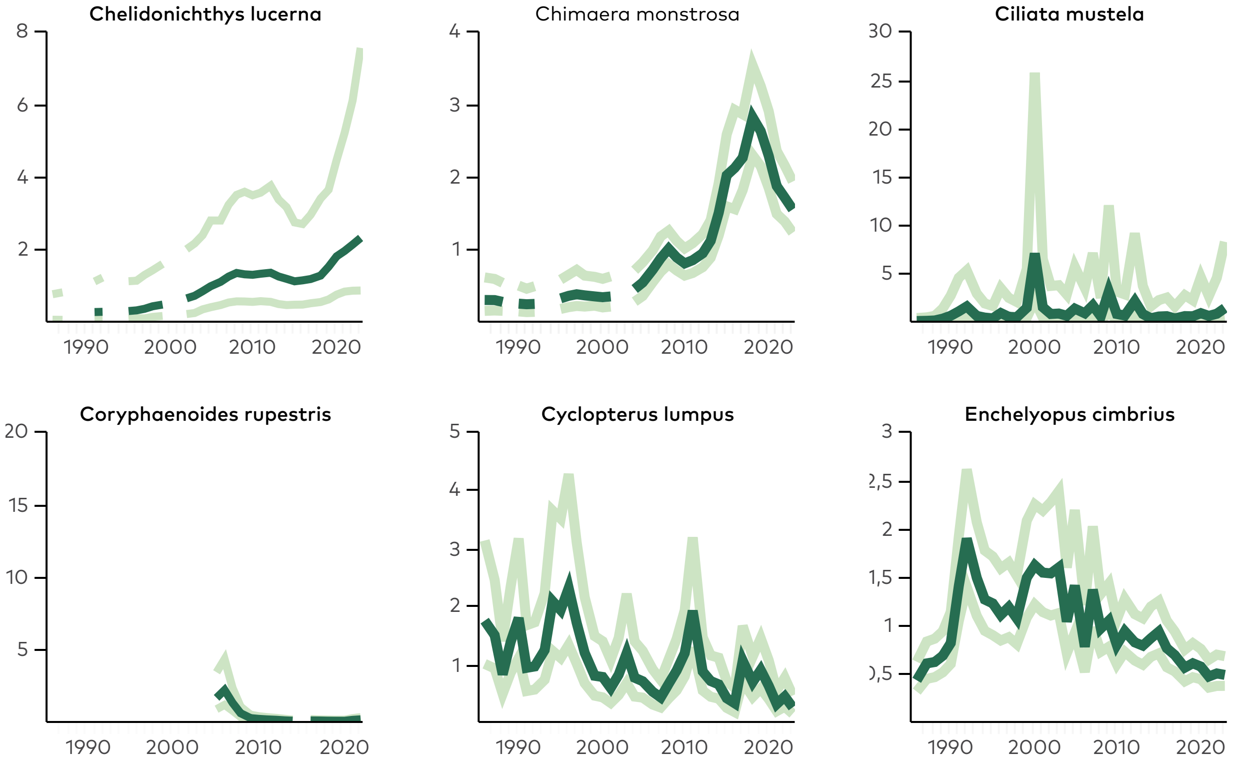
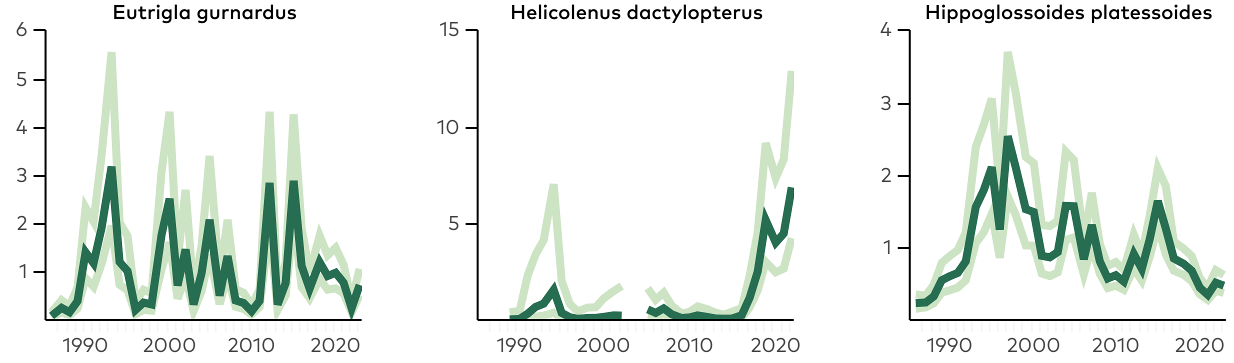
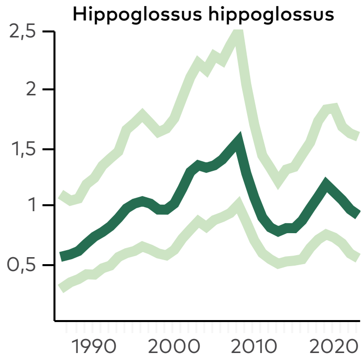
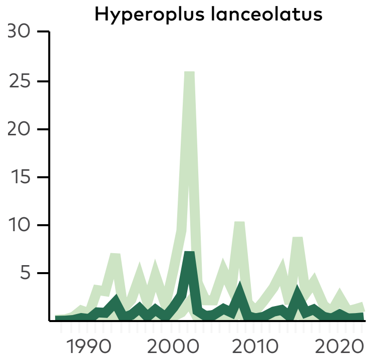
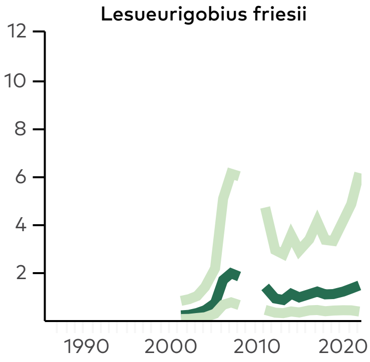


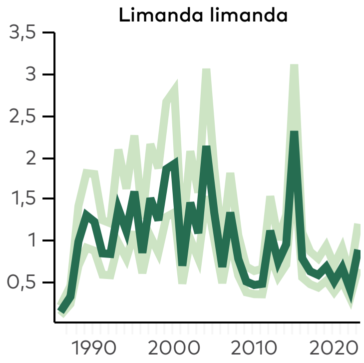
Figure S3: Relative abundance for species 16-30 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

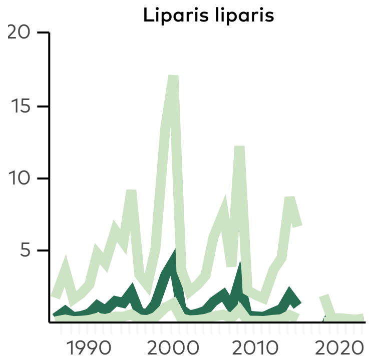


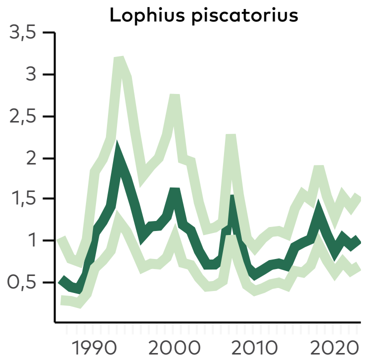

Hippoglossus hippoglossus

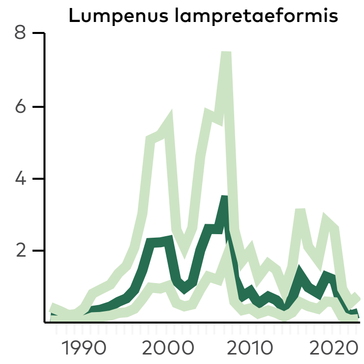

Hyperoplus lanceolatus

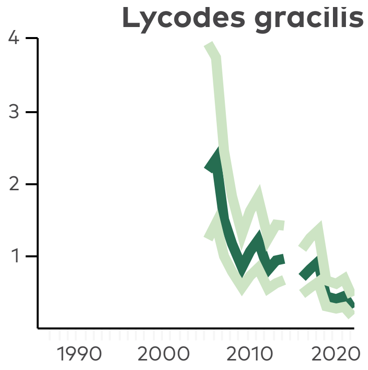

Lesueurigobius friesii

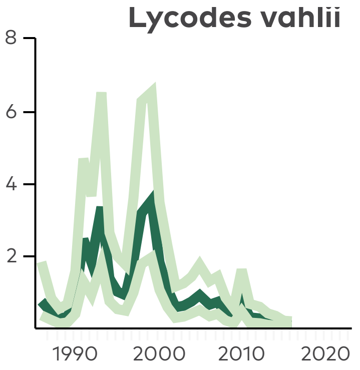

Limanda limanda

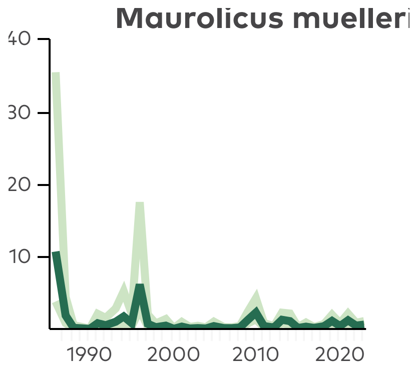

Liparis liparis

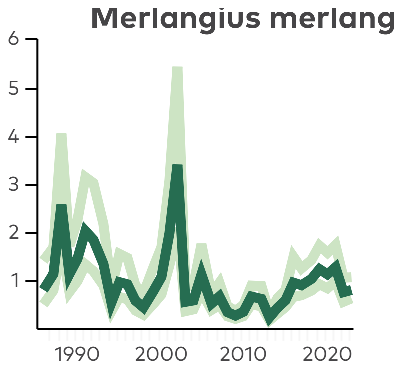

Lophius piscatorius


Lumpenus lampretaeformis


Lycodes gracilis


Lycodes vahlii


Maurolicus muelleri


Merlangius merlang

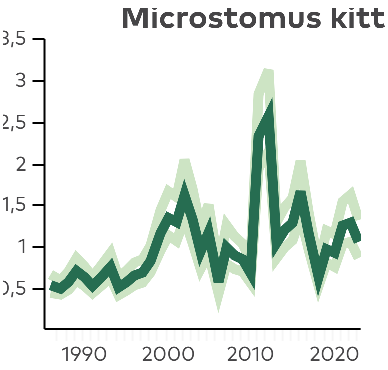
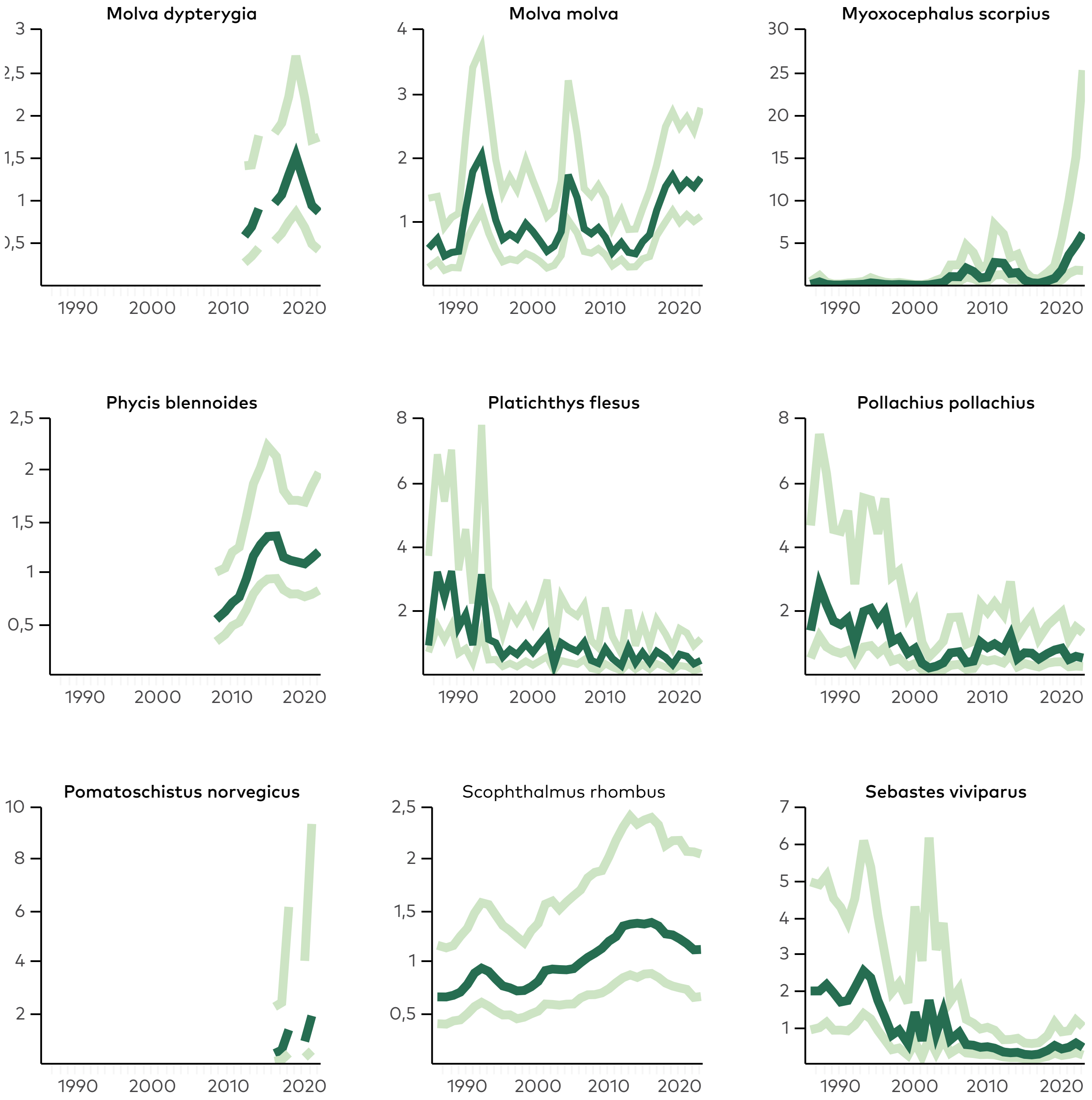
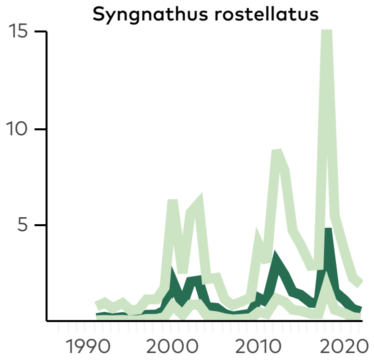
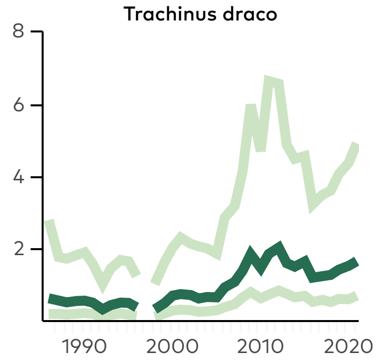

Microstomus kitt

Figure S4: Relative abundance for species 31-45 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

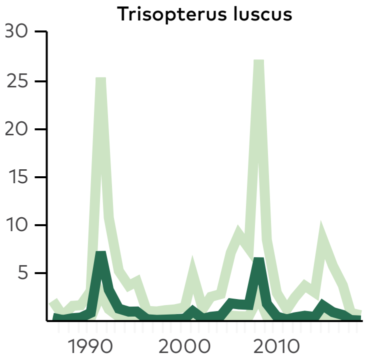




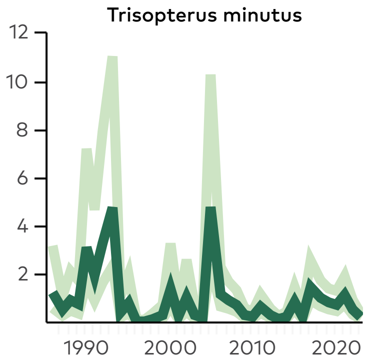
Syngnathus rostellatus



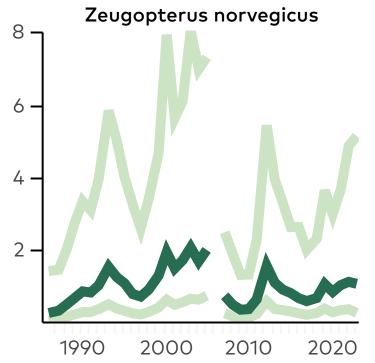
Trachinus draco



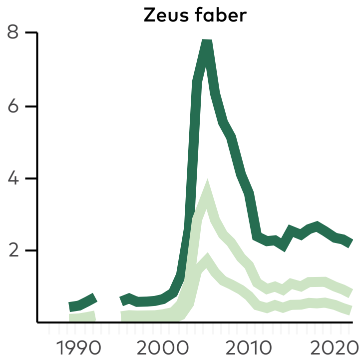
Trisopterus luscus



Trisopterus minutus



Zeugopterus norvegicus



Zeus faber

Figure S5: Average distribution over period 2013-2022 for species 1-15 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

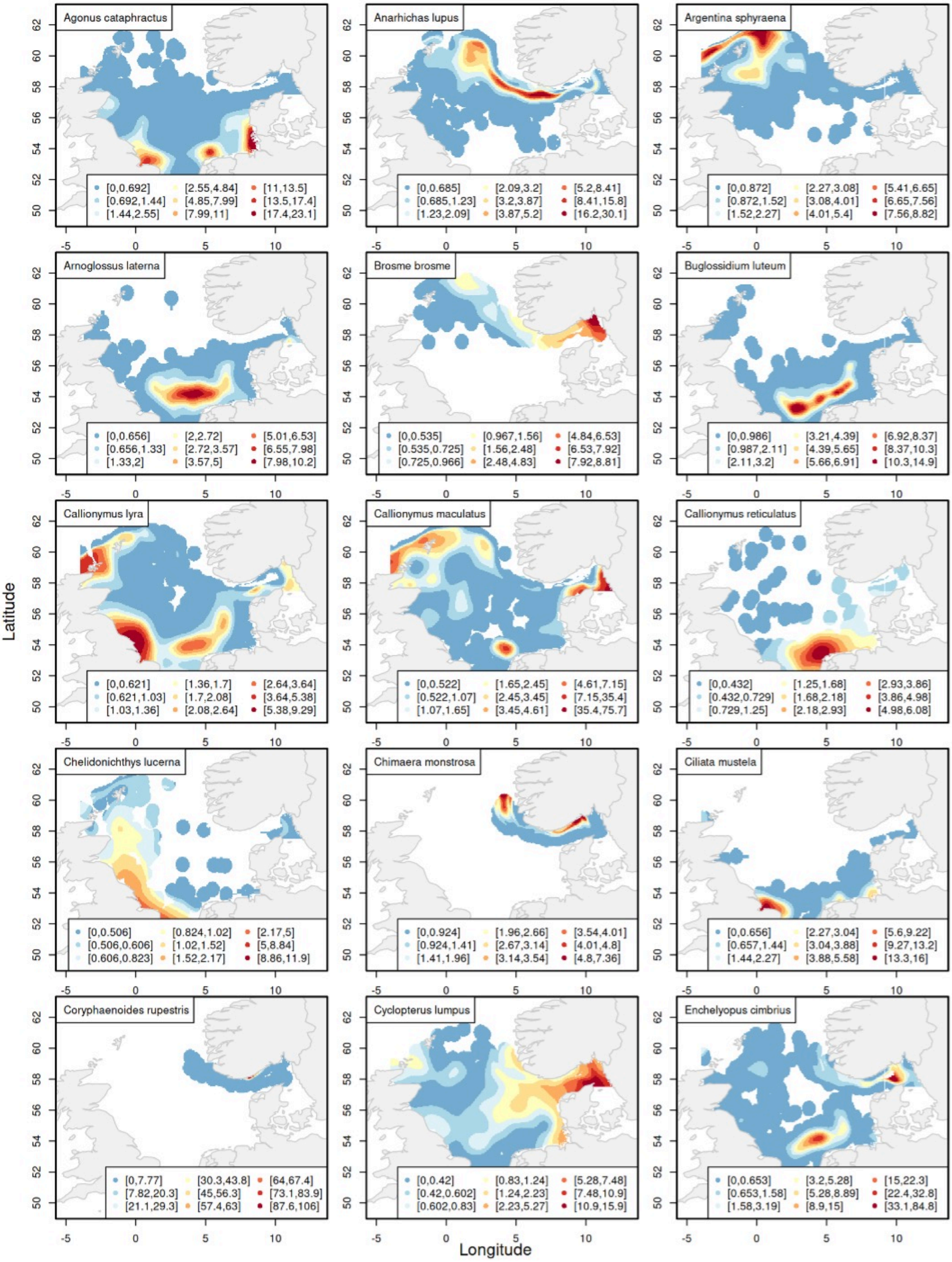


Figure S6: Average distribution over period 2013-2022 for species 16-30 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

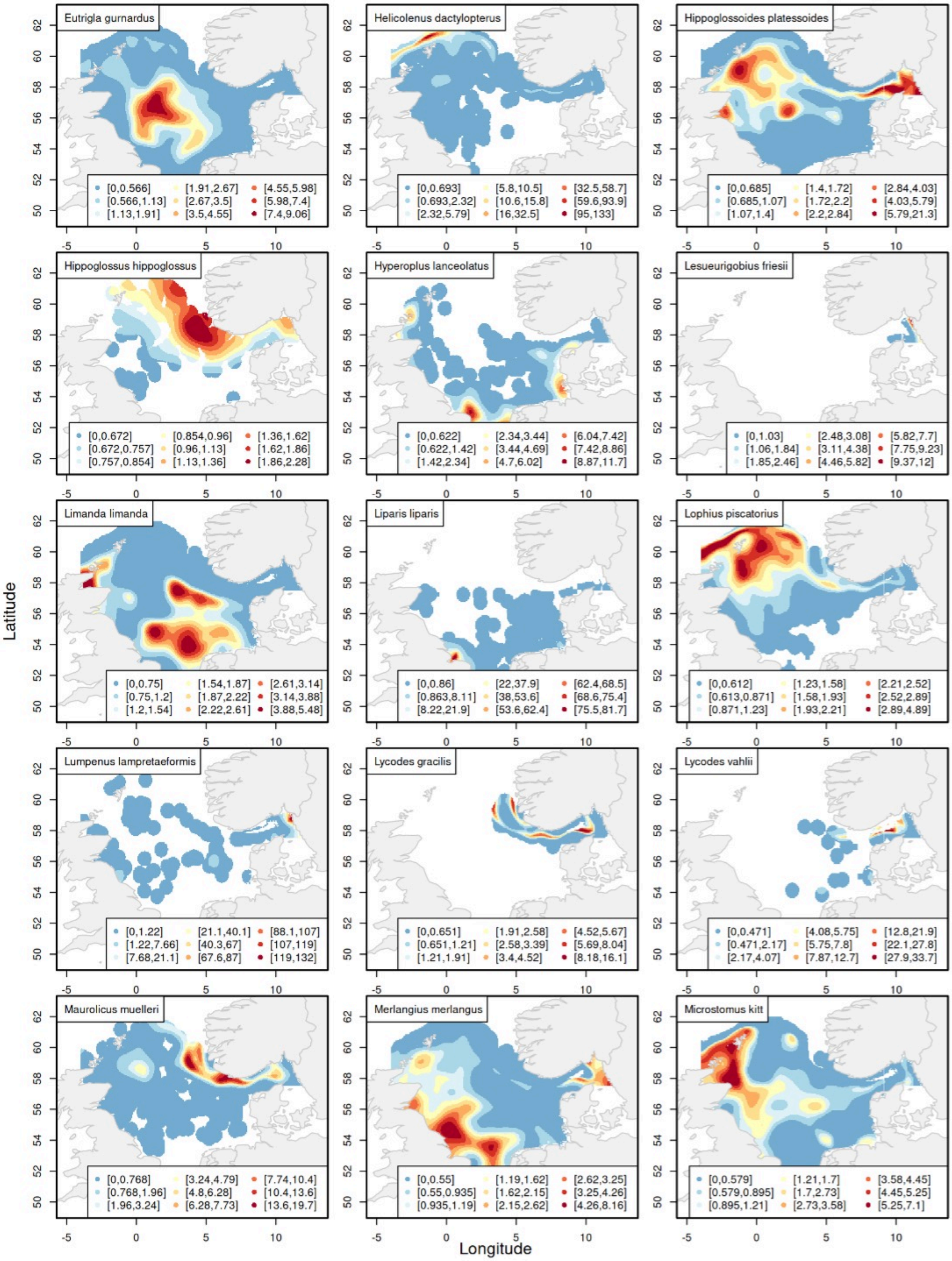


Figure S7: Average distribution over period 2013-2022 for species 31-45 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

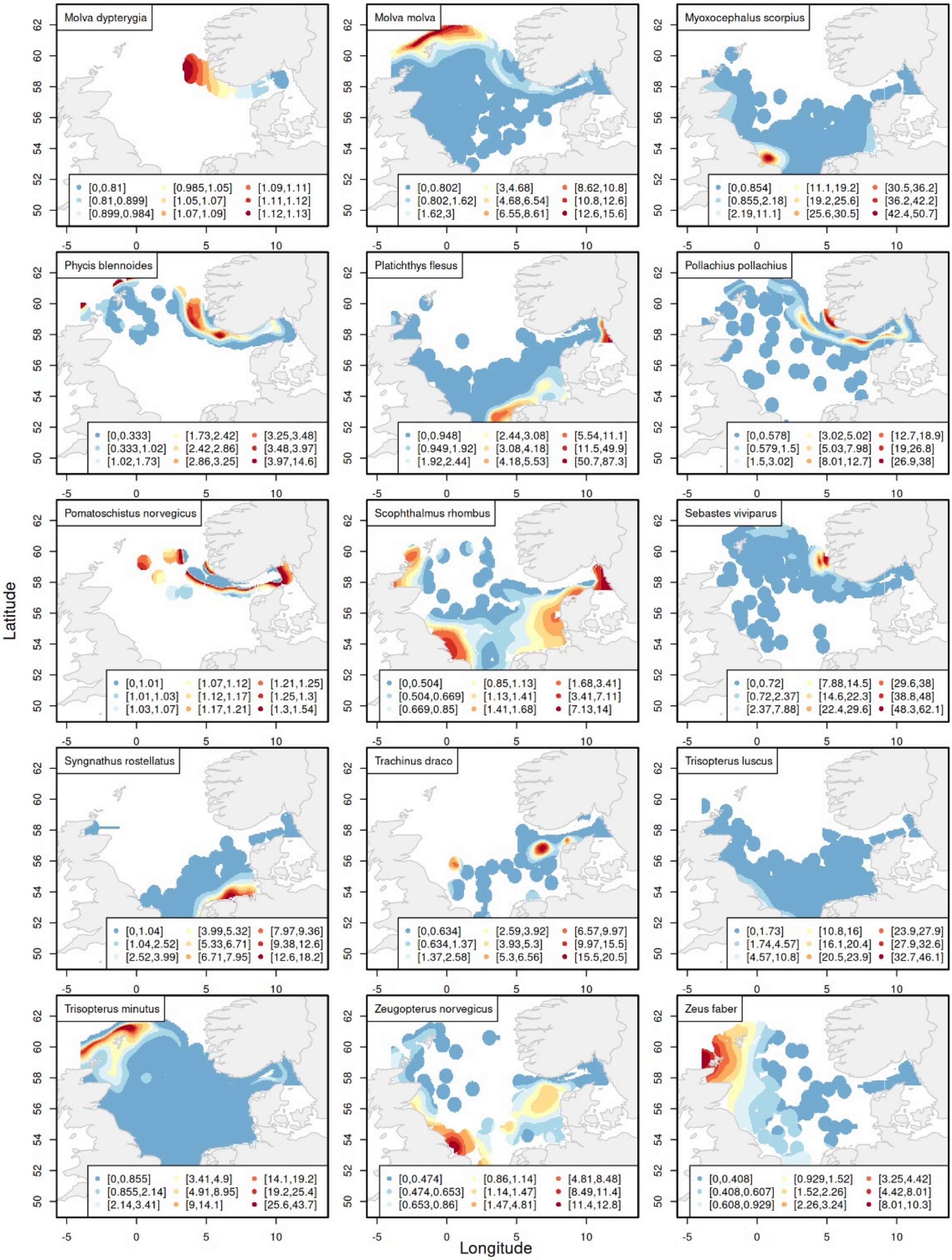


Figure S8: Average coefficient of variation (CV) over period 2013-2022 for species 1-15 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

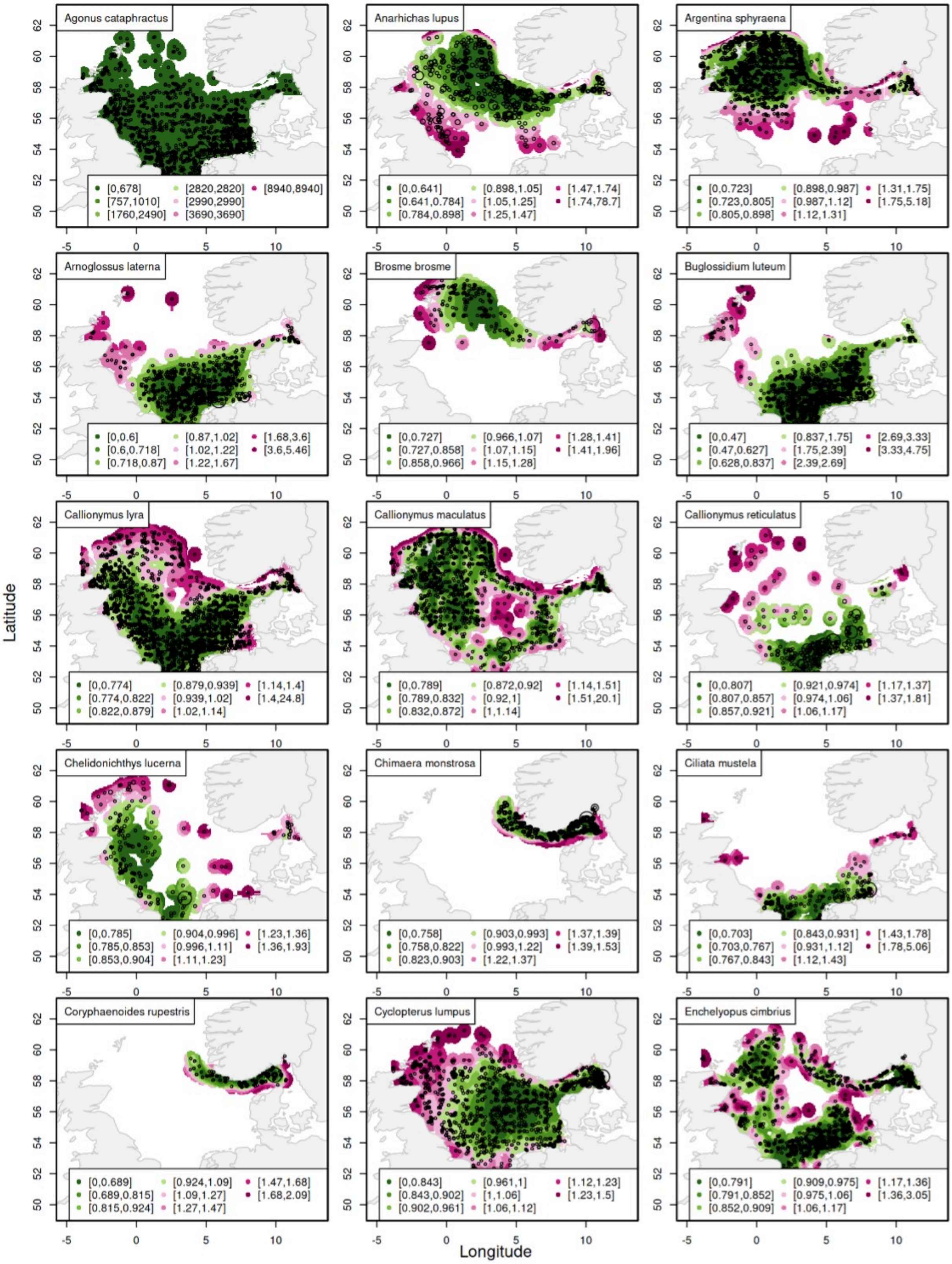


Figure S9: Average coefficient of variation (CV) over period 2013-2022 for species 16-30 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

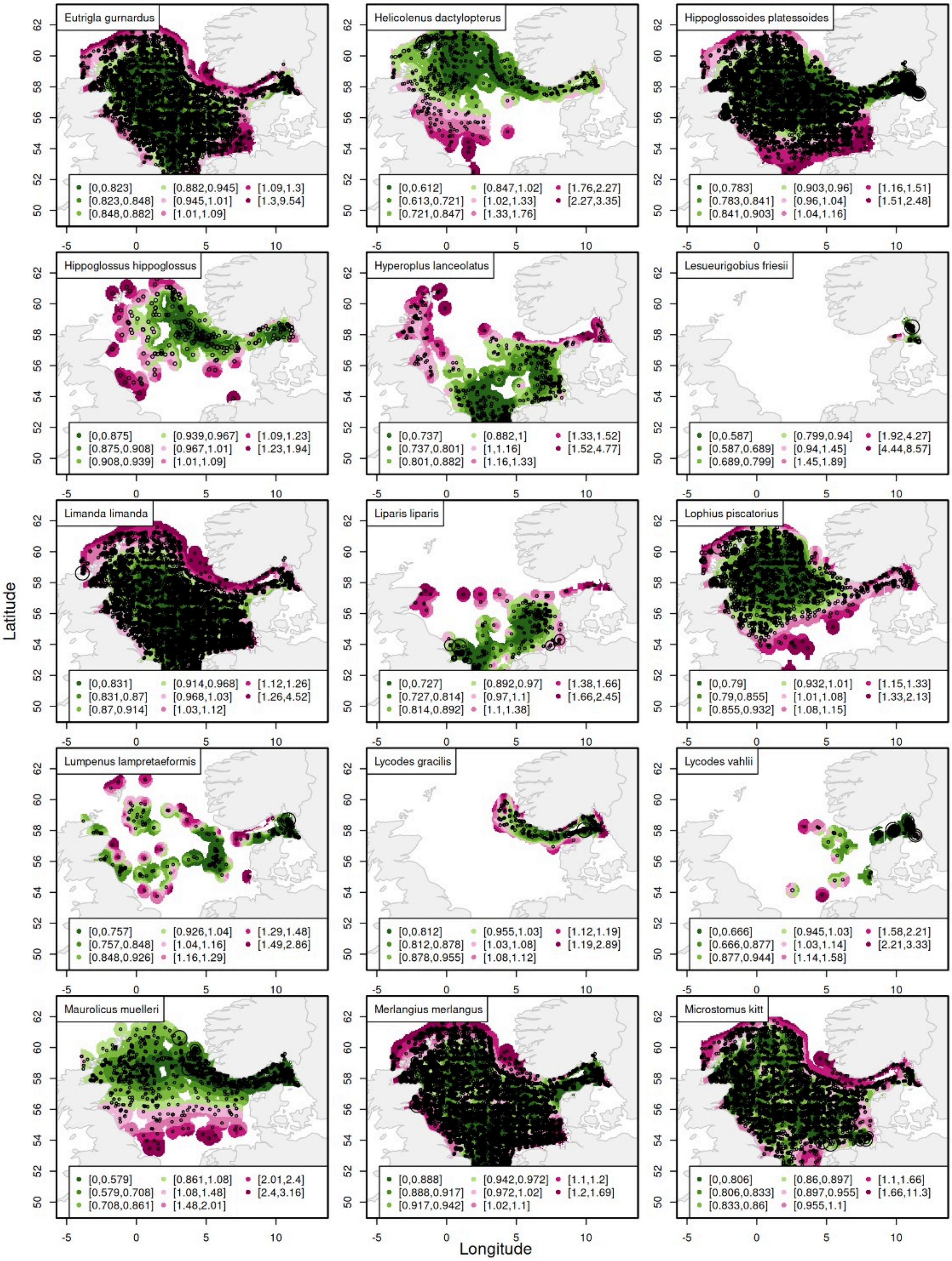
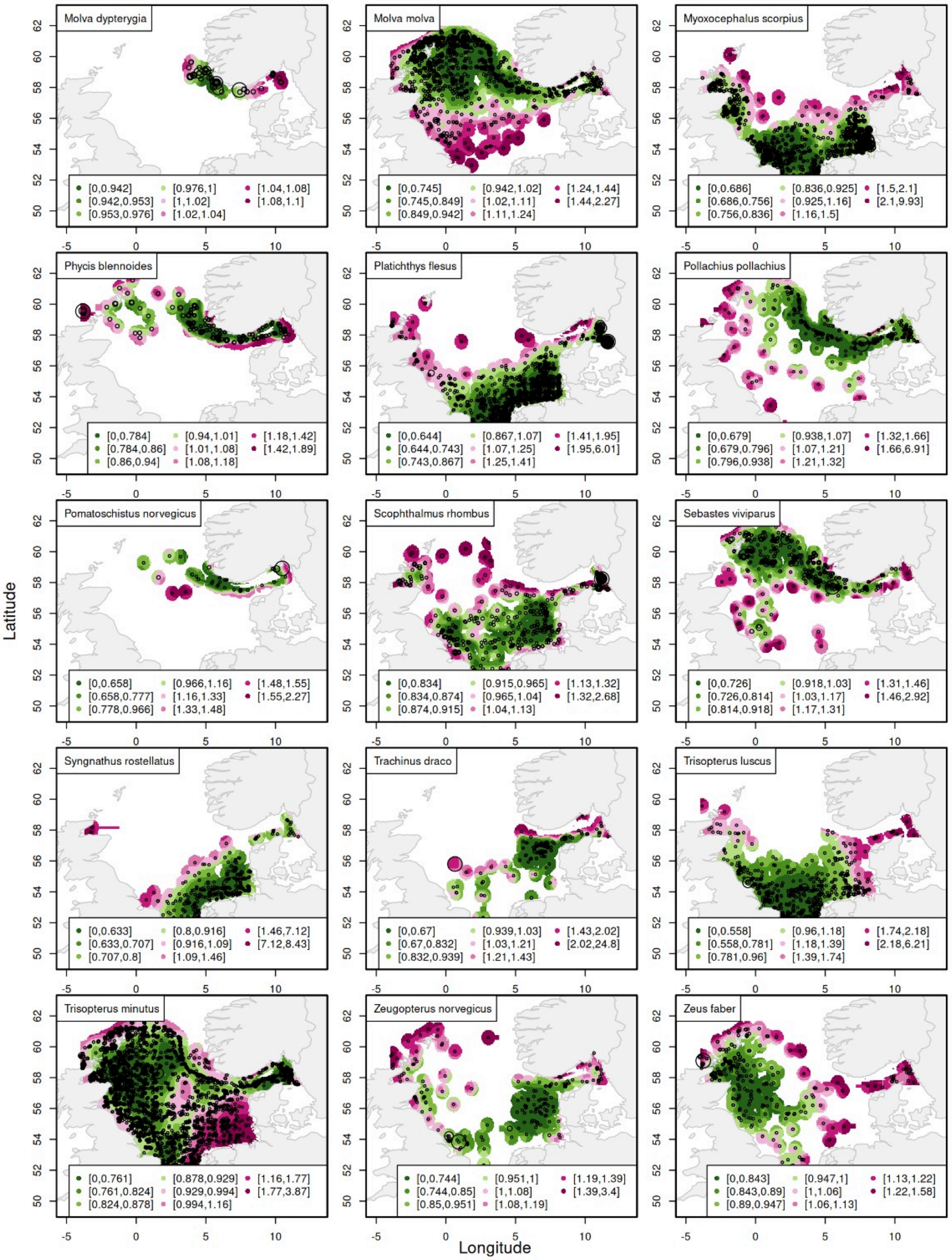


Figure S10: Average coefficient of variation (CV) over period 2013-2022 for species 31-45 of 45 species with reliable relative abundance trend in the surveys (CV < 150%) (species with "x" in column "S" in Table S2).

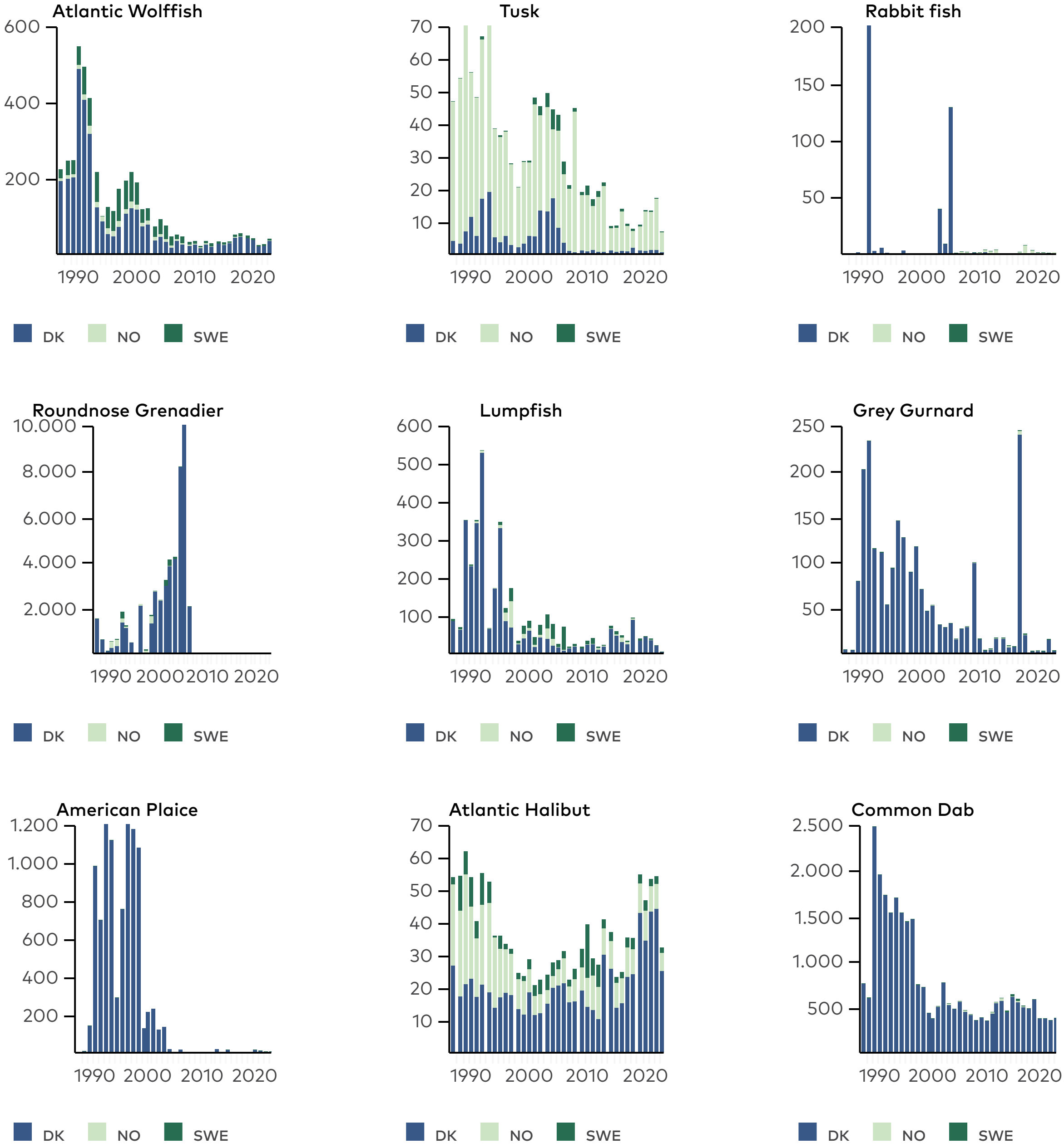


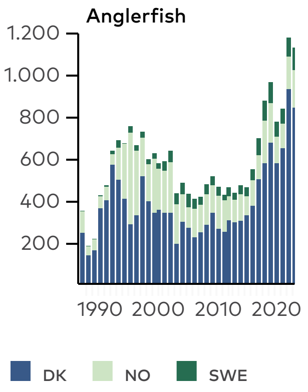
Supplementary Section 4: Landings

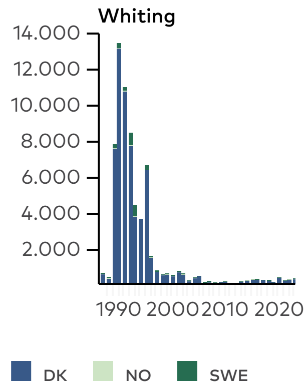
Table S4: Species that were observed in both survey catches and commercial landings. The list of species was developed with experts from all three countries (Sweden, Norway, and Denmark).

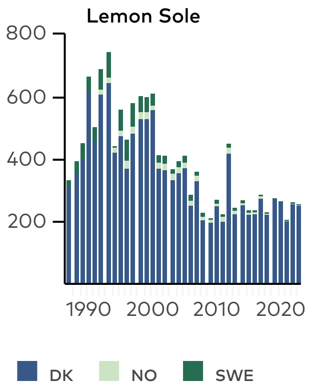
Species	Latin	Family	Order	Danish	Swedish	Norwegian
Whiting	*Merlangius merlangus*	Gadidae	Gadiformes	Hvilling	Vitling	Hvitting
American Plaice	*Hippoglossoides platessoides*	Pleuronectidae	Pleuronectiformes	Håising	Lerskädda	Gapeflyndre
Common Dab	*Limanda limanda*	Pleuronectidae	Pleuronectiformes	Ising	Sandskädda	Sandflyndre
Grey Gurnard	*Eutrigla gurnardus*	Triglidae	Perciformes	Knurhane	Knorrhane, knot	Knurr
Rabbit fish	*Chimaera monstrosa*	Chimaeridae	Chimaeriformes	Havmus	Havsmus	Havmus
Lemon Sole	*Microstomus kitt*	Pleuronectidae	Pleuronectiformes	Rødtunge	Bergskädda, Bergtunga	Lomre
European Flounder	*Platichthys flesus*	Pleuronectidae	Pleuronectiformes	Skrubbe	Skrubbskädda, Flundra	Skrubbe
Roundnose Grenadier	*Coryphaenoides rupestris*	Macrouridae	Gadiformes	Skolæst	Skoläst	Skolest
Lumpsucker	*Cyclopterus lumpus*	Cyclopteridae	Perciformes	Stenbider, kulso	Sjurygg, kvabbso, stenbit	Rognkjeks
Pollack	*Pollachius pollachius*	Gadidae	Gadiformes	Lyssej/lubbe	Bleka, lyrtorsk	Lyr
Brill	*Scophthalmus rhombus*	Scophthalmidae	Pleuronectiformes	Slethvarre	Slätvar	Slettvar
Anglerfish	*Lophius piscatorius*	Lophiidae	Lophiiformes	Havtaske	Marulk	Breiflabb
Ling	*Molva molva*	Lotidae	Gadiformes	Lange	Långa	Lange
Atlantic Wolffish	*Anarhichas lupus*	Anarhichadidae	Perciformes	Havkat	Havskatt	Gråsteinbit
Atlantic Halibut	*Hippoglossus hippoglossus*	Pleuronectidae	Pleuronectiformes	Helleflynder	Hälleflundra	Kveite
Greater Forkbeard	*Phycis blennoides*	Phycidae	Gadiformes	Skælbrosme	Fjällbrosme	Skjellbrosme
John Dory	*Zeus faber*	Zeidae	Zeiformes	Sankt Petersfisk	Sanktpersfisk	Sanktpetersfisk
Tusk	*Brosme brosme*	Lotidae	Gadiformes	Brosme	Lubb	Brosme
Blue Ling	*Molva dypterygia*	Lotidae	Gadiformes	Byrkelange	Birkelånga	Blålange

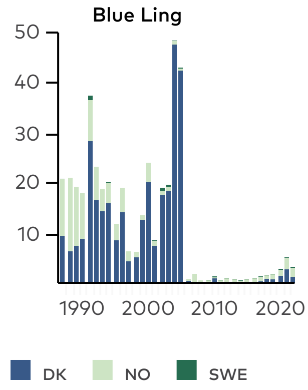
Figure S11: Landings (in tonnes) by species and country for 1987 to 2023 in Skagerrak. Note that due to the scale of the y-axes some of the lower landing's years appear to be zero, however, they are only small in comparison to historical landings as Figure SX shows.

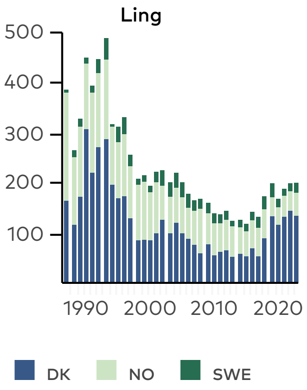


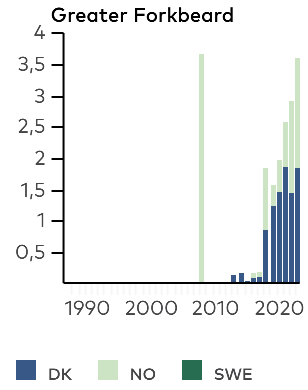

Anglerfish

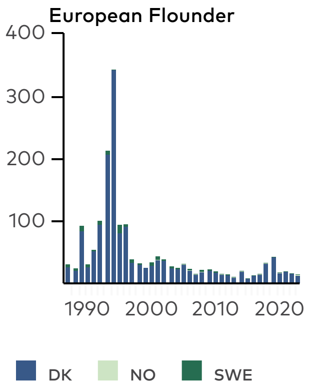

Whiting

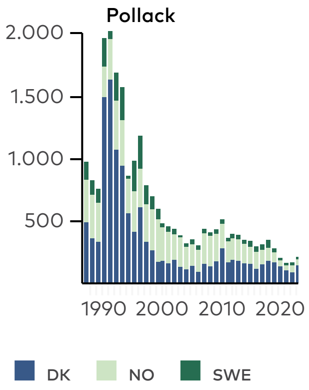

Lemon Sole

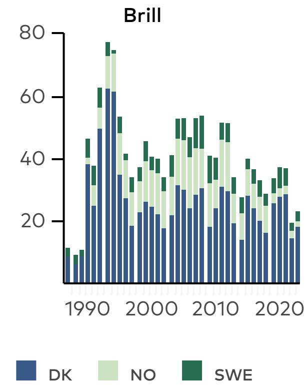

Blue Ling


Ling


Greater Forkbeard


European Flounder


Pollack


Brill

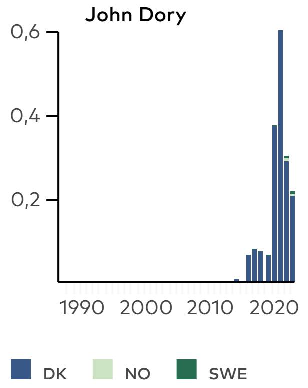
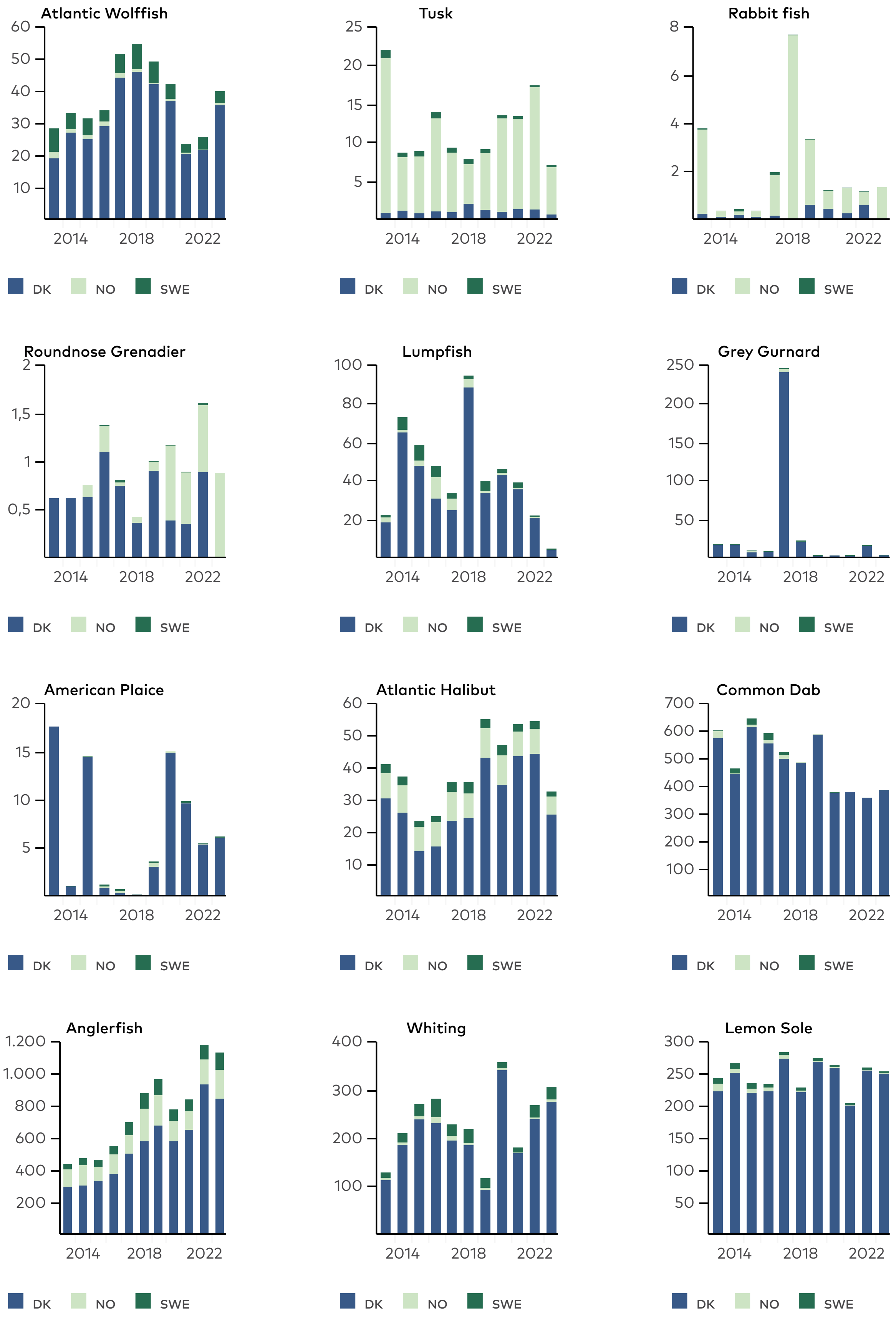
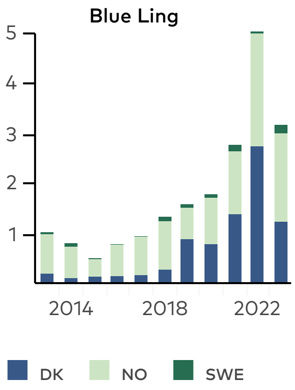
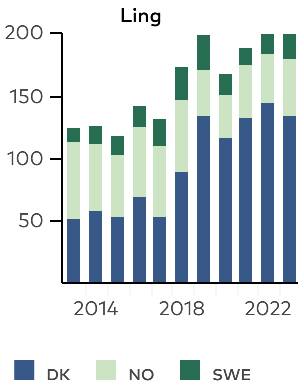
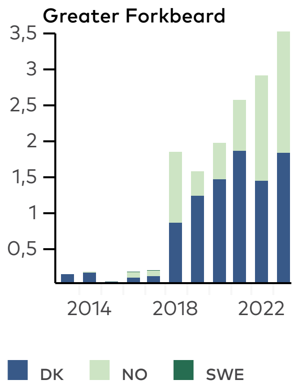

John Dory

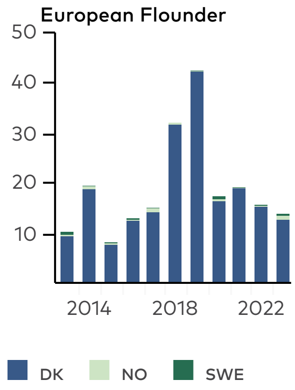
Figure S12: Landings (in tonnes) by species and country for 2013 to 2023 in Skagerrak.

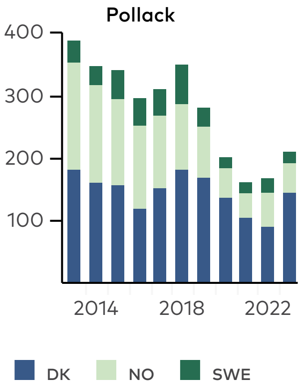



Blue Ling
5
4
3
2
1
2014
2018
2022
DK
NO
SWE


Ling
200
150
100
50
2014
2018
2022
DK
NO
SWE


Greater Forkbeard
3,5
3
2,5
2
1,5
1
0,5
2014
2018
2022
DK
NO
SWE


European Flounder
50
40
30
20
10
2014
2018
2022
DK
NO
SWE


Pollack
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300
200
100
2014
2018
2022
DK
NO
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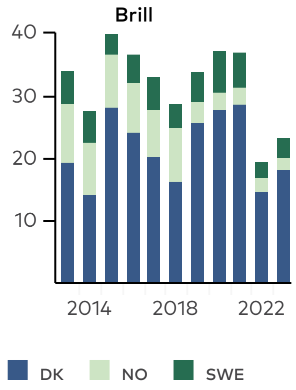
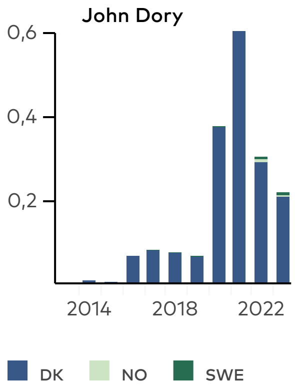

Brill
40
30
20
10
2014
2018
2022
DK
NO
SWE

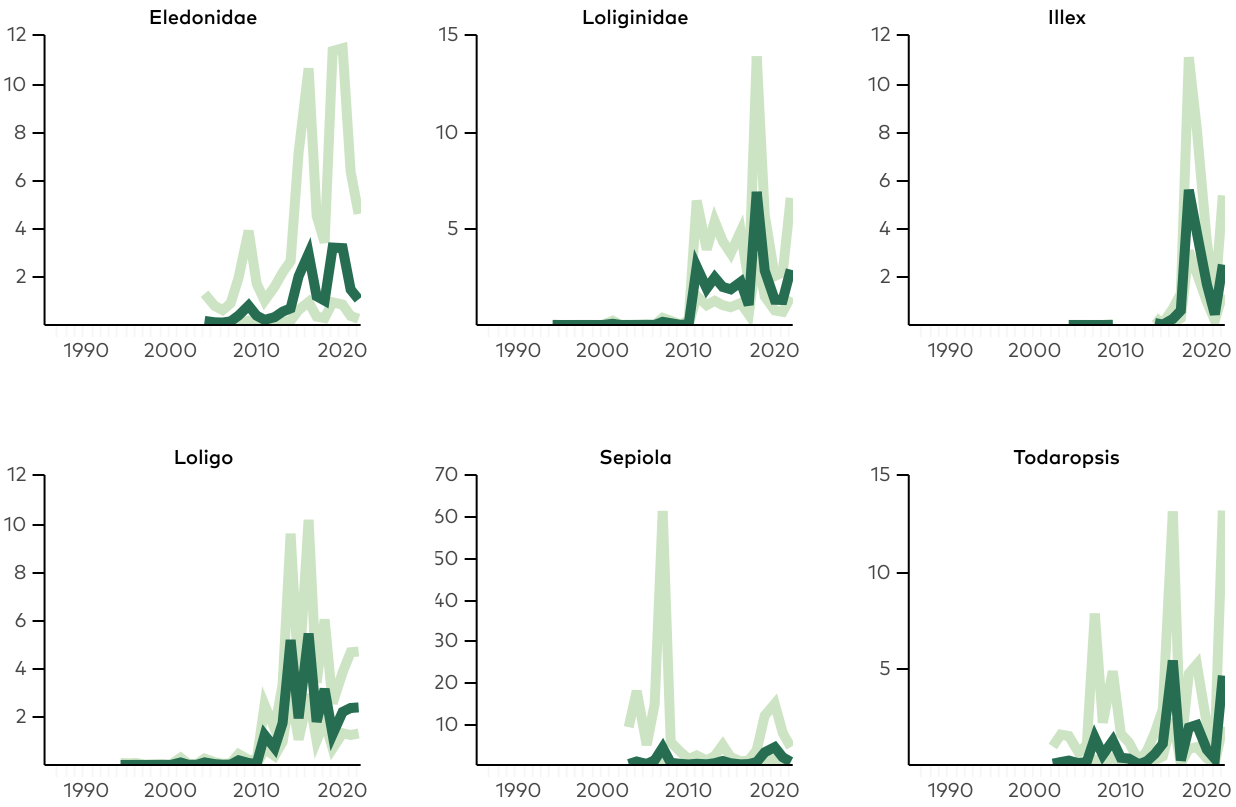

John Dory
0,6
0,4
0,2
2014
2018
2022
DK
NO
SWE

Supplementary Section 5: Cephalopods

Table S5: Twenty-nine Cephalopods observed in the two surveys.

Aphia_ID	Lowest taxonomic level	Family	Order	Hauls_NOSS	Hauls_NS-IBTS	Hauls_Total
138138	Alloteuthis	Loliginidae	Myopsida	12	48	60
153131	Alloteuthis subulata	Loliginidae	Myopsida	19	3188	3207
138265	Bathypolypus	Bathypolypodidae	Octopoda	19	20	39
140596	Bathypolypus arcticus	Bathypolypodidae	Octopoda	3	0	3
11707	Cephalopoda			222	0	222
11709	Coleoidea			29	0	29
140600	Eledone cirrhosa	Eledonidae	Octopoda	0	8	8
138036	Gonatus	Gonatidae	Oegopsida	4	0	4
138278	Illex	Ommastrephidae	Oegopsida	0	212	212
140621	Illex coindetii	Ommastrephidae	Oegopsida	73	136	209
11734	Loliginidae	Loliginidae	Myopsida	0	4	4
138139	Loligo	Loliginidae	Myopsida	49	12	61
140270	Loligo forbesii	Loliginidae	Myopsida	12	1748	1760
140271	Loligo vulgaris	Loliginidae	Myopsida	7	12	19
11718	Octopoda		Octopoda	8	0	8
140605	Octopus vulgaris	Octopodidae	Octopoda	2	0	2
11760	Ommastrephidae	Ommastrephidae	Oegopsida	4	0	4
141448	Rondeletiola minor	Sepiolidae	Sepiida	1	0	1
138481	Rossia	Sepiolidae	Sepiida	0	4	4
141449	Rossia macrosoma	Sepiolidae	Sepiida	1	0	1
153083	Rossia palpebrosa	Sepiolidae	Sepiida	2	0	2
138482	Sepietta	Sepiolidae	Sepiida	14	4	18
141450	Sepietta neglecta	Sepiolidae	Sepiida	1	0	1
141452	Sepietta oweniana	Sepiolidae	Sepiida	4	156	160
11723	Sepiidae	Sepiidae	Sepiida	0	8	8
138483	Sepiola	Sepiolidae	Sepiida	8	0	8
141454	Sepiola atlantica	Sepiolidae	Sepiida	0	60	60
140624	Todarodes sagittatus	Ommastrephidae	Oegopsida	3	0	3
140625	Todaropsis eblanae	Ommastrephidae	Oegopsida	18	136	154

Figure S13: Abundance by lower taxonomic levels (first row = Family; second and third row = Genus) for NS-IBTS survey.



About this publication

Improving nature management and marine protection in Skagerrak – Knowledge synthesis for conservation planning, ecosystem-based fisheries management and expanding offshore wind farms.

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