Environmental mapping and screening of the offshore wind potential in Denmark

Sensitivity mapping: Fish

Danish Energy Agency - Energistyrelsen

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Table of contents

1. Preface

Background for the report and relation to other activities

This report contributes to the project "*Environmental mapping and screening of the offshore wind potential in Denmark*" initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the programme "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by NIRAS, Aarhus University (Department of Ecoscience) and DTU Wind.

The overall project consists of four tasks defined by the Danish Energy Agency (https://ens.dk/ansvarsomraader/vindmoeller-paa-hav/planlaegning-af-fremtidens-havvindmoelleparker):

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.
2. Technical screening and assessment of the overall offshore wind potential in Denmark.
3. Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighbouring countries.
4. Assessment of barriers and potentials in relation to coexistence.

This report addresses one component of Task 1: sensitivity mapping. Specifically, it provides an overview of areas within Danish offshore regions that are likely to be particularly vulnerable to offshore wind farm development regarding fish based on available data. Other subjects within Task 1 - such as birds, marine mammals, bats, benthic habitats, wind and hydrodynamics and ecosystem modelling - will be presented in separate reports in late 2024 and early 2025. A synthesis of all topics under Task 1 will be published in 2025.

The project has relied predominantly on historical data, with minimal new data collection. As a result, the sensitivity mapping is dependent on the availability and accessibility of pre-existing data across specific subject areas. From the outset, significant effort was made to incorporate all relevant data to comprehensively address the task requirements. However, certain existing datasets could not be accessed. Section 3.1 specifies the data sources used in the sensitivity mapping for seabirds and outlines additional existing data. It is important to recognise that sensitivity mapping serves as a dynamic tool, which can be updated as new data becomes available.

2. Aim

This sensitivity screening presents an overview of a selection of marine fishes within Danish waters that have a high ecological importance and are considered to be some of the most sensitive species in relation to the specific pressures experienced during the construction and operation of Offshore Wind Farms (OWF). More than 200 fish species live or frequent the Danish marine territory, but only a group of these are relevant for this analysis due to their specific behavioural, physiological, or ecological traits and requirements that make them sensitive to pressures produced by OWF's. This sensitivity analysis aims to assess species-specific sensitivity to various pressures related to OWF's.

The overall goal is to identify marine areas, within the Danish EEZ (Exclusive Economic Zone), that represent areas of high importance based on relative abundance and spawning and/or nursery habitats during different life-stages for the relevant fish species. The species-specific sensitivity to primary OWF pressures (underwater noise, suspended sediment and sedimentation, habitat loss etc.) is evaluated through a literature review, including important fish life stages: Eggs/larvae and juveniles, and foraging and spawning adults. Hereafter, mapping areas of life-stage specific importance (general distribution, adult distribution, spawning distribution, and nursery areas), are undertaken by compiling several data sources and identifying sensitive areas based on a range of relative abundance or density levels grouped according to the lowest (Low), medium (Medium) and highest (High) relative abundance for each investigated species. Finally, a consolidated (combined) sensitivity map was made for each of the pressures introduced by the construction and operation of OWF's, which included only the fish species and life stages considered most sensitive to the specific pressures.

In summary, this sensitivity screening aims to produce a total sensitivity assessment for fishes, including maps showing the distribution of the fish species of concern regarding OWF operation and construction, and their relevant life stages, within the Danish marine territory.

3. Methods

3.1 Data availability

For mapping areas of importance/sensitivity for a series of fish species based on their relative abundance, regarding general and life-history specific (spawning and juvenile) distribution, different data sources with distinct capabilities were used. Background information and capabilities of these sources are supplied below.

3.1.1 General distribution

To investigate general spatial distribution throughout the Danish Sea territory, two separate datasets where applied, which produces two distinct visualizations of fish distribution: catch data from the Danish fisheries, provided by the Danish Fisheries Agency, and data from the ICES (International Council for the Exploration of the Sea) DATRAS surveys. The two data sources were applied to fully take advantage of their different capabilities regarding visual representation of distribution. The standardized ICES surveys provide key insight into the overall adult distribution throughout the North and Baltic Sea and are useful in mapping the ecological key areas for the metapopulation, across national borders (further description is found in section 3.1.2). In contrast, the Danish fisheries catch data is primarily positioned within the Danish Sea territory, providing insight into local distribution of fish based on catch weight. These distinctions support each other, by illustrating whether high density areas in Danish waters are just local high-density areas, or areas of importance for the larger metapopulation.

With the assumption that commercial fishing primarily takes place in areas that support a large lucrative catch of their target species, fishing position and catch can be used as a proxy for fish abundance. Within Danish waters, all fishing vessels longer than 12 meters are required to have a VMS-system (Vessel Monitoring System) installed, which continuously registers the vessels position at a fixed interval (often 60 minutes). These continuously registered GPS-positions allow for estimation of traveled haversine distance between coordinates, and thus travel speed due to the fixed time registration.

In addition to the VMS-system, fishing vessels must fill out a logbook, registering species-specific catch (kg), fishing gear used, and time and place of initial fishing position. As the different gear types have specific speed requirements when actively fishing (see Table 3.1 and Figure 3.1), vessel speeds can be used to separate vessel activities into cruising to and from fishing areas and actively fishing.

Table 3.1. Estimated speed ranges of different gear types when actively fishing. Speed estimates derived from speed frequency graphs from VMS data. Data from Danish Fisheries

Gear type	Speed during active fishing (knots)
Bottom trawl	1 - 4
Beam trawl	1 - 4
Pelagic trawl	2 - 5
Gillnets	0,2 - 3
Seine nets	0,2 - 4
Other gear	0,2 – 3

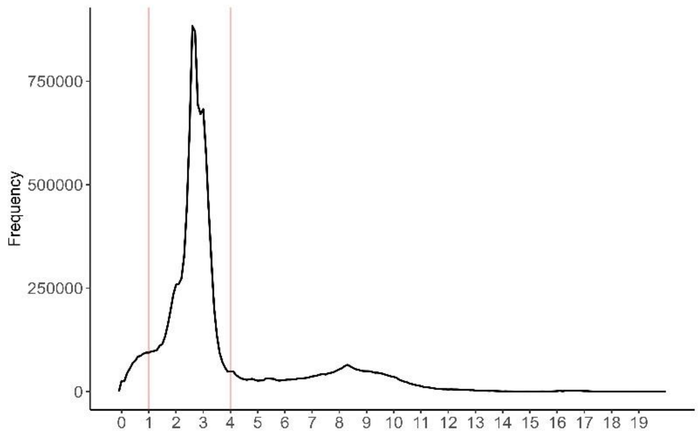


Figure 3.1. Visualization of gear speed when fishing vessels area actively fishing. The vertical red lines indicate the selected span of vessel speeds that indicate active fishing with bottom trawls. Data from Danish Fisheries Agency.

Thus, by combining VMS data with logbook data, it is possible to indicate the areas where fishing vessels were actively fishing. Furthermore, as the logbook includes species-specific catch, it is possible to produce species-specific distribution maps and grade the importance of these areas. To reduce the inclusion of negligible or minor by-catch, the species-specific analysis only included data when the species were in the top three of the catch for a specific fishing event. However, because most sharks and rays registered in the fisheries data are as by-catch, the fisheries datasets that showed the presence of elasmobranchs were not filtered to only include the top three catches, as in the other fishes.

Gear-specific fishing speeds were determined by observing the frequency of travelling speeds throughout the entire dataset (2017-2023), and identifying the most occupied speed range that represented known gear capabilities for gear actively fishing (Figure 3.1).

Although this report utilizes fisheries data, it is not designed to evaluate OWF impacts on the Danish fisheries distribution or economy, but only fish communities in a fish ecology perspective. The screening of OWF impacts on the Danish fisheries industry will be presented in a separate report.

3.1.2 Life-history specific distribution

Investigating life-history specific distribution requires biologically relevant information on individual traits, such as size, age, and maturity class, not supplied by the fisheries data. Instead, biologically relevant data was supplied by the DATRAS database (*Database of Trawl Surveys*). DATRAS is an online database organized by an international collaboration of research institutions and ICES (*International Council for the Exploration of the Sea*), containing a series of standardized fish surveys that investigates varying species and habitats. The standardized nature and high-resolution sampling and investigation of individual biological traits (species, maturity, age, and length), makes this database applicable for investigating life-history specific spatial distribution.

For this report a total of three surveys were used. Two surveys covering the entire Danish marine territory: The related and broad-spectrum bottom trawl surveys NS-IBTS (North Sea – International Bottom Trawl Survey (ICES, 2020)) and BITS (Baltic International Trawl Survey (ICES, 2017)). Survey data from 2000 through 2023 was included in the analysis, and the total sampled positions can be seen in Figure 3.2. Furthermore, data from the North Sea Sandeel Survey (NSSS)(between 2008 through 2013, was used to investigate the distribution of sandeel in the North Sea.

NS-IBTS (*North Sea – International Bottom Trawl Survey*)

The NS-IBTS is an international collaboration between research institutions from Germany, France, England, Scotland, Netherlands, Norway, Sweden, and Denmark to survey the North Sea fish populations, primarily targeting demersal (the part of the water column near the seabed) fish species.

The methodology of the NS-IBTS is centered around bottom trawling, a technique that involves towing a trawl net along the sea floor to collect marine organisms. To ensure the reliability and comparability of the data, the survey follows standardized protocols. This standardization includes using consistent types of gear (GOV – Grand Overture Vertical) and mesh size (max 200mm mesh, 20mm codend), maintaining specific trawling durations and speeds, within specific areas and depth ranges (< 250 meters) (ICES, 2019).

The survey is conducted seasonally, typically in the first and third quarters of the year, to capture the seasonal variations in fish populations. During each survey, trawls are performed within fixed statistical rectangles across the North Sea, Skagerrak, and Kattegat, encompassing a diverse range of habitats and depths. At each station, the trawl is deployed and towed along the seabed for a standard duration, usually 30 minutes, at a consistent speed of about 4 knots. This method ensures that the samples collected are representative and comparable among locations.

After each trawl, the catch is sorted by species, and detailed biological data are collected. This includes measuring the length, weight, age, sex, and maturity stage of individual fish to understand population structure and dynamics. Non-fish species, such as invertebrates, are also recorded to provide a comprehensive overview of the benthic community. Additionally, environmental parameters like water temperature, salinity, and depth are measured at each station to help analyze the relationship between environmental conditions and species distribution.

By following these standardized methodologies, the NS-IBTS ensures the collection of high-quality, comparable data across time and space, which is essential for effective monitoring and assessment of the North Sea's marine fish populations.

BITS (*Baltic international trawl survey*)
The BITS is an international collaboration between the countries sharing the Baltic Sea: Denmark, Estonia, Finland, Germany, Latvia, Poland, Russia, Lithuania, and Sweden. Like the NS-IBTS, the BITS survey demersal fishes through standardized bottom trawling, in the Kattegat and the Baltic Sea.

Like the NS-IBTS, the BITS uses bottom trawling as its method of data collection. Trawling is conducted using standardized gear, with consistent trawl durations and speeds to ensure that the data are comparable across different survey periods and regions. The BITS sampling protocol states that the used trawl gear depends on vessel size, where either a smaller TV3 #520 (520 mesh circumference opening) used exclusively in the inner Danish waters until west of Bornholm or a larger TV3 #930 (930 mesh circumference opening) primarily used in the Baltic waters east of Bornholm (ICES, 2017). Both trawls use a towing speed of approximately 3 knots (ICES, 2017). The BITS also conducts its surveys seasonally, typically in the first and fourth quarters of the year, to account for seasonal variations in fish populations. During each survey, trawling is performed within predetermined grid cells (statistical rectangles) across the Baltic Sea and Kattegat, encompassing a variety of habitats and depths to capture a representative sample of the marine community.

NSSS (*North Sea Sandeel Survey*)
The North Sea sandeel survey conducts yearly field sampling of sandeel in late November or early December, to explore sandeel abundance and recruitment in the North Sea (ICES, 2022). The NSSS has been ongoing since 2008 and follows a standardized protocol, to ensure comparability among years by survey participants. The survey utilizes a modified scallop dredge to sample and measure the abundance of sandeel in the seabed, which are sampled during the night. The survey targets the majority of the sandeel habitats in the North Sea, where sampling occurs at fixed stations within these habitats. At each station, three 10-minute straight hauls are conducted, angular to each other in a formation that, preferably, resembles a star. All caught sandeel are identified to species level and measured (total length). A subset of 10 fish per half-centimeter length class are weighed and age estimated through otolith increment analysis. The careful sampling and fish processing allows for detailed analysis of sandeel distribution within the appropriate habitats and tracking of the yearly development of sandeel abundance and recruitment in the North Sea.

Standardizing inter- and intra-survey parameters allows for spatiotemporal analysis of fish populations and comparison of abundances across the greater North Sea and Baltic Sea area. Furthermore, the dataset allows mapping distribution according to age, size, and maturity classes, to highlight any spatiotemporal differences with respect to life history structuring including nursery-, foraging- and spawning areas. Throughout this report, this specific dataset is referred to as the ICES data set and/or the maturity data.

3.2 Data summary

In the process of data acquisition several data sources were evaluated in terms of usefulness for the present analysis. These were assessed with regard to sample size, sampling method, geographic extent, data quality, peer reviewing and overall availability. Initially a total of five useful data sources were identified. However, these were later reduced to two, as three were excluded due to data availability, incompatibility, or redundancy.
The seven most recent full years (2017-2023) from the fisheries data were included in order to best exhibit the most recent distribution of sensitive fishes. However, due to the unique capabilities of interpreting results from the standardized ICES surveys, which also included maturity and age-specific data, it is possible to highlight and confirm both present and historically important areas of distribution, particularly spawning areas for different fish species, by including a large number of years of survey data. As fish population levels are not constant over time but vary due to both natural recruitment dynamics and varying environmental conditions, as well as potential effects from fisheries, fish distributions and area use over time. For instance, the re-use of historic spawning areas has been shown to occur when environmental conditions improve, and fish populations increase. Thus, to include the potential importance of areas that may be utilized by fish species during different stages of their populations or during differing environmental cues a total of 24 years of ICES survey data were included in the analysis. To take into consideration data on spawning individuals from the different seasonal surveys (Q1, Q3 and Q4), the abundances were summed (not averaged), and thus data is considered to represent where spawning individuals were observed, thus indicating the location of spawning grounds, regardless of the season. Furthermore, NS-IBTS survey data was used for the North Sea, Skagerrak and parts of Kattegat, while BITS survey data was used for parts of the Kattegat, inner Danish waters and around Bornholm.

An overview of the five initial data sources and their status for inclusion can be found in Table 3.2.

DATRAS data extraction

Two types of data were extracted from the DATRAS database with different parameters needed for mapping the relative abundance of different fish species, including spawning individuals, and juveniles. These are given in the following:

1. Two data types were extracted from the DATRAS database: HH and CA
   A. HH – represented data of the haul characteristics, such as date, time, coordinates, gear specifications, haul duration and distance, and environmental conditions.
   B. CA – represented data on biological information for individual fish such as length, weight, sex, sexual maturity stage and age.

After extraction, parameters from the HH and CA were merged, in order to get haul-specific information, for the fish registered in the CA data set.

The maturity stages from the CA data set are divided into several categories representing the following maturity stages:

61 / A / Ba: **Immature/juvenile** (data used in the juvenile relative abundance plots and mapping).

62 / B / Bb: **Maturing** (data used in the adults relative abundance plots and mapping)

63 / C / Ca / Cb : **Spawning** (data used in spawning plots and mapping of spawning areas)

64 / D / Da / Db: **Spent** (data used in the adults relative abundance plots and mapping)

65 /E: **Resting/skip spawning** (data used in the adults relative abundance plot and mapping)

66 / F: **Abnormal** (data used in the adults relative abundance plots and mapping).

Table 3.2. Data summary for fish sensitivity, along with status for each dataset. The three datasets that were not included (Fish Atlas, IMR and HELCOM) could have been useful, but were excluded due to various reasons, such as incompatibility of data structure and sources (Fish atlas) and raw data being unavailable (IMR and HELCOM).

Data summary					
Data description	**Project**	**Time period**	**Geographical area**	**Data source**	**Data status**
Fish life stage spatial distribution	NS-IBTS, BITS, NSSS	2000-2023 2008-2023	North Sea, Kattegat, and Baltic Sea	ICES DATRAS	Included
Danish fishery catch and spatial distribution	Danish fishery registrations	2017-2023	North Sea, Kattegat, and Baltic Sea	Danish Fisheries Agency	Included
Fish spatial distribution, from multiple source observations	Fish Atlas	Not applicable (various sources)	Danish Sea territory: North Sea, Kattegat, and Baltic Sea	Natural History Museum of Denmark, Copenhagen University	Not included
North Sea spawning site modelling	Various projects on species spatial spawning distributions	Not applicable (various sources)	North Sea	Institute of marine research, Norway (IMR)	Unavailable
Kattegat and Baltic Sea spawning site modelling	Various projects on species spatial spawning distributions	Not applicable (various sources)	Kattegat and Baltic Sea	HELCOM	Unavailable

3.3 Data Analysis

The sensitivity analysis is split into two investigations. First, an assessment of species-specific sensitivity to the various pressures imposed by the construction and operation of OWF, based on a literature review. This was followed by a species-specific spatial analysis of the general and life-history specific distribution within Danish waters. The maps produced by the spatial analysis illustrate areas of varying importance based on relative abundance and will be addressed as a proxy for the general area specific sensitivity.

3.3.1 Specific sensitivity grading

Fish are an extremely diverse group, and vary significantly in behavior, ecology, physiology, and specific requirements among co-existing species and, to some extent, populations. The trait diversity among fishes suggests that in a management perspective, species should receive individual sensitivity assessment for each of the related pressures, to limit negative impact with the establishment of OWF. Further, these pressures may have life-stage specific impacts, where the fragile egg and larvae stages could have specific sensitivities different from adult conspecifics. Pressures related to OWF are described in section 4.

Through review of literature, each species, and related life-stages (eggs and larvae, juveniles, adults, and spawning fishes) will be assigned a pressure-specific sensitivity score. In cases where literature availability is limited, information of closely related or functionally similar fish species will be used. Specific species sensitivity to relevant pressures are described in section 4.

3.3.2 Spatial analysis and sensitivity classification

Fish species vary regarding population size and structure, biotic/abiotic requirements, life history traits (spawning and migration) and overall general distribution. This is further diversified in Danish waters as the strong salinity difference between the North Sea and Baltic Sea significantly affect community structure. The differences in ecology combined with inter-species variation in data-availability makes applying a single distribution index less valid and complicated. To map distribution an overall process was applied to all species but tailored to fit the individual data-availability.

Due to the significant salinity gradient between the North and Baltic Sea, fish species presence varies throughout the Danish waters. Salinity is a key factor affecting fitness in marine animals and often forces adaptation and population structuring across the gradient. This is observed with the presence of North Sea, Kattegat, and Baltic cod, which are genetically distinct populations, thriving under different salinity conditions (WGBFAS, 2023). Often populations occupy specific areas during spawning with limited interpopulation mixing, while spatial distribution may have considerable overlap among populations outside the spawning season (Hüssy, Albertsen, Krüger-Johnsen, & Hansen, 2024; Hansen, et al., 2020). As populations may differ significantly in respect to abundance and spawning stock biomass, population/Basin-specific spatial analysis, to limit dilution of key areas of smaller populations, was applied. The Danish marine territory was separated into three distinct basins: The North Sea and Skagerrak, Kattegat, and West Baltic + Bornholm. Spatial analysis of fish areal density was completed for each species, separated in the three delimited basins (Figure 3.1).

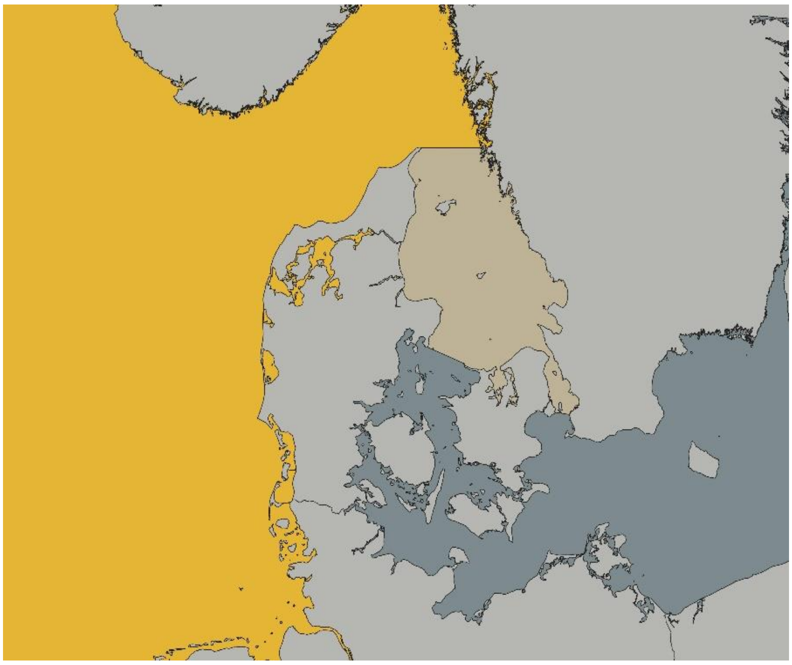


Figure 3.1. A map of the studied sea area around Denmark, with each specific region separated by color: North Sea and Skagerrak (orange), Kattegat (beige) and West Baltic including Bornholm (dark grey).

Raster-format maps were produced illustrating areas of ranked importance (no data, low, medium, and high) for the general distribution and potential spawning /nursery areas. These were based on the abundance data acquired from the Danish fisheries (general distribution) and adult/spawning/juvenile-abundance data from the ICES DATRAS database.

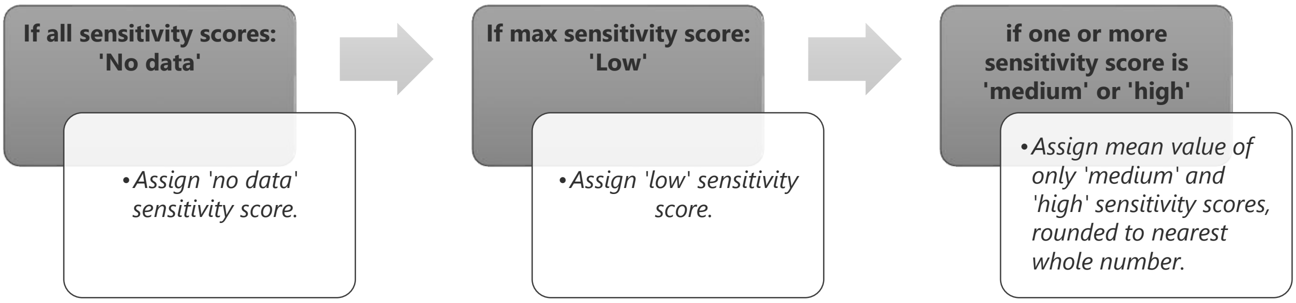
Sensitivity grading was based on data aggregation and density estimation within the preconstructed reference grid covering the Danish Sea territory. This was done through Kernel Density Estimation (KDE), which is a statistics tool used to generate heatmaps, based on data distribution. By assigning each datapoint a kernel value, the algorithm summarizes the total kernel value present within a set radius from each datapoint. Within a 1*1 km grid, the algorithm assigns each cell a density estimates for the contained data, based on the amount of datapoints within the specific radius. A smoothing function, with a set bandwidth is then applied to the density estimates, which produces fine-scale resolution of continuous density values.

The radius applied to the KDE was set to 25 km for the ICES (adult, spawning and juvenile distribution) data and 1 km for the fisheries data. Because of the more limited spatial coverage of the ICES data points, the use of 25 km KDE was used to expand the information from the ICES data into the near region under the assumption that this was the best fit for the data capabilities and that results also realistically represent the relative abundances of the near regional population. Furthermore, the data points of the fisheries data are not based on individual fish, like the ICES data, but fishing positions tied to a catch weight. Therefore, data-points assigned kernel values were applied a weight-factor by their catch-weight, so the larger catches were of higher importance. Thus, prior to summarizing kernel values, each datapoint's kernel values were adjusted by its catch weight, effectively estimating the total catch within the set radius.

Next, each grid cell was compared against one another and sorted into statistically distinct size groups, representing the lowest (Low), medium (Medium) and highest (High) relative abundances with respect to fisheries and ICES data separately. The comparison aimed to assess the similarities and differences between the values associated with each grid cell, which could represent various metrics such as species abundance or ecological significance. The next step involved sorting the grid cells into low, medium, and high relative abundance groups based on these comparisons, ensuring that the groups were distinct from one another. This sorting process was conducted separately for fisheries data and ICES data, as each dataset may have exhibited different patterns.

To achieve this, Natural Jenks cluster analysis was employed. This is a statistical method designed to classify data points by identifying natural breaks within the dataset. It groups raster cells into classes by minimizing the variance within each class and maximizing the variance between different classes. In other words, it identifies points in the data where values significantly shift, creating distinct clusters that are meaningful. The aim of the Natural Jenks cluster analysis method is to ensure that the grid cells within each group are as similar as possible, while the differences between groups are maximized. By applying Natural Jenks cluster analysis, the grid cells were mathematically separated into four distinct clusters: 'No data', 'low density', 'medium density', and 'high density', representing areas with no data and the lowest, medium, and highest relative abundances. The 'No data' cluster represented grid cells with missing data, while the other three clusters reflected varying levels of density based on the underlying KDE estimations. Cells in the 'low density' group had the lowest values, while those in the 'medium density' and 'high density' groups represented these groupings with increasingly higher fish abundance. The analyzed datasets allowed for a series of distinct maps, visualizing the spatial distribution of important life stages, including general-, adult-, spawning- and juvenile distribution.

These species-specific life-history maps were used to produce a set of consolidated pressure-specific sensitivity maps, showing the average distribution and relative abundance of species and life stages sensitive to the presented pressure imposed by the construction and operation of OWF: Habitat change/loss and increased EMF, suspended material, sedimentation and noise during the construction, operational and decommissioning phases. These maps combined only the species-specific life stage maps that were specifically sensitive to the investigated pressure. For instance, only elasmobranchs are considered sensitive to an increase in EMF intensity, and thus only the fisheries and ICES data for this group are aggregated in the EMF-specific sensitivity map.



Flowchart 3.1. Process visualization of weighted-means calculation of consolidated sensitivity scores. The process is done by an if-else principle, meaning that the illustrated process is sequential. An if-else algorithm checks if an argument is valid and assigns a value if true. If the argument is not valid the algorithm moves on to the next argument. The algorithm first checks if any data is present in the investigated grid cell, and assigns 'No data', in cases of no data. If data is present, it checks if the highest score is 'low' and assigns that sensitivity score if the argument is true. Finally, if 'medium' or 'high' sensitivity scores are present, the mean value, rounded to the nearest integer is used to assign a 'medium' and/or 'high' sensitivity score.

The consolidated pressure-specific maps were produced by calculating the average sensitivity score for each cell in the reference grid, based on species and life stage specific abundance that were assessed to be sensitive to the specific pressure. However, as sensitivity scores of each of the included maps were combined into a single value, the representation of sensitive species was ensured by calculating weighted averages. In a specific case where only a single species had a sensitivity score above 'low' within a specific cell, the arithmetic mean would downscale this species' sensitivity to 'low,' thus underestimating the area's importance. The weighted mean sensitivity score was calculated through an algorithm, which analyzed the combined grid cell values in a sequential set of tasks. An illustration of the constructed algorithm is presented in flowchart 3.1. The algorithm performs a series of checks on the combined sensitivities of each cell, to assign the new, combined, sensitivity score. First the grid cell is checked for data presence, and assigns 'No data' if no sensitivity scoring is found. If the highest sensitivity registered is 'low', the combined sensitivity score is assigned 'low'. Finally, if one or more sensitivity scores of 'medium' or 'high' are found, the algorithm extracts all instances of these higher sensitivity scores and calculates the mean value, rounded to the nearest integer, leaving out all 'no data' and 'low' sensitivity scores from the calculation. As this report screens for fish sensitivity across several species, it is crucial to ensure that all individual sensitivity scores are represented conservatively. Therefore, the reasoning behind the last step of the algorithm is to force the sensitivity scoring to portray enlarged sensitivities, even if this only represents a single species. The consolidated pressure-specific sensitivity maps were further combined with a max-aggregation approach, where each specific grid cell was assigned the maximum value observed in the corresponding cell across all six pressure specific maps. This produced a single conservative, consolidated map, portraying area-specific worst-case scenario sensitivity scores for fishes' sensitive to the pressures imposed by the construction and operation of OWF's.

3.4 Knowledge gaps and data limitations

Each data source has its strengths and weaknesses, depending on survey scope and sampling method, including time of year and sampled area. The nature of all fishing gears is their selectivity, and different gears are designed to capture a selected subset of the fish community. Therefore, fish surveys are often susceptible to biased sampling, as the gear is always better at catching some species compared to others.

While the fisheries dataset is useful for the present analysis, it is important to remember that 'sampling' are not standardized to any degree (gear type, tow time etc.). The fisheries dataset is bound by selectivity in relation to areas and species, as fishermen have an economic interest in large catches of specific species with limited bycatch. Additionally, gear used by fishing vessels have specific requirements and limitations, where for instance towed gear along the bottom (beam/bottom trawl, dredges, and seine nets) are primarily used on soft sediment (sand/gravel/mud) and kept away from reefs and hard structures. Furthermore, dependent on vessel size and gear type, depth also becomes a limiting factor and may exclude fishing from shallow regions. Finally, TAC (total allowable catch), quotas and area-specific fisheries restrictions (e.g. trawling ban in the Sound) may further affect how well the data represents the true population. This suggests the mapping of catches of a particular species, visualize where vessels can fish and where the largest catches are landed, rather than the specific species distribution. This is especially relevant in high-value species, where well-suited or key areas show non-representative fish abundances when compared to other areas and may potentially be assessed differently than the true pattern. One instance is the waters North of the island Læsø which is a historically important spawning area for Atlantic cod but have shown low productivity in later years (WGBFAS, 2023). Theoretically, this area should be ranked as an important spawning area, as it has previously been highly suitable for spawning. However, the recently low abundance of spawning cod may be disguising the historical pattern of importance that may be revitalized with an increase in cod spawning population size.

By using the largest catches as a proxy for key sensitive areas, species that are abundant as bycatch may be overrepresented in areas that do not align with their true areas of relatively high density. This is particularly the case for flounder (*Platichthys flesus*), which are common bycatch in the more targeted sandeel, nephrops and cod fisheries, resulting in their fisheries-based general distribution resembling that of these species. However, as this report includes several analyses of distribution, such correlations are visualized through differentiation between the general and adult distribution.

The inclusion of 'no data' in the analysis is consequently not a direct measure of absence of that species, rather than an absence of fisheries activity. Due to the comparatively high selectivity of fisheries due to targeting specific species, lack of standardization and potential inter-area differences in quotas, wide extrapolation through modelling was dismissed, as it is not possible to distinguish between absence of fishes and absence of favorable catches in this data set.

The ICES DATRAS bottom trawl surveys are effectively the inverse of the fisheries data, as they rely on qualitative sampling rather than quantity. By following a standardized towing protocol that regulates sampling in time and space, comparison across years, areas and surveys are straightforward. However, compared to the fisheries, only a limited number of vessels and effort are used in these surveys, meaning that much less data is available. This limits precision for spatial modelling, as the coarse data distribution cannot support as high a resolution as the fisheries data. This is further complicated by the choice of specific sampling periods, where only Q1 and Q3/4 are sampled, meaning that any spawning activity etc. in Q2 or Q4 (NS-IBTS) / Q3 (BITS) are not registered. This can be problematic in the case of spawning site estimations, as the lack of data on summer spawners would potentially exclude specific sites for such species. This is likely the case for the West Baltic herring, where high spawning activity is found between March and June around the island of Rügen and in Greifswald Bay, Germany (Jørgensen H. et.al., 2005). This pattern was not captured by the spatial analysis for spawning herring. The ICES spawning data should not be considered immediate spawning area estimation, but a rough proxy based on the distribution of spawning ready fishes. However, based on the spawning strategy of some fishes, these estimations are more precise than others. For instance, Atlantic cod are batch spawners, meaning that they release their eggs in smaller portions over multiple weeks or months. Thus, batch spawners stay a longer period of time at spawning sites compared to total spawners, thus increasing the chances of capturing their true spawning distribution when sampling. Therefore, dependent on life history traits there may be species-specific precision in estimation of spawning areas.

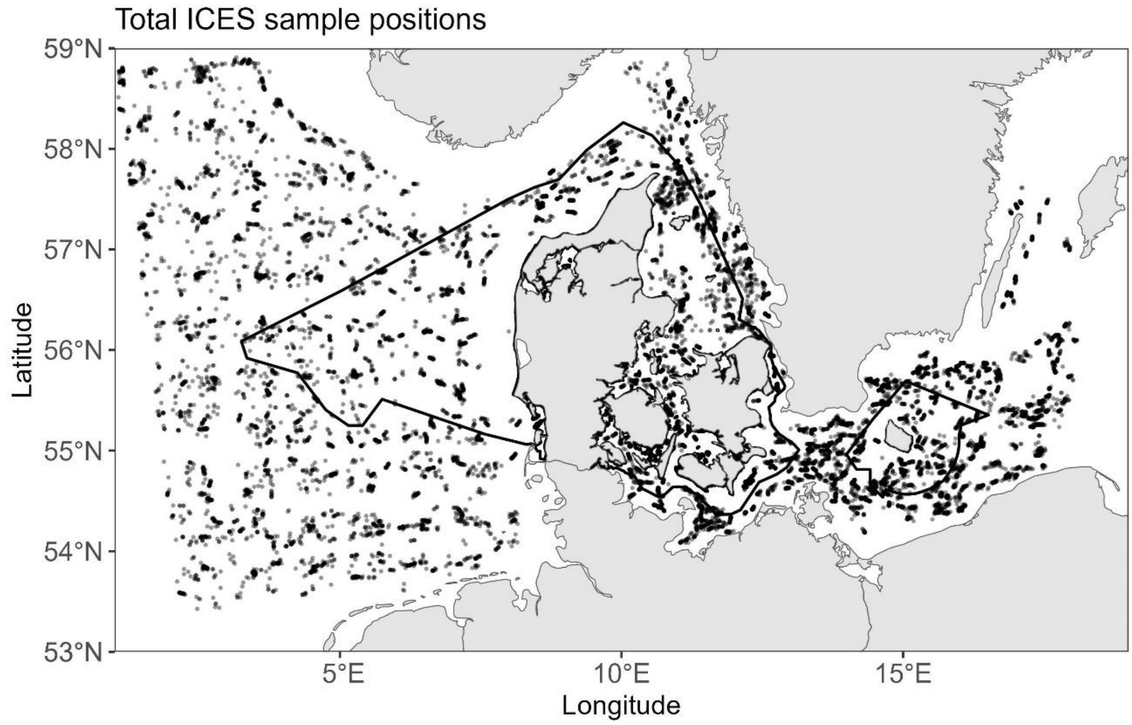


Figure 3.2. Positions sampled during the ICES surveys, data from 2000 through 2023.

While areas with no data from the fisheries source were considered to signify that the areas were not fished due to low fish abundance, the same cannot be assumed from the ICES data. As the NS-IBTS and BITS follow standardized survey protocols, sampling sites are not chosen due to fish abundance. Most of the Danish marine territory is covered by the surveys, however the Western and southwestern part of Kattegat (delimited by Jutland east coast, Læsø, Anholt and Northern coast of Zealand) are excluded from the survey (due to shallow depths and other restrictive factors). In theory, these areas could be of great importance for several fishes but cannot be evaluated based on present data sources. Similarly, due to the surveys using bottom trawls for sampling, there are some minimum depth restrictions that limit the sampling of coastal waters. Sampling positions for the NS-IBTS and BITS surveys from 2000 through 2023 can be seen in Figure 3.2. Coastal waters are often important habitats for juvenile fishes and can thus be underrepresented in the juvenile distribution maps, due to limited sampling. Instead, high density juvenile estimations in offshore areas in immediate proximity to the coast, may be used as a proxy for nearby important coastal nursery areas. However, this is only applicable for fishes where juvenile stages reside coastally (i.e. European Plaice and flounder), and not for species where juvenile fish generally reside at greater depths (i.e. Haddock). In conclusion, while relative abundance maps of the different fish species and groups outline areas that can be considered to be sensitive to OWF pressures based on the potential abundance of the specific fish species, it is important to note that there is a degree of uncertainty in the relative abundance (sensitivity maps) maps, particularly in the transitional borders between the high, medium and low relative abundances outlined in the maps. This is both due to assumptions based on the choice of using a KDE of 25 km^2 and the inherent uncertainties in the data and mapping.

4. Sensitivity of fishes to OWF pressures

The construction, operation, and decommissioning phases of offshore wind farms all exert different environmental pressures on fish and fish communities. The sensitivity of fish and/or fish groups to these pressures often depends on whether fish are pelagic or bottom dwelling, or whether they possess anatomical or behavioral traits or ecological demands that make them more or less sensitive to the specific pressures. Thus, sensitivity to pressures is often species-specific and furthermore can also be dependent on the vulnerability of the different life-stages (adult, juveniles and egg and larvae stages) and events. These include events such as spawning and the spawning areas that indirectly indicate where early-life stages (eggs, larvae, and juveniles) are most common. In the following section, a summary of the primary potential pressures from establishing winds farms are given along with their potential effects to fish and fish populations with reference to the sensitivity of specific fish species and their early life-stages (fish eggs and larvae) where information is available. The following is a list of the pressures from establishing offshore wind farms that will be dealt with:

- Increased underwater noise (construction and operational phase)
- Increased suspended material and sedimentation
- Electromagnetic fields (EMF)
- Habitat disturbance, habitat loss and change (artificial reefs)
- Hydrographic changes

4.1 Underwater noise

Underwater noise created from wind farm construction and operation are likely to be a main source of pressure to fish. While sound pressure level (dB re 1 μPa) is most often the quantified acoustic variable, sound can be described in many ways. Sound exposure level (SEL [dB re 1 $\mu Pa^2 \cdot s$]) is used to accumulate the acoustic energy of an exposure over time. Other parameters, such as acoustic particle motion (PM), are particularly important for fishes but such parameters are often overlooked because of the difficulty in quantifying them. The construction and operation of wind farms will create underwater noise that most fish species can hear and potentially be affected by, depending on their species-specific sensitivity to sound, and stage of their life cycle. Fish species do not hear equally well at all frequencies (Popper, A.N., Hawkins A.D., Sand O., and Sisneros J.A., 2019), thus, the sensitivity of different fish species to underwater noise will be dependent on whether the frequency range of the noise source corresponds with the frequency range that specific fish species can hear. The potential impact of noise on different fish species will also depend on the magnitude (dB) of the noise, and its temporal and spatial scope. For understanding purposes, the effects on fish during episodes from extreme noise to the perception of noise can be placed into category zones along a gradient of increasing distance from the noise source (see Figure 4.1).Figure Very loud, impulsive underwater noise from, for example pile driving of wind farm foundations during the construction phase, is capable of inflicting direct damage to tissue and auditory cell loss, and eventually mortality in fish near the source (zone of Injury). Underwater noise of less magnitude can lead to short-term hearing impairment (zone of Impairment) and/or physiological stress responses leading to behavioral changes such as fish moving away (fleeing) or avoiding areas with increased noise levels. Sounds of yet a lower magnitude can mask (zone of Masking) or disrupt important communication (zone of Audibility) signals that can influence behavior within or between species, and for predator avoidance, and prey detection. Further consequences of temporary hearing impairment and auditory disruption are that fish may be disrupted in foraging and/or breeding.

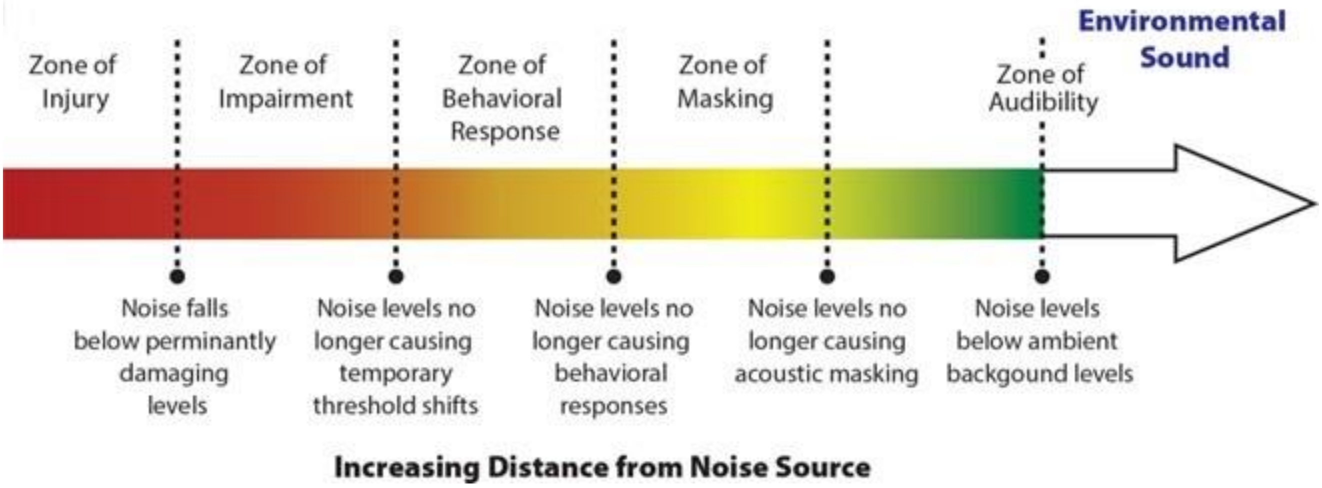


Figure 4.1. The potential effects of noise with distance from source. Generally, noise and impact on individual fish and fish communities may be greater closer to the source. Effects change with increasing distance from the source, as the acoustic signals change and levels decrease. Figure from Mooney et al. 2020 (Mooney, T.A., Andersson, M.H. and Stanley, J., 2020), modified from Dooling and Blumenrath (Dooling, R.J., and S.H. Blumenrath, 2013).

Underwater noise during wind farm construction and operations

The establishment of wind farm structures and activities involved during wind farm construction creates a variety of potential noise sources and levels. The creation of underwater noise by wind farms can in general, be split up into noise, often intense, produced during the construction phase, primarily when establishing turbine foundations by pile driving and during jetting and trenching when burying subsea cables (Tougaard, J. and Mikaelsen, M., 2018) (Tougaard, J., Hermannsen, L. and Madsen, P., 2020) and less intense underwater noise originating from mechanical movements and vibrations from turbine gear boxes, structures and rotor blades etc. created during the operational phase. The wind farm construction phase is usually one of the shortest phases during an OWF's lifetime (often 1-3 years). Despite this "short" timeframe, construction activities potentially produce the most acute noise exposures to the surrounding ecosystems and fish communities. One of the most significant activities creating increased underwater noise is the installation of foundations from pile driving monopile foundations (Tougaard, J. and Mikaelsen, M., 2018). Other sources of increased underwater noise during the construction period can come from pile driving, drilling, and/or digging other types of turbine foundations (tripod and jacket) and burying cables into the sediment by jetting or trenching activities. All these construction activities can create underwater noise that can potentially affect fish in all stages of their development.

Underwater noise created by turbines, gear boxes, wing rotation and generator during the operational phase of OWF's are of comparatively low intensity and will vary such that the level of noise changes with varying wind speeds (Betke, 2014). Because of their relatively low intensity levels, effects on fish from noise created by operational wind farms are not expected to cause any hearing loss (Betke, 2014). However, because underwater noise generated by operating wind farms are of low frequencies (<1 kHz) (Tougaard, J., Hermannsen, L. and Madsen, P., 2020), these sounds can be heard by the majority of fish as frequencies generally overlap with the auditory and frequency range of many known species (Andersson et al., 2017)(Mooney et al., 2020).

Furthermore, during both the construction and operation of wind farms, increased underwater noise of low intensity will be produced by construction and maintenance vessels. The underwater noise created during the construction phase of the wind farm is short-term, while the underwater noise created during wind farm operations is long-term, more constant and lasting the lifetime of the wind farm installations.

Which fish species are most sensitive to underwater noise
In general, the frequencies where most fish hear best coincide with the frequency ranges of the underwater noise (20-1KHz) that is both produced by activities during the construction phase such as pile driving, jetting and trenching during burial of subsea cables, as well as underwater noise produced from mechanical vibrations during the operational phase, as well as noise from both construction and maintenance vessels (Tougaard, J. and Mikaelsen, M., 2018) (Tougaard, J., Hermannsen, L. and Madsen, P., 2020) (Bellmann, 2018; Richardson, Malme, Green, & Thomson, 1995).

There is, however, a large diversity in how different fish species can hear underwater noise. Generally, fish species that do not have specialized hearing organs can hear in the low frequency range that spans from low infrasound (<20 Hz) to a few 100 Hz (Sand & Karlsen, 2000) (Popper, A.N., Hawkins A.D., Sand O., and Sisneros J.A., 2019). This is relevant for all fish species that do not have a swim bladder (a gas-filled chamber), which include many bottom-dwelling fish, such as flatfish species and gobies etc., cartilaginous fish such as sharks, skates and rays, and highly energetic fish such as mackerel and tuna, which are fast swimmers that rely on their swimming abilities and not swim bladders to maintain position in the water column. In contrast, the most sensitive species to underwater noise are fish with a swim bladder such as the clupeids (herring, sprat), and codfish (for example Atlantic cod and Haddock) (Popper & Hawkins 2014). Fish species such as herring and sprat can be considered hearing specialists, as they have a connection between their inner ear and the swim bladder, which greatly improves their hearing, and thus these species can hear in a wide range of frequencies from infrasound up to approx. 8 kHz, although with decreasing sensitivity the higher the frequency (Sand & Karlsen, 2000; Enger, 1967). For Atlantic cod and other codfish that have a swim bladder, they do not have the same connection to the inner ear as clupeids and can thus hear underwater noise up to approximately 500 Hz (Chapman & Hawkins, 1973).

Fish eggs and fish larvae
While all life stages of fish can be affected by increased underwater noise, it may often be the earliest life stages - fish eggs and larvae - that may be extra sensitive because these life stages are often more fragile than juvenile and adult fish and these stages have limited mobility, and cannot escape or move away from an area of intense noise as they primarily drift with water currents. There are very few studies on the effects of extreme noise on eggs and larvae, however there is a noise threshold given by Andersen *et al.* (Andersson et al., 2017) indicating a general increase in mortality of fish eggs and larvae of cod and herring when exposed to extreme underwater noise, at a similar level to pile driving of wind farm turbines. Although, Andersen *et al.* (Andersson et al., 2017) indicates the threshold for tolerance to intense underwater noise by eggs and larvae is high, the fact that fish eggs and larvae can be injured and experience high mortality close to a source of extreme noise such as pile driving, leads to including areas of their expected occurrence (spawning areas) in the sensitivity mapping.

Modelled underwater threshold levels for impacts to fish, eggs, and larvae
Because knowledge of how different fish species are affected by underwater noise is an area of limited knowledge, there are no established Danish guidelines for tolerance limits for fish. The Swedish Environmental Protection Agency has, however, used available data to produce threshold levels of intense underwater noise for mortality and tissue damage, as well as permanent hearing loss (PTS) leading to mortality for the clupeid herring, the codfish Atlantic cod, as well as for fish eggs and fish larvae (Andersson et al., 2017). There are, however, no threshold levels for temporary hearing loss (TTS) for these species, or noise levels that would cause fish to be move away from (displaced) or avoid an area with increased noise, however (Popper, 2014) has presented threshold levels for temporary hearing loss for fish with swim bladders and thus, these values were used to represent threshold levels for sensitive fish such as clupeids and codfish. Over the last decade, the threshold values from Andersson et. al. (2017) and Popper et. al. (2014) have been used in modelling the expected distance of an extreme source of noise (such as pile driving) where potential tissue damage and permanent injury to adult fish

and fish eggs and larvae will occur, and the distance range where temporary hearing loss, and potential behavioral responses such as fish fleeing from a noise source will occur. As a worst-case scenario the sensitive fish species herring and cod were used as a proxy for these distant thresholds.

In connection with wind farm operations, low frequency noise and vibrations, primarily originating from mechanical movement in turbine gear boxes, generators and rotating wings, will be transferred to the water near each wind farm turbine installation. In contrast to the intense underwater noise from establishing installations during the wind farm construction phase, underwater noise generated during wind farm operations is less intense, but more constant and will be transmitted during the lifetime of the wind farm. Even though underwater noise produced during wind farm operations can most probably be heard by the fish species near the turbines there is no evidence that fish experiencing this "noise" change their behavior and are displaced leading to less abundance near these installations. In general, the studies investigating changes in the abundance of fish and the number of fish species around a wind farm turbine in operation and nearby control areas, indicate that there is either an increase or no difference in the abundance of fish near wind farm turbines ((Stenberg et. al., 2011) (Stenberg, 2015) (Reubens J.T., Degraer S., and Vincx M., 2014) (Methratta E.T. and Dardick, 2019). Some species do, however, communicate with con-specifics and thus rely on communication to spawn, indicate territory and show aggression etc. For example, Atlantic cod is a vocal species that communicates using low frequency sounds during courtship (spawning) and when showing aggression and fleeing behavior to it conspecifics (Meager et al., 2017). Similar seasonal communication, including communication between males and females during the pawning period is also observed in the codfish haddock (*Melanogrammus aeglefinus*) (Casaretto, L., Picciulin, M., & Hawkins, A. D., 2015). Thus, even though the effects on fish, especially associated with the long-term exposure, may be overlooked due to the relatively low level of noise caused during OWF operations, there is the potential that constant low intensity underwater noise from wind from operations can induce physiological stress and possibly mask or disturb the detection of biologically important signals in fish that use sound for communication. This, for example, may be particularly important in the codfish Atlantic cod and haddock cod, particularly if sounds are produced near their spawning grounds.

Intense underwater noise created during the construction phase can potentially affect any fish species and their early life stages; eggs and larvae within the near vicinity (zone of injury) of the source. Similarly, there are many fish species that can be affected by intense underwater noise that can cause temporary hearing loss and/or behavioral response causing them to flee and be displaced from an area of intense noise. This pressure is probably greatest in fish with specialized hearing organs such as clupeids or swim bladders such as codfish etc., which are those most sensitive to pressures from underwater noise. Furthermore, species such as the codfish Atlantic cod and haddock that use sound for communication between conspecifics particularly during spawning, may experience their communication is masked or disturbed by underwater noise created during the construction and operational phase.

4.2 Suspended material and sedimentation

During the construction of the wind farm turbine foundations and burial activities of inter-array cables between turbines and export cables to land, these activities will create a temporary increase in the concentration of suspended material, which will eventually lead to an increase in sedimentation. The pressures of increased suspended sediments and sedimentation on marine organisms from these activities are typically local and temporary but can be considerably detrimental on a local scale and in the near vicinity of the construction or cable burial activities. Broad plumes of increased suspended sediments or large deposits of sedimentation may induce a behavioral response that cause fish to temporarily move away or flee from an area and potentially affect food organisms and benthic habitats.

Increased suspended sediment in the marine environment if large enough can potentially affect oxygen uptake in fish and create respiratory stress due to increased respiration rates. Similarly, fish eggs and larvae are particularly sensitive to high suspended sediment concentrations and sedimentation as sediment can adhere to pelagic fish eggs leading to decreased buoyancy and causing them to sink to the bottom or smother benthic eggs and larvae and increase mortality. Increased suspended sediment can also indirectly affect food intake by reducing visibility or negatively affecting prey availability.

The effect of the pressures to fish, fish eggs and larvae from increased suspended sediment is determined by the level of sediment concentrations and the duration of the exposure. Furthermore, the sensitivity of fish to increased suspended sediment and sedimentation is species-specific and typically related to whether fish are pelagic or typically bottom dwelling. The most likely effect of increased suspended material will be an avoidance behavior in fish, which will flee or be displaced from the area where increased suspended sediment occurs (FeBEC, 2013). Bottom dwelling fish, such as flatfish and other species associated with a benthic lifestyle are more tolerant of suspended material than pelagic fish, which are more sensitive. This may be particularly true for clupeids such as herring and sprat, which forage by filtering food through their gills and thus are sensitive to the level of suspended sedimentation. An older study showed that juvenile herring avoided areas where the concentration of suspended sediment was between 9-12 mg/l (Johnston & Wildish, 1981). Similarly, laboratory and field investigations of coastal OWFs showed that pelagic species such as herring and smelt began to flee areas when the concentration of fine-grained suspended sediment reached approximately 10 mg l^{-1} and 20 mg l^{-1}, respectively (COWI/VKI, 1992). In connection with the construction of the Øresund Bridge (Appelberg, Holmqvist, & Lagerfelt, 2005) and a literature review related to the construction of the Fehmarn Belt, a threshold value for avoidance behavior by pelagic fish species based on avoidance by clupeids and the semi-benthic codfish whiting and Atlantic cod was set at 10 mg/l. Avoidance behavior by bottom dwelling species such as flatfish was expected at suspended sediment concentrations at 50 mg/l and above (FeBEC, 2013). Although these threshold values are conservative and associated with some degree of uncertainty, as they were based on laboratory studies,, the indications in studies generally show that pelagic fish species such as the clupeids herring and sprat and to a certain degree semi-benthic species such as whiting and Atlantic cod, are less tolerant of the pressure of increased suspended sediment than most other bottom-dwelling fish (FeBEC, 2013).

Fish eggs and larvae exposed to high sediment concentrations and sedimentation are more vulnerable due to lower mobility and reduced ability to escape these pressures. Studies on cod eggs, which are pelagic, have shown a change in buoyancy of the eggs at suspended sediment concentrations above 2-5 mg/l, and increased mortality at suspended concentrations over 100 mg/l (Hansson, 1995; FeBEC, 2013) (Westerberg et al, 1996). Similarly, a review of existing literature found no increased mortality in fish eggs and larvae at suspended concentrations below 100 mg/l, thus indicating that most fish eggs are to a degree tolerant of high suspended sediment that may even be significantly higher than 100mg/l (Karlsson, M., Kraufvelin, P. og Östman, Ö., 2020). This was supported by a study showing that the development or survival rate of herring eggs were not affected by exposure to concentrations of suspended sediment of 300-500 mg/l for one day (Kioerboe, Frantsen, Jensen, & Nohr, 1981), and herring eggs exposed to suspended sediment concentrations of 50 mg/l up to 14 days did not show signs of increased mortality (FeBEC, 2010).

Bottom dwelling fish species and the benthic eggs from species that are benthic spawners, such as sandeels, herring and most sharks and rays etc., could potentially be affected by an increase in sedimentation leading to displacement from impacted areas and the physical burial of eggs and/or reduced availability of oxygen and thus increased mortality. Furthermore, increased sedimentation can also degrade seabed habitats by reducing the quantity and availability of food organisms and thus food resources, and making areas of impact less suitable as feeding, spawning and or nursery grounds.

Periods of increased suspended material and sedimentation naturally occur in the marine environment after periods with high winds and storms and in areas near the coast where the energy from wave and currents continually suspend and re-suspend bottom material. For example in the Sound (Øresund) concentrations of suspended sediment of 40 mg/l have been measured during storms, while in the North Sea average levels of suspended sediment at a NOVANA station have been measured at 15-20 mg/l and up to 50-60 mg/l (Miljødata.dk, 2022), up to 185 mg/l along the coast (Rambøll, 2020) and as high as 800-1000 mg/l in the Wadden Sea after a storm (Andersen & Pejrup, 2001). These periodic episodes of increased suspended sediment and sedimentation indicate that fish in their different life stages natural experience varying degrees of suspended sediment and sedimentation in the environment.

Fish species and life stages sensitive to an increase in suspended sediment and sedimentation.
In conclusion, the literature suggests that episodes of increased suspended sediments may induce a behavioral response displacing fish from an area of high concentrations, by either causing fish to flee or creating a form of barrier where fish will stay away from an area with high suspended sediment. Literature suggests that the pressure from increased suspended sediment is greatest on pelagic species, with studies indicating the clupeids herring and sprat, but some codfish as well, are more sensitive to this pressure than benthic fish. Increased suspended sediment and sedimentation may have a negative effect on the early life stages of fish; fish eggs and larvae, as these stages are potentially more vulnerable to these pressures due to little or no mobility and thus only little ability to escape these pressures. Thus, focusing on the sensitivity of the aforementioned fish species and life stages, the pelagic fish herring, sprat and the codfish Atlantic cod, along with the early life stages of fish; fish eggs and larvae, as represented by spawning areas, were chosen for mapping sensitivity of where these species have been observed, including their spawning grounds where early life stages are expected to be present.

4.3 Electromagnetic fields (EMF)

Both electric and magnetic fields (EMF's) occur naturally in the marine environment. The most important natural magnetic field is the Earth's magnetic field, which has field strengths varying between 30-70 µT (Tesla). In the Danish waters, the field strengths are roughly 50 µT (NOAA, 2019), where local changes in strength slightly vary due to changes in the magnetic elements in the liquid layer of the earth's crust.

Operational power cables between wind farm turbines (inter-array cables) and from the wind farm to land (export cables) generate localized electric and magnetic fields when in operation. By definition, electromagnetic fields (EMF's) have both magnetic fields, which are created from the movement of electrical current within the cable, while the voltage applied to the cable produces an electric field, which can often be contained within the cable. Electric and magnetic field intensities decrease rapidly with increasing distance from an operating cable, and thus cable burial depth plays an important role in the intensity of the EMF that may be detected on the seabed surface along the cable route. Similarly, the propagation of EMF's and their strength around cables is directly dependent on the electrical current flowing through the cable, which fluctuates with wind speed and energy production. Most wind farm inter-array and export cables will be buried between 1-1.5 meters in the seabed, limiting the perception of the electromagnetic fields on the seabed surface above the cable to within a few meters (Offshore Wind Facts, 2024). Buried cables from 10 existing offshore wind farms were estimated to have an electric and magnetic field between 2.5-10µV/m and 1.6-18µT at the sediment surface (Normandeau, Exponent, Tricas, & Gill, 2011). Similarly, EMFs created by export cables from large offshore wind farms buried at 1.5 meters depth were estimated to be 14µT at the sediment surface directly above the cable (Hutchison, Z., Gill, A.B., Sigray, P., He, H. and King, J.W, 2021). Thus, because the earths geomagnetic field in Denmark is approximately 50µT (NOAA, 2019), in comparison to these values, the EMF's created from wind farm subsea cables are significantly weaker than the natural magnetic field, provided cables are buried to 1 meter or more.

Many marine fish are known to be sensitive to natural electromagnetic fields, however, at present, there is only sparse literature describing the extent to which fish perceive and are affected by EMF's. Natural electromagnetic fields can provide important ecological cues to species such as salmon and European eel (*Anguilla Anguilla*) as they obtain directional cues important for navigation from the Earth's geomagnetic field and associated electric fields (Gill, AB., Gloyne-Philips I., Kimber, J., Sigray, P., 2014). In contrast, sensitivity to electromagnetic fields in sharks, skates, and rays (elasmobranchs) are used to find prey, avoid predation and find conspecifics in a more local environment. Thus, these species and taxonomic groups can detect and potentially be affected by the local EMF's created around operational cables from wind farms.

In general, as a taxonomic group, elasmobranchs or sharks, rays and skates are considered to be the group of fish most sensitive to electromagnetic fields (Hutchison, 2020) (Keller, 2021) (Anderson, 2017). What makes this group so sensitive is that they have specialized electroreceptors called "ampullae of Lorenzini", which they use to detect electric fields generated by prey. Elasmobranchs have been found to be able to sense changes in electric fields of as little as 0.005 µV/cm, and changes in magnetic fields from 0.002-0.005 µT (Nyqvist, 2020). However, in contrast to the potential of EMF's repelling or triggering an avoidance response in elasmobranchs, research generally suggests the opposite, that EMF in the order of magnitude found around offshore power cables can cause forms of attraction and increased prey searching behavior. Although there is limited research on elasmobranchs that occur in the North Sea, research to the closely related little skate (*Leucoraja erinacea*) showed increased overall activity and increased foraging behavior when exposed to EMF's from HVDC subsea cables (Hutchison, 2020). In the same field experiment, results suggested that the skates moved larger distances and rested less when exposed to EMF's. Whether these behavioral changes could have an effect on the population level is unknown. In contrast, an experiment of the thornback ray (*Raya clavata*), small-spotted catshark (*Scyliorhinus canicula*) and the spiny dogfish (*Squalus acanthias*) conducted around a 50 Hz AC subsea cable, did not find a consistent effect of EMF's on their behavior, although some of the individuals did seem to respond to EMF's with increased activity (Gill, 2009). Similarly, experiments on juvenile thornback rays did show an increase in active behavior when exposed to a 450 µT AC (50 Hz) or DC field, but only during one period in their investigations and not in another (Kimber, 2014). It has been suggested that elasmobranchs can learn and habituate when their foraging response triggered by man-made EMF's is not rewarded (Kimber, 2014). This has been attributed to similarities to an appropriate response that would occur in their natural habitats, suggesting that elasmobranchs learn to ignore non-profitable stimuli leading to hard-to-catch prey or false signals of prey (Heinrich, D. D., Huveneers, T. M., Dhellemmes, F., Brown, C., 2022).

Results of studies at the species level of other bottom dwelling fish species vary from finding no change in the spatial distribution, swimming speed or distance moved in drifting larvae of sandeel (*Ammodytes marinus*) when exposed to EMF's of similar intensity as those produced by subsea cables, to small changes in behavior in some species, such as reduced swimming activity in haddock larvae etc. (Cresci, et al., 2022b; Wyman, et al., 2018; Westerberg & Lagenfelt, 2008; Danish Energy Agency, 2013). There is evidence that plaice, salmonids, and European eels use magnetic fields for orientation, and that Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) use geomagnetic fields when migrating in the open sea (Bergström, F., & Berström, 2013) (Formicki, Korzelecka-Orkisz, & Tanski, 2019), but it is highly uncertain that these species can potentially register EMF's around wind farms and subsea cables. For a variety of flatfish species (plaice, dab and sole), a study comparing the abundance of these species along operating wind farm cables with a reference area did not find any differences (van Hal, Volwater, & Neitzel, 2022).

In conclusion, a recent literature review investigating the potential effects of EMF on early life stages, juvenile and adult fish movement and migratory behavior summarized that at present, investigations indicate that EMF near subsea cables are unlikely to pose a barrier to migration success, while limited deviations in expected movement patterns (e.g., reduced swimming speed or searching behavior) in some studies appear to be contrasting and possibly indicate traits that are more species or individual specific. Similarly, conclusions from reviewing four empirical field studies investigating the effect of EMF's from subsea cables on the spatial patterns and composition of fish communities indicated there were no significant differences in fish abundance, richness or community composition, and thus the empirical studies indicate only very limited or non-existing evidence of negative effects (Svendsen, et. al., 2022).

At present, results from the limited number of studies investigating the effects of EMF emitted by offshore cables on different fish species varies. Elasmobranchs seem to show potential changes in behavior, in the form of increased activity or foraging behavior. This response combined with their high sensitivity to electromagnetic fields suggests that elasmobranchs (sharks, rays, and skates) as a group are considered as those to be the most sensitive to EMF's created by wind farm subsea cables and potentially susceptible to their effects. This was also pointed out in several reviews of the effects of EMF in a variety of fish species, in which it was concluded that the most relevant group in the North Sea with regard to potential effects from EMF on marine fish species were the elasmobranchs: sharks and rays (Svendsen, et. al., 2022) (Hermans, A. and Schilt B., 2022). Thus, the group elasmobranchs were also chosen for the sensitivity mapping of areas where species in this group may be present at higher densities in relation to the potential pressure of EMF's generated by wind farm inter-array and export cables during offshore wind farms operations.

4.4 Habitat disturbance and loss/change

The establishment of a wind farm including the installation of turbine foundations and laying and burial of inter-array and export cables will result in temporary local disturbance/destruction and permanent replacement of existing fish habitats. Regardless of where wind farm cable installation takes place the laying and burial activities will inevitably affect several different fish habitats, potentially including soft bottom, mixed (mosaic of soft-bottom, gravel and stone habitats), as well as hard bottom habitats. Disturbed or short-term destruction of fish habitats creates a reduction of potential important habitat, food resources and in areas where benthic spawners have eggs or larvae an increase in mortality to these fragile early life stages. Benthic fauna in soft bottom habitats or food for benthic fish are, however, known to recover quickly (months to a few years) from intense seabed disturbances (Hygum, 1993) (Newell, Seiderer, & Hitchcock, 1998) (Støttrup et al., 2007). While in contrast, hard bottom habitats can take considerably longer, and although the first organisms such as mussels and macroalgae (where light is sufficient) will colonize a recovering hard bottom habitat within the first years (Møhlenberg, et al., 2008) it could potentially take 8-10 years before a well-established hard bottom fish habitat has fully recovered (Dahl, Støttrup, Stenberg, Berggreen, & Jensen, 2016). Many fish species will, however, utilize recovering habitats during their natural succession as they increasingly provide food and refuge during recovery.

A permanent loss of fish habitats will occur when naturally occurring habitats are replaced by turbine foundations, protective stone, and other hard bottom substrates in the form of concrete and steel structures. The effects of new structures and loss of habitat as well as the addition of new habitats on different fish species and the fish community can potentially be both positive and negative.

The overall impact and ecological value to fish of replacing naturally occurring habitats with new artificial habitats, albeit eventually functioning as new natural hard bottom habitats, depends on the location of foundations, water depth and water current regimes and the material installations are made of, including its heterogeneity etc. Furthermore, the pressure of habitat loss to fish is also dependent on the quantity of the lost habitat and the dependency of affected fish species on the lost habitat. Species that are associated with soft bottom habitats, such as a diverse variety of flatfish etc., are considerably robust and mobile and because of the relatively limited amount of habitat that is generally lost when establishing wind farm installations, will generally be able to find and utilize comparable habitats in the local and regional area. In contrast, fish species such as the groups of sandeel (*Ammodytes spp*.) are highly dependent on specific sand sediment and any relatively large loss of their habitats may have a substantial impact on these species, as their preferred habitat is often limited. Similarly, many fish species and groups such as wrasses (Labridae), juvenile cod, and a variety of other hard bottom associated species are also dependent on a well-functioning hard bottom habitat to provide food sources, shelter, and protection. An increase in hard bottom habitats will, however, increase with the introduction of wind farm installations and foundation protection and thus potential lost hard bottom habitats will be replaced with hard substrate "artificial reefs." There are not many studies investigating the difference in fish assemblages before and after the construction of wind farms and those that have been undertaken indicate different forms of influence. One investigation showed that there was an increase in the abundance of fish within a wind farm area in comparison to a control area (Methratta E.T. and Dardick, 2019). Similarly in an investigation of the Danish wind farm Horns Rev 1 seven years after it was established there were observed more fish that included Labridae spp., rock gunnel (*Pholis gunnellus*) and juvenile Atlantic cod around the turbine foundations than in the surrounding area (Stenberg et. al., 2011). An investigation of a Belgium wind farm showed similar observations as more juveniles of the codfish Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) were observed near the wind farm foundations (Reubens J.T., Degraer S., and Vincx M., 2014) than before.

In general, pelagic species of fish are not expected to be influenced by the loss of benthic habitat or the introduction of hard substrates that eventually become "artificial reefs" from the establishment of wind farms.

On a local scale, the potential loss of specific habitats due to the installation of wind farms may have the greatest negative impact on fish species that are highly dependent on specific benthic habitats and thus sensitive to the pressures leading to loss or impairment to these habitats. These species include sandeels (*Ammodytes spp*) that are highly dependent on specific sand bottom habitats, and a variety of fish species associated with stone reefs.

4.5 Hydrographic changes (reduced wind and mixture)

The presence of offshore wind farm turbine foundations and other installations can potentially create local or regional hydrographic changes including shifting currents and increasing turbulence in the water column. These changes could lead to potentially affecting sediment transport and deposition as well and water mixing, and thus changes in the local pelagic and benthic habitats and on large scale changes in water temperature, salinity and current speed and direction. Fish are often dependent on multiple habitats during their life cycle, where events such as spawning, egg and larvae drift, settling in nursery and feeding areas and migration routes can be highly integrated with specific hydrographic regimes and events. Furthermore, fish are either pelagic spawners or demersal (bottom) spawners, and because pelagic spawning often takes place at specific depths, often in the same regional areas, hydrographic conditions play an important role in regulating spawning area boundaries. Potential changes in local currents may thus have a considerable impact on spawning success due to effects on egg and larval drift and the environmental characteristics of the environment they are living in. Demersal or bottom spawners often spawn on specific habitats that are species-specific, where eggs are typically laid on the seabed, in vegetation or on rocks. Changes in current speeds, leading to scouring and suspension/re-suspension of local sediment around wind turbines could have a negative effect by both potentially altering important seabed habitats of different fish species, but also on the success of benthic spawners and the survival success of their eggs and larvae/juveniles.

When assessing the implications of hydrographic changes for fish and their communities on a local scale, indirect pressures include potential changes in turbulence and stratification (temperature or salinity changes) and resulting impacts on sediment resuspension or sedimentation that affects seabed habitats. While the effects of each hydrodynamic parameter on fish ecology appear to be well studied (Liao, J.C., and A. Cotel, 2013)(

(Kjelland, M.E., C.M. Woodley, T.M. Swannack, and D.L. Smith, 2015) (Wenger, et al, 2017), studies of the direct pressures from hydrographic changes related to OWFs are few. A study of Horns Reef in the North Sea after deployment of the wind farm indicated changes in densities of the most commonly occurring fish, whiting (*Merlangius merlangus*) and dab (*Limanda limanda*), but these changes were mostly attributed to general fluctuations of these fish population in the North Sea according to fish stock assessments (Stenberg, 2015). In the same investigations, acoustic surveys indicated no significant differences in the abundance or distribution patterns of pelagic and demersal fish, between a control site and the wind farm area, or inside the potential impact area that could cause hydrographic changes between foundations (Stenberg, 2015). Similarly, OWF's induced hydrodynamic changes investigated in several OWF's did not appear to have a significant direct or indirect influence on changes in pelagic fish distribution, as determined from hydroacoustic records (Floeter, J. et al, 2017). A single investigation from the effects of potential hydrographic changes did, however, find elevated abundances of pelagic fish, most likely mackerel, within 100 m of underwater construction sites (Schröder, 2013).

On a regional scale, implications of changes in hydrography and pressure on fish and fish communities from the effects of wind farms is challenging to investigate. A wind farm or series of wind farms may reduce wind speed by "removing" energy from an area during operations. Although there will be some local sea surface turbulence caused by rotating wings (blades), the main effects of reducing energy will be on the sea surface currents and circulation downwind the wind farm. These effects can cause changes in the upwelling and downwelling dynamics of the water masses due to the altered properties and energy in the force of wind (Broström, 2008). In shallow waters in the German Bight, wind farm installations caused a turbulent wake and tidal currents, which significantly affected mixing of water local masses (Carpenter JR, 2016). Similarly, in a study modelling the change in hydrodynamics in the Irish Sea due to a wind farm, an increase in tidal water levels up to a 7% was observed (Cazenave P.W., 2016).

Fish species and life stages sensitive to hydrographical changes
A number of factors make it difficult to assess potential changes in hydrographic regimes from wind farms and impacts on fish species and communities, primarily due to the spatial and temporal variability of the natural marine systems (Bergström et al., 2013; Floeter et al., 2017). This is compounded by the unknown effects of accelerating climate change. Due to the hydrodynamic variability in OWF areas described, and for example, the annual variability in recruitment of juvenile fish, which can differ by a factor of five for plaice, 50 for sole, and more than 100 for haddock in the North Sea (OSPAR, 2000), it is difficult to isolate the negative impacts of changes local and regional hydrographical regimes potentially due to OWF. Despite this, there are some potential implications to fish and fish populations due to possible changes in local and regional hydrodynamics leading to changes in wind and water current regimes, sediment transport and seabed habitats from wind farm installations and operation. Changes in water current and circulation could affect the hydrographic regimes in typical spawning areas leading to potential changes in drift of pelagic fish eggs and larval. This could ultimately affect the destinations of where developed eggs and larvae settle and ultimately determine survival rates. Changes in local seabed habitats can also have an effect on fish that have strict habitat requirements, such as sandeel, by potentially reducing and changing important habitats.

4.6 Choice of fish species and groups for sensitivity analysis and mapping

The pressures to the environment from establishing offshore wind farms can in principle potentially affect either directly or indirectly, all the fish species that are within the region of its construction and operation. However, for the vast majority of fish species, information on the potential impact from the specific pressures (increased underwater noise, temporary and permanent changes in habitat, Electromagnetic fields (EMF) along subsea cables etc.) due to establishing wind farms have not been studied or are limited in knowledge. From the summary of the pressures and brief reference to different fish species or groups of fish and different life stages most sensitive to the specific pressures in sections 4.1-4.5 a number of fish species or fish groups were presented. When possible for the sensitivity analysis, it was also of interest to choose "keystone species" that are not only sensitive to one or mere pressures but are also considered to play a crucial part in maintaining the structure and health of the marine ecosystem due their role as a dominant predator or prey species. Thus, if a keystone species were strongly affected by the pressures exerted by offshore wind farms, then the potential for significant changes in the fish community and ecosystem would increase. Furthermore, for the purpose of creating a spatial analysis with sensitivity maps for fish for the entire Danish marine area, broad scale data on distributions and densities of selected fish species or groups would also be needed.

A summary of the primary pressures and the fish component most relevant to include in a sensitivity analysis is given in Table 4.1.

Table 4.1. A summary of the primary pressures and the fish components most sensitive and relevant to include in the sensitivity analysis and form the foundation for mapping of sensitive areas.

Pressure	Project Phase	Effect	Fish component – most relevant
Increased suspended sediment	Construction + Decommissioning	Behavioral avoidance response - displacement from impact zone. Reduced visual ability – impairment in searching for food Increased coverage and sinking of fish eggs	Pelagic fish species: - Atlantic herring and sprat - Atlantic cod and haddock Spawning areas of fish species with pelagic eggs/larvae: - Atlantic cod and haddock - Sprat - European plaice - European flounder - Common dab
Increased sedimentation	Construction + Decommissioning	Behavioral avoidance response - displacement from impact zone. Burial of benthic eggs – reduced/impairment of O2 uptake Habitat degradation creating less suitable feeding, spawning and/or nursery grounds	Benthic fish species: - Sandeel (*Ammodytes spp.*) - European plaice - European flounder - Common dab - Elasmobranchs (rays, skates, and sharks). Spawning areas of fish species with benthic eggs/larvae: - Sandeel (*Ammodytes spp.*) - Atlantic herring - Elasmobranchs (sharks and rays)
Increased underwater noise	Construction + Operation + Decommissioning	Underwater noise and impact on individual animals may be greater the closer to	Zone of injury – near extreme noise source: All fish species and spawning areas.

Pressure	Project Phase	Effect	Fish component – most relevant
Establishing foundations; Pile-driving etc., burying in-ter-array and export cables, increased vessel activity dur-ing construction and opera-tional maintenance		The source i.e. affects change with in-creasing distance from the source. Zone of injury: PTS (Permanent hearing loss) and tissue injury near source of pres-sure. Causing mortality Zone of impairment: TTS (Temporary hearing loss). Causing temporary hearing loss and stress responses. Zone of behavioral response : Underwater noise cause an avoidance response in fish - displacement of fish from pressure zone. Zone of masking : Underwater noise can mask/disturb intra- and interspecific noise signals by fish used for communica-tion, predator avoidance, and prey detec-tion.	Fish with highest sensitivity to in-creased underwater noise are those with swim bladders and specialized hearing organs and because noise is used for communication (spawning etc.): - Atlantic herring and sprat - Atlantic cod and haddock - Spawning areas of fish species with pelagic eggs/larvae Life-stage of fish with high sensitivity to extreme increased underwater noise because they have little or no mobility to avoid impact zone. Spawn-ing areas of fish species with pelagic eggs/larvae: - Atlantic cod and haddock - Sprat - European plaice - European flounder - Common dab
Underwater noise – low fre-quency (mechanical motion, vibrations etc.)	Operation	Potentially masking/disturbing intra- and interspecific noise signals by fish used for communication, predator avoidance, and prey detection. Potential masking/disturbing of signals by fish used for communication, predator avoidance, and prey detection.	Fish sensitive to noise because noise is used for communication (intra-spe-cific communication and spawning etc.): - Atlantic cod and haddock - Atlantic herring and sprat
Negative habitat changes – foundation protection (scourings) and turbines	Operation	Reduction and loss of habitat	Fish species dependent on specific habitats: - Sandeel (*Ammodytes spp*.) Fish species attracted to introduced hard bottom substrates (habitats): - Atlantic cod and haddock
Electromagnetic fields – In-ter-array and export cables	Operation	Displacement, reduced ability to find food, and/or barrier effect (migration) across cables	Primarily benthic fish with electrore-ceptors: - Elasmobranch (sharks and rays)

With these criteria as a guideline, eight fish species and one fish group elasmobranchs that are widespread in the fish communities in Danish marine waters were chosen as the focal species to represent the fish communities as a whole, and as a "proxy" in relation to mapping the sensitivity of the fish to the potential pressures from establishing wind farms. The eight species and one group of species selected for spatial analysis due to their sensitivity to pressures and ecological role are:

- Atlantic cod (*Gadus morhua*)
- Haddock (*Melanogrammus aeglefinus*)
- Sandeel (*Ammodytes spp*.)
- Common dab (*Limanda limanda*)
- European plaice (*Pleuronectes platessa*)
- European flounder (*Platichthys flesus*)
- Atlantic herring (*Clupea harengus*)
- European sprat (*Sprattus sprattus*)
- Elasmobranchs (sharks, rays, and skates)

5. Fish species

The presented fish groups (Gadoids, sandeel, flatfishes, Clupeids, and elasmobranchs) that were included in the sensitivity analysis, will in the following section be described with regard to their group-specific ecological traits. Each group will further be divided into species, for which the results of the spatial analysis and how it ties to their species-specific ecology and life-stage distribution are presented.

5.1 Gadoids

Gadoids (*Gadiformes*) is a larger order of fish, consisting of 13 families, widely distributed in the Danish waters, from the North Sea to the eastern part of the Baltic Sea. Gadoids are an important part of the North and Baltic Sea ecosystems, serving as both predators and prey for many marine organisms. Several species in this group have significant commercial interest, and in recent years, there has been a decline in population sizes due to fishing and changes in climate and environmental conditions. Their significant presence in fisheries and their role in ecosystems make gadoids an important focus area in planning OWF projects. While gadoids are a diverse order, the vast majority share certain physiological and ecological traits that make them susceptible to disturbances related to OWF construction. Most gadoids are demersal fishes, positioned above the sea floor, and only spend time pelagically during migration (diel-vertical and/or spawning) and feeding on seasonal occurrence of pelagic prey (i.e. Atlantic herring) (ICES, 1997; Hislop, et al., 2015; Ojaveer, 2003; Adlerstein, Temming, & Mergardt, 2002). While most gadoids are demersal and close to the seafloor, a few species are primarily pelagic, such as Saithe (*Pollachius virens*), and thus more associated with mid-water and surface (pelagic) environment. Thus, these species are not relevant for the present analysis.

Regarding habitat preference, gadoids are often generalists and can be found throughout many different habitats, depending on their life stage. Eggs and larvae are entirely pelagic, and drift with the ocean currents, often towards coastal nursery areas (Munk & Nielsen, Eggs and larvae of North Sea fishes, 2005; Russel, 1976). These early life stages have a naturally high mortality and are/may be sensitive to many external impacts (sedimentation, increased turbidity, sound pressure etc.). Nursery areas are often characterized by complexity (eelgrass meadows, boulder reefs etc.) where the juvenile fish can seek prey and refuge. With age, juvenile fish slowly seek and migrate towards adult foraging areas, where their distribution depends on species-specific habitat preference and habitat availability. Adult gadoids are found around complex structures such as boulder reefs, Kelp forests and ship wrecks, or mixed/soft substrates such as sand and gravel (Reubens, van Colen, Degraer, & Vincx, 2013; Hoffmann & Carl, 2019b; Hoffmann, Carl, & Møller, 2021). However, very few species are found to prefer muddy sediments, with a high composition of silt. At time of spawning, gadoids generally gather at species/population specific spawning sites. Some gadoids show high spawning site fidelity, meaning that loss of habitat around these areas may significantly impact spawning potential (Stelzenmüller, Ellis, & Rogers, 2010).

Common for all life stages is the presence of a significant swim bladder, that supports neutral buoyancy, and in certain species vocal communication. Species such as Atlantic cod and Atlantic haddock show advanced communication through sound production, especially relevant for courtship behavior, and are often called hearing-specialists (Hawkins & Popper, 2020; Bremner, Trippel, & Terhune, 2002). Disruption of these signals may negatively affect reproductive success, through limited mate attraction. Further, during the construction phase, pile driving, and related high sound pressure may harm or disperse adults and harm larvae/juveniles.

The Gadoids included in this analysis are generally sensitive to spawning-habitat loss (population-specific sand banks/areas), noise-pollution interrupting mating calls and potential behavior and mortality changes for eggs and larvae. The gadoids included are Atlantic cod (*Gadus morhua*) and Atlantic haddock (*Melanogrammus aeglefinus*).

5.1.1 Atlantic cod (*Gadus morhua*)

Spatial distribution

The distribution of cod can be divided into specific categories representing nursery, spawning and foraging areas. Adult individuals primarily inhabit demersal zones near reefs, mixed bottoms and similar habitat types often with some structure but can also be found in open waters during migration and spawning. Cod is a partially migratory fish, alternating between diffusely distributed nursery and foraging areas and fixed population-specific spawning areas. Some locally restricted populations, coastal and fjord cod, mature, spawn and forage in the same area (Opdal, Vikebø, & Fiksen, 2011; Knutsen, et al., 2018; Mose Jørgensen, Neuheimer, Jorde, Knutsen, & Grønkjaer, 2020). Figure 5.1 shows the general distribution of cod in Danish waters, located along the Norwegian trench, southeastern Kattegat, the western Baltic Sea and waters around Bornholm and Arkona Basin. When compared to the adult distribution, derived from the ICES data, similar distribution patterns are apparent within the Baltic Sea, Skagerrak, and inner Danish waters (Figure 5.2), However, outside the Danish territory, along the Norwegian trench, the ICES data indicated areas of lower sensitivity compared to that of the fisheries data. This inconsistency in the North Sea suggests that compared to the standardized ICES surveys, there may be an overrepresentation of cod in the fisheries in this area.

For Atlantic cod, pelagic spawning occurs in specific spawning areas; generally located around sandy banks, with high population-specific site fidelity. In the Kattegat, individuals from North Sea populations mix with the non-migratory local Kattegat cod outside the spawning season but migrate back to specific areas during spawning (January-February) (Hansen, et al., 2020). Spawning occurs with males occupying small territories in the spawning area and competes for females through vocal sounds and other mating behaviors. Historically, spawning has occurred in specific areas in the Danish waters, dependent on populations: West Baltic/Kattegat and East Baltic cod. The West Baltic/Kattegat cod population have been known to spawn within the Danish Belts, Kiel Bay, and Mecklenburg Bay, as well as the southeastern Kattegat stretching along the Swedish west coast (Hüssy, Review of western Baltic cod (Gadus morhua) recruitment dynamics, 2011). East Baltic cod have been known to spawn in the Arkona Basin and Bornholm Basin (Bagge, Thurow, Steffensen, & Bay, 1994). Figure 5.3 shows that spatial aggregation of spawning individuals sampled in the ICES surveys correlates with the historic spawning distributions. The highest densities of spawning individuals were found around Kiel and Mecklenburg Bay and the southeastern parts of Kattegat, corresponding with the expected primary spawning areas for west Baltic cod. Only a medium score was achieved within the Arkona Basin and around Bornholm, the primary spawning areas for East Baltic cod in Danish waters, which may be due to lower abundance or the spawning time being outside the sampling time of BITS (Q1 and Q4).

After spawning, the pelagic eggs and larvae drift with the currents, until they move towards the bottom during the juvenile stage (at a length of 4-5 cm). Juvenile cod generally reside in coastal nursery areas, where eelgrass meadows, boulder reefs, mixed bottoms and diverse structures provide refuge and prey items (Munk & Nielsen, Eggs and larvae of North Sea fishes, 2005). The juvenile map (Figure 5.4) shows a pattern resembling that of the adult distribution, with widespread areas of high sensitivities throughout Kattegat and Skagerrak, while showing primarily medium sensitivities in the Baltic Sea. However, north of Bornholm around the bay of Hanö, an area of high sensitivity indicates a local important nursery area for juvenile cod.

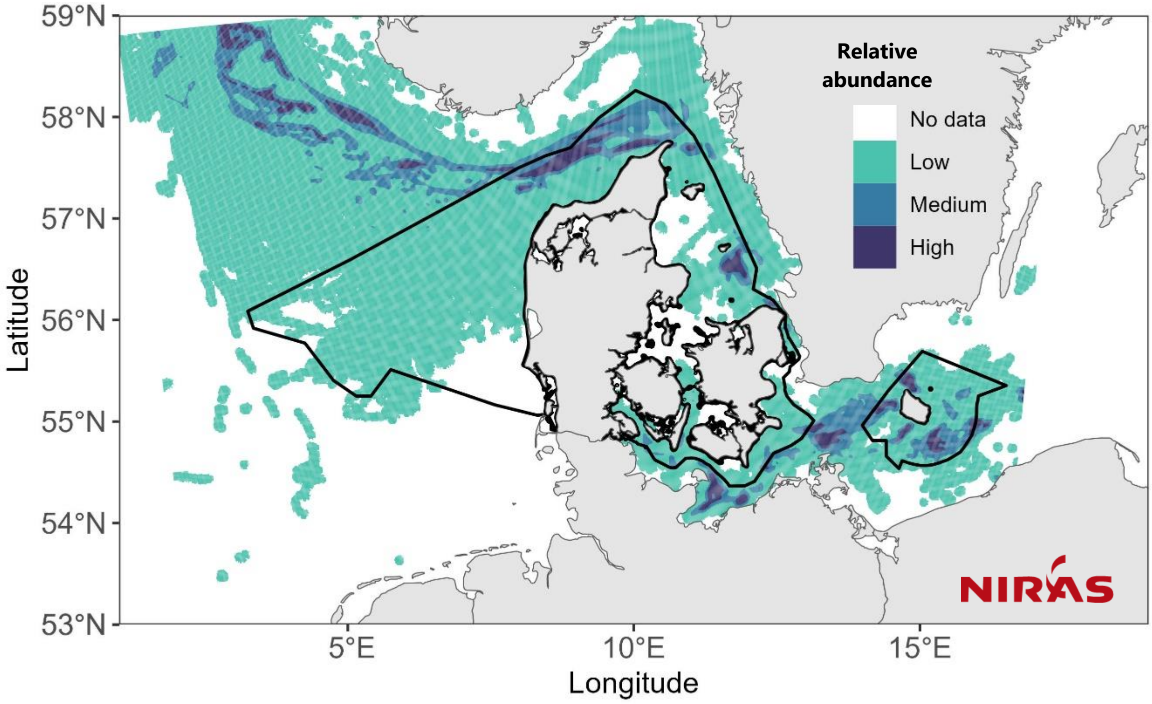


Figure 5.1. General distribution of Atlantic cod (Gadus morhua), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where cod were in the top three weight of all species caught.

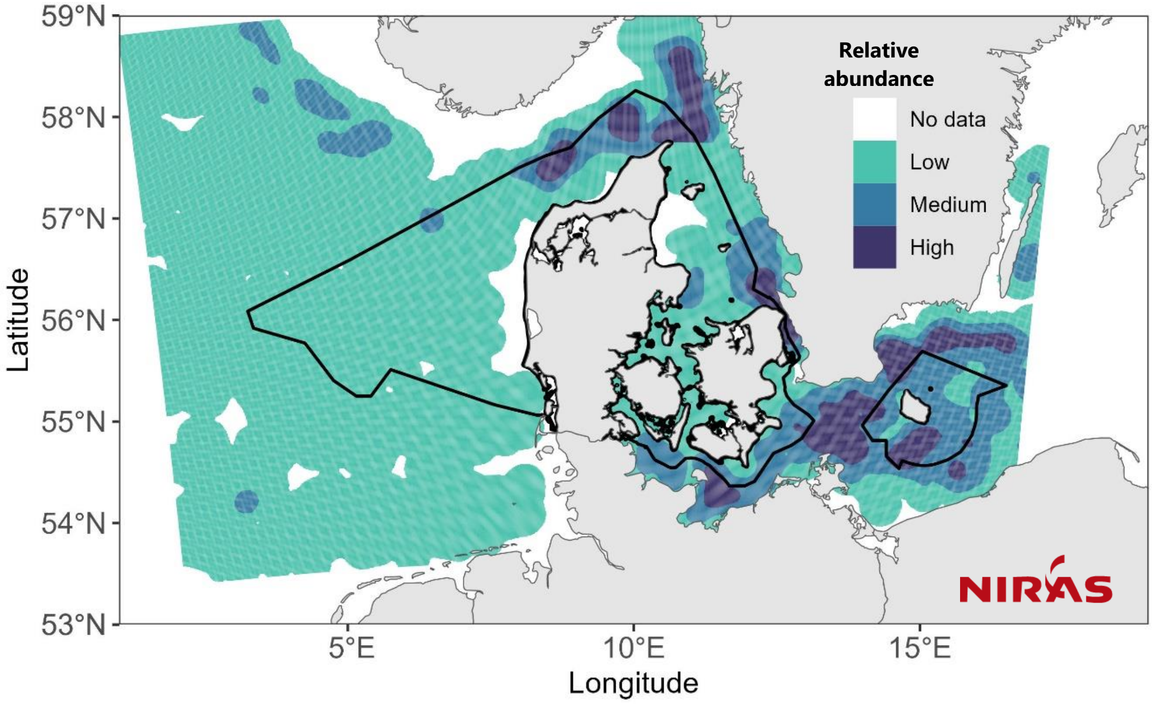


Figure 5.2. Distribution of adult Atlantic cod (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

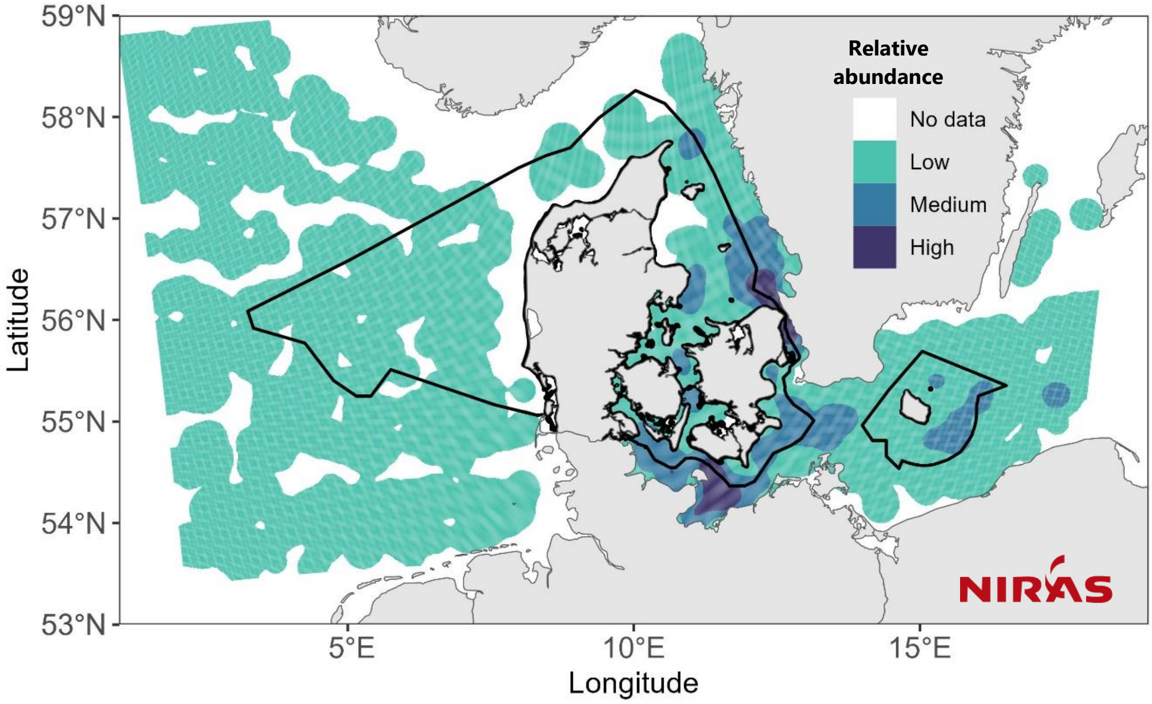


Figure 5.3. Distribution of spawning-ready Atlantic cod, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

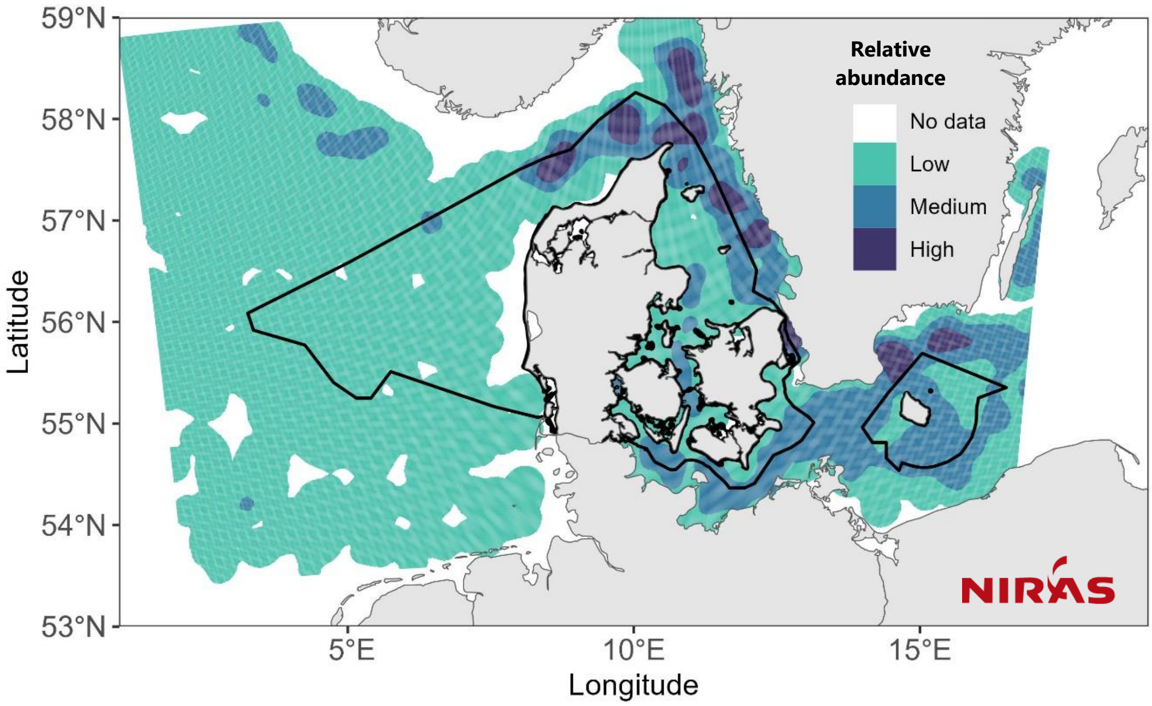


Figure 5.4. Distribution of juvenile Atlantic cod, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.1.2 Haddock (*Melanogrammus aeglefinus*)

Spatial distribution

Haddock has been shown to prefer marine water of average salinity (32-35 ppt), where juveniles are found in shallower water, while adults are more common in deeper water, and thus often considered a species found off-shore (Hoffmann & Carl, Kuller, 2019b). The fisheries-based general distribution supports these preferences and shows that the highest density of fishes is generally located around deep areas (Figure 5.5). This is specifically the northernmost part of the Danish EEZ next to the Norwegian trench in Skagerrak, and smaller areas north and east of Læsø, which correlates with the deeper parts of the Kattegat. Similarly, in the maps derived from fishery data, there is an aggregation of medium-high densities in the westernmost part of the Danish EEZ; however these correlate with the high density areas of sandeel, which may signify that haddock may make up a substantial proportion of the bycatch in the sandeel fisheries. This is further emphasized with the ICES-based adult distribution showing high density areas in the Kattegat, Skagerrak, and Northern North Sea, but low densities in the western part of the Danish EEZ (Figure 5.6).

The distribution of spawning haddock individuals shows that the medium and highest densities are found around the northern and western part of the North Sea (Figure 5.7.). This correlates well with surveys from the literature stating that the most productive spawning areas in the North Sea, are found in the northern North Sea between Scotland and Norway (Hoffmann & Carl, 2019b; González-Irusta & Wright, 2016). Furthermore, within the south-eastern part of the Kattegat there is a small area with medium and high density values. This area is found to be important for Gadoid and other Danish fishes, where many aggregate for spawning. However, haddock are not expected to undertake in any significant spawning in this area, due to their preference for higher salinities by both adults, eggs, and larvae. Instead, the individuals ready to spawn within the Kattegat may migrate towards the North Sea spawning areas before doing so.

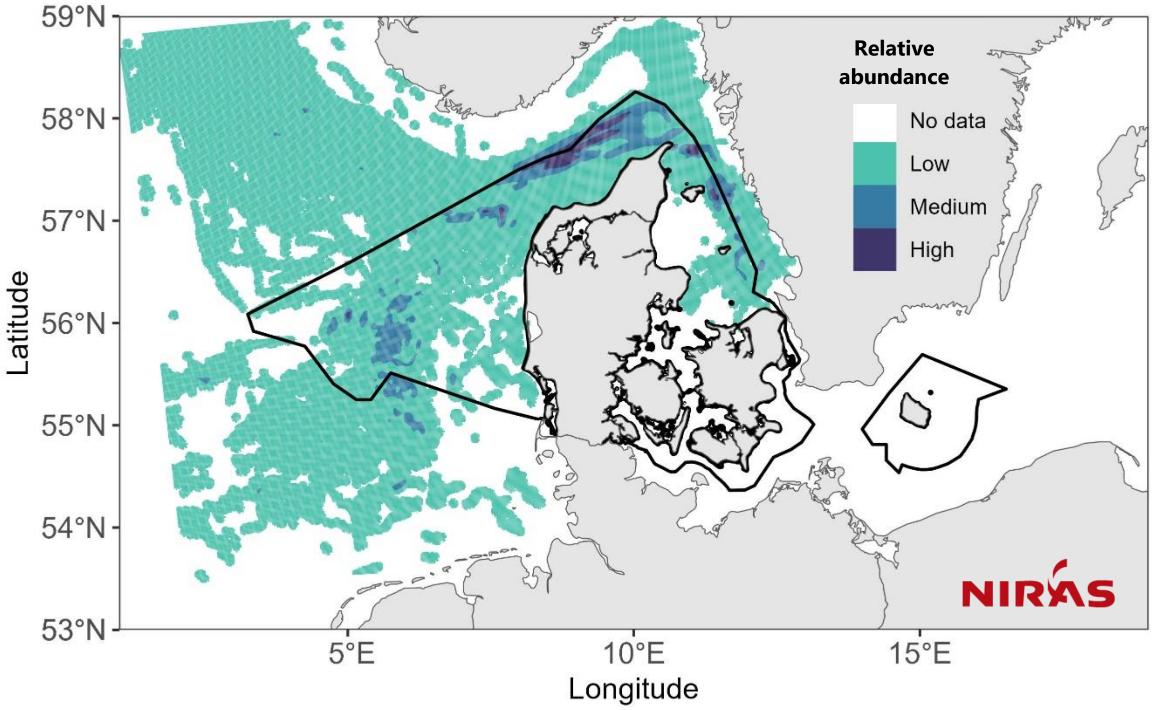


Figure 5.5. General distribution of haddock (Melanogrammus aeglefinus), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where haddock were in the top three weight of all species caught.

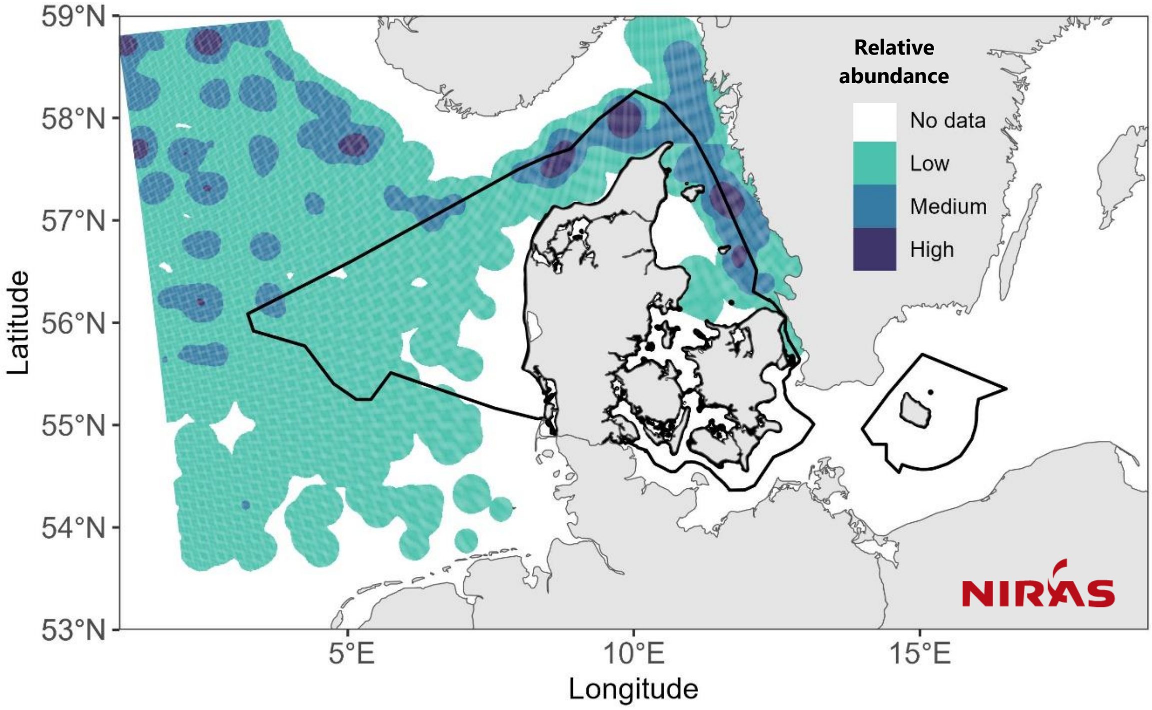


Figure 5.6. Distribution of adult haddock (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

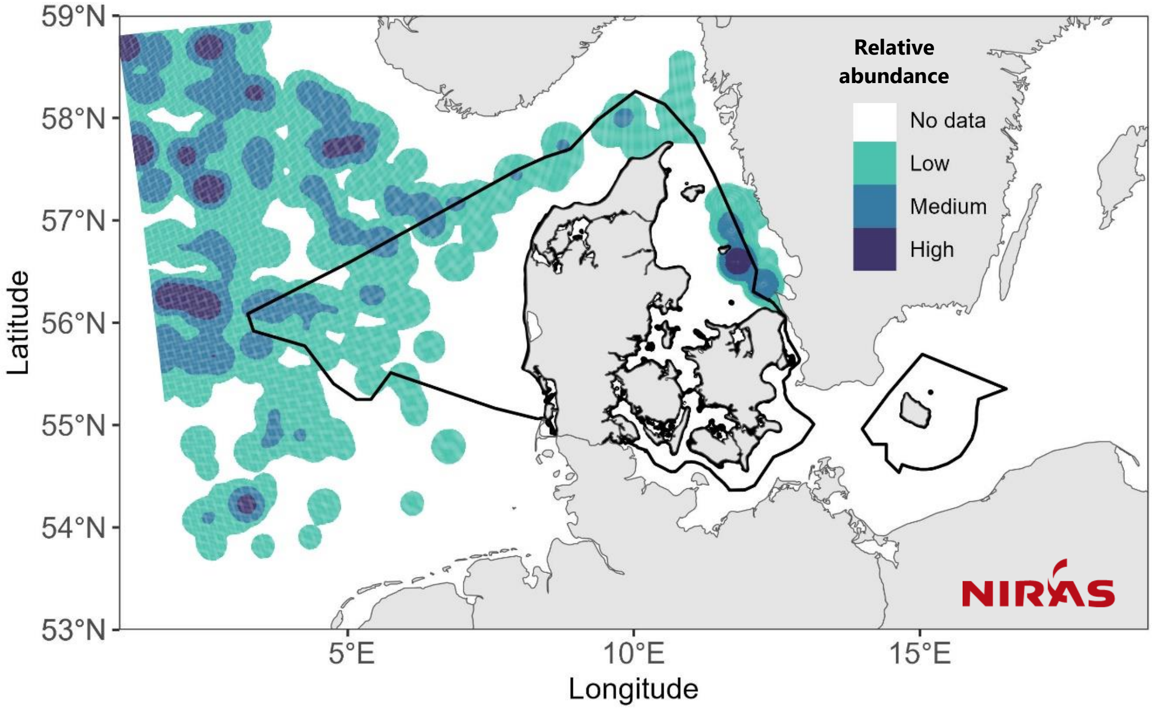


Figure 5.7. Distribution of spawning-ready haddock grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

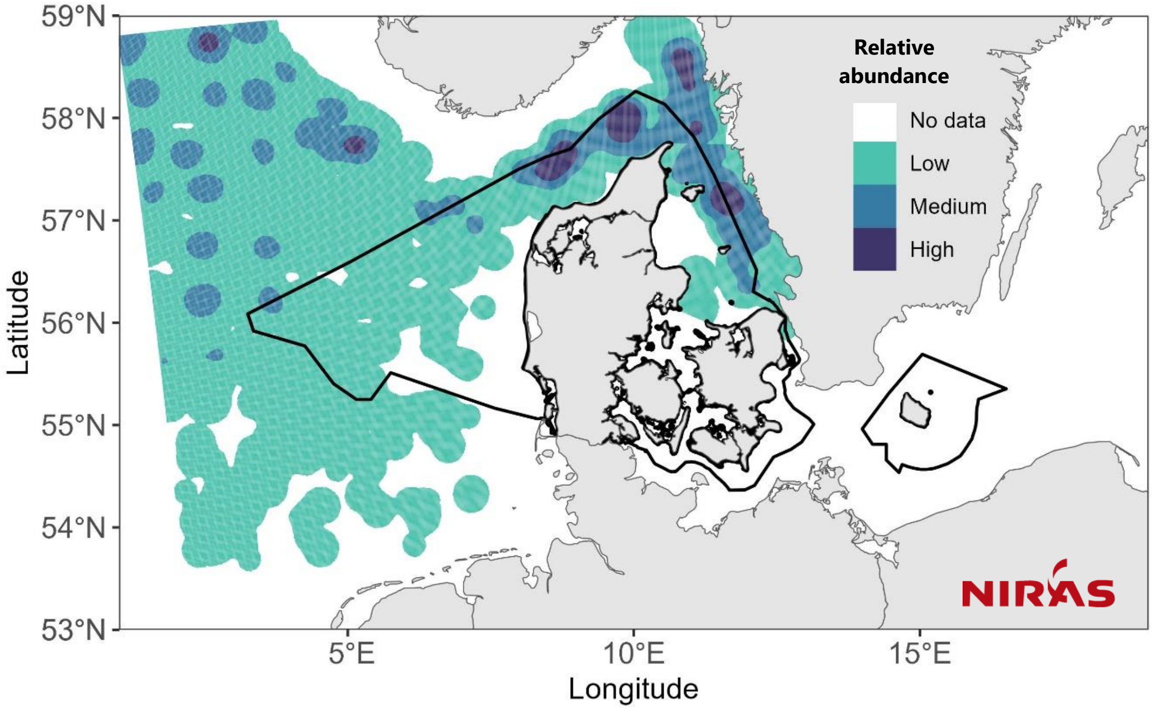


Figure 5.8 - Distribution of juvenile haddock, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

In contrast to many other gadoids, juvenile haddock do not usually reside in coastal communities, but inhabit the same, deep, areas as the adults (Hoffmann & Carl, Kuller, 2019b). This can be seen in the juvenile distribution map where high and medium density areas correlate with the adult distribution, around the deeper areas of the Danish marine territory (Figure 5.8). There are also high haddock densities around important spawning areas in the northern North Sea, which similarly show the preference of greater depths for juvenile haddock.

5.2 Sandeel (*Ammodytes spp.*)

Sandeel is a common name shared by a group of fishes that are widely distributed throughout the entire Danish marine territory. Several species are found within the greater North Sea and Baltic Sea, but due to large morphological similarity, they have historically been treated collectively (Sparholt, 2015). They function as a keystone species within their occupied habitat, as their seasonal high lipid content and high areal density form the basis of the diet of numerous fish, birds, and mammals.

Sandeel have a unique behavior, where they live buried with their heads exposed in the upper part of the seabed for most of their lives, and are only free-swimming for a few months during foraging (April-July) and spawning (December-January), which only occurs during daylight (Munk & Nielsen, Eggs and larvae of North Sea fishes, 2005; Russel, 1976). When buried in the sediment, the burrows are not kept open, meaning that the fish ventilate through interstitial water (within-sediment water), and quickly expend available dissolved oxygen. Therefore, sandeel have strict requirements for sediment composition, where sandy and semi-coarse sediment characteristics allow for faster replenishment of interstitial water and dissolved oxygen content. Additionally, the presence of silt in the burrows increases the risk of inhibiting respiration, as the fine particles clog the gill filaments, and limits gas-exchange. Furthermore, the largest individuals have been found to prefer coarser sediment types, potentially due to their higher metabolic oxygen requirements. Studies have shown that the highest areal fish densities were observed in sediments composed of a small amount of <2% silt (0.1-63 micrometer grain size) and a large amount of coarser sand (0.25-2 mm grain size). Sandeel are not found in sediments with a silt content above 4% (Holland, Greenstreet, Gibb, Fraser, & Robertson, 2005).

During spawning, sandeel leave their burrows and release their eggs on the seabed, where they adhere to sand. The hatching period is long (20-33 days, depending on temperature and oxygen conditions) (Christensen, Jensen, Moesgaard, St John, & Schrum, 2008; Wright, 2009; Regnier, Gibb, & Wight, 2018). During incubation coarse sediment composition also plays a crucial role, as the egg viability (survival) is vulnerable to excessive fine sediment covering. Generally, eggs are released in the same areas as the spawners burrow. After hatching, the larvae transition to a pelagic life, where they drift with the ocean currents. The earliest food source consists of nauplius stages of copepods, and as sandeel juveniles grow, they begin to consume larger copepod stages. The primary food source for adult sandeel consists of the largest copepod stages, and other small organisms such as polychaetes and fish eggs and larvae (Munk, Møller, Warnar, Hintze, & Carl, 2019a).

Sandeel has been chosen for this sensitivity analysis due to their high sediment composition requirements leading to very specific habitats and areas for spawning and foraging, and the eggs and larvae's susceptibility to sedimentation.

Spatial distribution

While sandeel are abundant in the North Sea and estimated to be approximately 15% of the total fish biomass, areas with optimal sediment composition are only limited and patchy. Consequently, sandeel areal densities can be remarkably high (>1000 individuals / m^2) in ideal areas (Jensen, Moesgaard, Rindorf, Dalskov, & Brogaard, 2002). Such areas are shown in the general distribution map, where patchy, close proximity, areas of high sandeel density are spread throughout the Danish part of the North Sea (Figure 5.10.). While sandeel are found within the Kattegat and Baltic Sea (*A. tobianus and H. lanceolatus*) they are in smaller abundances compared to the population in the North Sea. These areas are not represented in the analysis, as there are very few or no well-established abundant sandeel populations or targeted fisheries taking place in the Kattegat and Baltic Sea.

Because the sampling period of the NS-IBTS and BITS are undertaken during the sedentary period of sandeel where they remain partially submerged in the sediment, there is little to no mature adult sandeel caught in these surveys and this data cannot be used to indicate sandeel spawning sites. However, the NSSS provide abundance data on sandeel in the established North Sea habitats, and show a consistent pattern to that of the fisheries distribution (Figure 5.9). Sandeel generally spawn in close proximity to the sediment in which they reside, and their overall distribution can thus be used as a rough approximation of their spawning areas (Christensen, Jensen, Moesgaard, St John, & Schrum, 2008).

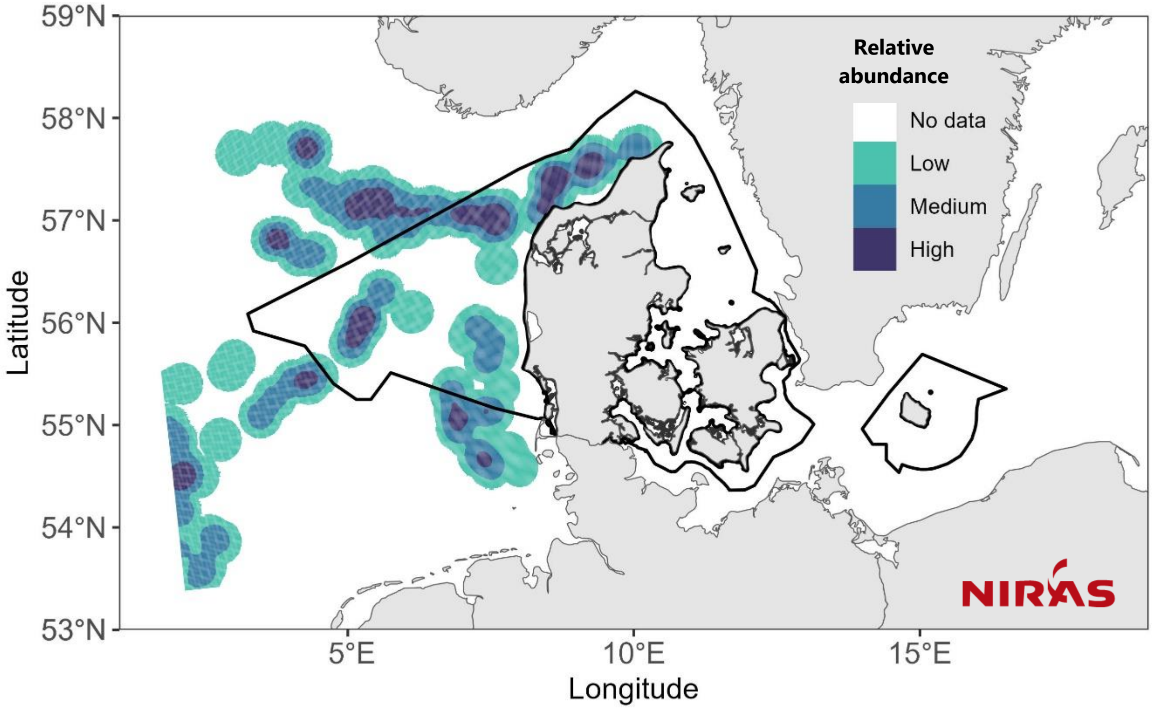


Figure 5.9. Distribution of sandeel (Ammodytes spp.), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The spatial distribution is based on the standardized survey North Sea Sandeel Survey (NSSS) from ICES DATRAS database.

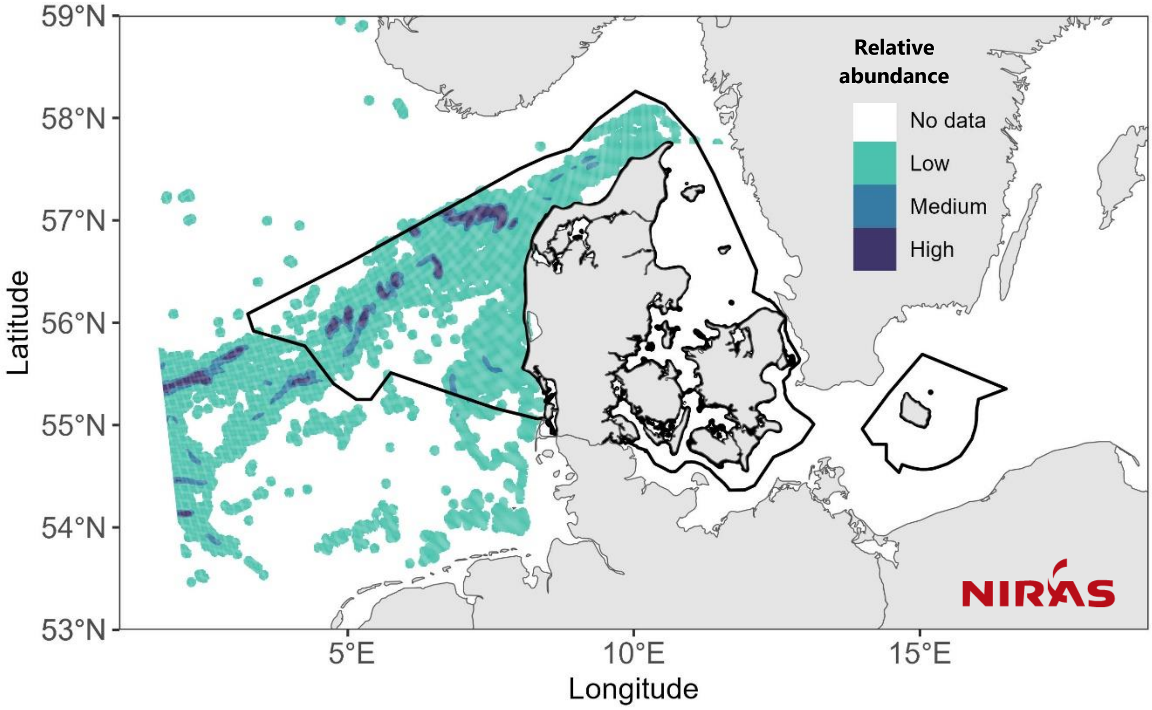


Figure 5.10. General distribution of sandeel (Ammodytes spp.), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where sandeel were in the top three weight of all species caught.

5.3 Flatfishes

Flatfishes (*Pleuronectiformes*) is an order of bony fishes and, as their name suggests, have a distinctive flattened body shape, adapted for demersal life on the seafloor. Their unique morphology allows them to blend into their surroundings, providing them with effective camouflage against predators and enhancing their hunting efficiency. These flat-bodied fish are prominent members of the coastal and offshore-benthic ecosystem, contributing to both ecological dynamics and commercial fisheries. However, they face various challenges, including habitat degradation and fishing pressures, necessitating sensitivity consideration in the planning of Offshore Wind Farm (OWF) projects.

Throughout their life cycle, flatfish exhibit specific habitat preferences. Eggs are typically released pelagically, where they drift with currents before and after hatching into larvae. After hatching, the larvae are morphologically distinct from adults by having a swim bladder for pelagic buoyancy and bilateral symmetry (Munk & Nielsen, 2005; Russel, 1976). Before settling on the seafloor, the larvae undergo extreme transformation through metamorphosis. During this transition, the body widens and flattens, the eyes migrate to one side and the swim bladder is reduced and reabsorbed. The adoption of the characteristic flat shape perfectly adapts the now juvenile individual to a benthic life (Carl & Møller, 2019a; Carl, LeBras, & Ulrich, 2019b).

Juvenile and adult flatfishes are often found in areas with soft/mixed substrates, such as sandy bottoms, where they forage for benthic invertebrates and fish. Often, juveniles have limited capacity to burrow into the sediment but lie on top of muddy and sandy sediments. Adults that can burrow into the sediment, are often not found in sediments with a high composition of silt, as the small particles may obstruct gas exchange by clogging gill filaments (Gibsen & Robb, 1992; Lauria, Vaz, Martin, Mackinson, & Carpentier, 2011). Many flatfishes, especially the coastal European plaice (*Pleuronectes platessa*), common dab (*Limanda limanda*) and European flounder (*Platichthys flesus*), are found in high densities around hard/complex structures (eel grass meadows, boulder reefs, piers, wrecks etc.), where they hunt in the transition zone between soft and hard substrates (Buyse, et al., 2023; Buyse, et al., 2023).

The flatfishes included in this analysis are chosen due to their sensitivity to potential habitat loss (foraging and spawning), and noise and sedimentation impacts on mortality of eggs and larvae, from OWF projects. The flatfish included is European plaice (*Pleuronectes platessa*), European flounder (*Platichthys flesus*) and common dab (*Limanda limanda*), and their specific biology and sensitivity evaluation is described below.

5.3.1 Common dab (*Limanda limanda*)

Spatial distribution

The fisheries-based general distribution for dab shows high sensitivity areas in the northern and southernmost parts of the Danish EEZ. More specifically, the areas with high sensitivity were observed in the Skagerrak, along the Norwegian trench, North of Læsø in the Kattegat and throughout the West Baltic, specifically in Kiel and Mecklenburg bay, including Fehmarn Belt (Figure 5.11). However, when comparing the fisheries-based distribution and the ICES-based adult distribution, there is some inconsistent distribution in the Kattegat and the North Sea. In the Skagerrak and the Kattegat south of Læsø, the two data sources show inverse patterns, where the standardized ICES survey-data show a high fish density/sensitivity throughout the Kattegat, while the fishery based data indicate at most, only a medium sensitivity in a small area of the Kattegat (Figure 5.12.). Dab is not a primarily targeted species in the fisheries but is a common bycatch in demersal fisheries targeting plaice, sole, cod and Norway lobster "nephrops" (ICES, 2019). The ICES-based data shows that adults are distributed throughout much of the Danish EEZ, with several areas of high sensitivity found in in the inner Danish waters. Similarly, areas with medium to high sensitivity are found in patches throughout the North Sea, with a large area found off the Jutland west coast. The Skagerrak and waters around Bornholm seem to be of less importance, with areas primarily being of low sensitivity.

Dab are not known to have any specific spawning areas, but spawn throughout their adult distribution. Density of the pelagic eggs and larvae have been shown to correlate with spawner/adult density and depth, suggesting that important spawning sites are deep areas containing large densities of mature adults (Otterstrøm, 1914). Within the inner Danish waters, the spawning distribution overlaps with the adult distribution, showing areas of medium-high sensitivity classification in most of the Kattegat and West Baltic, including the deep Arkona Basin (Figure 5.13.). The map of spawning adults indicated the North Sea generally had areas of low to medium sensitivity throughout; however, this may not visualize the true spawning pattern, but a statistical artifact where a much higher abundance of spawning adults in the inner Danish waters, skew the lower spawner abundance in the North Sea towards areas that indicate a classification of low sensitivity. Furthermore, dab in the North Sea spawn between April and June, which is a period outside the NS-IBTS survey sampling periods (Q1 and Q3) (Russel, 1976; Munk & Nielsen, 2005). Thus, the true spawning distribution within the North Sea may not be truly presented in the ICES data, due to temporal mismatch between sampling and spawning. Instead spawning in the North Sea could be considered to be represented by the adult distribution. The Juvenile distribution resembles that of the spawning distribution, with the vast majority of juvenile dab found within the inner Danish water, in the West Baltic, Southeast Kattegat and the Sound (Figure 5.14.).

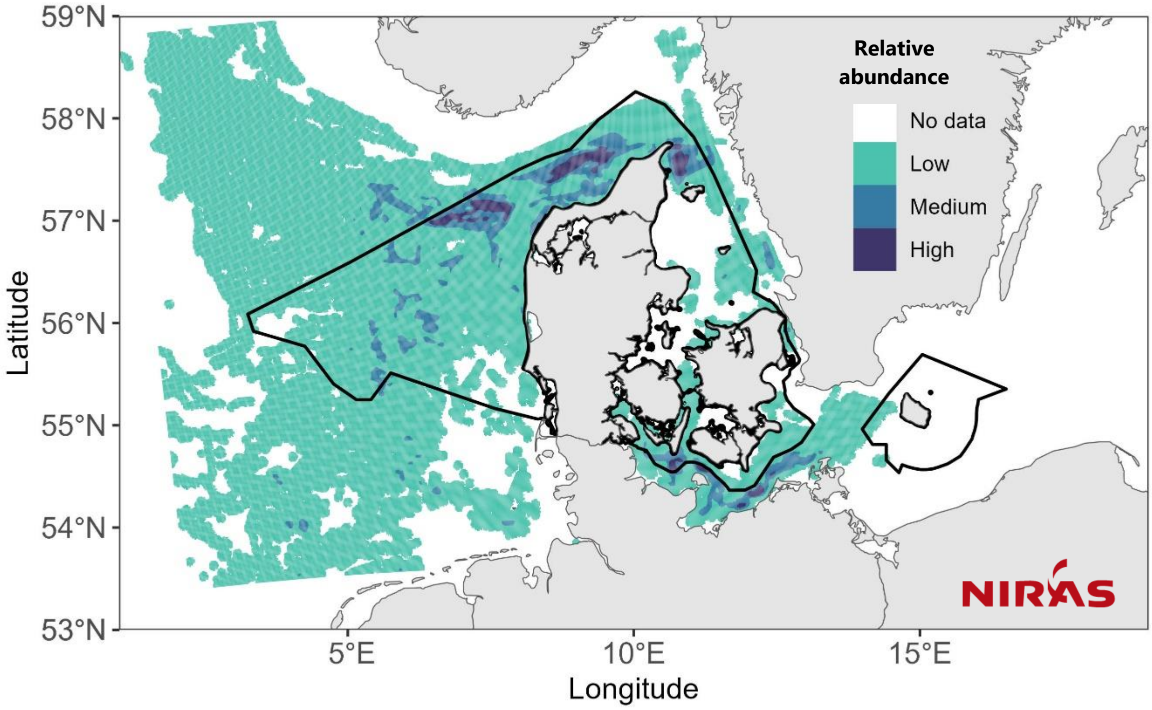


Figure 5.11. General distribution of common dab (Limanda limanda), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where dab was in the top three weight of all species caught.

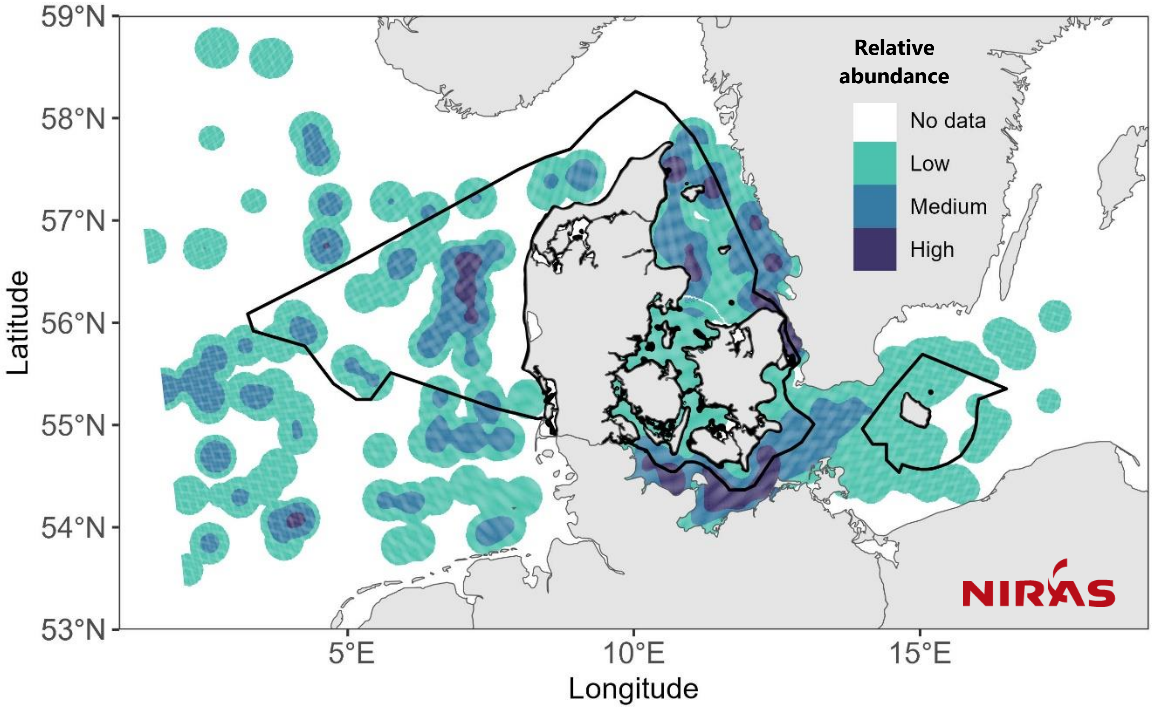


Figure 5.12. Distribution of adult common dab (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the ICES DATRAS surveys.

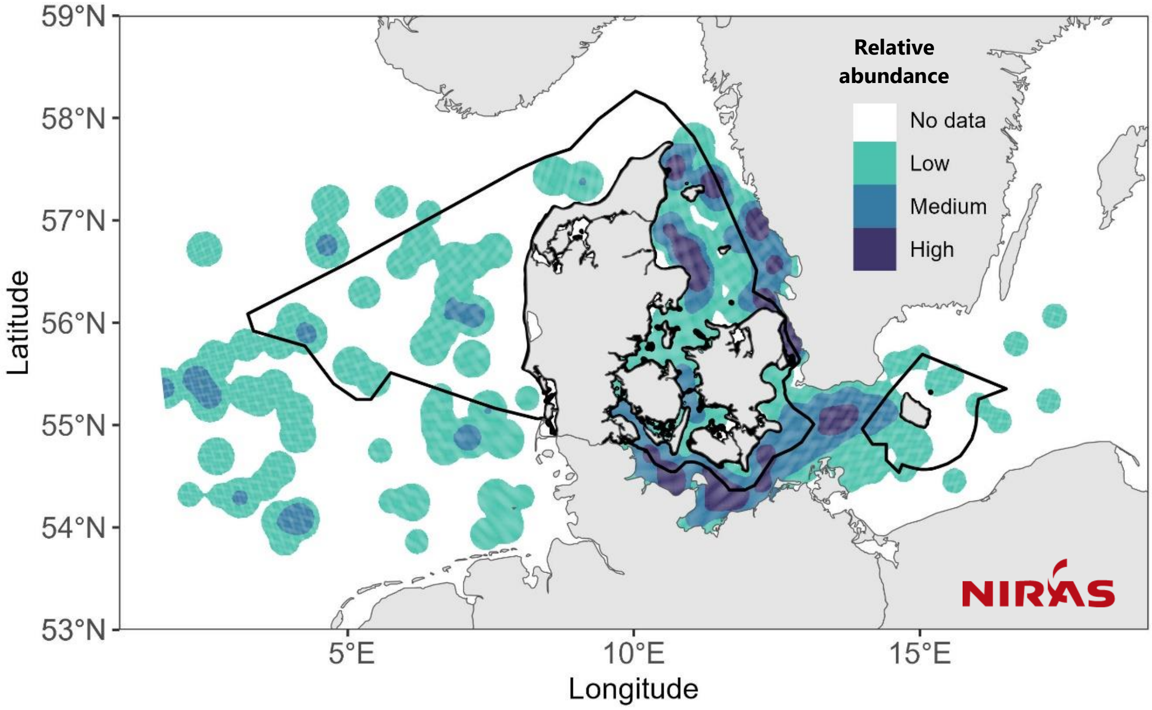


Figure 5.13. Distribution of spawning-ready common dab grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

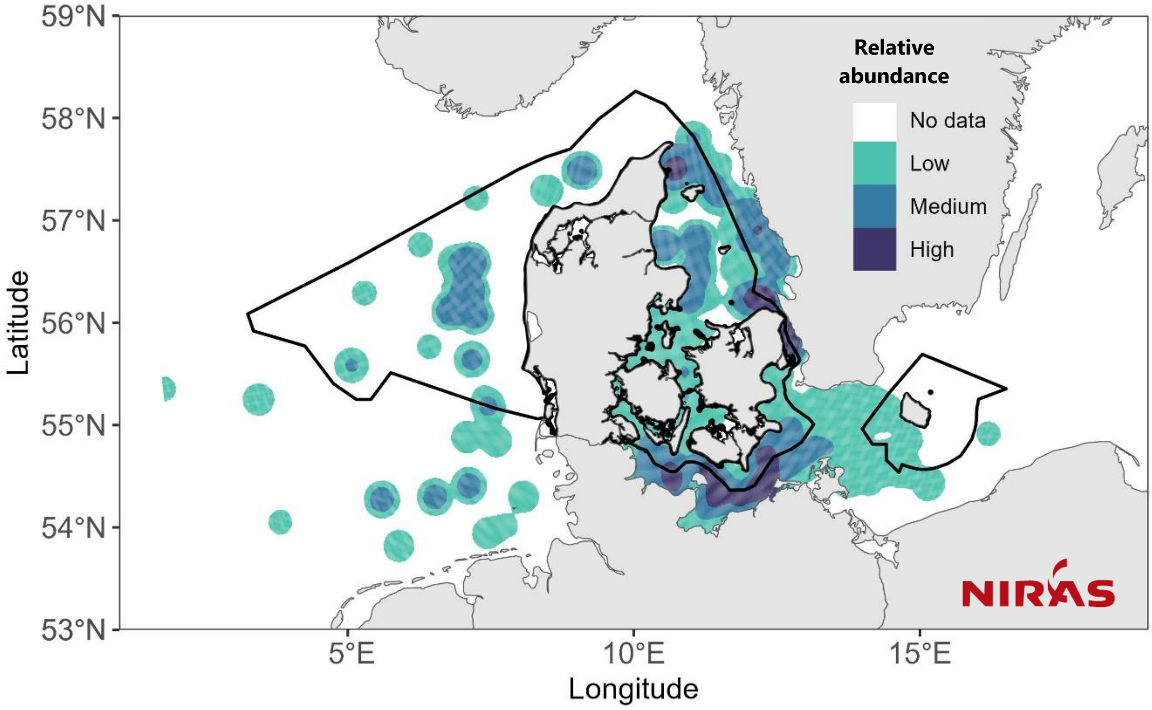


Figure 5.14. Distribution of juvenile common dab, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.3.2 European plaice (*Pleuronectes platessa*)

Spatial distribution

European plaice are distributed throughout the Danish marine territory due to their great salinity tolerance and depth range, which stretch from the coast to 100-200 meters (Carl, LeBras, & Ulrich, 2019b). On the general distribution map, the highest densities were found along the Norwegian trench, generally in areas of greater depths within the North Sea (Figure 5.15.). Within the Kattegat and West Baltic, high density scores were achieved in the southeastern part of Kattegat and around Kiel bight. The adult distribution from the ICES data does not resemble the pattern produced by the fisheries data. Rather than being focused the North Sea, the ICES adult distribution show widespread high sensitivities throughout the Skagerrak, West Baltic, and inner Danish waters, suggesting that plaice may be overrepresented in the fisheries data for certain areas of the North Sea (Figure 5.16.). However, the general and adult distribution correlate in three specific regions: Skagerrak, Southeastern Kattegat and around Mecklenburg Bay. These overlap of high scores from different data sources provide credibility to the assigned sensitivity for the specific regions.

Within Danish waters, there are two distinct spawning stocks that occupy different regions: The southern North Sea and the West Baltic/Kattegat. Often considered the most important is the southern North Sea, where high spawning activity happens at 10-40 meters depth along the Danish, German, and Dutch coast (Carl, LeBras, & Ulrich, 2019b). This correlates with the produced spawning map (Figure 5.17.), where the Southwestern quadrant is estimated as medium-to high density of spawning individuals. Within the Kattegat and West Baltic, high density of spawning fishes is found south of Anholt, Kiel bay, Fehmarn Belt, Mecklenburg Bay, and the waters around Bornholm, supporting the literature consensus of plaice spawning areas in the greater Baltic Sea (Carl, LeBras, & Ulrich, 2019b).

After spawning, the eggs and larvae remain pelagic until settlement, which generally occurs in coastal waters, where the highest initial density is generally found at less than two meters depth (Rijnsdorp, Van Stralen, & Van Der Veer, 1985; Gibson, Robb, Wennhage, & Burrows, 2002). With growth, the juveniles move out to greater depths. The pelagic stages are transported from advection, where offspring of the two spawning stocks often mix within the inner Danish waters, in which they are distributed throughout its entirety. The juvenile distribution map exhibits a pattern of preference for coastal habitats, where most of the inner Danish waters and Skagerrak have high estimated juvenile density (Figure 5.18). In fact, in the Kattegat and West Baltic, medium to highest density was anywhere the ICES surveys sampled. Within the North Sea, the highest observed areas are of medium sensitivity and were only located in two areas west of Ringkøbing Fjord.

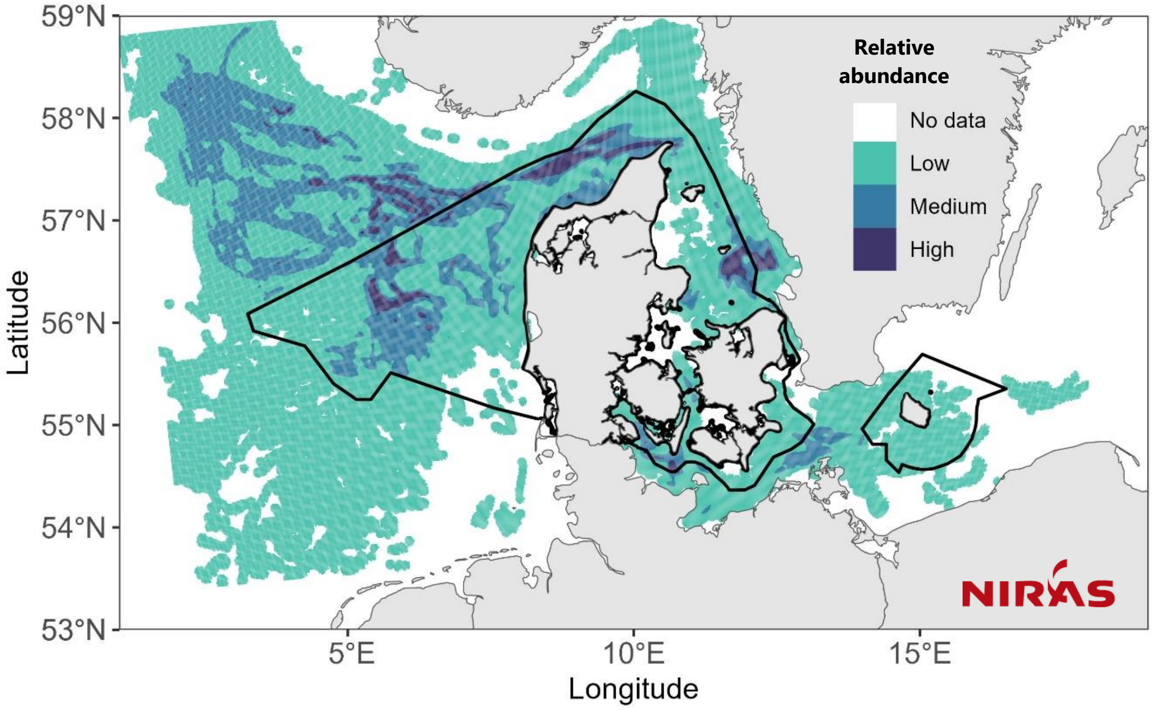


Figure 5.15. General distribution of plaice (Pleuronectes platessa), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where plaice was in the top three weight of all species caught.

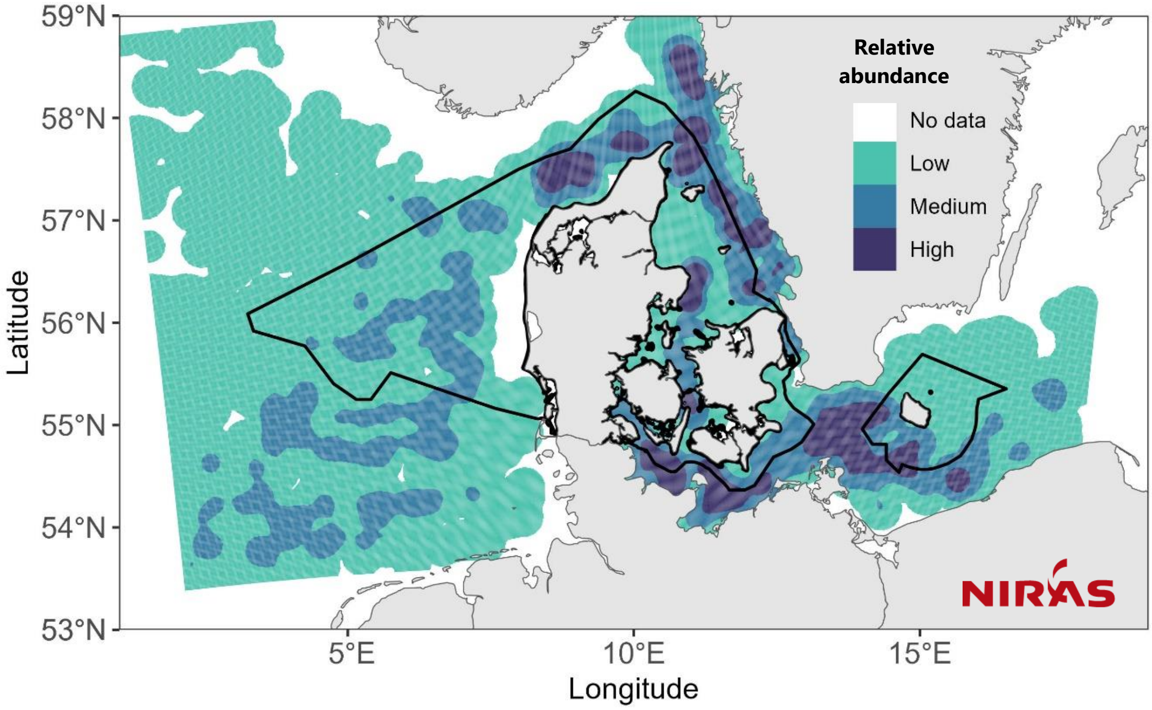


Figure 5.16. Distribution of adult plaice (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the ICES DATRAS surveys.

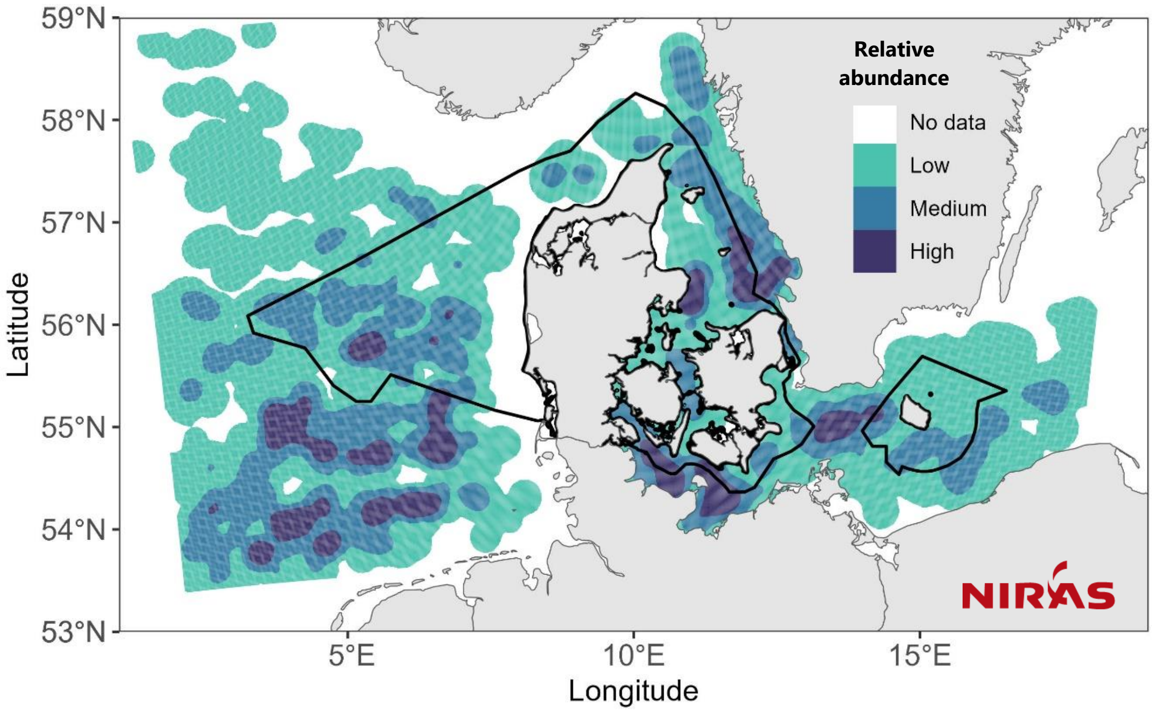


Figure 5.17. Distribution of spawning ready plaice, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

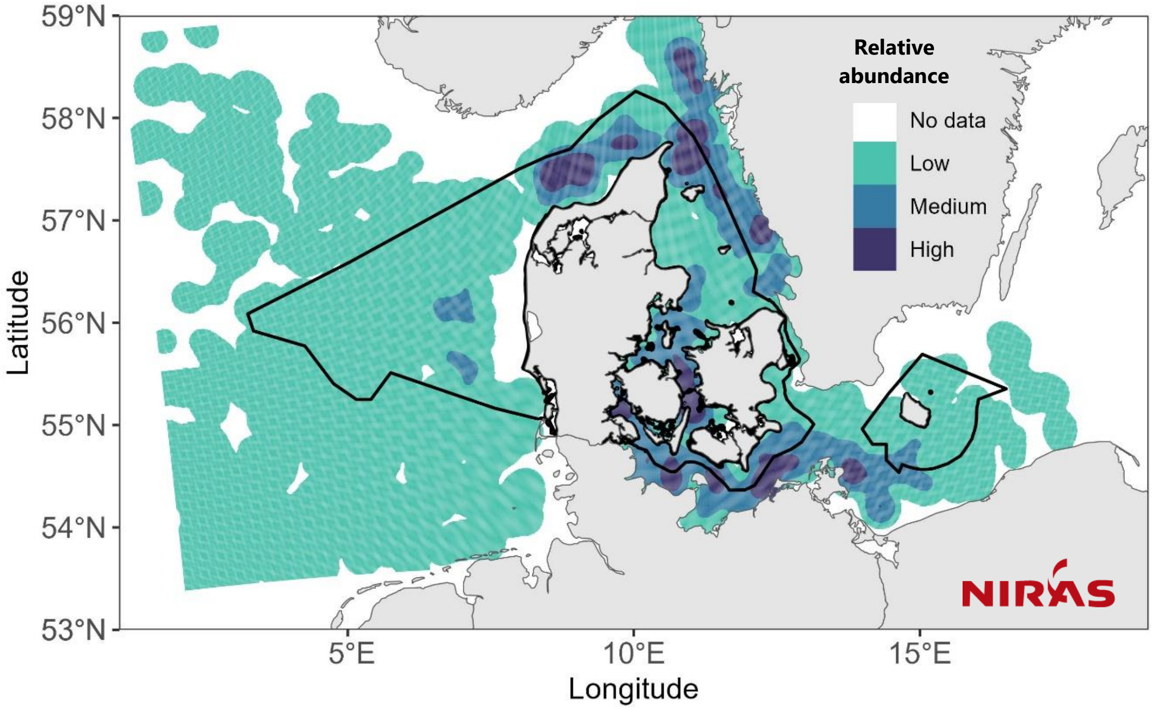


Figure 5.18. Distribution of juvenile plaice, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.3.3 European flounder (*Platichthys flesus*)

Spatial distribution

European flounder is a brackish fish species preferring less saline marine waters, and more often linked to coastal communities compared to the other flatfish species. Within the Danish fisheries, flounder is often not a target species, but a valuable by-catch in benthic and demersal fisheries (ICES, 2023). The general distribution map shows patchy areas of high sensitivity in the Arkona basin and the waters around Bornholm (Figure 5.19.), which is further supported by the adult distribution from the ICES data that shows a similar, although more diffuse, distribution in these areas (Figure 5.20.). The adult distribution also indicates areas of high sensitivity in the Kiel and Mecklenburg bay, as well as a small area north of Öland in Sweden.

Due to European flounder undertaking little to no spawning migration, the distribution of spawning-ready fishes correlates with the overall distribution of adult fishes. High sensitivity spawning areas are located in patches in the Kiel and Mecklenburg bay, Arkona basin, Bornholm waters, Hanö bight and North of Öland (Figure 5.21.).

The juvenile distribution of European flounder differs significantly from the adult and spawning distribution. Although the extent of the areas of low sensitivity are similar to the adult areas across the different ICES-based distributions, areas of high sensitivity for juveniles are only found in the Hanö Bight and north of Öland (Figure 5.22.). Juvenile flounder reside in coastal nursery areas, often found at depths between 1-2 meters. Sampling at these depth ranges is not possible by the bottom trawling sampling methods used by the ICES surveys, and thus juvenile flounder are significantly underrepresented in the ICES data.

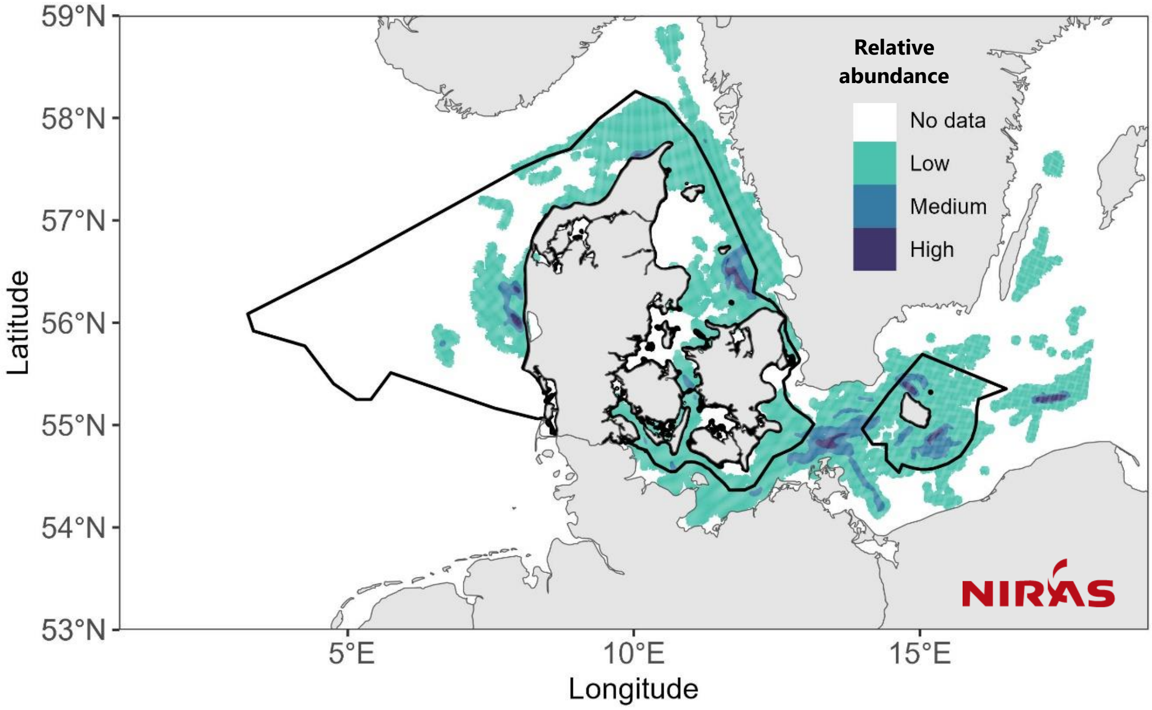


Figure 5.19. General distribution of flounder (Platichthys flesus), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where flounder was in the top three weight of all species caught.

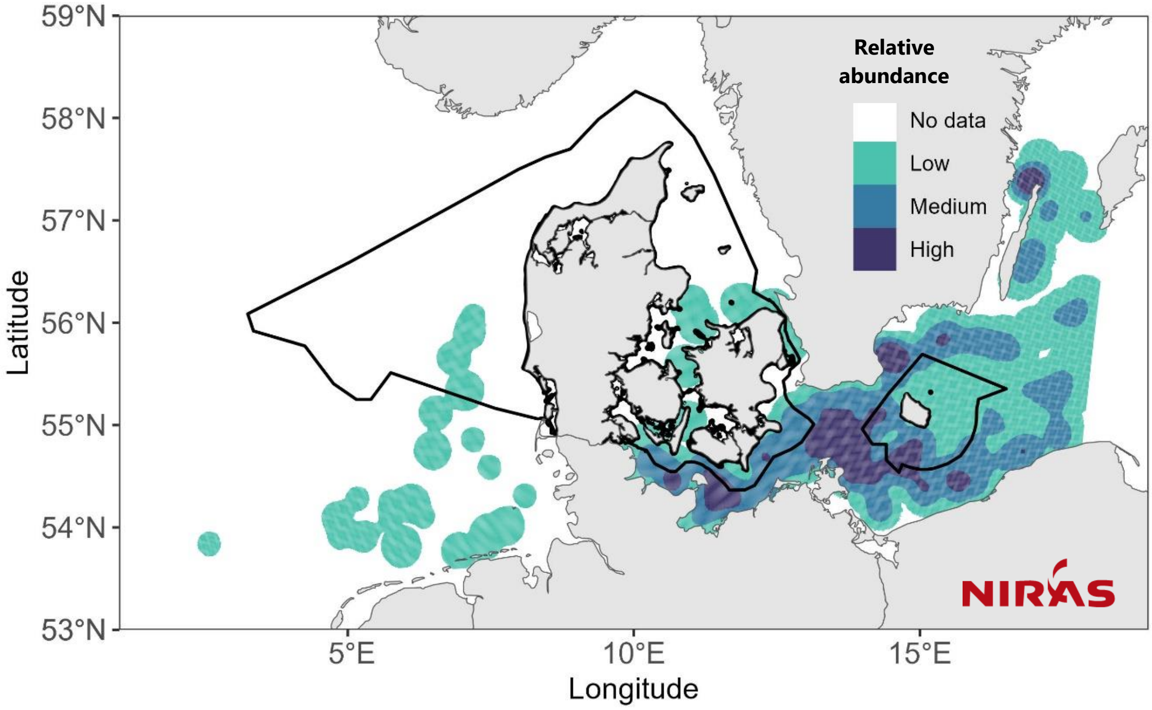


Figure 5.20. Distribution of adult flounder (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the ICES DATRAS surveys.

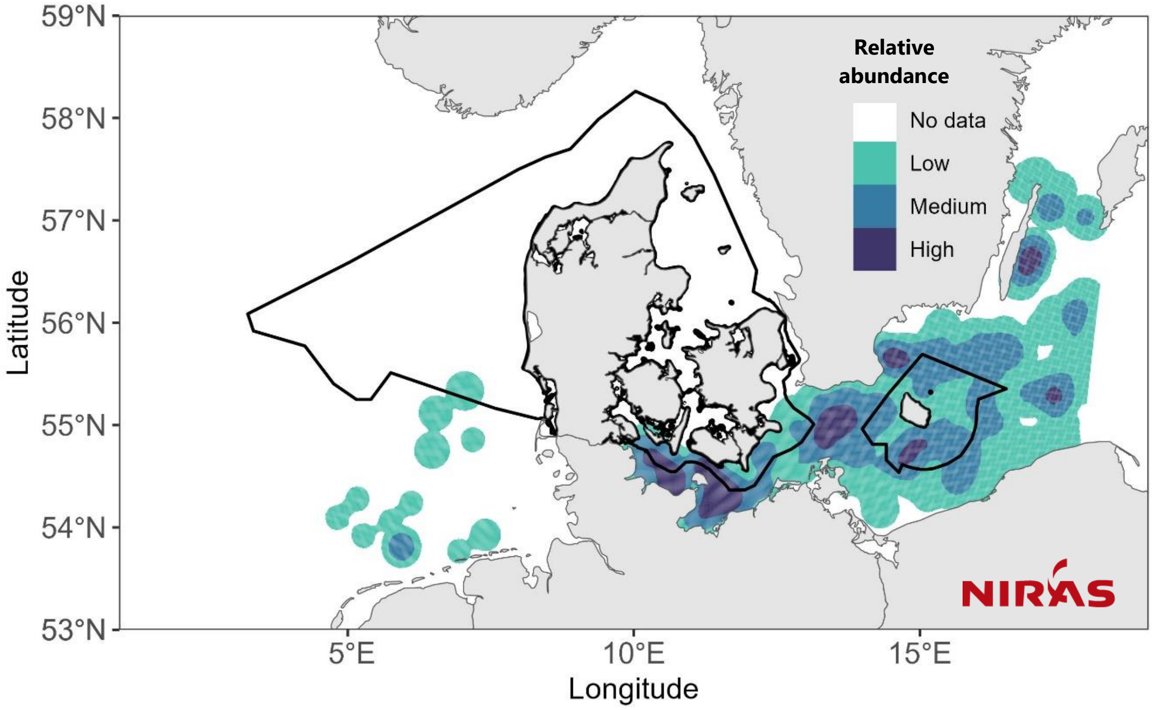


Figure 5.21. Distribution of spawning ready flounder, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

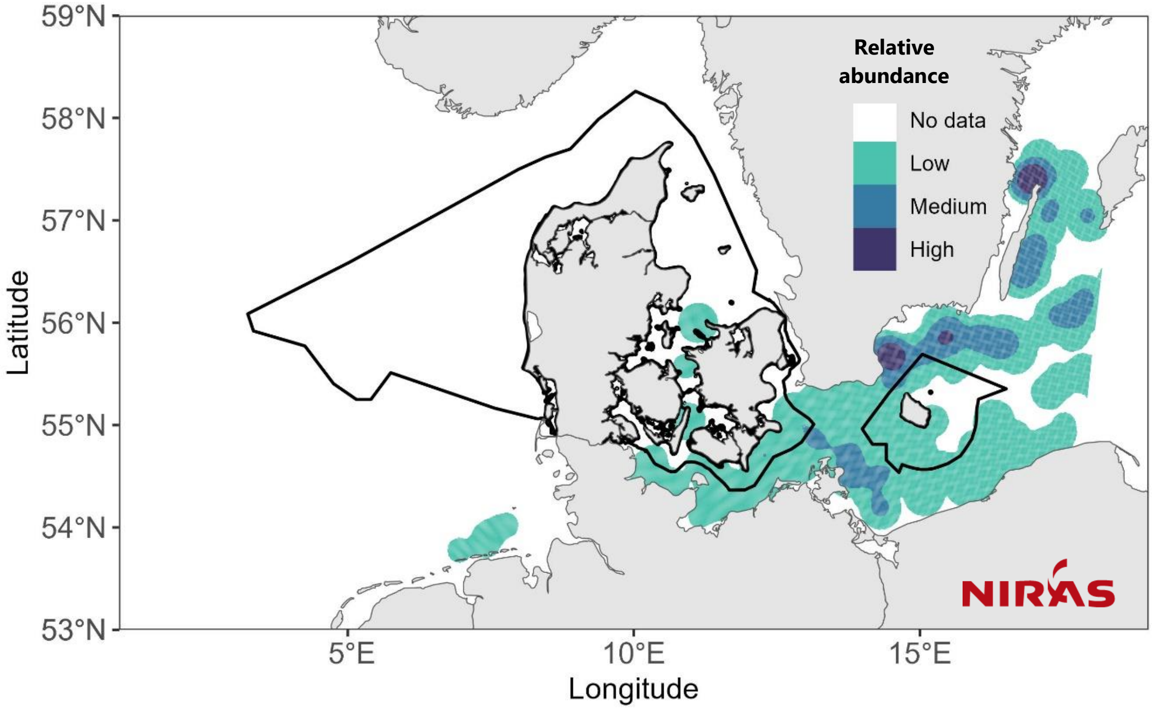


Figure 5.22. Distribution of juvenile flounder, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.4 Clupeids

Clupeids (*Clupeidae*) are a group of small pelagic fishes that are a crucial component of the marine ecosystems in the North Sea, Kattegat, and Baltic Sea. These small, pelagic fish play significant roles in the food web, acting as both prey and predator, and are vital to both ecological balance and the fishing industry in these regions. Clupeids are schooling fishes, and found in enormous aggregations, which in extreme cases have been observed as several km long and wide (Munk & Carl, 2019b). These giant schools have historically been termed herring mountains. Clupeids are filter feeders, primarily consuming planktonic organisms (phytoplankton, zooplankton and fish eggs and larvae), where copepods are a crucial component of their diet (Munk & Carl, 2019b; Hoffmann & Carl, 2019a). With the enormous local densities, their role as predators consuming massive quantities of planktonic organisms help regulate plankton populations and significantly contribute to the energy transfer within the marine ecosystem. As prey, they are a crucial food source for various predators, including larger fish, like cod and mackerel, seabirds, and marine mammals like seals and porpoises.

Within the Danish marine territory, the dominating clupeids are Atlantic herring (*Clupea harengus*) and European sprat (*Sprattus sprattus*). These species are similar in anatomy, morphology and general distribution but differ in certain ecological traits. Herring spawn within coastal communities, where eggs are released and fertilized on sand/gravel bottoms, with a specific range of grain sizes and often with vegetation (Munk & Carl, 2019b). Here eggs remain until hatching, after which they enter the pelagic larval stage. In contrast, sprat spawn pelagically, where they target deeper areas, as the free-floating eggs rely on achieving neutral buoyancy, controlled by salinity (Otterstrøm, 1914; Russel, 1976). While being reproductively isolated from one another, the genetic similarities of these species have been shown to allow viable hybridization in laboratory conditions. Further, herring in Danish waters are a metapopulation, composed of multiple reproductively isolated populations, that spawn at distinct locations and seasons (Munk & Carl, 2019b).

Atlantic herring are known for their acute sense of hearing and are most sensitive to frequencies between 100 and 1200 Hz (Enger, 1967). However, recent studies propose that their sound sensitivity may be far higher, comparable to that of pacific herring (*Clupea pallasii*), which detects frequencies up to 5000 Hz. This ability is crucial for their survival as it helps them avoid predators, such as toothed whales, and communicate with other herring within the school (Simon, Wahlberg, & Miller, 2007). Atlantic herring are also known to produce sounds, which are thought to play a role in schooling behavior and possibly in mating. Their hearing capabilities are well-adapted to their environment, making them highly responsive to auditory cues, and potentially noise pollution, in the ocean. Hearing ability of sprat is poorly studied. However, the morphological structure of the organs linked to hearing in clupeids, have been shown to be remarkably similar to that of herring (Allen, Blaxter, & Denton, 1976). Due to the general morphological and anatomical similarities, the sound sensitivity of herring can be used as a proxy for acoustics in sprat.

Atlantic herring and European sprat were included in this analysis due to their ecological importance and high acoustic sensitivity, which may have both a destructive and disruptive impact on several life stages and behavioral traits, during construction and operation of OWF. Furthermore, increased sedimentation may affect hatch-success of demersal herring eggs, and increased turbidity and suspended material may reduce feeding efficiency of these plankton feeding fishes. life history specific sensitivity assessment and spatial distribution are described for both herring and sprat in the following sections.

5.4.1 Atlantic herring (*Clupea harengus*)

Spatial distribution

The general distribution of herring based on fishery data shows patchy areas of relative high abundance (sensitivity) in the western, northwestern, and northern parts of the Danish EEZ (Figure 5.23.). These areas correlate with the ICES-based adult distribution within the Skagerrak but does not align in the western EEZ, where only medium sensitivity values are observed in the adult distribution (Figure 5.24.). The greatest difference is found in the Kattegat where the general distribution from fishery data only indicates areas of no or low sensitivity, while the adult distribution from ICES data indicates areas of high sensitivity throughout the region. Similarly, the distribution of adults indicates high sensitivity areas south and east of Bornholm along the Polish coast, contrasting with the fisheries data that only show areas of high densities north of Bornholm along the Swedish coast (Figure 5.24). The high sensitivity areas around Öland and Gotland found in the fisheries data, are not present in the ICES data, possibly due to limited ICES sampling, as herring distribution from fishery data is known to extend far into the Baltic Sea.

The herring present in Danish waters originate from one of three distinct spawning populations: the North Sea, the West Baltic, and the central Baltic population. The North Sea population spawn along the eastern coast of Great Britain, from the Shetland islands to the English Channel. However, there is limited spawning in the Danish part of the North Sea, as shown on Figure 5.25.. This contradicts known spawning patterns where spring spawning herring enter the Danish western fjords, such as Ringkøbing fjord, to spawn (Munk & Carl, 2019b). Thus, the methods used to indicate areas of sensitivity underestimate the presence of this spawning stock, presumably due to a lack of coastal ICES sampling. The pelagic larvae produced from this spawning population drift throughout Danish waters, from advection and current flows, where settling larvae and early juveniles occupy coastal nursery areas along the west coast, Skagerrak, and the Kattegat. The presence of these juvenile stages on the west coast can be inferred from the difference in juvenile and spawning distribution.

The West Baltic population spawn along the coast around the Danish islands and German coast, where especially the inner waters around Rügen is of high importance as a spawning site. Interestingly, these areas are portrayed as being low or having no sensitivity, suggesting low spawning importance. Much of this population migrate between the western Baltic spawning areas, and foraging areas in the Skagerrak and Kattegat (Ruzzante, et al., 2006; Munk & Carl, 2019b; Jørgensen, Hansen, Bekkevold, Ruzzante, & Loeschcke, 2005; Jørgensen H. et.al., 2005). The none or low densities of spawning West Baltic herring may be due to limited trawling capabilities in coastal areas and Rügen waters, as well as the sampling period is outside the period of spawning which occurs around Q2 (Jørgensen H. et.al., 2005). While some herring spawn within the Kattegat, the difference between adult and spawning ready herring supports the literary consensus that herring move out of the Kattegat when ready for spawning. The pelagic larvae and later juveniles occupy the coastal areas within the West Baltic and Kattegat – where areas of relatively high juvenile density were only observed throughout the Kattegat region. Finally, the central Baltic herring population generally spawn in coastal areas and east of Bornholm. Like the western Baltic herring , juveniles grow up coastally and slowly move towards greater depths after 1-2 years (Munk & Carl, 2019b). The relatively high juvenile density east of Bornholm correlates with the distribution of the spawning individuals (Figure 5.26). For both the western Baltic and central Baltic populations, the strategy to spawn coastally complicates sampling of mature spawning-ready herring at their spawning sites. Instead, the surveys show an overrepresented number of spawning-ready herring at greater depths, most probably in transit to spawning sites. The mapping of mature spawning-ready herring that spawn coastally may give us a rough estimation of the coastline where spawning by herring may be taking place.

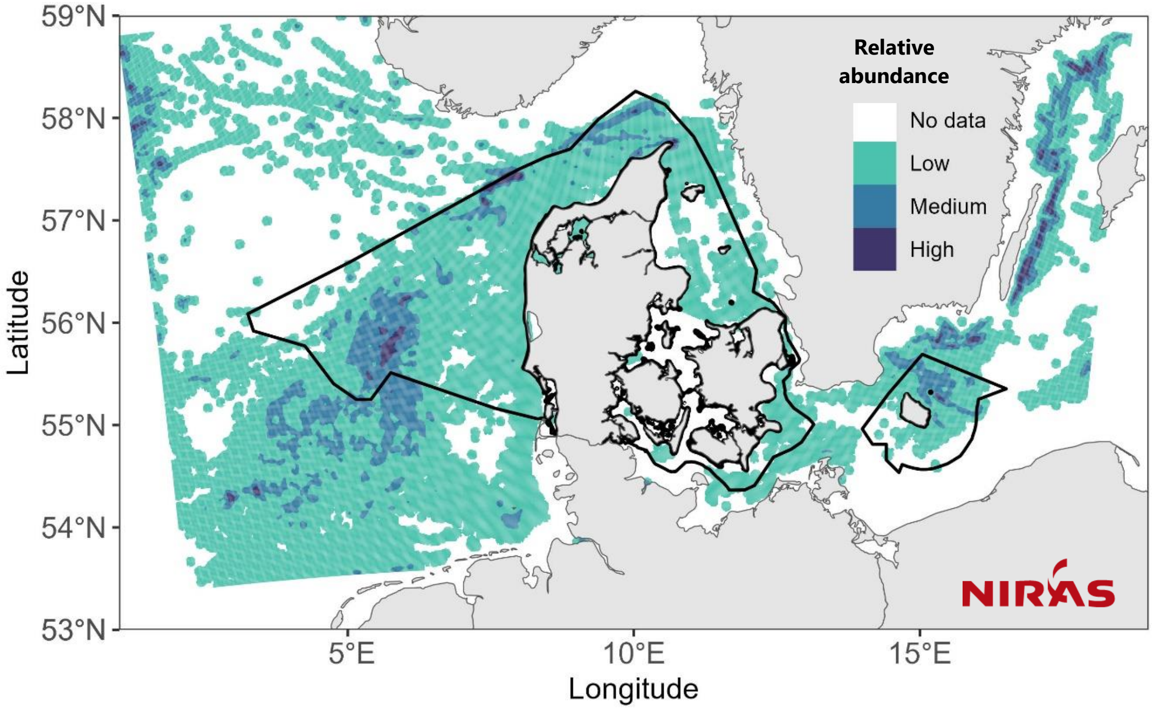


Figure 5.23. General distribution of Atlantic herring (Clupea harengus), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where herring was in the top three weight of all species caught.

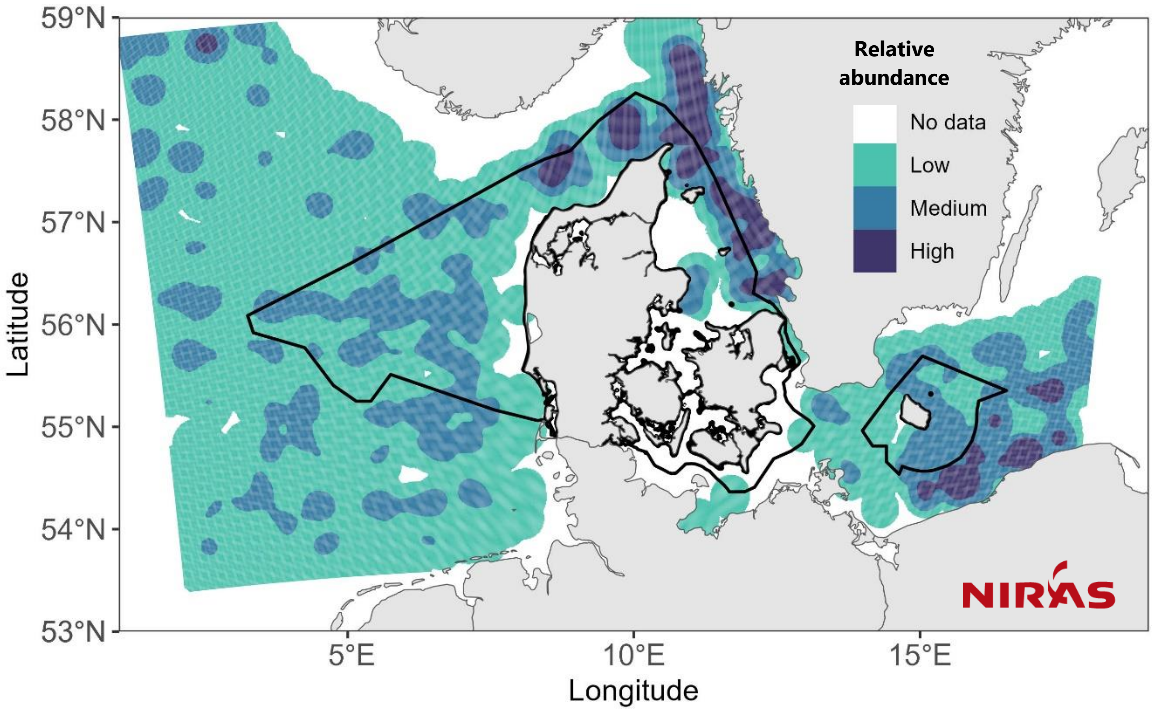


Figure 5.24. Distribution of adult herring (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the ICES DATRAS surveys.

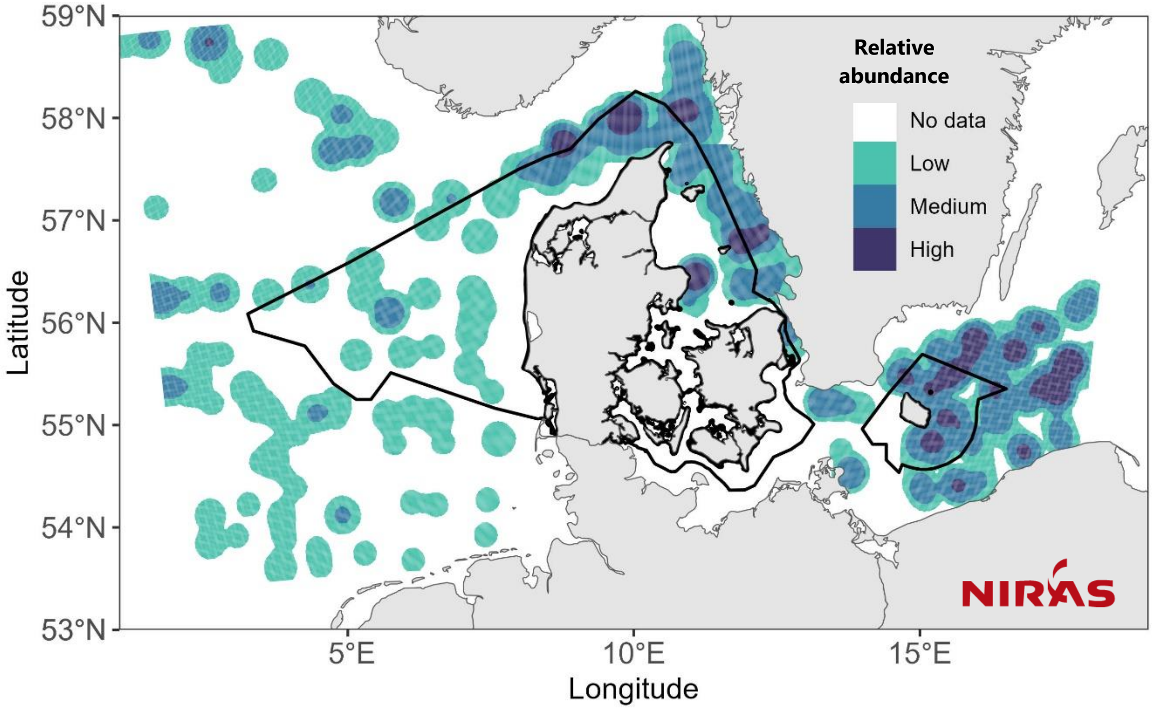


Figure 5.25. Distribution of spawning-ready herring, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

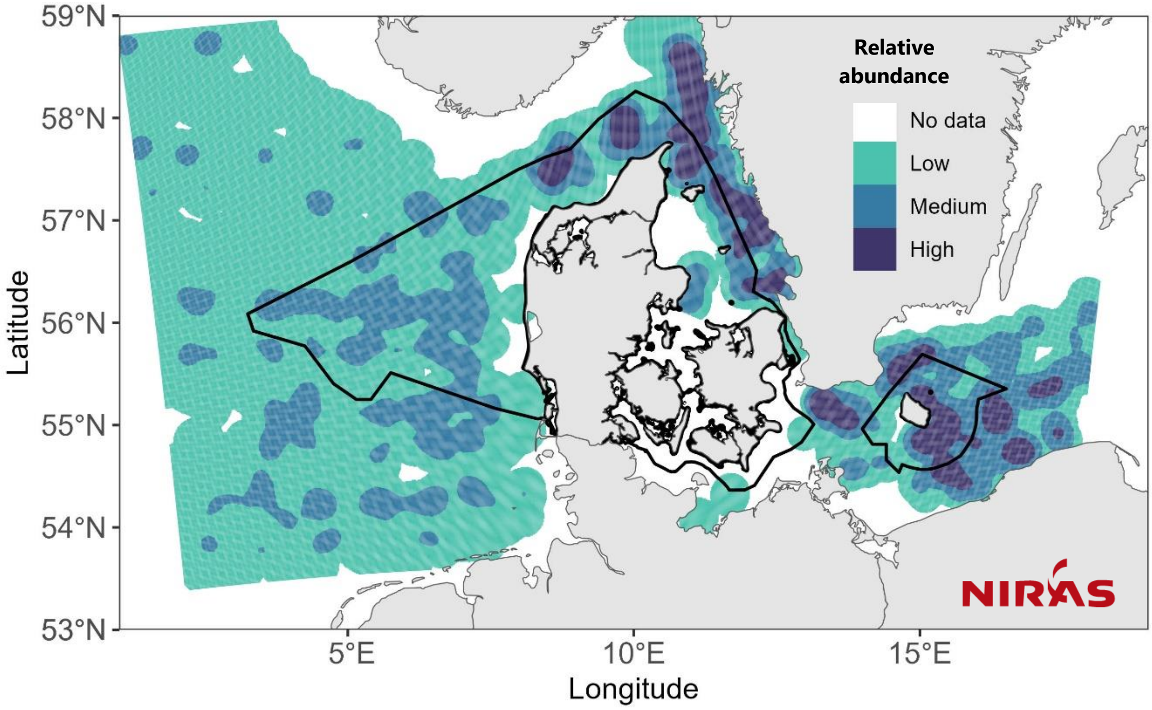


Figure 5.26. Distribution of juvenile herring, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.4.2 European sprat (*Sprattus sprattus*)

Spatial distribution

The general distribution for sprat shows a wide but patchy distribution throughout the North and Baltic Sea. Within the North Sea, the greatest densities were found in the western part of the Danish EEZ as well as the marine waters around Helgoland (Figure 5.27.). Within Kattegat, an area of highest relative abundance (high sensitivity) is found north of Læsø, with little to no presence of sprat in the remainder of the region. Finally, areas of relatively high sensitivity were observed in the waters northeast of Bornholm and in the area around the Swedish islands, Öland and Gotland.

Although more diffusely distributed, the adult distribution of sprat indicates that there is a relatively high density of sprat throughout the Danish waters (Figure 5.28.). Most of the eastern part of the North Sea (Danish, German, and Dutch west coast) has a broad distribution of relatively high sensitivity areas, which extend into the Skagerrak and Kattegat. Kattegat specifically has a large number of areas classified as medium to high sensitivity throughout most of the region. The west Baltic and Arkona Basin is of low importance, according to little to no registration of sprat in both the fisheries and ICES data. The adult sprat distribution according to ICES data shows areas of high sensitivity both south and east of Bornholm. This correlates with the distribution of high sensitivity areas from the fisheries data. However, the areas of high sensitivity around Öland and Gotland derived from the fisheries data, are not present in the ICES data, likely due to limited ICES sampling (Figure 3.2), rather than indicating the end of the sprat's distribution.

Sprat spawning distribution differs significantly from the overall adult distribution, where most spawning-ready sprat are observed in the central-eastern North Sea (Danish, German, and Dutch west coast) and the waters around Bornholm (Figure 5.29.) (Hoffmann & Carl, 2019a). According to distribution maps the Kattegat does not appear to be of importance as a spawning area. Sprat produce pelagic eggs and larvae, thus after spawning, the eggs and larvae are carried away from the spawning site currents through advection (Hoffmann & Carl, 2019a; Munk & Nielsen, 2005; Russel, 1976). Sprat eggs and larvae are carried towards coastal nursery areas, and often transported into the inner Danish waters, i.e., Kattegat. Indications of this pattern can be seen in the juvenile distribution (Figure 5.30.), with areas of high juvenile densities throughout Skagerrak and the Kattegat, similar to the adult distribution. Interestingly, the western part of the North Sea, which generally had adult and spawning areas of high sensitivity, is at most classified as having areas of medium sensitivity for juvenile sprat. Finally, a relatively high density of juvenile sprat was found in several patches east of Bornholm.

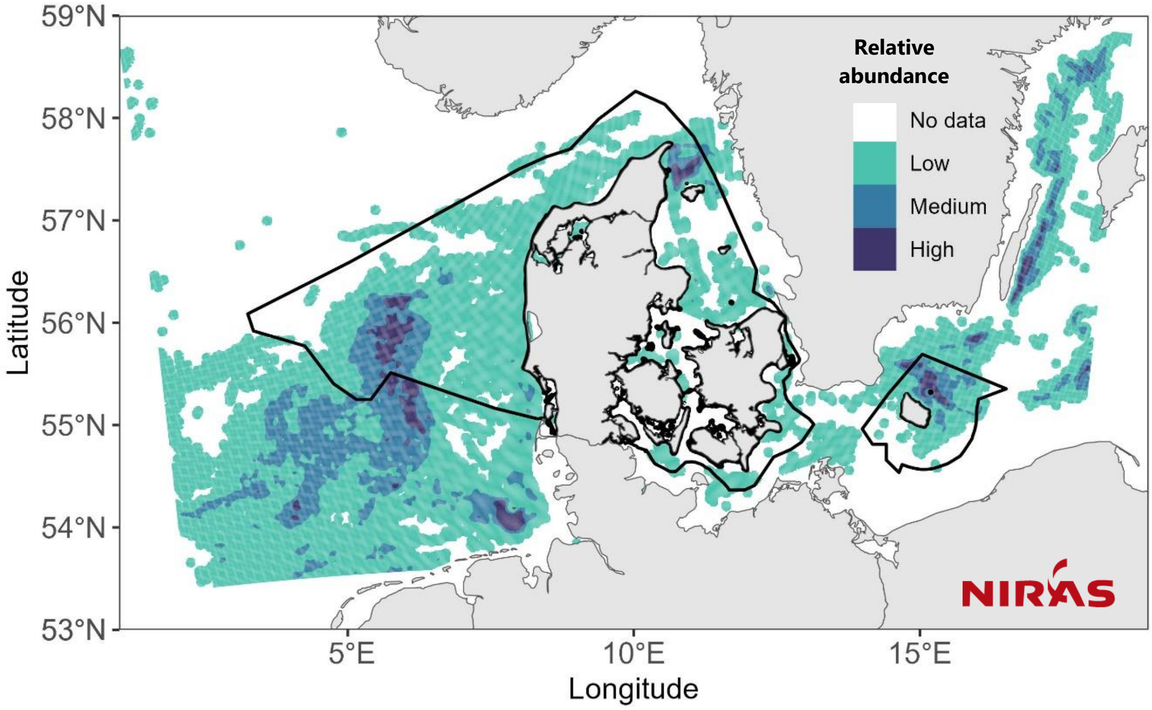


Figure 5.27. General distribution of Atlantic sprat (Sprattus sprattus), grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and include only catches where sprat was in the top three weight of all species caught.

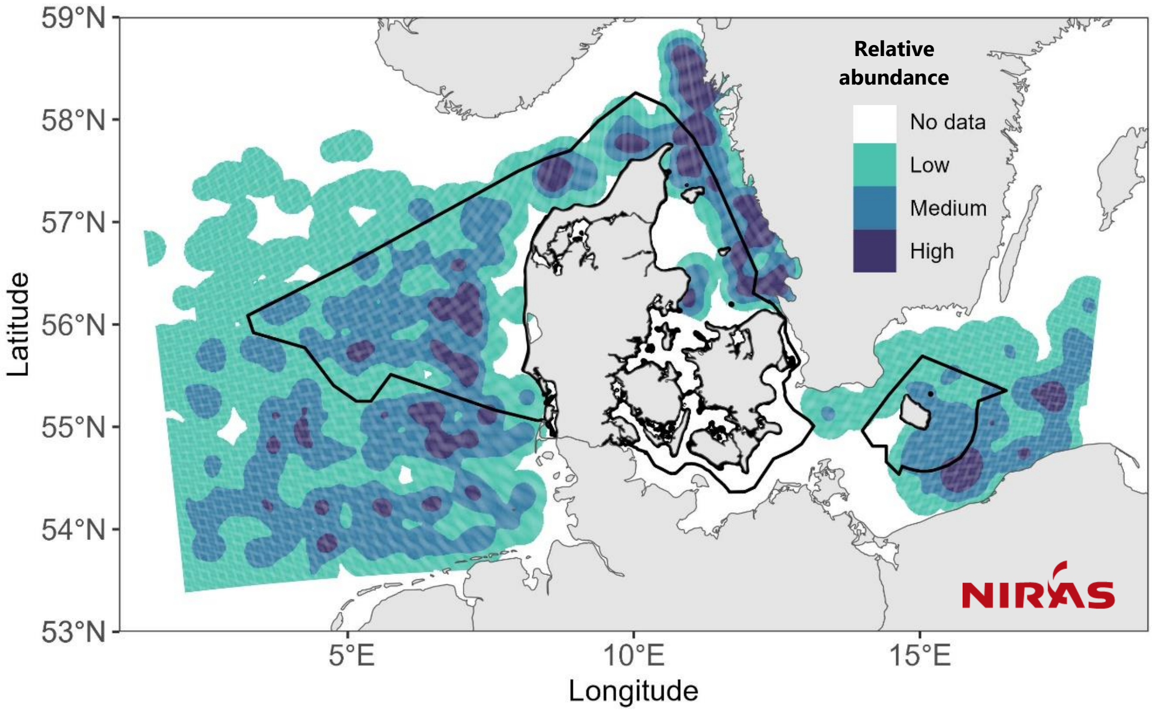


Figure 5.28. Distribution of adult sprat (excluding spawning individuals), grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the ICES DATRAS surveys.

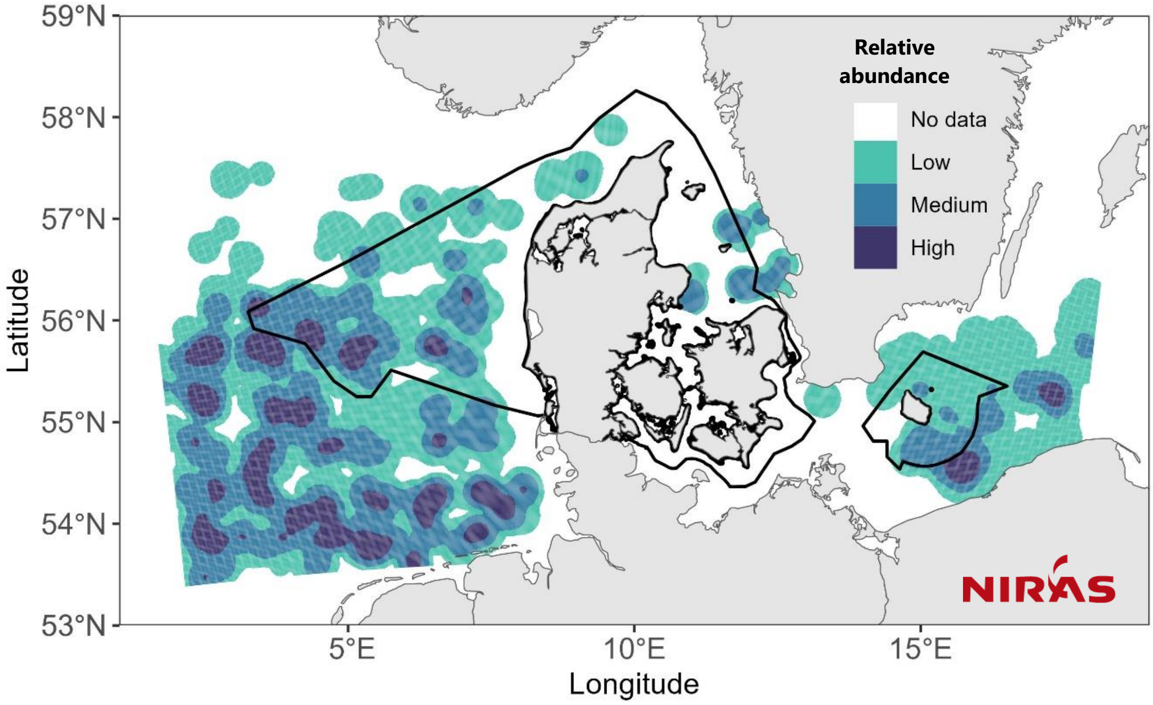


Figure 5.29. Distribution of spawning-ready sprat, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

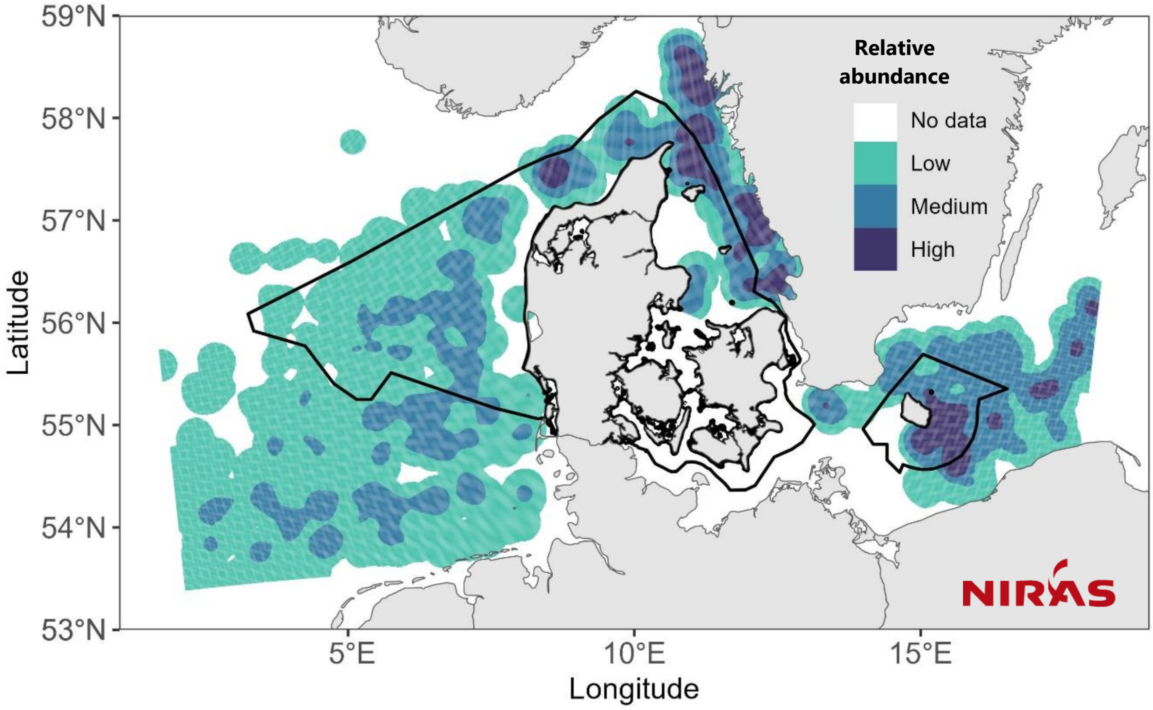


Figure 5.30. Distribution of juvenile sprat, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.5 Elasmobranchs

Elasmobranchs are a subclass of cartilaginous fish that includes sharks, rays, and skates. The diversity within this major phylogenetic group is enormous and stretches from filter feeding species to the second largest fish, basking sharks (*Cetorhinus maximus*), to the small deep-sea velvet belly lantern shark (*Etmopterus spinax*).

Table 5.1: Elasmobranch species and non-taxonomic groups included in the spatial distribution analysis. The fisheries and ICES column signify which dataset each species/group was registered in.

Common name	Scientific name	Fisheries	ICES
Blackmouth catshark	*Galeus melastomus*	x	x
Blonde ray	*Raja brachyura*	x	x
Blue skate	*Dipturus batis*	x	x
Longnosed skate	*Dipturus oxyrinchus*	x	x
Norwegian skate	*Dipturus nidarosiensis*	x	
Spiny dogfish	*Squalus acanthias*	x	x
Porbeagle shark	*Lamna nasus*	x	
Sailray	*Rajella lintea*	x	
Small-eyed ray	*Raja microocellata*	x	
Small-spotted catshark	*Scyliorhinus canicula*	x	x
Spotted ray	*Raja montagui*	x	x
Thornback ray	*Raja clavata*	x	x
Tope shark	*Galeorhinus galeus*	x	x
White skate	*Bathyraja spinosissima*	x	
Starry smooth-hound	*Mustelus asteria*		x
Common smooth-hound	*Mustelus mustelus*		x
common stingray	*Dasyatis pastinaca*		x
Thorny skate	*Amblyraja radiata*		x
Shagreen ray	*Leucoraja fullonica*		x
Cuckoo ray	*Leucoraja naevus*		x
Velvet belly lanternshark	*Etmopterus spinax*		x
Non-taxonomic groups			
Catsharks, nurse/smooth-hounds sp.	-	x	x
Rays, stingrays, skates, mantas sp.	-	x	x

Elasmobranchs occupy most habitats, where rays and skates generally are benthic on soft sediments, while sharks are found throughout the water column, and utilize both soft, hard, and complex habitat types. Compared to other fishes, elasmobranchs have a very long generation time (>10 years), which in combination with slow growth and low fecundity, makes their populations sensitive and environmental changes and exploitation (Fisk, Miller, & Fogarty, 2001). Recovery from population declines can be slow, emphasizing the need for sustainable management and conservation efforts to protect these species. Furthermore, many elasmobranchs lay eggs on the seafloor (demersal spawners), where eggs often develop without parental care for extended periods of time (6-12 months) dependent on species (Tokunaga, Watanabe, Kawano, & Kawabata, 2022). This long development time makes benthic elasmobranch eggs vulnerable to pressures such as increased sedimentation, as burial of their egg cases reduce oxygen availability and hinders development, which may be of concern in the construction phase of OWF. Elasmobranchs also have a specialized and sensitive sensory organ called the 'ampullae of Lorenzini', which allows the detection of electromagnetic fields (EMF). This sensory system is also known as electroreception. Electroreception is utilized for predation, by detecting weak bioelectric signals in prey's nervous system, and navigation in migrating species by detecting geomagnetic fields for orientation (Paulin, 1995). The multiple sub-surface inter-array and export cables from establishing OWF's produce electromagnetic fields that potentially complicate local elasmobranchs predation and navigation ability.

As a result, elasmobranchs have been included in the sensitivity analysis due to their long, low fecundity, generation time, early life sensitivity to sedimentation and their extremely sensitive electroreception, all of which may be affected during the construction and operation of OWF's.

Elasmobranch species within Danish waters have for this report been grouped, as there is only limited data on the distribution and abundances of the different species from this group, which are typically constituted by small populations that are not targeted or caught in large amounts in the fisheries or ICES surveys limiting data availability for species-specific analysis. Furthermore, due to poor taxonomic precision, especially from the fisheries data, many elasmobranchs from fishery data were included in non-taxonomic groups (Sharks sp. and rays sp.). An overview of the included species/groups are presented in Table 5.1. As most sharks and rays registered in the fisheries data are from by-catch, the fisheries data were not filtered to only include elasmobranchs if they were in the top three catches by weight, as was done in the other fishes (see section 3.3).

Spatial distribution

Overall, the extent of the general distribution patterns illustrated by the fisheries data do not correspond with the more limited distribution patterns observed from the ICES database. The fisheries-based distribution indicates areas of relatively high densities along the Norwegian trench and the deeper parts of Skagerrak, and areas of relatively low densities throughout the North Sea and shallower areas of the Skagerrak (Figure 5.31:). This pattern also corresponds to the fisheries pattern for cod and haddock (Figure 5.1 and Figure 5.5), suggesting that observed elasmobranchs are a product of being by-catch from bottom trawling in the Skagerrak region. The ICES distribution shows a slightly different pattern with the most elasmobranchs registered in the middle and northern North Sea and parts of Skagerrak (Figure 5.32:).

However, while fisheries data and ICES survey data indicate differences in their portrayal of where areas of highest-density (high sensitivity) are observed, the distribution plots show some overall similarities in distribution, particularly in the low abundance of elasmobranchs when moving towards the Baltic Sea, where salinities and depths are significantly lower than the North Sea.

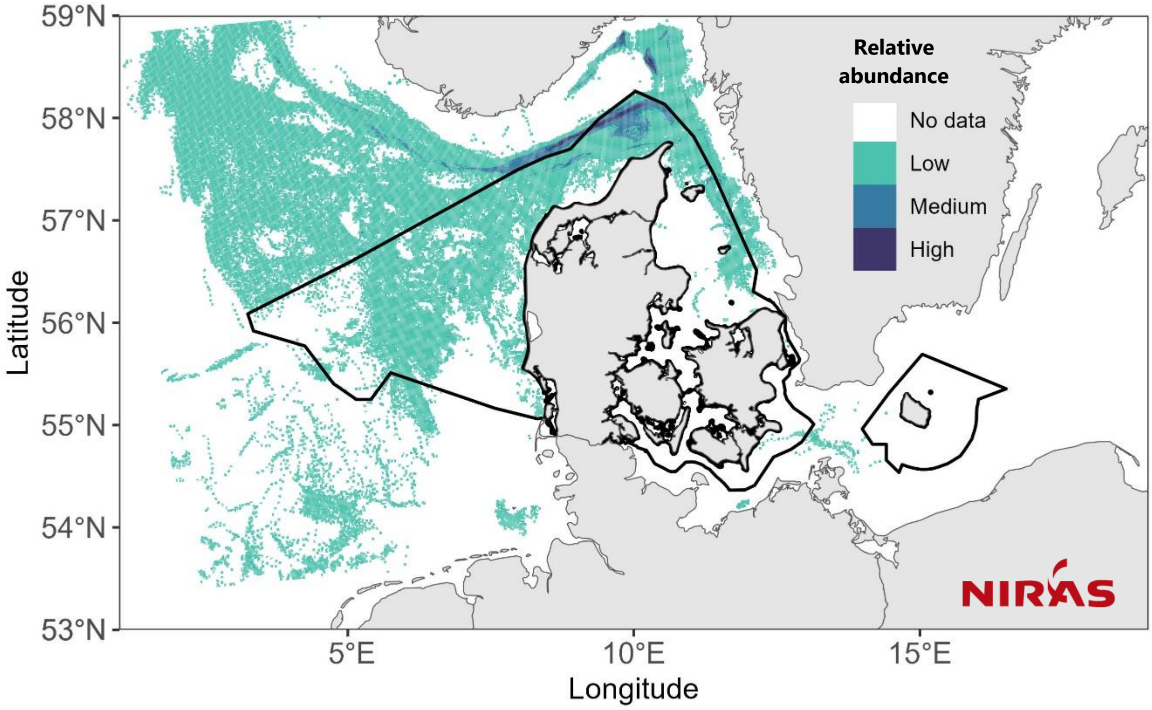


Figure 5.31: General distribution of elasmobranchs, grouped into three relative abundance categories, dependent on areal density: Low, medium, and high. The general distribution is based on fisheries data, from Danish vessels above 12 meters, and including all catches of elasmobranchs.

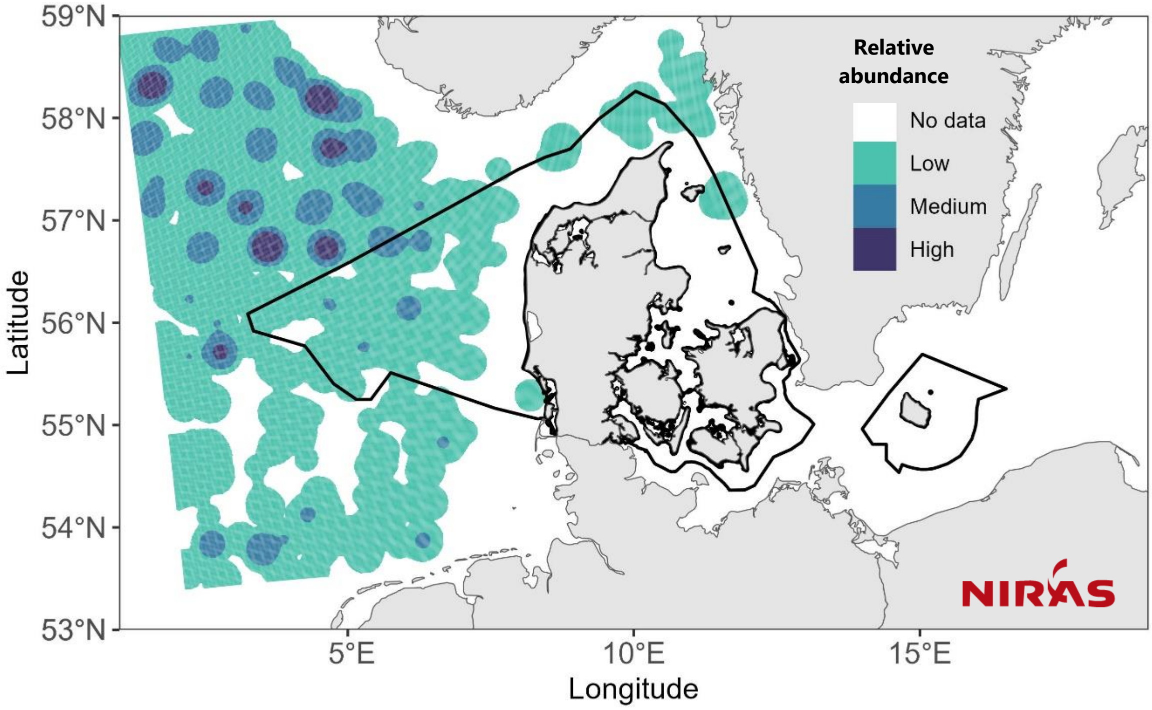


Figure 5.32: Distribution of elasmobranchs, grouped into three relative abundance categories, based on areal density: Low, medium, and high. This distribution is based on maturity data from the standardized surveys from ICES DATRAS database.

5.6 Endangered and protected species

Among the vast amount of full/semi-marine fishes in Danish waters, few are significantly protected from legislations, such as Annex II and IV of the European Habitat Directive. Annex II protects a selection of fishes within Natura 2000 areas: Twaite shad (*Alosa fallax*), Allis shad (*Alosa alosa*), sea lamprey (*Petromyzon marinus*), Houting (*Coregonus oxyrhynchus*) and sturgeon (*Acipenser sturio*). The latter two, Houting and sturgeon, are further protected by the Annex IV, meaning that they are fully protected throughout their distribution, within European waters. The protection of these species is due to conservation status, generally based on low population size. While these species may potentially be sensitive to the impacts imposed by OWF, there is limited research to base an assessment on the effects of these pressures. Twaite shad and Allis shad are close relatives of herring and sprat and may thus share a higher sensitivity to noise during the construction phase. Sea lamprey, sturgeon and houting are all species that alternate between fresh and salt water for migration or foraging and may utilize the earths electromagnetic field for navigation – which may be disturbed during the operational phase of OWF. However, the sensitivity and physiological capabilities of these species needs to be further researched, and their low abundance (small population size) and lack of representation in fishery and survey data are not enough to make quantitative or qualitative estimations to map the distribution and areas of sensitivity for any of these species. Therefore, while protected species are crucial to consider in the screening of the OWF potential within Danish waters, the inclusion of these were not possible from the present data availability.

6. Pressure-specific sensitivity mapping

The following section introduces mapping of the most sensitive areas based on the fish and fish components that are affected by the primary pressures from construction and operation of OWF (sediment spillage, increased underwater noise produced during wind farm construction and operations, habitat loss from installations and scour protection and Electromagnetic fields (EMF) created around operating wind farm cables). Finally, an overall pressure-specific sensitivity map is produced to give a consolidated overview of sensitive areas based on the spatial distribution and abundance of the sensitive fish species/groups chosen for this analysis.

Underwater noise

The construction and operational phase of OWF imposes different pressures with regard to increased noise levels. During the construction phase of offshore wind farms (OWF), pile driving during foundation installation can create the most intense underwater noise and may pose risks to fragile early life stages (eggs and larvae) of fishes and species with pressure-sensitive anatomical structures, such as swim bladders, potentially causing harm, displacement or disruption of communication. The relevant fish species and early life stages included in the noise (construction phase) sensitivity map includes all fish species/groups with swim bladders (cod, haddock, herring and sprat), as well as spawning maps for species that produce pelagic eggs and larvae (cod, haddock, sprat, plaice, flounder and dab). In contrast, less intense low frequency noise during the operational phase is not expected to be at harmful sound intensities but may disrupt external interactions within and between species that communicate through acoustical means, both in terms of general communication and during spawning. Among fish species cod, haddock, sprat, and herring may be particularly sensitive to underwater noise, as they utilize vocal communication amongst conspecifics, especially during the spawning period. Thus, all life stage maps of the species cod, haddock, herring, and sprat are included in the noise (operational phase) sensitivity map. Interestingly, within the Danish EEZ the sensitive maps for noise in the construction and operational phase are very similar, with several relatively large areas of relatively high-sensitivity observed along the Danish EEZ border in the Skagerrak and Kattegat, and in nearly the entire area of the Sound (Figure 6.1 and Figure 6.2) between Zealand (Sjælland), Denmark and Skåne, Sweden. The relatively high-sensitivity areas throughout the Kattegat and the Skagerrak are represented by spawning areas and the general distribution of the aforementioned clupeids and gadoids, while the areas of relatively high-sensitivity in the Sound represents an important spawning area of cod, which further extends into the southeastern Kattegat. The only significant difference between the maps depicting the pressure-specific sensitivity to underwater noise during the construction and operational phases are found off the north-eastern shore of Jutland, where relatively high densities of foraging and spawning dab and plaice were observed in the data (Figure 5.12., Figure 5.13., Figure 5.16., Figure 5.17.). This area is dominated by shallow sand substrate habitats, generally dominated by flatfishes, which is further supported by these areas representing highly sensitive areas in dab, and plaice, which have a high preference for this type of habitat. However, while a high density of spawning individuals was found in this area, it is not particularly known as a high-fidelity spawning area for these species.

Outside the Danish EEZ, close to the border, there is several large high sensitivity areas in the Mecklenburg Bight, Arkona basin and waters around Bornholm. These areas are important foraging and/or spawning areas for nearly all gadoids (except for haddock), clupeids and flatfish species included in this report. The most noteworthy high sensitivity areas outside the Danish EEZ are the Mecklenburg Bight and the Arkona Basin (Figure 6.1), which are considered crucial spawning areas for dab (Figure 5.13.), flounder (Figure 5.21.), plaice (Figure 5.17.) and cod (Figure 5.3) and are the primary source of offspring in the western Baltic populations of these species. While these areas are outside the Danish EEZ, the potential effect of pressures from the construction and operation of offshore windfarms positioned close to the border, may influence species distribution and reproductive fitness in these areas.

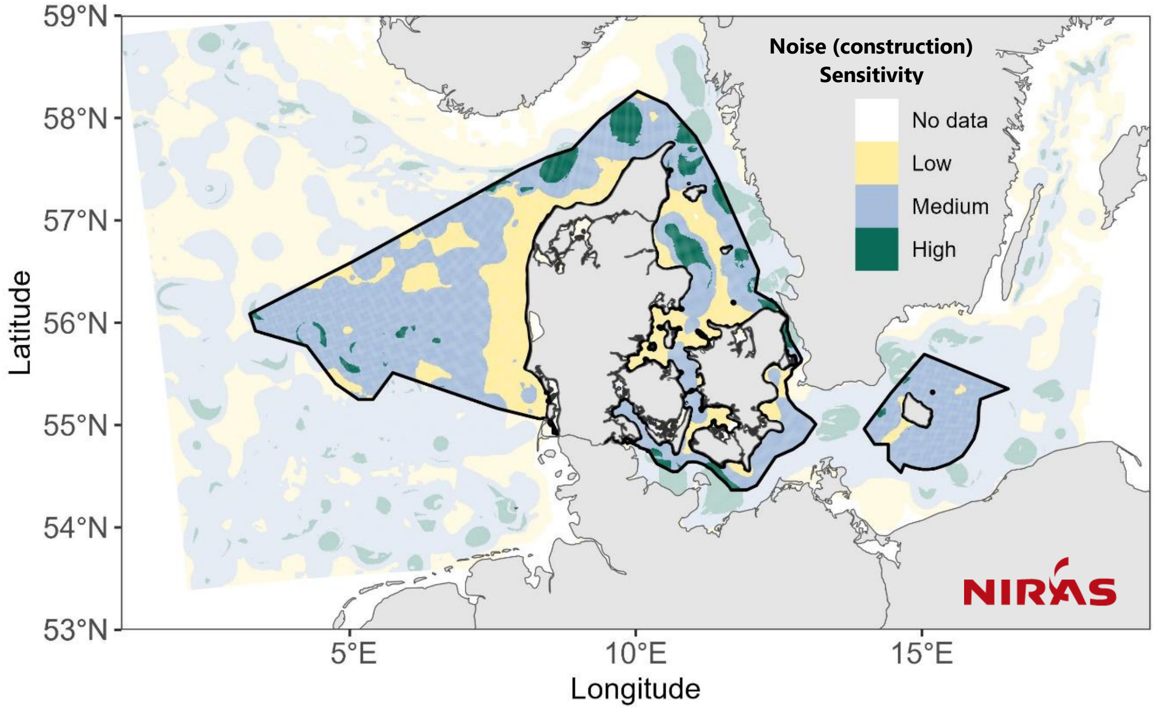


Figure 6.1. Pressure-specific map showing the distribution of fish species and the relevant life stages sensitive to an increase in noise during the construction phase. These scores are calculated by the previously described alternative weight-means protocol, analyzing noise (construction phase) sensitivity scores of the species described in Table 4.1.

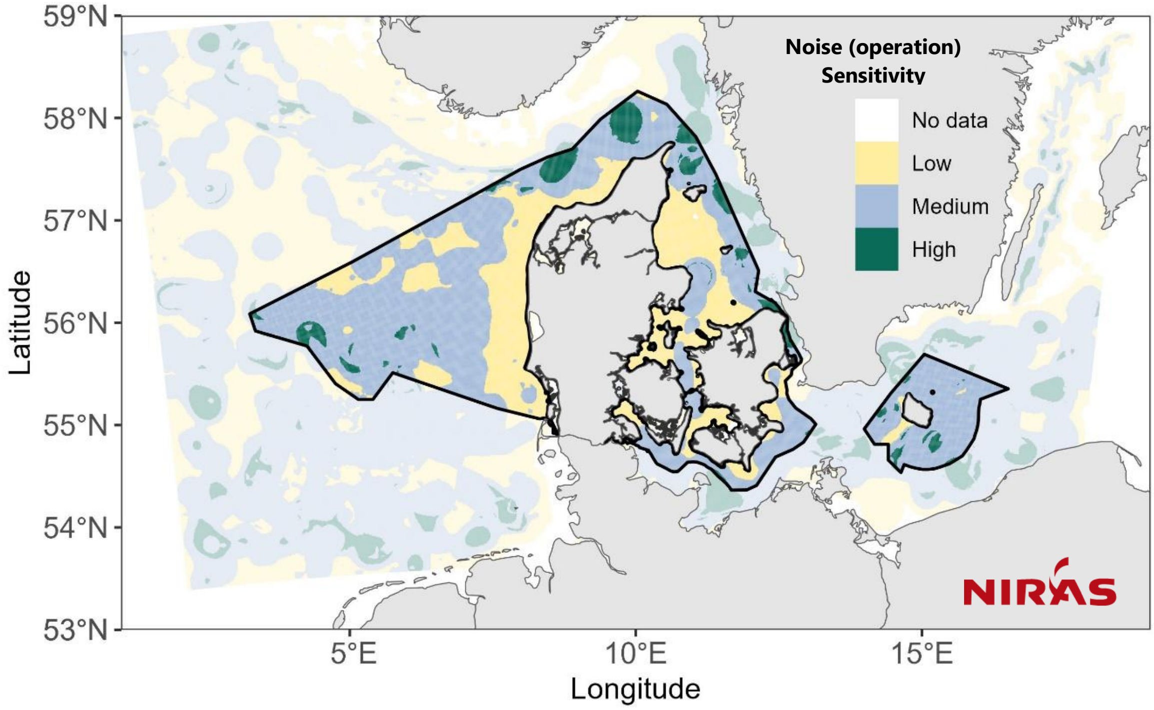


Figure 6.2. Pressure-specific map showing the distribution of fish species and the relevant life stages sensitive to an increase in noise during the operational phase. These scores are calculated by the previously described alternative weight-means protocol, analyzing noise (operation phase) sensitivity scores of the species described in Table 4.1.

Suspended sediment and sedimentation

An increase in suspended material in the water phase during the construction of OWF are expected to temporarily decrease fitness of pelagic species and life stages, through potentially reducing foraging and prey detection of larvae and adult stages, gill-filament clogging of filter-feeding species (herring and sprat) as well as increased mortality of eggs due to sinking caused by suspended adhesion. Furthermore, an increase in suspended material in the water phase will cause displacement of sensitive fish as they move away from areas of increased suspended sediment in the water column. The suspended material specific sensitivity map covers all pelagic life stages, specifically: All stages of Atlantic cod, haddock and sprat, all non-spawning stages of herring, and all fish species with pelagic eggs and larvae (dab, plaice, and flounder). Because these included identical species and life stages of fish species/groups to those sensitive to increased noise during the construction phase, the distribution of areas of sensitivity in the pressure-specific sensitivity map for increased suspended sediment were the same. Sensitive areas extend along the Danish EEZ border from the Skagerrak to The Sound, as well as in a large area northeast of Jutland due to a significant abundance of foraging and spawning dab and plaice (Figure 6.3). An increase in suspended material is followed by an increase in sedimentation, which primarily affects demersal species and fish species have demersal early life stages such as demersal eggs. Increased sedimentation is most harmful for benthic eggs, as sediment coverage reduces the oxygen supply and thus increases mortality of eggs through suffocation. Species with benthic egg stages in this report include herring, sandeel and several species of sharks and rays (Elasmobranchs). However juvenile and adult demersal fish species are not expected to be directly affected by increased sedimentation due to their mobility as they can generally move away or displaced from an area of increased suspended sediment. Indirectly, increased sedimentation can affect demersal fish by affecting their food intake by reducing visibility or negatively affecting prey availability on the seabed. The demersal fishes expected to be affected by increased sedimentation include sandeel, flatfish and elasmobranchs. Throughout the Skagerrak and Kattegat, the overall distribution of high sensitivity areas from increased sedimentation resembles the pattern of increased suspended material, with several small areas offshore along the border of the Danish EEZ. However, the distribution of areas of sensitivity differs significantly in two regions in the North Sea and Baltic Sea. Several areas of high sensitivity are found throughout the western part of the North Sea, as derived according the overall distribution of sandeel (Figure 5.9, Figure 5.10.), where both the ecology of adults and eggs are potentially negatively affected by an increase in sedimentation.

Although the areas of high sensitivity to fish in the pressure-specific sensitivity map for increased sedimentation overlap with high sensitivity areas due to increased suspended sediment, the overall sensitivity for sedimentation within Kattegat is much smaller than that of increased suspended material (Figure 6.3 and Figure 6.4). Moving into the west Baltic and Bornholm several, large high sensitivity areas are present both within and immediately outside the Danish EEZ. Not including the Little Belt the scope of the sensitivity analysis, including the waters of the Belt sea (the Great Belt and the Sound) all include areas of high sensitivity, primarily due to the presence of juvenile and adult fishes of dab and plaice (Figure 5.12., Figure 5.14. , Figure 5.16. and Figure 5.18). This further extends into the western Baltic where large areas in Kiel and Mecklenburg Bight extend across the Danish-German EEZ border. These areas in the western Baltic are specifically important for several life stages of the flatfish species included in this report (Figure 5.11-Figure 5.22). Finally, within Danish waters around Bornholm, several large areas of high sensitivity that extend into both German, Swedish and Polish EEZ are present. These areas include the spawning areas of Baltic herring, as well as the general and adult distribution plaice and flounder (Figure 5.16., Figure 5.19., Figure 5.20. and Figure 5.25.).

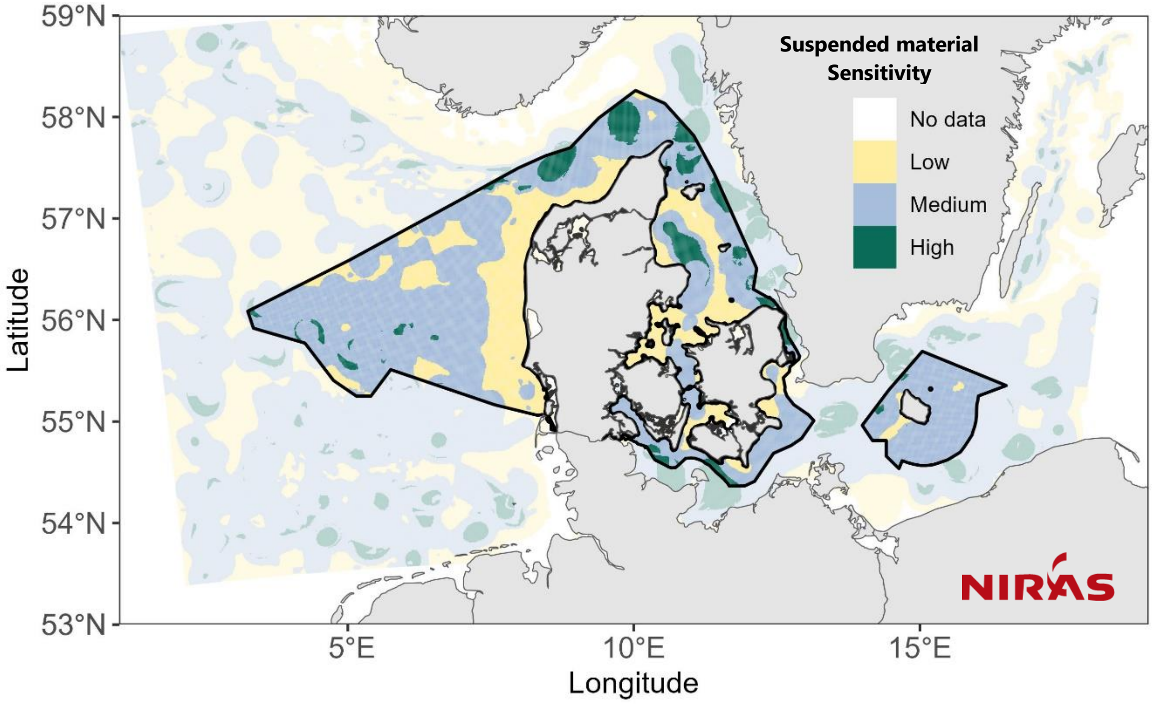


Figure 6.3. Pressure-specific map showing the distribution of fish species and the relevant life stages sensitive to an increase in suspended material. These scores are calculated by the previously described alternative weight-means protocol, analyzing suspended material sensitivity scores of the species described in Table 4.1.

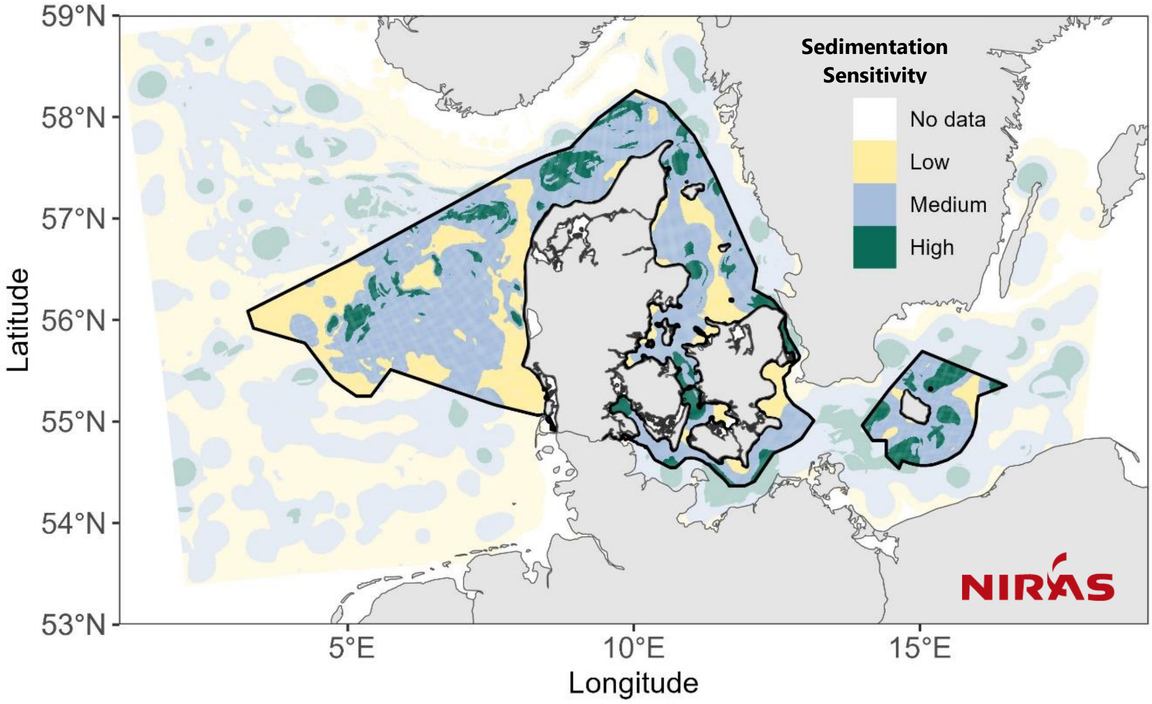


Figure 6.4. Pressure-specific map showing the distribution of fish species and the relevant life stages sensitive to an increase in sedimentation. These scores are calculated by the previously described alternative weight-means protocol, analyzing sedimentation sensitivity scores of the species described in Table 4.1.

Electromagnetic fields (EMF's)

The EMF-specific sensitivity map (Figure 6.5) includes only data on elasmobranch distribution, as these are the only fish species/group with a well-documented perception of electromagnetic fields that might lead them to being considerably sensitive and affected by EMF's around operating inter-array and export cables from OWF's. Areas of high sensitivity based on elasmobranchs abundance are observed in the Skagerrak region, within Danish waters, and the northwest North Sea outside the Danish EEZ (see Figure 5.31: and Figure 5.32:). Differences in the distribution of elasmobranchs and areas of sensitivity depend on the investigated dataset used for mapping, where registration of sensitive areas within the Danish EEZ are primarily derived from the fisheries data. However, because the fisheries targeting elasmobranchs are limited, it can be assumed that the sensitive areas depicting where most of the registrations of elasmobranchs, are probably a byproduct of by-catch in other fisheries, which allocate effort in specific areas, such as the fisheries targeting Atlantic cod (Figure 5.1). In contrast, the standardized ICES survey program may be a better measure of the true distribution of species of elasmobranchs, as data from these surveys are from standardized sampling methods. Therefore, while the fisheries data shows that elasmobranchs are present in relatively high numbers within the Skagerrak area, it is likely less representative of the true distribution within Danish waters.

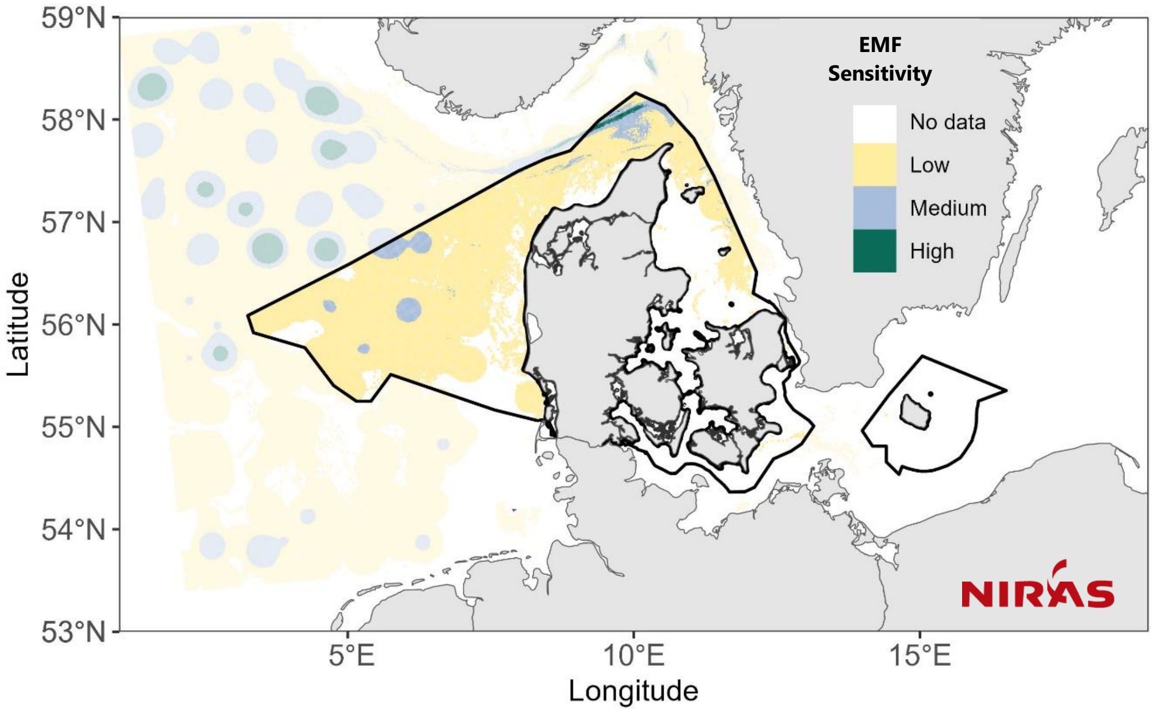


Figure 6.5. Pressure-specific map showing the distribution of fish species and the relevant life stages sensitive to an increase in EMF intensity. These scores are calculated by the previously described alternative weight-means protocol, analyzing EMF sensitivity scores of the species described in Table 4.1.

Habitat disturbance and loss

Certain species may be positively affected through habitat disturbance and change, and introduction of hard reef-like substrates introduced from the OWF foundations and scour protection. However, as this sensitivity analysis is focused on the potential negative effects of pressures to fish and their populations, only species affected adversely from a change/loss in habitat are included in the pressure-specific sensitivity map. Sandeels have highly specific demands to habitats with a specific substrate composition. These habitats are in limited supply, and sandeels are therefore considered to be a species that have the potential to be negatively affected by a considerable loss in habitat. Any reduction in their preferred habitat or change in substrate composition can be assumed to potentially limit their distribution. Because sandeels are a primary group of species considered to be negatively affected by a change in habitat, the pressure-specific map (Figure 6.6) is comparable to the sandeel distribution maps (Figure 5.9, Figure 5.10.). Areas with high sensitivity to a loss or change in habitat are thus observed in specific patchy areas within the parts of the Danish EEZ in the North Sea. Within the investigated grid, the majority of high sensitivity scores are found within the Danish EEZ.

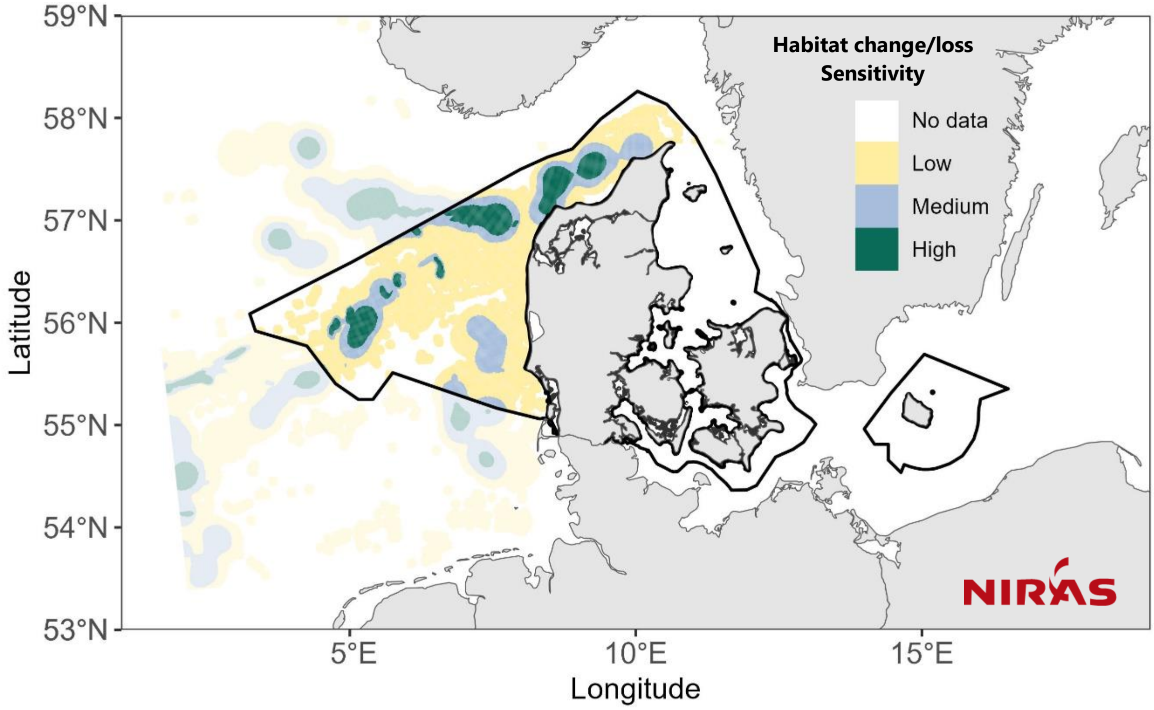


Figure 6.6. Pressure-specific map showing the distribution of fish species (primarily sandeel) and the relevant life stages sensitive to a change/loss in seabed habitat type with the construction of OWF. These scores are calculated by the previously described alternative weight-means protocol, analyzing habitat change/loss sensitivity scores of the species described in Table 4.1.

Hydrographic changes

As mentioned in section 4.5, local and regional hydrographic characteristics may change in the presence of offshore wind farm installations including turbine foundations and scour protective material etc. These installations can act as obstacles that can shift water currents and create turbulence that could affect local sediment transport (sediment resuspension and sedimentation), water mixing, and thus changes in the local pelagic and benthic habitats. Sensitivity maps from pressures such as increased sediment suspension and sedimentation, potential changes in seabed habitat and the fish species and life-stages that are sensitive to these pressures have already been produced. On a regional scale, implications of the changes in hydrography from the effects of wind farms and this pressure on fish and fish communities is challenging to predict, primarily because potential hydrographical driven by the cumulative effects of many turbine installations in each wind farm operation, as well as the cumulative effects from several wind farms in a region has not been investigated. A large wind farm or series of wind farms can reduce wind speed and remove energy from an area, potentially causing changes in water currents and circulation downwind the wind farm. These effects may cause changes in the upwelling and downwelling dynamics of marine water masses, which in turn can impact fish species and communities on a broad scale. Thus, the pressures and impact from possible effects on the hydrography in a region, can in theory affect and have an impact on all fish species and fish communities. However, because other large-scale factors such as natural recruitment variability, spatial and temporal variability of natural marine systems and factors from accelerating climate change will also play a role in affecting the dynamics of fish populations and distribution, it may be difficult to isolate large scale hydrographic changes from wind farms. With these uncertainties, it is not currently possible to isolate specific fish species or groups that would be sensitive to large-scale hydrographical changes from wind farms, and thus no pressure-specific map was made for this pressure.

Overall pressure-specific sensitivity map

When combining all the fish components (fish species and groups) considered most relevant in a pressure-specific sensitivity map, through max-value aggregation, it is possible to present an overall OWF pressure-specific distribution of sensitive areas within Danish waters. This map can be used to give an overview and highlight potential areas of greater sensitivity to the most sensitive fish to pressures from the construction and operation of offshore wind farms. In the North Sea there are generally more areas of lower sensitivities compared to the Inner Danish waters. In fact, within the Danish EEZ of the North Sea, areas of high sensitivity are generally more patchy and much smaller. In the North Sea the multiple small areas of high sensitivities on the max-aggregation map (Figure 6.7) within the Danish EEZ, strongly reflect the distribution of sandeel (Figure 5.10.), suggesting that these areas of high sensitivity can be primarily attributed to this fish group. Small areas of high sensitivity areas are also observed just off the coast of Jutland, near the Ringkøbing fjord, and derived from an area of high density from the general distribution of flounder (Figure 5.19). In the Skagerrak and Kattegat moving into the inner Danish marine waters there are several areas of high sensitivity spread along and/or across the border of the Danish EEZ. The corridor extending from Skagerrak and along the Swedish west coast, represents an area of great depths and water exchange between the North Sea and western Baltic; where the general water flow is a surface current of brackish Baltic flowing out and a high salinity bottom inflow from the North Sea. This produces a dynamic ecosystem within the Kattegat that can support fish species of both Baltic and North Sea origin. In fact, reproductively separated populations often intermix in this area during foraging (cod) or use this corridor during migration (herring). Furthermore, water currents often carry eggs and larvae from spawning of both local and distant populations outside this body of water, which settle at nursery areas typically along the coasts. Both active and passive transport of different fish life stages, and other organisms/prey such as zooplankton, within this corridor and throughout the Skagerrak and Kattegat, produces a dynamic ecosystem utilized by several fish species for foraging, spawning and nursery habitats. This is visualized by the occurrence of several areas of high sensitivity spread throughout the corridor between Skagerrak and the Sound on nearly all pressure-specific sensitivity maps. Moreover, all species investigated (except for sandeel) are to a certain degree represented with area of high sensitivity within the corridor. The waters around Bornholm also represent areas of high sensitivity on the max-aggregation map (Figure 6.7). As Bornholm is rather isolated offshore within the Baltic Sea, it often attracts both adults, spawning and juvenile fishes such as the species cod, plaice, flounder, sprat, and herring. Both functioning as a region or gathering point for these species, and where fish in different life stages may be attracted to the shallower coastal waters, for refuge and foraging.

In summary, the individual pressure-specific sensitivity maps show varying patterns of sensitive areas across the Danish EEZ, suggesting differing distributions of the sensitive species and their different life stages. However, when the individual maps are consolidated, distinct patterns appear, indicating that areas in the North Sea are generally of lower sensitivity compared to the inner Danish and western Baltic waters. Many of the high sensitivity areas also cross national (EEZ) borders, suggesting that pressures from the construction of OWF's near border areas of the Danish territory, may also impact sensitive fish species and important habitats in foreign territories.

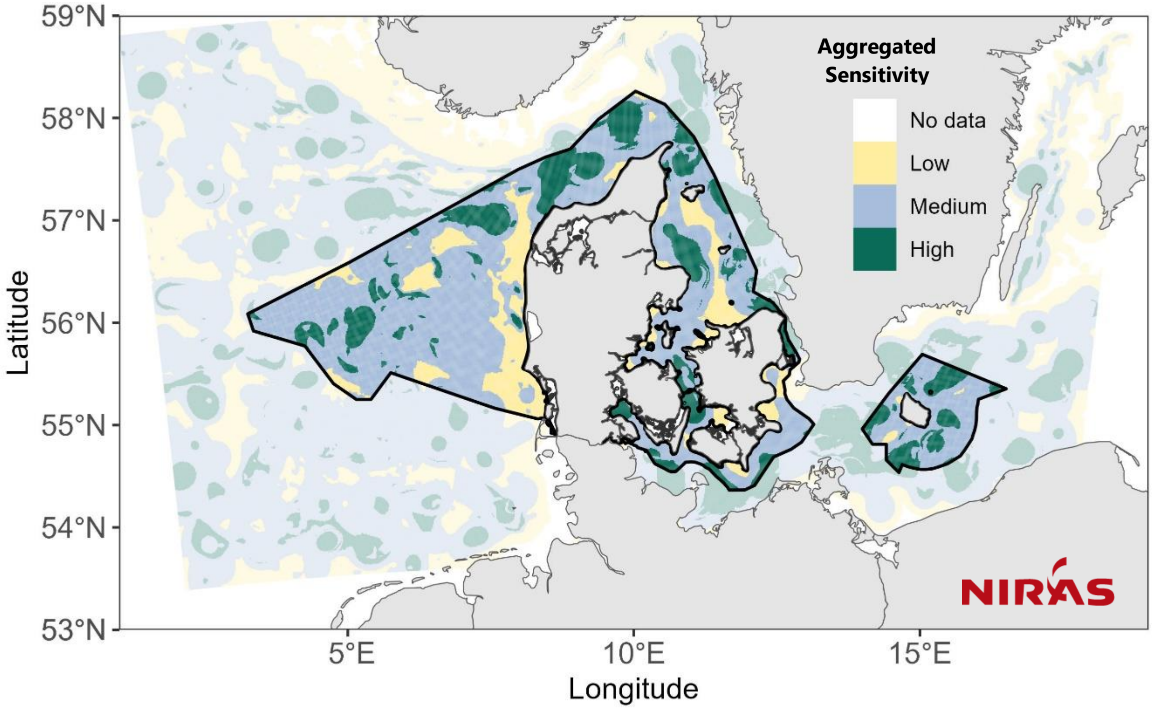


Figure 6.7. Total map combining the previous six pressure-specific sensitivity maps showing the overall distribution of fish species and the relevant life stages sensitive to the pressures imposed by OWF. This map is produced with a max-value approach, visualizing the highest sensitivity registered within each cell, across the pressure-specific maps.

7. Discussion and conclusions

The Danish marine environment is diverse in terms of fish species, with over 200 species present seasonally or continuously. However, in relation to offshore wind farms, there is generally only a subset of these species that possess anatomical, behavioral, or ecological traits, which make them most sensitive to the pressures that come with the construction, operation, and decommissioning of OWF's. Furthermore, it is important to note that the most intense pressures from establishing OWF's, such as intense underwater noise, sediment spillage and temporary habitat disturbance from introducing turbine and transformer foundations and burying inter-array and export cables, occur during the construction phase. These pressures are typically short-term, local and their effects on fish generally reversible over time. This also includes the most sensitive fish species and their populations. Moreover, the permanent pressures of habitat loss due to turbine and protective material footprints, low frequency, and less intense underwater noise from mechanical vibrations near turbines and electromagnetic fields (EMF's) produced from operating subsea cables are pressures producing local effects. In general, effects from the different pressures from OWF's are only considered to effect a number of individuals relatively close to the source of pressure, where it is difficult to determine or measure a pressure influence at the population level.

To screen the Danish marine environment and highlight potential areas of concern with regard to fish sensitivity to the pressures from establishing OWF's, a sensitivity analysis was conducted to select fish species or groups considered sensitive to these pressures and/or of ecological importance to the marine environment as keystone species. Data of their abundance in different life stages was used for spatial analysis and mapping of species-life-stage specific distribution. The nine species selected for spatial analysis, through the sensitivity analysis were:

- Atlantic cod (*Gadus morhua*)
- Haddock (*Melanogrammus aeglefinus*)
- Sandeel (*Ammodytes spp*.)
- Common dab (*Limanda limanda*)
- European plaice (*Pleuronectes platessa*)
- European flounder (*Platichthys flesus*)
- Atlantic herring (*Clupea harengus*)
- European sprat (*Sprattus sprattus*)
- Elasmobranchs (sharks and rays)

These selected species were determined to have an increased sensitivity at one or more life-stages (adult, spawning, juvenile and eggs and larvae) to several of the main pressures expected during the construction and operation of offshore wind farms. Furthermore, these species are also considered to represent a broad spectrum of Danish fish species sensitive to OWF pressures, and thus to a certain degree can be used as a proxy for indicating areas of sensitivity for fish and their populations. While several other species are undoubtedly sensitive to some of the pressures related to OWF's, the chosen species were considered to be most relevant based on overall sensitivity and their ecological importance. Furthermore, the availability of data to map their abundance was also an important criteria. This does not rule out the possibility of including other fish species or groups in a follow-up or extended analysis of fish sensitivity to pressures created from establishing OWF's, but at present, this is outside the framework of this initial sensitivity analysis.

Species and life-stage specific distribution was investigated through spatial analysis on two distinct data sets (ICES fish surveys and Commercial Fisheries), and analyzed by means of kernel density estimation and cluster analysis. Fish density was used as a proxy for fish sensitivity, indicating that the areas with the highest relative fish abundance were scored as the most sensitive. The species and stage specific analysis was further divided into Basin-specific results (North Sea, Kattegat, and Baltic Sea) in order to account for differences in local population size levels. Although the present investigation utilizes fisheries data to represent fish species distribution, these results are not considered to represent the sensitivity of the commercial fisheries to OWF's impact; and thus these results should only be interpreted in an ecological perspective. Further investigation of the sensitivity of commercial fisheries (distribution and economy), will be investigated in task two of the overall project for the Danish Energy Agency.

Pressure-specific sensitivity maps were produced by aggregation of weighted means from the sensitivity scores of species life stages that were sensitive to each of the six pressures: Habitat change/loss and increase in EMF, suspended material, sedimentation and noise during the construction, operational and decommissioning phases. Each pressure specific map highlighted areas with high accumulated abundance of species sensitive to the specific pressure. These maps were further combined into a maximum aggregation map, where the highest value of each cell was illustrated to create a conservative distributional map of all species and life stages specifically sensitive to the pressures imposed by the construction of OWF's. Among the areas with overall high sensitivity scoring, most were located within inner Danish waters and the Baltic, where most of the investigated species shared these high sensitivity areas to some degree. In the North Sea, small and patchy areas of high sensitivity (primarily represented the distribution of sandeel) were found within the Danish EEZ. In general, several sensitive areas extended across national borders, meaning that disturbing or affecting these areas could potentially affect local fish densities in neighboring territories.

The sensitivity scoring presented in this report is based on fish densities, suggesting that areas with high abundance of fishes' result in a high sensitivity score. As many of the pressures are temporary, and thus only affect individual fish for a limited time, it can be expected that strategically planning construction activities outside critical time periods, such as spawning and migration events, may limit the negative effect on sensitive local populations. In contrast, more permanent pressures, such as increased EMF's around cables, operational noise, and habitat change/loss, may effectively limit the distribution or anatomical capabilities of sensitive fishes such as sharks, rays, clupeids and sandeel etc. However, there is evidence that some fish become accustomed to pressures from EMF's and operational noise over time and thus affects from these pressures may have little or no negative impact. Similarly, impacts to fish due to loss of habitat can generally be considered low, due to the relatively limited amount of seabed loss due to OWF installations. However, if OWF installations lead to a substantial loss of important fish habitats of limited availability, particularly for fish species that are highly dependent on specific habitats such as the ecological keystone species sandeel, then removal or loss of these habitats can potentially reduce their distribution and local abundance, and in the case for sandeels, potentially limit a crucial food source for many fishes, birds and marine mammals.

In general, an area with a high sensitivity score for fish, should not necessarily be considered an exclusion zone for establishing an OWF, but more an indication of an area that may be of specific importance to fish and their communities sensitive to some pressures from OWF's, during an eventual screening and planning phase. While many of the pressures to fish and their populations from establishing OWF's are local, short-term and often reversible in their impacts, primarily because the mobility of fishes allows them to move away from a source of pressure. However, some life-stages, such as fragile eggs and larvae may be of greater concern when exposed to some of the extreme pressures, as these life stages generally drift with currents and have limited control of their movements and thus are potentially exposed to pressures over a longer period of time. Thus, construction and operation of OWF's around, for example, important spawning areas (such as southeastern Kattegat, the Sound, the Arkona basin and Kiel-Mecklenburg Bay to name a few), should be carefully planned, as increased mortality of fish in the early-stage of their development may significantly impact recruitment and local population levels.

The present sensitivity maps are based on data gathered over several years and are thus a mapping of the spatial distribution based on historic population levels of the species in focus. Fish population size can vary significantly between years due to both anthropogenic stressors (fisheries, etc.) and/or natural variation (climate variability, recruitment success). Due to changing climate conditions, rising ocean temperatures may drastically alter the distribution of temperate fish species, causing some species to move towards colder northern waters or introducing new southern species into warming waters. This may alter the ecological structure of the Danish fish communities, and potential disrupt the patterns presented in this report. Likewise, the overall state of the marine areas may change over time, where future food web structuring and abiotic conditions make previously productive areas less hospitable, and thus change species distribution. The cumulative effects of anthropogenic and natural impacts on ecological and oceanic conditions create significant uncertainty in predicting fish distribution in the future. Human activities, such as offshore wind farm installations, fish exploitation from fisheries, and climate change, interact with natural phenomena like ocean currents and temperature fluctuations to change the environment for fish. Furthermore, the construction of several OWF's could have significant cumulative effects, as the presence of multiple instances of each previously described pressure may result in synergistic negative impacts on sensitive fishes. In contrast, the increasing introduction of hard substrates creating artificial reefs that are a valuable habitat for some species, create a positive environment for reef associated organisms and places of refuge and foraging areas for reef associated fish species. Thus, this complex interplay makes it challenging to determine how these factors will collectively influence the movement and distribution of fish species, and consequently, our understanding of future fish distribution patterns and populations. In conclusion, while relative abundance maps of the different fish species and groups outline areas that can be considered to be sensitive to OWF pressures based on current relative abundance, it is important to note that fish abundance in areas is by no means static. This fact combined with uncertainty in data and mapping particularly in the transitional borders between the high, medium, and low relative abundances representing sensitivity, leads to some uncertainty associated with the interpreting maps.

Cumulative effects are investigated in task three, in the overall project for the Danish Energy Agency, evaluating potential impacts of several of the aforementioned factors.

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