# SENSITIVITY MAPPING OF HARBOUR SEALS, GREY SEALS AND HARBOUR PORPOISES TO THE CONSTRUCTION AND OPERATION OF OFFSHORE WIND FARMS IN DANISH WATERS

Scientific Report from DCE – Danish Centre for Environment and Energy no. 644 2025

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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Abstract: We assessed the sensitivity of harbour seal (*Phoca vitulina*), grey seal (*Halichoerus grypus*), and harbour porpoise (*Phocoena phocoena*) populations to offshore wind farms in Danish waters. Sensitivity was defined as the relative abundance of a species, multiplied by the consequence of constructing a wind farm in a given area, where we considered consequences across both construction and operation of the wind farms. Consequences were assessed based on published studies and expert knowledge. The division of the resulting sensitivity maps into areas where sensitivity is highest, medium and lowest also corresponds to areas where offshore wind farms are expected to have relatively high or low impacts on the population.

Keywords: Sensitivity mapping; Marine mammals; offshore wind farms

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# Contents

# Preface

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 fine-screening and assessment of the overall offshore wind potential based on the sensitivity mapping and relevant technical parameters.
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 harbour seals, grey seals and harbour porpoises based on available data. Other subjects within Task 1—such as fish, 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 largely 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. Sections 2.3 and 3 specify the data sources used in the sensitivity mapping for marine mammals 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.

The project management teams at both AU and NIRAS have contributed to the description of the background for the report and the relation to other activities in the preface. The report and the work contained within are solely the responsibility of the authors.

# Summary

This report provides an assessment of the sensitivity of harbour seal (*Phoca vitulina*), grey seal (*Halichoerus grypus*), and harbour porpoise (*Phocoena phocoena*) populations to offshore wind farms in Danish waters. We combine species distribution maps and publicly available studies on the effects of construction and operation of offshore wind farms to identify areas with the highest, medium and lowest sensitivity for each species. We define sensitivity as the relative abundance of a species, multiplied by the consequence of constructing a wind farm in a given area. Both are scaled to lie in the range 0–1. Whereas several studies have investigated the short-term effects of individual wind turbines, few studies have addressed the long-term consequences of entire wind farms. Published studies were therefore supplemented with expert knowledge, which enabled pinpointing populations and areas where the consequence of establishing a wind farm would be particularly large (e.g., breeding grounds). The rationale for the judgements is discussed. The authors underline that this assessment is limited due to the scarcity of studies on consequences of offshore wind on the spatial and temporal scales that would be needed to more fully understand animal sensitivities and due to the limited knowledge of the joint impacts of multiple wind farms and the cumulative impacts of different stressors. We highlight specific types of data that should be collected to produce more robust predictions of marine mammal sensitivity to offshore wind farms.

# 1 Introduction

## 1.1 The expansion of the wind energy sector to marine ecosystems

The rapidly changing climate and growing human populations contribute to an increasing demand for sustainable energy. Offshore wind plays an essential role securing the transition to renewable energy, which is needed to achieve the European goals of a more than 55% net reduction of greenhouse gas emissions by 2030 and climate neutrality by 2050 (European Commission, 2020; "European Council meeting," 2020), but the sensitivity of marine species and ecosystems to this expansion of offshore wind is poorly understood.

Since the establishment of the first offshore wind farm in 1991, the European offshore wind capacity has grown to 34 GW in 2023, and is expected to reach 83 GW by 2030 (Costanzo and Brindley, 2024). This increase can be largely attributed to the expansion of existing wind farms and construction of new ones, as well as technological advancements within the field of offshore wind turbines, extending the capacity of individual turbines from 450 kW (Vindeby, 1991) to 3600 kW in 2012 (Anholt), to 9500 kW in 2020 (Borssele III/IV), to 12000-14700 kW in 2023-2026 (Vineyard Wind 1 & Dogger Bank), and to 18-20 MW prototypes in 2024 (Shantou City and Hainan, China) (Bilgili et al., 2022; Avangrid, 2023; Buljan, 2024a; Memija, 2024; Buljan, 2024b). Currently, 15-17 MW (i.e. 15000-17000 kW) turbines are planned for in Denmark (Thor Offshore Wind Farm), Germany, Poland, and the Netherlands (Buch and Kjaer, 2015; Bilgili et al., 2022; Jakobsen, 2024; Norling et al., 2024). The higher capacity is directly linked to an increase of the physical size of the wind turbines (up to 10 m in diameter) and the rotor swept diameter, which has increased from 35 m in 1991 (Vindeby, DK), to 164 m in 2017 (Blyth, UK and Burbo Bank Extension, UK), to 220 m in 2023-2026 (Vineyard Wind 1 & Dogger Bank), and to 260-292 m in 2024 (Shantou City and Hainan, China) (Bilgili et al., 2022; Avangrid, 2023; Buljan, 2024a; Memija, 2024; Buljan, 2024b). Furthermore, changes in the size and type of the foundations (e.g. gravity base, monopile, high-rise pile cap, jacket, bottom-fixed and different types of floating offshore wind platforms (FOWPs)) and variation in the distance between turbines will occur.

The installation of an increasing number of turbines with larger turbine sizes will impact marine species on several levels. The construction of turbines results in high levels of anthropogenic noise, particularly for foundations installed with percussive piling (monopiles and jacket foundations). The noise emitted from percussive piling increases with the increasing hammer energy required to install the larger foundations (Bellmann et al., 2020). Although radiated noise levels can be reduced substantially by appropriate noise abatement techniques such as air bubble curtains, noise levels are expected to continue to affect a wide range of species (in particular marine mammals and fish) representing different trophic levels in the food chain (Bailey et al., 2010; Mueller-Blenkle et al., 2010; Herbert-Read et al., 2017; Jones et al., 2020; Duarte et al., 2021; Jézéquel et al., 2022). In addition, the turbines will influence wind speeds and currents in an area extending many kilometers behind the wind farms (Schultze et al., 2020; Floeter et al., 2022), yet the consequences to the marine ecosystem are not well understood. As the long-term ecological effects of the establishment of the next generation of offshore wind farms arise through complex interactions between the pre-existing habitats and physical changes induced by the wind farms (e.g. the creation of artificial reefs, changes in currents and turbulence, sand banks and the local sea floor), the impacts of these changes on resident and visiting species are likely site specific and remain largely unknown (Van Berkel et al., 2020; Galparsoro et al., 2022; Watson et al., 2024). Thus, continuous monitoring and development of new modelling frameworks are required.

## 1.2 Impacts of offshore wind farms on marine mammals

Marine mammals depend on sounds for communication and foraging, and concerns regarding the impacts of wind farm construction noise initially sparked investigations of how cetaceans and pinnipeds respond to offshore wind farms (Edrén et al., 2004; Carstensen et al., 2006; Tougaard et al., 2006, 2009a, 2009b; Edrén et al., 2010; Mueller-Blenkle et al., 2010; Bailey et al., 2010; Dähne et al., 2013, 2014; Russell et al., 2016; Herbert-Read et al., 2017; Jones et al., 2020; Duarte et al., 2021; Jézéquel et al., 2022). Impacts of high sound levels on marine mammals include acoustic trauma (noise induced hearing loss), communication masking, exclusion from habitats and behavioral changes (Brandt et al., 2011; Graham et al., 2019; Whyte et al., 2020). One of the major consequences of pile driving is the risk of acoustic trauma. Unmitigated pile driving produces short pulses of very high sound pressure, which affect both porpoises and seals within a range of > 1000 $km^2$ (Tougaard et al., 2009a; Dähne et al., 2013; Brandt et al., 2018). In the attempt to reduce the radiated noise, abatement measures such as bubble curtains and noise mitigation screens can be used (Bellmann et al., 2020; Koschinski and Lüdemann, 2020). Indeed, the use of bubble curtains and other abatement techniques have proven to be effective in minimizing the risk of hearing loss and temporary habitat loss for harbour porpoises (Dähne et al., 2017; Tougaard and Dähne, 2017) and is therefore considered Best Available Technology (BAT). The Danish Guidelines for pile driving (Danish Energy Agency, 2023) specifies when noise abatement is required, which in practice includes all pile driving activities. Such noise abatement includes acoustic deterrent devices (ADD) such as 'seal scarers' and pingers (Brandt et al., 2013; Verfuss et al., 2016; Mikkelsen et al., 2017). The kind of mitigation measures that are required to avoid undesirable underwater noise levels and impacts on marine mammals varies among projects and is identified as part of the project specific environmental impact assessment. Yet, the use of ADD and other deterrence do not reduce the displacement of cetaceans and pinnipeds caused by the pile driving noise. Only noise abatement or alternative, less noisy installation procedures can alleviate the disturbance impact.

While several studies have investigated the effects of offshore wind farm construction noise on marine mammals, little is known about the potential negative or positive impacts of operating wind farms. These impacts could result from changes in prey densities, e.g. through aggregations of prey around turbine foundations ("artificial reef effects"; e.g. Degraer et al., 2020) or reduced levels of commercial fishing inside the wind farms due to restrictions or difficulties maneuvering around the turbines. Further, operating wind turbines also emit noise, which may affect some marine mammals up to a few hundred meters from the turbines (Tougaard et al., 2009b, 2020; Bellmann et al., 2023). Very few studies have assessed how marine mammals are influenced by operating wind farms (Scheidat et al., 2011; Teilmann and Carstensen, 2012; Thompson et al., 2013), and it is not well understood whether the overall consequences of wind farms will be positive, negative, or neutral. Further, the consequences of wind farms are likely to depend on the environmental context, including proximity to other wind farms, other sources of disturbance, background noise and prey availability inside and in areas outside the wind farms. Thus, the assessment of how sensitive marine mammals will be to offshore wind farms is inherently associated with a large degree of uncertainty.

## 1.3 Marine mammal sensitivity mapping

Sensitivity maps are considered an effective tool for the identification of areas where the establishment of offshore wind farms might negatively impact sensitive resident species and where disturbances should be avoided (European Commission, 2020). In this assessment, we will produce species specific sensitivity maps to highlight areas where the resident harbour seals, grey seals and harbour porpoises may be sensitive to the development of offshore wind farms.

A first step towards estimating the sensitivity of each marine mammal species is to map its distribution (Faulkner et al., 2018). In this study, we do this based on habitat suitability models. These models use observations of animals (from telemetry or arial survey data) to determine under which environmental conditions the animals occur and use these relationships to generate distribution maps (Norberg et al., 2019; van Beest et al., 2022). The distribution maps can be used to pinpoint areas (habitats) that are intensively used and presumably of high importance to each species. In this study, we scale the relative abundance to lie in the range 0–1.

The second step is to assess the long-term consequences of establishing a wind farm. This assessment considers how animals at different life stages and seasons are influenced by wind farms during the relatively brief construction phase as well as during the post-construction phase. It includes considerations regarding the impact of offshore wind farms on population density, which may differ among foraging areas and breeding grounds. It also considers the distance between individual turbines, as the impact of a wind farm is likely to be smaller when individual turbines are spaced far apart. The assessment is done for one population at a time, as some populations may be considered particularly vulnerable, thus causing the impact of a given disturbance to be large. Whenever possible, the consequences of establishing wind farms are based on published studies, but due to the lack of published data the evaluation is further supported by expert knowledge.

Finally, the sensitivity of harbour seals, grey seals and harbour porpoises to wind farms is quantified as the relative abundance multiplied by the consequence of establishing wind farms (which, like relative abundance, is scaled to lie in the range 0–1). For each species, the relative abundance is calculated for one population at a time, focusing on the part of the population that occurs in Danish waters. The study thus provides an increased understanding of where the populations will be relatively strongly influenced by the construction and operation of wind farms. At the same time, it highlights where we have too little data on either relative species abundance or the long-term and large-scale effects of wind farms to characterize areas as being of relatively high, medium, or low importance for the three species.

# 2 Background

## 2.1 Study area

The study area covers the total Danish EEZ area, which includes the North Sea, inner Danish waters and the western Baltic Sea. As such, the area spans a broad variety of habitats with pronounced variation in depth, tides, salinity, substrate and temperature. The North Sea is an epicontinental sea surrounded by Great Britain, Norway, Denmark, Germany, the Netherlands and Belgium, and is connected to the Atlantic Ocean through the English Channel in the south and the Norwegian Sea in the north. It expresses a diverse geography with deep fjords and cliffs to the north and sandy beaches, sandbanks, estuaries and mudflats to the south. In the Danish part of the North Sea, the coastline covers sandy beaches, mudflats and sandbanks. The Baltic Sea is a partly enclosed, brackish sea connected to the North Sea by the intermediate waters (the Belt Sea, Danish Straits, Kattegat and Skagerrak). The whole region is impacted by a water influx from the North Sea that provides high salinity water and increased oxygen supply that is mixed with a freshwater influx from the adjacent catchment areas, resulting in a salinity gradient from marine waters in the North Sea to brackish waters at the northernmost end of the Baltic Sea. With a water renewal time of ~30 years, the Baltic Sea is particularly vulnerable to eutrophication and accumulation of chemical substances impacting the health of resident wildlife.

## 2.2 Key species

Denmark's three most common marine mammals are the harbor seal, grey seal, and harbor porpoise. All three species are protected under the EU's Habitats Directive. Protected areas, known as Natura 2000 sites, have been designated for all three species. Minke whales (*Balaenoptera acutorostrata*), white beaked dolphins (*Lagenorhynchus albirostris*) and bottlenose dolphins (*Tursiops truncatus*) are also native species of the North Sea, but knowledge of their distribution and studies on the effect of offshore windfarms on these species are currently limited. Several other marine mammal species are occasional or rare visitors. All cetacean species must be protected throughout their entire range according to EU's Habitats Directive and should be considered during the scoping process for specific projects in the North Sea to evaluate whether they might be relevant on a case-by-case basis (Tougaard et al., 2021). Due to data deficiency, only harbour seals, grey seals and harbour porpoises are included in the sensitivity mapping in this report.

### Pinnipeds

The Danish coastlines of the North Sea and the Baltic Sea are inhabited by two pinniped species, the harbour seal and the grey seal. After years of extensive hunting and exposure to persistent organic pollutants (POPs) and heavy metals (Hg), leading to dramatic declines and local extinctions of harbour seal and grey seal populations, both species have been protected in Denmark since 1967 (grey seal) and 1976 (harbour seal) and are currently recovering (Bergman, 2007; Brasseur et al., 2018; Dietz et al., 2021; Galatius et al., 2019; Ross et al., 1996; Sonne et al., 2020). The harbour seal and grey seal are listed in the EU Habitats Directive annex II (meaning they must be protected by designation of special areas of conservation) and annex V (meaning they are considered species of community interest whose taking in the wild and exploitation may be subject to management measures). Both species are listed as Least Concern by IUCN (Bowen, D., 2016; Lowry, L., 2016), yet the grey seal is locally considered a vulnerable species by the Danish Red List (Moeslund et al., 2023b, 2023a). According to the IUCN red list, the threats to the two species are anthropogenic activities related to the fishing industry (bycatch in nets, reduced food availability and habitat destruction), pollution (industrial and agricultural), noise pollution, climate related habitat changes and recreational activities (physical disturbance and noise). Harbour seals and grey seals rely on their hearing for airborne and underwater vocalization in relation to social interactions such as delineation of territory, advertisement of dominance status, mating and brood care (Schusterman et al., 1970; Hanggi and Schusterman, 1994; Kastak and Schusterman, 1998; Van Parijs et al., 1999; Sabinsky et al., 2017).

**Harbour seal**

The harbour seal is the most widely distributed pinniped in the world, with a circumpolar distribution range covering temperate to arctic regions in the North Atlantic (30-78.5°N) and North Pacific (28-61.2°N) (Blanchet et al., 2021). It is a non-migratory resident species to the coastal waters of the North Sea, the inner Danish waters and the southwestern Baltic, where it is found hauling out on sand banks, beaches and rocky shores (Dietz et al., 2013; Teilmann et al., 2020).

As semi-aquatic animals, harbour seals spend a large portion of their life on shore, where they rest, reproduce and moult (Dietz et al., 2013). The time spent on land varies with season and peaks during the pupping- (June-July), the mating- (July-August) and the moulting seasons (August-September), where especially the adult seals show strong site fidelity (Dietz et al., 2013). Unlike the case of their ice-dwelling relatives, harbour seal pups shed and replace their lanugo fur with water repellent adult fur in the uterus, enabling them to swim shortly after being born (Oftedal et al., 1991). The pups nurse for 3-4 weeks to develop an insulating blubber layer, which reduces heat loss and act as an energy reserve providing the time they need to develop their hunting skills. Females are ready to mate when the pups are weaned, and mating occurs in the water surrounding the haul-out sites from late June to early August (Boness et al., 2006). During this period (June-September), the seals are especially vulnerable to disturbances near their haul out sites, which they use for nursing (3-4 weeks post-birth), mating (post nursing) and moulting.

The geographic distance and the strong site fidelity to breeding sites expressed by harbour seals are promotors of the significant population structure and locally adapted unique populations identified by population genetic studies (Olsen et al., 2014; Liu et al., 2022). By combining knowledge on movements and population genetics, the Danish harbour seals have been divided into a minimum of 4 populations (the Southwestern Baltic, Kattegat, Central Limfjord and the Wadden Sea), each of which adds to the genetic diversity of the species (Olsen et al., 2014).

Harbour seals are opportunistic/generalist feeders, and analyses of scats (otolith identification and molecular analyses) have revealed a large spatial and seasonal variation in their diet, with sandeels (*Ammodytidae spp.*), black goby (*Gobius niger*), Atlantic cod (*Gadus morhua*) and dab (*Limanda limanda*) as primary prey at locations in the Southwestern part of the Baltic Sea and Kattegat, Norway pout (*Trisopterus esmarkii*), sandeels, whiting (*Merlangius merlangus*) and Atlantic cod in Skagerrak, and black goby, sand goby (*Pomatoschistus minutus*), and Atlantic herring (*Clupea harengus*) in the Limfjord (Andersen et al., 2007; Scharff-Olsen et al., 2019).

Since the protection of the harbour seal, the population size has increased significantly with a few set-backs caused by two major epizootics of Phocine Distemper Virus in 1988 and 2002 (Dietz et al., 1989; Härkönen et al., 2006; Stokholm et al., 2019), a minor unusual mortality event in 2007, possibly associated with algae toxins and Klebsiella infections (Mollerup et al., 2024), and spillover of avian influenza (H10N7) in 2014 (Krog et al., 2015; Zohari et al., 2014). The population is considered to have reached its carrying capacity in some regions, but a decreasing tendency in population development has been observed in some areas over the past decade, possibly due to disturbance, prey availability or competition with the larger grey seal.

**Grey seal**
The grey seal is widely distributed across temperate and subarctic parts of the North Atlantic, with haul-outs along the coasts of Northeast America, Iceland, the Faroe Islands, Norway, Russia (Kola Peninsula), the entire North Sea region, including the Wadden Sea, as well as the Danish Belts and the Baltic Sea (Härkönen et al., 2007; Bowen, D., 2016). Their distribution range and habitat preferences overlap with the harbour seal, and the two species occur in sympatry across multiple haul-out sites in Denmark, including the southwestern Baltic, Kattegat, Skagerrak, the Western Limfjord, and the Wadden Sea. While the grey seal primarily feeds on fish and squid, it has been observed feeding on birds and marine mammals, including harbour seals, small grey seals and harbour porpoises (Bouveroux et al., 2014; Brownlow et al., 2016; Haelters, 2012; Jauniaux et al., 2014; Leopold et al., 2015; Scharff-Olsen et al., 2019; Van Neer et al., 2015). The annual breeding and moulting cycles of grey seals are distinct from those of the harbour seals and vary across its three main populations in NW Atlantic, NE Atlantic and the Baltic Sea (Graves et al., 2009; Klimova et al., 2014; Fietz et al., 2016). The NE Atlantic population moults in March-April and gives birth from December to January, whereas the Baltic population moults in May-June with a pupping season from late February to March (Galatius et al., 2024b). The grey seal was common and widespread in Danish waters until the 19th century, where hunting caused its decline and extinction as a breeding species (Olsen et al., 2018). The first grey seal pup was observed in Danish waters in 2003 in the Baltic Sea (Galatius et al., 2020), and in 2014 the first pup was observed in the Danish Wadden Sea (Jensen et al., 2015). Subadult and adult grey seals now occur regularly and in increasing numbers in the Wadden Sea, Kattegat and the Baltic Sea, but the annual total pup count is still low, at about 10 animals or less (Søgaard et al., 2018; Galatius et al., 2020; Hansen and Høgslund, 2021).

## Cetaceans

**Harbour porpoise**
Harbour porpoises are widely distributed in the North Atlantic from USA and Canada to Western Greenland, Iceland, the Faroe Islands, Norway, the North Sea, the Baltic Sea and southwards to Iberia, and West Africa. The porpoise is absent from the Mediterranean Sea, but a separate population inhabits the Black Sea. Porpoises typically occur in coastal areas, but during winter porpoises are found in large parts of the North Atlantic (Hammond et al., 2008; Nielsen et al., 2018). Porpoises are found throughout Danish Waters, however, rarely in the Limfjord and around Bornholm. Based on genetics, morphology

and movement patterns, harbour porpoises around Denmark are divided into three populations: The North Sea (including – Skagerrak), the Belt Sea (including Kattegat, the Danish Straits and the western part of the Baltic Sea) and the Baltic Proper (Wiemann et al., 2010; Galatius et al., 2012; Sveegaard et al., 2015; Celemín et al., 2023). In addition, a fourth possible population in the Wadden Sea has recently been suggested based on genetic data (Autenrieth et al., 2024), however, more studies are needed before this can be confirmed. In both the North Sea, Belt Sea, and Baltic Proper populations, calves are born from April to September with a peak in June-July (Sonntag et al., 1999), and the calves are entirely dependent on their mother for the first ten months of their life, where they suckle and slowly learn to hunt before they become independent.

The available knowledge on distribution and abundance of harbour porpoises in Danish waters comes from aerial surveys (covering the North Sea and Belt Sea population), porpoises tagged with satellite transmitters (mainly covering the Belt Sea and Skagerrak) and extensive passive acoustic monitoring (in the Danish Baltic Proper around Bornholm and specific smaller high-density areas in the Belt Sea).

The population size of harbour porpoises in the North Sea was estimated to be stable at just above 300,000 individuals in the period 1994-2022 (SCANS I-IV), with the latest estimate from 2022 (SCANS-IV) being 338,918 individuals (95% CI = 243,063-476,203; CV = 0.17 (Gilles et al., 2023; Hammond et al., 2017).

The Belt Sea population and the Baltic proper population are classified in the HELCOM Red List as Vulnerable (VU) and Critically Endangered (CR), respectively (Benke et al., 2014; Sveegaard et al., 2015; ASCOBANS, 2016). The distribution range of the Belt Sea population covers Kattegat, the Belt Sea, the Sound and the German Baltic and consists of an estimated population size of 14,403 individuals (95% CI = 9,555–21,769; CV = 0.21) (Gilles et al., 2023; Owen et al., 2024). This is a drastic decline from previous estimates, and a recent study estimated that over the past 18 years there has been a strong negative trend (-2.7% p.a.; 95% CI: -4.1%; + 1.3%) in abundance, with a 90.5% probability (Owen et al., 2024).

The Baltic Proper population inhabits the water of the Baltic Proper with ~500 individuals (95% CI = 71-1105; CV = 0.68) (Amundin et al., 2022) and an estimated number of mature individuals of less than 250 (Carlström et al., 2023). Both the Belt Sea population and the Baltic Proper population are threatened by anthropogenic activities such as bycatch, prey depletion and chemical and noise pollution (Owen et al., 2024).

Harbour porpoises are listed in Annex IV of the Habitats Directive and evaluated as Least Concern in the North Sea by IUCN (Braulik et al., 2020). Threats according to the IUCN Red List categories are 1) Fishing: bycatch in nets, reduced food availability and habitat destruction, 2) Pollution from industry and agriculture, 3) Noise pollution, 4) Climate and habitat changes, 5) Recreational activities: physical disturbances and noise.

## 2.3 Review on consequences of offshore wind farms on marine mammals

In this section, we review current knowledge on marine mammal responses to the underwater noise generated during the construction phase of offshore wind farms as well as their long-term impacts, building on cumulated data since the first wind farm was built in 1991 (Vindeby, Denmark). The reviewed studies were identified by an extensive literature search conducted at Google Scholar by using search words: "marine mammals", "seals", "harbour porpoises", and "offshore wind farms". The results of the review have been summarized in a table providing a short overview of the main findings of scientific papers and environmental reports conducted to examine the effects of the construction phase and operational phase on seals and harbour porpoises.

Investigations of harbour seal and grey seal responses to pile driving activities largely rely on tagging seals with satellite transmitter tags at neighboring haul-out sites. The satellite tags ideally reveal movement patterns and behavioral responses (e.g. unusual speed acceleration, cessation of horizontal movement and the sudden initiation of travel from a longer stationary period of the seals before, during and after pile driving) (Russell et al., 2016; Aarts et al., 2018). Investigations of effects of the construction and operational phases on harbour porpoise most often rely on static passive acoustic monitoring (PAM), which is used to detect porpoise echolocation clicks (recorded by T-PODs, C-PODs or F-PODs). The recordings of clicks provide insight to the level of presence/absence of harbour porpoises before, during and after wind farm construction activities (Carstensen et al., 2006; Tougaard et al., 2009a; Verfuss et al., 2016). These surveys are often supported by aerial or boat based line transect surveys recording observations of the small cetaceans (e.g. Dähne et al., 2013; Kyhn et al., 2024).

### Construction phase - effects of pile driving on marine mammals

The construction phase of offshore wind farms includes all activities from pre-investigations and construction up until its finished. The potential detrimental impacts include geophysical surveys and fastening of turbines to the ocean floor, which have different impacts depending on the type of foundation. At present, the main offshore wind foundation types in Scandinavian waters are gravity-based foundations, monopiles, and jacket foundations. The two latter involve pile driving, which occurs as repeated hammering (every 1-2 seconds) of foundations into the sea floor for up to several hours per turbine (Graham et al., 2019). Unmitigated pile driving produces low-frequency sound waves covering an area of > 1000 $km^2$ (Tougaard et al., 2009a; Dähne et al., 2013; Brandt et al., 2018). As both marine mammals and fish are highly dependent on their ability to hear and/or detect sound pressures in their surroundings, concerns towards such noise pollution initially sparked investigations of cetaceans' and pinnipeds' response to the activities (Carstensen et al., 2006; Madsen et al., 2006; Tougaard et al., 2009b; Mueller-Blenkle et al., 2010; Bailey et al., 2010; Herbert-Read et al., 2017).

**Pinnipeds**
To date, harbour seals and grey seals are the most extensively studied pinnipeds with respect to potential effects induced by the construction of offshore wind farms. The current literature covers surveys from 11 offshore wind farms spread across Danish, German, Dutch, and English waters (see table 1-2). The two seal species communicate at low frequencies, below 1 kHz, which creates an overlap between pile driving noise and the sound level at which the seals communicate. The underwater vocal behavior of both seal species is poorly known but thought to take place primarily near the haul-out sites and in particular during the mating season.

The harbour seals inhabiting Danish waters are most vulnerable during the pupping- (June-July), mating- (July-August) and molting seasons (August-September), where adult harbour seals show strong site-fidelity and rely heavily on access to undisturbed sandbanks and beaches to nurse their pups and sustain a healthy energy level (Dietz et al., 2013). During this period, vocalization is used between mothers and pups (Sauvé et al., 2015), while males use vocalizations to establish their territory, attract females and secure the next generation of harbour seals (Van Parijs et al., 1999). Thus, low frequency disturbances in close vicinity to haulout sites during this period could potentially impact the survival rate of pups or cause reductions in successful matings, leading to reductions in pup productivity the following year. At the same time, the seals spend more time on land during the molting season, which would mean less exposure to underwater noise. However, a change towards spending less time on land during the molting season has been observed in recent years, indicating that the seals are more dependent on feeding during the molting period and, hence, will be more vulnerable to disturbances when they are on their important foraging trips (Vance et al., 2021; Nachtsheim et al., 2023). Thus, while masking of the communication calls from distant pile driving is not regarded as a significant issue, it remains to be tested against empirical data.

During the construction phase, most studies report a decline in seal densities at haulout sites or in the area within a range of up to 25 km from pile driving activity (Edrén et al., 2004, 2010; Skeate et al., 2012; Russell et al., 2016; Whyte et al., 2020). Yet, the effect seems to be relatively short-term, with seal densities returning to pre-piling levels within 2 hours of piling cessation in the Wash area (Russell et al., 2016). Haulout behavior of harbour and grey seals was investigated 4 km from a wind farm (Nysted, Denmark) construction site. No significant reduction in seal numbers was found (Edrén et al., 2010). An observation, which is further supported by the return of several seals exposed to pile driving at distances < 20 km during the pile driving period at the Luchterduinen (Kirkwood et al., 2015). However, the short-term effect may be the result of a strong motivation to visit the area due to e.g. high availability of prey or the lack of prey elsewhere, which counteracts the instinct to leave the area (Kirkwood et al., 2015).

In summary, past studies showed a temporary displacement of seals of up to 25 km during pile driving. However, as the seal density seemed to return to pre-piling levels, the effect is generally considered to be short-term. Yet, the impact may vary due to seasonal timing if dispersal occurs during breeding, nursing and moulting periods, when the seals are the most vulnerable.

**Harbour porpoises**

To date, the harbour porpoise is the most extensively studied marine mammal with respect to potential effects of constructing offshore wind farms. The current literature covers 23 offshore wind farms spread across Denmark, Germany, Netherlands, Sweden, Belgium, Scotland, England and one baseline study in Maine (USA) (see table 3-4). Pile driving impacts harbour porpoises through behavioral disturbance and, possibly, acoustic trauma at the highest levels, but masking of their echolocation is considered unlikely, as there is very little overlap between the ultrasonic signals used in echolocation and communication and the pile driving noise. This is particularly true for pile driving noise with noise abatement in place (Tougaard and Dähne, 2017). Studies agree that pile driving activities lead to displacement of harbour porpoises (Carstensen et al., 2006; Tougaard et al., 2009a; Thompson et al., 2010; Brandt et al., 2011; Dähne et al., 2013, 2014; Haelters et al., 2015; Brandt et al., 2016; Vallejo et al., 2017; Brandt et al., 2018; Nabe-Nielsen et al., 2018; Graham et al., 2019; Benhemma-Le Gall et al., 2021). The displacement range varied from < 26 km from a pile driving site by Beatrice Offshore Wind Farm & Moray East Offshore Wind Farm (Benhemma-Le Gall et al., 2021; Graham et al., 2019; Van Geel et al., 2023), to ~ 17 km from pile driving at Horns Reef and the German Bight (Brandt et al., 2011, 2016, 2018), to 20-23 km at Alpha ventus OWF, Thorntonbank Wind Farm, and at locations at Middelgrunden, Vindeby and Bockstigen-Valar (Tougaard et al., 2009a; Dähne et al., 2013, 2014; Haelters et al., 2015). The differences in displacement ranges recorded during the construction phase at different wind farms can be attributed to local variation in ecological, geological and behavioral inputs as well as the use of mitigation measures, limiting sound emissions from pile driving, but may also simply be a reflection of differences in monitoring protocols and statistical designs. The effect is considered to be short-term (Carstensen et al., 2006; Dähne et al., 2014; Scheidat et al., 2011; Thompson et al., 2010; Vallejo et al., 2017) with an estimated return of the harbour porpoises of around 1-3 days in the German Bight, by Horns Reef and the Beatrice OWF within a < 3 km distance from the impact site (Brandt et al., 2018, 2011, 2016; Rose et al., 2019; Thompson et al., 2020). In addition, other studies calculated the return of harbour porpoises to be between 6-10 hours (Dähne et al., 2017; Nabe-Nielsen et al., 2018). Interestingly, investigations using surveillance by passive acoustic monitoring have indicated that the scale of response declined over time meaning that disturbance impacts of long-term piling projects may cause relatively less diversion (Graham et al., 2019). Other factors such as vessel traffic related to the pile driving activities have been linked to an increased probability of response (Graham et al., 2019). Yet the level of harbor porpoise responses is best explained by the distance to the pile driving site and the noise levels received within their high-frequency hearing range (Graham et al., 2019), implying that efforts made to reduce noise exposure would be beneficial.

While direct acoustic effects relating to the construction phase and knowledge regarding how harbour porpoises respond to the acoustic disturbances are relatively well covered, the main impacts of wind farm construction are likely related to displacement from foraging grounds and the reduced fitness associated with such displacement as well as potential mother-calf separation. Displacement from foraging grounds has been intensively studied in recent years (Gallagher et al., 2021; Nabe-Nielsen et al., 2014; Nabe-Nielsen et al., 2018), which makes it possible to directly link lost foraging opportunities around wind farm construction sites to population effects via Population Consequence of Disturbance (PCoD) models. These models can directly account for seasonal variability in prey and energy needs, thus making them suitable for marine spatial planning aimed at reducing the population effects of offshore wind developments. However, there are several additional unknowns that need to be investigated more closely, including long-term impacts of wind farms on the spatial distribution of calving grounds, where harbour porpoises may be particularly vulnerable, as well as the likelihood of mother-calf separation. Harbour porpoise calves are highly dependent on their mother during the first 10-11 months of their life (Lockyer, 2003; Teilmann et al., 2007), during which they are highly sensitive to activities that may separate them from their mother. The the calving period lasts from April–September for the Danish harbour porpoise populations, with a peak in June–July, while mating occurs in the first 1-2 months after the birth of a calf (Sonntag et al., 1999). Indeed, recent studies suggest that mature female harbour porpoises are most vulnerable to disturbances in late summer and the autumn, where they need to increase their body fat insulation to survive the cold winter months, while at the same time potentially being pregnant and nursing a calf only a few months of age (Gallagher et al., 2021).

In summary, during the construction phase pile driving induces varying degrees of displacement of harbour porpoises. Similarly to the seal studies, effects of pile driving seem to be short-term, but the displacement may cause a loss of energy intake, the impact of which is poorly understood. Bubble curtains greatly limit the displacement, possibly reducing the time until animals return, and can thereby minimize the energetic loss. Based on current knowledge, it is impossible to pinpoint specific breeding areas, yet summer and autumn are considered important for their survival and reproduction.

### Operational phase - effects of turbine noise and reef effects on marine mammals

The operational phase of a wind farm lasts approximately 25 years, during which introduction of continuous noise from the wind turbines and OWF-related service traffic may result in masking of low-frequency seal communication as well as displacement or attraction to the turbines (Bellmann et al., 2023). Operating wind turbines emit low-frequency noise (< 500 Hz), which originates in the nacelle and reaches the water through vibrations in the tower. The noise radiates into the water, where it may affect marine mammals up to a few hundred meters from the turbines (Tougaard et al., 2009b, 2020; Bellmann et al., 2023).

In addition, the presence of underwater structures (here the foundations) provides a change in substrate that may cause a "reef effect", which can change the biodiversity in the area and potentially also affect the availability of the fish that marine mammals prey on.

#### Pinnipeds

Relatively few studies investigating the impact of operational offshore windfarms on seals are available, and none of them contain sufficient spatio-temporal data to provide a firm answer to whether the effects are non-existing, negative or positive. While the audibility for harbour seals has been estimated to be between 100 m to several kilometers from the foundation (Tougaard et al., 2009b), none of the published studies report any direct negative effects of offshore wind farms (Tougaard et al., 2006; McConnell et al., 2012; Russell et al., 2014, 2016). One study demonstrated that individual seals spend considerable time very close to turbine foundations, likely foraging in the scour protection (Russell et al., 2014). A lack of change in haulout behavior at a haulout site 4 km from Nysted Offshore wind farm was also reported (Edrén et al., 2010). Seals may be more sensitive to the sound emissions compared to harbour porpoises due to the low-frequency spectrum of their communication and their reliance on haulout sites. Yet, due to their broadband repertoire of sounds, masking is not considered to affect harbour seals unless they are in close vicinity of a foundation (Tougaard et al., 2009b). Furthermore, the effect of noise emissions will largely rely on behavioral patterns of the seals, the type of wind farm, the physical environment and ecological conditions influencing the area.

Indirect effects of wind farms, such as erosion of sandbanks, have been observed post construction of offshore windfarms (personal observation Anders Galatius), which must be considered a negative impact. In contrast, evidence of marine mammal foraging activities by anthropogenic constructions on the sea floor points to a positive response to the presence of structures such as pipelines, oil rigs and wind turbines (Russell et al., 2014; Arnould et al., 2015; Todd et al., 2020). Recordings of increased seal usage of a wind farm at the Wash may have been promoted by a general increase in usage of the neighboring area and could therefore not solely be attributed to the presence of the wind farm (Russell et al., 2016). In addition, visual evidence of foraging activity and successful capture of prey by seals and other top predators in close vicinity to pipelines, umbilicals and platforms further support the hypothesis that the anthropogenic structures are used as foraging sites (Arnould et al., 2015; Todd et al., 2020).

In summary, long-term effects during the operational phase are still poorly understood and likely highly dependent on local ecological, physical and geological changes arising due to the presence of the wind farm as well as noise connected to operation activities, changes in fishing activities and artificial reef effects.

**Harbour porpoises**

In line with the harbour seals and grey seals, relatively few investigations have been conducted exploring the effects of an operational wind farm on harbour porpoises. The audibility of turbine noise for harbour porpoises has been estimated to extend 20-70 m from the foundation of the smaller turbines, up to 2 MW (Tougaard et al., 2009b). The sound emissions of operating wind turbines are only audible to porpoises very close to the foundations (Tougaard et al., 2009b, 2020) and it is considered incapable of damaging or masking the high-frequency communication of harbour porpoises (Tougaard et al., 2009). Most of the published studies report no direct positive or negative effects of operating offshore wind farms on harbour porpoises (Thompson et al., 2010; Scheidat et al., 2011; Vallejo et al., 2017; Leemans and Fijn, 2024). However, one study conducted at Borssele and neighboring Belgian waters indicated lower densities of porpoises within 500 m of the turbines, quantified from aerial surveys, but with low statistical power (Leemans and Fijn, 2024). Interestingly, the probability of detecting a porpoise decreased at closer distances to the turbines, suggesting that harbour porpoises avoid the turbines or that their prey does (Leemans and Fijn, 2024). So far, the results of this study stand alone and further documentation at other OWFs (by PODs or tagging) is needed to support such observations, which could also arise due to issues unrelated to the wind farm, for example differences in prey availability due to different substrate composition.

The long-term effects of operating offshore wind farms on harbour porpoises have been studied at three wind farms. At Nysted (72 turbines, gravity foundations), at Horns Reef I (80 turbines, mono piles), and at Egmond aan Zee in the Netherlands (36 turbines, mono piles). At Nysted, a prolonged negative effect was found on the harbour porpoises even 8 years after construction compared to a baseline 10 km away, however, a gradual recovery was found over the years (Teilmann and Carstensen, 2012). The number of porpoise observations was still around 70% lower 8 years after construction, compared to before construction. However, the cause of the decrease remains unknown, and another study on the same wind farm did not detect a decline in porpoise activity at closer range within 1.4 km from the turbines (Diederichs et al., 2008). At Horns Reef I, no significant negative or positive effects were found during the first year of operation of the wind farm. In contrast to both Nysted and Horns Reef I, the results from Egmond aan Zee showed a pronounced and significant increase in harbour porpoise acoustic activity inside the operating wind farm compared to the baseline. The cause for these differences is unknown, however, the area surrounding Egmond aan Zee is known for heavy shipping traffic and intensive trawling, and the ban of shipping and fishing inside the wind farm may have provided a 'sanctuary' for the porpoises (Scheidat et al., 2011).

In summary, long-term data is sparse and insufficient to firmly conclude whether wind farms may negatively or positively affect harbour porpoises. Yet, behavioral responses of harbour porpoises to the low-frequency noise emissions produced during the operational phase seem unlikely, unless they get very close to the foundations (Tougaard et al., 2009a). The noise is not capable of exceeding any of the threshold levels for hearing damage, and the sound cannot mask the high-frequency acoustic communication of harbour porpoises (Tougaard et al., 2009a). However, porpoises in different areas may react differently to other disturbances in the surroundings of the turbines, including noise from service vessels and potentially moving wings.

**Reef effects**

Scour protection (rocks placed to protect the foundation) of wind turbines introduces new hard substrates that act as artificial reefs and can be colonized by algae and epifauna, resulting in high biomasses e.g. of mussels and amphipods (Petersen and Malm, 2006). These changes are expected to promote an increase in fish density and general biodiversity of the area, attracting members of the megafauna such as marine mammals, sharks and large fish (Todd et al., 2020). While artificial reefs may increase the diversity of fish and other species at the wind farms, they will also result in loss of the original habitats and potentially expose soft sediment species to hard sediment predators (Degraer et al., 2020). Fishing activities such as trawling in the wind farm areas may be reduced in some areas and prohibited in others, thus, the wind farms could partly serve as a sanctuary for fish and increase predictable prey availability for marine mammals as suggested for oil platforms (Clausen et al., 2021).

**Table 1.** Published literature investigating seal responses to the construction (pile driving activities) and operation of offshore wind farms. Following abbreviations were used: HS = harbour seal, GS = grey seal, BS = baseline surveys, PC = pre-construction, CP = construction phase, CPW = construction phase as a whole, PD = pile-driving, OP = operational phase, HO = haul-out site, AS = aerial surveys, VO = visual observations, TLP = time-lapse photography, SELss = predicted single-strike sound exposure levels, OWF = offshore wind farm.

| Species | n | Season | Year | Location | Tag/method | Phase | Reference |
|---|---|---|---|---|---|---|---|
| HS | 4 | Apr.-Apr. | 2001/2 | Rødsand | Kiwi 101, SPOT2, SDR-T16 | BS | (Dietz et al., 2003) |
| *GS* | 6 | Nov.-Mar. | 2000/2 | Rødsand | Kiwi 101, SPOT2, SDR-T16 | BS | (Dietz et al., 2003) |
| *HS* | 10 | Jan.-Jun. | 2002 | Horns Reef | SDR-T16 | BS | (Tougaard et al., 2003) |
| *HS & GS* | NA | Apr. 2002 – Oct. 2003 | 2002/3 | Rødsand | Wildlife camera | CP | (Edrén et al., 2004) |
| *HS* | PC:5+3* CP:3+3* SOP:4+6* OP:1+6* | Jan. 2002/Nov. 2005 | 2002/05 | Rømø | SDR-T16, SPOT2, SPOT4, and dataloggers | PC,CP,OP | (Tougaard et al., 2006) |
| *HS* | 41/19 | S-W | 2004? | German Bight | ARGOS satellite tag | BS | (Brasseur et al., 2010) |
| *HS & GS* | NA | 1PC: Jun-Aug 2PC: Apr-Aug CP: Aug-Nov OP: Dec-Dec | 2001/4 | Rødsand | AS, VO, TLP | CP | (Edrén et al., 2010) |
| *HS & GS* | NA | Apr.-Sep. | PC: 2002/3 CP: 2004 OP: 2005/6 | Scroby Sands | AS | PC,CP,OP | (Skeate et al., 2012) |
| *HS & GS* | HS: 5 GS: 5 | HS: Feb.-Jun. GS: Oct. | HS: 2009/10 GS: 2009/10 | Rødsand | GPS/GSM | OP | (McConnell et al., 2012) |
| *HS* | 89 | | 1997-2008 | Netherlands – OWF Egmond aan Zee | SDR16, DRD, SDRL, GPS phone | PC,OP | (Brasseur et al., 2012) |
| *HS & GS* | HS: 12, GS: 15 | Mar.-Dec. | 2013 | Luchterduinen | GPS/GSM | PC | (Kirkwood et al., 2014) |
| *HS & GS* | HS: 20, GS: 20 | HS: Mar.-Jul. GS: Apr.-Oct. | 2014 | Luchterduinen | GPS/GSM | CP | (Kirkwood et al., 2015) |
| *HS* | 24 | Jan-May | 2012 | The Lincs OWF (UK) | GPS/GSM | CP | (Hastie et al., 2015) |
| *HS* | 22 | Jan.- | 2012 | The Wash | GPS/GSM | CP | (Hastie et al., 2016) |
| HS | CP: 19, OP: 23 | CP: Oct-Mar., OP: Jan. | 2003-2006, 2012 | The Wash | ARGOS & GPS | CP, OP | (Russell et al., 2016) |
| *GS* | 36 (PD: 20) | Apr.-Jan. Apr.-Feb. | 2014/16 | Luchterduinen & Gemini | GPS/GSM | CP | (Aarts et al., 2018) |
| HS | 24 | Jan.- | 2012 | The Wash, the Lincs | SMRU, GPS/GSM | PD | (Whyte et al., 2020) |

**Table 2.** Published literature investigating seal responses to the construction (pile driving activities) and operation of offshore wind farms. Following abbreviations were used: HS = harbour seal, GS = grey seal, HP = harbour porpoise, PC = pre-construction, CP = construction phase, CPW = construction phase as a whole, PD = pile driving, OP = operational phase, HO = haul-out site, SELss = predicted single-strike sound exposure levels, OWF = offshore wind farm.

| Species | Windfarm | Foundations | Mitigation | Response/impact | Reference |
|---|---|---|---|---|---|
| HS & GS | Nysted OWF | Concrete | Seal scarer/HP pinger | Observed a reduction in seals at nearby HO. | (Edrén et al., 2004, 2010) |
| HS | Horns Rev OWF | Steel monopile | Ramp up & deterring devices | Very low statistical power as the tagged animals did not enter the area of interest. | (Tougaard et al., 2006) |
| HS & GS | Nysted OWF, Rødsand II OWF | Concrete | NA | OP: no detectable attraction to, or repulsion from, the individual turbine towers. | (McConnell et al., 2012) |
| HS & GS | Scroby Sands OWF | Monopile | NA | CP: decline in HS haulout count. | (Skeate et al., 2012) |
| HS | Netherlands – OWF Egmond aan Zee | Steel monopile | NA | After construction, tagged seals extend their distribution towards the wind farms. | (Brasseur et al., 2012) |
| *HS & GS* | Luchterduinen OWF | Monopile | Faunaguard (HP deterrent) | Seals exposed to PD even at close ranges (< 20 km) returned to the area on subsequent trips. | (Kirkwood et al., 2015) |
| HS | The Lincs OWF | Steel monopile | Ramp-up | During PD seals kept a > 6.7 km distance to the PD site. | (Hastie et al., 2016) |
| HS | Inner Dowsing, Lynn, Sheringham Shoal, the Lincs OWF | Monopile | NA | CPW: no displacement<br>PD: significant displacement was reported with a decrease in seal density of up to 25 km from the center of the OWF. The seal density returned to pre-piling levels within 2 hours of piling cessation.<br>OP: No displacement. | (Russell et al., 2016) (overlap with Hastie et al., 2016 data) |
| GS | Luchterduinen & Gemini OWF | Monopiles | Soft-start, HP deterrent (not Gemini) | PD: Behavioral changes | (Aarts et al., 2018) |
| HS | The Lincs OWF | Steel monopile | Ramp-up | PD: Predicted seal density significantly decreased within 25 km or above SELss (averaged across depths and pile installations) of 145 dB re. 1 $\mu Pa^2 s$. But uncertainty in estimated effects was reported. | (Whyte et al., 2020) (overlap with Hastie et al., 2016 data) |

**Table 3**. Selected metadata covering past studies investigating harbour porpoise responses to the construction (pile driving activities) and operation of offshore wind farms. Following abbreviations were used: HP = harbour porpoise, NA = Not Available, CP = construction phase, PD = pile-driving, OP = operation phase, PC = post-construction phase, AIS = vessel activity AIS data, ST = SoundTraps, VO = visual observations, DAS = digital arial surveys, NS = North Sea, FBAR = full bandwidth acoustic recorders, SAM = static acoustic monitoring, DAT = portable standard digital audio tape, OWP = offshore wind park, =WF = off-shore wind farm, SH = sensitive hydrophones.

| Species | Season | Year | Location | Method | Phase | Reference |
|---|---|---|---|---|---|---|
| HP | BS: Nov.-Jun. CP: Jul.-Nov. | BS: 2001/02 CP: 2002/03 | Nysted OWF | T-PODs | CP | (Carstensen et al., 2006) |
| HP | Mar.-Aug. | 2002 | Horns Reef | T-POD | CP | (Tougaard et al., 2009a) |
| HP | All year | Before 2006 | Middelgrunden, Vindeby, and Bockstigen-Valar | DAT | OP | (Tougaard et al., 2009b) |
| HP | 2005: Aug.-Oct. 2006: May-Oct. 2007: Jun.-Oct. | 2005/07 | Beatrice OWF | T-PODS | PD | (Thompson et al., 2010) |
| HP | Apr.-Sep. | 2008 | Horns Reef II | T-PODs | PD | (Brandt et al., 2011) |
| HP | Jun. – Jun. Apr. – Apr. | 2003/04, 2007/09 | OWP Egmond aan Zee | T-PODs | OP | (Scheidat et al., 2011) |
| HP | NA | 2001–12 | Nysted OWF | T-PODs | PC,CP,OP | (Teilmann and Carstensen, 2012) |
| HP | All year | AS: 2008/10 SAM: 2008/11 | Alpha ventus OWF | AS, SAM, | PC,CP,OP | (Dähne et al., 2013) |
| HP | All year | AS: 2008/12, | Alpha ventus OWF | AS, SAM, C-POD | PC,CP,OP | (Dähne et al., 2014) |
| HP | Mar.-Apr. | 2011 | Thorntonbank Wind Farm | AS | PC,CP | (Haelters et al., 2015) |
| HP | All year | AS: 2009/13 POD: 2010/13 | German Bight | AS,POD | CP | (Brandt et al., 2016) |
| HP | All year | 2013 | DanTysk OWF | C-PODs, DSG recorders, SH | CP | (Dähne et al., 2017) |
| HP | All year, 10 years | | The Robin Rigg OWF | boat-based line transect surveys | PC,CP,OP | (Vallejo et al., 2017) |
| HP | All year | POD: 2010/13 | German Bight | C-PODs | CP | (Brandt et al., 2018) |
| HP | Mar.-Dec. | 2017 | Beatrice OWF | CPODs | PC,CP | (Graham et al., 2019) |
| HP | | 2010-2016 2014-2016 | German Bight, Gescha 2 | CPODs, DAS | CP | (Rose et al., 2019) |
| HP | | 2017 | BOWL windfarm | CPODs | CP | (Thompson et al., 2020) |
| HP | PD/BOE: Apr.-Dec 2017, PD/MEO: May-Dec 2019 | 2017/19 | Beatrice OWF & Moray East OWF | CPOD, ST, SM2Ms, AIS | CP | (Benhemma-Le Gall et al., 2021) |
| HP | Nov. 2020 – Oct. 2022 | 2020/22 | Gulf of Maine & Southern New England | F-PODs | PC | (Holdman et al., 2023) |
| HP | Mar. 2018 – Jun. 2019 | 2018/19 | East Anglia ONE (EA1) | C-PODS, FBAR | PC, CP | (Van Geel et al., 2023) |
| HP | | 2007/09, 2018/21, 2020/21, 2019/21, 2021/23 | OWEZ, Luchter-duinen, Germini, Borssele, *Ship | VO, DAS | OP | (Leemans and Fijn, 2024) |

**Table 4**. Table of published literature investigating harbour porpoise responses to the construction (pile driving activities) and operation of offshore wind farms. Following abbreviations were used: HP = harbour porpoise, OWF = offshore wind farm, BOW = Beatrice Offshore Windfarm, EOW = Moray East Offshore Wind Farm, NA = Not Available, CP = construction phase, OP = operation phase, PC = post-construction phase, PD = pile-driving, CV = construction vessel, AHD = acoustic harassment devices, NMS = noise mitigation systems.

| Species | Location | Foundation | Mitigation | Response/impact | Reference |
|---|---|---|---|---|---|
| HP | Nysted OWF | Gravity Piling/vibration of steel sheet piles | AHD (> 200 m), 30 min before | Absence of HP detection during the construction possibly indicating a change in habitat-use by HP. Problem with pile driving statistics. | (Carstensen et al., 2006) |
| HP | Horns Reef | Monopile | Acoustic pingers (Aquamark100), seal scarer (Lofitek), ramp-up | The pile driving zone of responsiveness extends >20 km. Absence of grading in responses across stations with increasing distance from the construction site. | (Tougaard et al., 2009a) |
| HP | Middelgrunden, Vindeby, and Bockstigen-Valar | Gravity base, | NA | Audibility was low for harbor porpoises extending 20–70 m from the foundation and the noise is considered incapable of damaging or masking acoustic communication by seals and porpoises. | (Tougaard et al., 2009b) |
| HP | Beatrice OWF | Jacket | NA | Results from our acoustic monitoring of cetaceans suggest that there were no dramatic long-term changes in the use of the area around the turbines, but that there may have been a short-term response by porpoises occurring within 1–2 km of the site. Note no monitoring was conducted between 2–40 km. | (Thompson et al., 2010) |
| HP | Horns Reef II | Monopile | “Ramp-up” | Porpoise acoustic activity was reduced by 100% during 1 h after pile driving and stayed below normal levels for 24 to 72 h at a distance of 2.6 km from the construction site. This period gradually decreased with increasing distance. A negative effect was detectable out to a mean distance of 17.8 km. Consequently, porpoise activity and possibly abundance were reduced over the entire 5 months construction period. | (Brandt et al., 2011) |
| HP | Egmond aan Zee | Steel monopile | NA | OP: An increase in HP detections was observed in line with a general increase of HP in the NS. A higher acoustic activity inside of OWF was recorded compared to outside of the OWF. | (Scheidat et al., 2011) |
| HP | Nysted OWF | Concrete | NA | Significant declines in echolocation activity were recorded inside Nysted OWF since the baseline in 2001–2 and has not fully recovered to baseline levels yet. A gradual increase of echolocation inside the OWF (from 11% to 29% of the baseline level) has been | (Teilmann and Carstensen, 2012) |

| | | | | | |
|---|---|---|---|---|---|
| | | | | recorded since establishment of the OWF, possibly due to reduced fishing and to artificial reef effects. However, the short baseline may not be representative. | |
| HP | Alpha Ventus OWF | Jackets | Pingers and seal scarers | Low densities of HP during CP were reported. PD led to avoidance response of HP within 20 km from the noise source, and increased HP detection rates at sites 25 km and 50 km from the PD of HP. Longer pile driving durations lead to a longer displacement. | (Dähne et al., 2013, 2014) |
| HP | Alpha Ventus OWF | Jacket | Pingers | A geographical gradient shows that detection rates of HP are generally much lower in close vicinity of the windfarm regardless of pile driving activity.”<br>During PD: No positions between 11 and 23 km.<br>OP: Data limitations with the closest C-POD 0.5 km from a turbine. While very close-range effects may occur, they most probably do not have a larger scale effect on HP detection rates. | (Dähne et al., 2014) |
| HP | Thorntonbank Wind Farm | Jacket | NA | PC: A wide distribution of HP was reported in Belgian waters with highest densities in the western and northern part, but also the eastern where the PD would occur.<br>PD: No HP were observed in the area. The closest observation was made almost 21 km from the impact zone. | (Haelters et al., 2015) |
| HP | DanTysk OWF | Steel monopiles | Pingers, seal scarer, soft start and 1-2 bubble curtains | HP were deterred from a smaller area during mitigated PD compared to non-mitigated. Bubble curtains can reduce noise emissions (>1 kHz) and can be effective in reducing temporary habitat and risk of hearing loss. | (Dähne et al., 2017) |
| HP | The Robin Rigg OWF | Monopile | NA | CP: Significant reduction in HP abundance.<br>OP: No significant difference in HP abundance between PC and OP but the relative HP abundance was higher in the south of the study area during OP compared to PC and CP. | (Vallejo et al., 2017) |
| HP | BARD Offsore I (BARD), Borkum West II (BWII), DanTysk (DT), Global Tech I (GTI), Meerwind Süd/Ost (MSO), Nordsee Ost (NSO) and Riffgat (RG) | DT, MSO,RG: monopiles, BARD,BWII,GTI: tripods, NSO: jackets | Pingers and seal scarers (during the CP of all OWFs apart from BARD) | 1: HHP detections declined by over 90% at noise levels above 170 dB, but only by about 25% at noise levels between 145 and 150 dB. Analyses pooling all available POD-data yielded an effect range up to 17 km when analyzed with generalized additive models (GAM). Noise mitigation effectively reduced porpoise disturbance. Clear negative short-term effects lasting 1-2 days | (Brandt et al., 2016, 2018) |

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|---|---|---|---|---|---|
| | | | | during OWF construction but no indication of OWF negative impacts on the HP population was recorded<br>2: Found a maximum effect of PD with avoidance of < 17 km from PD site and < 14 km with NMS). Found a clear gradient in decline in HP detections after piling at noise levels of 143 dB re 1 $\mu Pa^2 s$. HP declines were reduced up to 2 km from PD for ~1-2 days. | |
| HP | Beatrice OWF | Jacket | NA | No evidence of a negative temporal trend in occurrence of HP in 2017 as a result of piling. Response diminishes over time. A 50% probability of response was recorded within 7.4 km (95% CI ¼ 5.7–9.4) at the first location piled, decreasing to 1.3 km (95% CI = 0.2–2.8) by the final location; representing 28% (95%CI= 21 – 35) and 18% (95% CI = 13–23) displacement of individuals within 26 km. AHD use and vessel activity increased response levels. | (Graham et al., 2019) |
| HP | German Bight OWFs | Monopiles, jacket foundations | Yes, in some piling events: 220 without and 354 piling events with NMS. | Noise-mitigation systems used in 2014 and 2016 were more efficient compared to those used in 2010-2013 in the German Bight. Yet, the displacement range was not reduced accordingly with effect ranges of 17 km (STD ER: 15-19 km) with an effect duration at close range before PD of 28 hours to 48 hours after PD**.** | (Rose et al., 2019) |
| HP | BOWL windfarm | Jacket foundations | Ramp up, ADD | HP exhibited a strong behavioral response to ADD playbacks. There is a need to optimize the duration of AHD playbacks depending on local densities and sensitivities of different species. | (Thompson et al., 2020) |
| HP | Beatrice OWF & Moray East OWF | BOW: Jacket foundation,<br>MEO: Jacket foundation | NA | PD: an 8–17% decline in porpoise occurrence with displacement < 12km from PD site and 4 km to CV. | (Benhemma-Le Gall et al., 2021) |
| HP | East Anglia ONE (EA1) | Jacket | NA | PD had negative effects, with an overall decrease in porpoise detection probability < 14.0 km from PD activity. | (Van Geel et al., 2023) |
| HP | OWEZ, Luchterduinen, Germini, Borssele | NA | NA | HPs were seen in the OWF year around with a peak in winter and small peaks in Sep.-Oct. Numbers stabilize at a distance of 500 m from the turbine. Densities did not differ inside vs outside. | (Leemans and Fijn, 2024) |

# 3 Methods

## 3.1 Species distribution mapping

To map where the different species are found, we used different kinds of habitat suitability models, also called 'species distribution models' (O'Toole et al., 2021), based on aerial survey data or tracking data. These models predict the distributions of species based on how observed occurrences are related to different kinds of environmental variables, assuming that the same environmental parameters influence occurrences in parts of the study area where no data were obtained. No data collection was conducted specifically for this project, and no new data analyses were undertaken (Appendix: Table 1). Instead, the results were obtained as part of other projects. Below, we describe the main differences between the habitat suitability models for the different populations of seals and harbour porpoises and the data used for the models.

## 3.2 Habitat suitability modelling: Seals

For the North Sea populations of harbour seal and grey seal, habitat suitability models were based on satellite tracking data for seals tagged at Helgoland (grey seals only) and by Thyborøn. These were collected in the period between 2018–2023. At Thyborøn, both harbour and grey seals were equipped with Wildlife Computers (WC) argos/GPS tags glued to the fur, and at Helgoland, only juvenile grey seals were caught and equipped with SMRU GPS tags (Sea mammal Research Institute Ltd.). After filtering out unrealistic positions, the dataset consisted of 75,732 positions for 27 harbour seals and 112,052 positions for 48 grey seals. Seal tagging and data analyses were done as part of a study regarding the impact of the proposed Energy Island in the North Sea (Kyhn et al., 2024), which can be consulted for details regarding tagging and data handling.

Habitat suitability models for the harbour seal population and the grey seal population in Skagerrak, Kattegat, the Belt Sea and the western Baltic were also constructed based on satellite and/or GPS tracking data. A total of 67 harbour seals were actively captured and tagged at haulout sites in Denmark (n=34), Sweden (n= 10) and Norway (n=23) during the period 2001-2022. A total of 61 grey seals were captured and tagged on haulout sites in Denmark (n=17), Sweden (n=13), Estonia (n=18) and Finland (n=13) during the period 2000-2023. Most seals (n=95) were fitted with SMRU GPS tags, while some of the seals captured on Danish haulout sites were fitted with argos tags (n= 12 for grey seals and n=27 for harbour seals). Detailed methods on how seals were captured, handled and tagged are provided elsewhere (Dietz et al., 2013; Van Beest et al., 2019). After filtering out unrealistic positions, the dataset consisted of 179,853 positions for harbour seals and 315,013 positions for grey seals (van Beest et al., in prep.).

Before building habitat suitability models, the filtered tracking data were standardized using state-space models (SSM) to obtain hourly estimates of seal locations. Afterwards, a habitat suitability model was built for each species and tagging site based on the position estimates from the SSMs. Habitat suitability was assessed using generalized additive models (GAMs) following the same approach as previously used for studying the distributions of seal populations in the North Sea (Aarts et al., 2008; Carter et al., 2022). Here, the presence of seals (SSM data vs. random positions; "pseudo-absences") was used as a binary dependent variable, and temperature, salinity, current strength, sea surface height, mixed layer depth, distance to tagging site, water depth and substrate type were used as predictors.

The species distribution maps were generated by using the habitat suitability models to predict the distribution of the seals that were based at different haul-out sites (i.e. one habitat suitability model and one prediction per haul-out site). These predictions were stacked to generate one distribution map for each population (i.e. two for harbour seal and two for grey seal). In the predictions for the North Sea populations, this was done after weighing the different maps by the number of seals that occurred at different haul-out sites (see details in Kyhn et al., 2024). Finally, the distribution maps were cropped to the Danish exclusive economic zone (EEZ) and re-scaled to lie in the range 0–1, where 1 indicates areas that are likely to be highly important for seals.

## 3.3 Habitat Suitability modelling: Harbour porpoise

For the North Sea harbour porpoise population, the species distribution mapping was based on dedicated aerial surveys conducted in various parts of the North Sea (Gilles et al., 2016). As this model uses animal counts as a predictor rather than presence absence data, it is referred to as a habitat-based density model. Animal occurrences were obtained using standardized line-transect survey methods that incorporated correction factors for missed animals on the transect line. The data sets were collected in the period 2005–2013 and included data from SCANS-II covering the entire North Sea and national surveys covering smaller areas. Predictions were based on generalized additive models mostly based on the same predictors as those used for the harbour seals. Within Danish waters, only summer surveys were available, and efforts were extremely low except in the Danish Dogger Bank area and the most southeastern North Sea. Consequently, only predictions for the summer months in these two smaller areas were used for the sensitivity mapping.

For harbour porpoises in the inner Danish waters and the southwestern Baltic, the species habitat suitability model was based on satellite tracking data (Appendix: Fig. A8-A9). Individual harbour porpoises were fitted with argos satellite tags after being incidentally trapped in pound nets, which are used in near-shore commercial fisheries in the Belt seas. These were collected over the period 2013–2022 as part of a long-term satellite telemetry monitoring program in Denmark (Teilmann et al., 2007; Sveegaard et al., 2011; Stalder et al., 2020). Pre-processing of location data included filtering out unlikely locations (Sveegaard et al., 2011) and the removal of locations on land and those collected within 24 hours after tagging (Van Beest et al., 2018). After the data cleaning process, 2,353 locations from 46 harbour porpoises remained.

Habitat suitability of harbour porpoises in the inner Danish waters was estimated through the machine learning algorithm maximum entropy (MaxEnt: Phillips et al., 2006). The output of MaxEnt models can be interpreted as a spatially explicit probability of habitat suitability (0=unsuitable habitat, 1=optimal habitat). We constructed separate MaxEnt models for each season using the pruning and variable selection procedures outlined below.

A total of 13 environmental variables were considered that were expected to influence habitat suitability of harbour porpoises (Edrén et al., 2010; Gilles et al., 2016; Isojunno et al., 2012). Static environmental variables included: “bathymetry (m)”, “seabed slope (°)”and “sediment type (categorical variable including sand, mud, bedrock and hard bottom complex)". Dynamic environmental variables included: "current velocity (m/s)", "mixed layer thickness (m)", "sea surface salinity (PSU)", "sea surface height (m)", and "sea surface temperature (°C)".

Multicollinearity among the 13 candidate predictor variables was substantial, and we therefore used a jackknife procedure to iteratively reduce model complexity until all pairwise correlations among all retained variables had Spearman's rho <0.7. Through this iterative procedure, five of the initial 13 predictor variables were subsequently dropped from further model development: the means of "sea surface salinity" and "sea surface temperature", the mean and standard deviation of "sea surface height (m)" and the SD of "current velocity".

Once the optimal model settings were identified for each season, we reran the models 100 times with each iteration using a randomly drawn subset of the presence locations (80%) and using the remaining 20% of presence locations for testing predictive performance (AUC) and to confirm lack of overfitting (OR10). All model iterations had AUC > 0.75, and most had OR10 <0.1, which are threshold values indicative of good predictive performance without model overfitting (Elith et al., 2006). In this report, we used the summer estimates (May–October) to predict porpoise distributions.

The Baltic Proper harbour porpoise population occurs in the area around the island of Bornholm and further east (Carlén et al., 2018). Animals equipped with satellite tags in the inner Danish waters rarely visit this region, which makes the model developed for that population unsuitable for predicting the general distribution of porpoises around Bornholm. Further, the tagged porpoises did not include animals from the Baltic Proper population. Instead, the relative importance of the Danish EEZ around Bornholm for harbour porpoises was obtained from HOLAS III (Sveegaard et al., 2022). As very few surveys have been carried out in the distribution range of the Baltic Proper harbour porpoise population, the HOLAS III assessment was based on results from the SAMBAH passive acoustic monitoring programme, which took place in the period 2011–2013 (Amundin et al., 2022). HOLAS III provides a direct assessment of the relative importance of the different areas for porpoises. As HOLAS III does not provide a measure of the relative abundance of the species on a continuous scale, the data provided are not suitable for calculating sensitivity as defined in the present study, so for the area around Bornholm the HOLAS estimates for the months May–October were used directly as a measure of sensitivity.

## 3.4 Sensitivity mapping

To provide a risk-based assessment covering the sensitivity of marine mammals to offshore wind farms, a sensitivity map was generated. Risk is typically defined as the probability of an event occurring multiplied by the expected consequence if the event occurs (Gibbs and Browman, 2015):

$$Risk = Likelihood * Consequence$$

The assessment presented here is based on this definition but recognizes that the likelihood can be interpreted as the relative density. We therefore define sensitivity as relative density (based on habitat suitability maps, scaled from 0–1) multiplied by the consequence of encountering a wind farm. We scale this consequence to lie in the range 0–1, with zero corresponding to no effect and one indicating that all animals are deterred by wind farms, and that they are excluded from the wind farm areas from the beginning of the construction phase and until the end of the operation phase has been decommissioned (i.e. the whole area; not just the area close to individual turbines).

*Sensitivity = Relative abundance * Consequences*

As such, the sensitivity maps are based on habitat suitability maps for individual species and regions combined with studies of how wind farms affect animals locally. The consequences may also vary in space, if there are certain areas where animals react more negatively to wind farms, but due to the scarcity of data on regional variations in the impact of offshore wind farms we decided to use a single consequence value for each species in this report. The consequence considers the impact of a wind farm on individual animals across the entire life span of the wind farm, including both the construction phase and the operational phase, while taking into account how long each of these phases lasts. The assessment of the impact of windfarm construction is based on windfarms that use noise mitigation.

The assessment of the consequence of encountering a wind farm is informed by observed changes in animal densities in the close vicinity of wind turbines, with avoidance signifying a negative impact. In the absence of data on how animals react to wind farms, impacts are assessed based on how animals are expected to react to habitat changes in the vicinity of wind farms. For example, wind farms could be expected to have negative effects on seals if fish were known to be scared away from wind farms. The impacts of wind farms likely differ among populations, as a temporary deterrence may have larger consequences in a very small population than in a large one. For this reason, we use different sensitivity cut-off limits for the different populations (i.e., the values setting the limits between areas with lowest, medium and highest sensitivity). These limits were based on best available knowledge.

While this type of sensitivity mapping can be used to determine the relative suitability of different regions for wind farm development, it is important to stress that it does not distinguish between species that are strictly protected and species that are not protected. Further, it may not fully account for long-term cumulative impacts of different stressors associated with wind farms, as these are not necessarily all known today. It may not fully account for changed fishing patterns, climate change effects or the combined impacts of multiple wind farms that jointly affect currents, productivity etc.

Polygons were added to the map reflecting the sensitivity level to the wind farms, pinpointing areas with lowest, medium, and highest sensitivity, and areas where missing data makes the model uninformative. The cut-off limits between highest, medium and lowest sensitivity were carefully adjusted to ensure that the distribution of areas with the highest and medium sensitivity covered regions that were considered to be of particular importance to the animals, and the rationale for the selection of consequence values and cut-off limits were discussed.

For harbour porpoises in the waters around Bornholm, the sensitivity map is directly based on distribution maps from the SAMBAH project (data collection 2011-2013, (Carlén et al., 2018)) as well as expert recommendations based on distribution maps developed for the HOLAS-III assessment in the

HELCOM region (Sveegaard et al., 2022). During the HOLAS-III assessment, the regions of medium or high importance for porpoises were determined, and we used the same categories for the sensitivity maps. The waters around Bornholm are located in the transition zone between the Belt Sea population and the Baltic Proper population. Consequently, it is likely that individuals from the critically endangered Baltic population may be present, and these should receive special protection.

# 4 Results

Our review of the available literature on consequences of offshore wind farms revealed considerable knowledge gaps. Whereas several studies have shown that seals and porpoises are likely to get deterred by the loud noises associated with pile driving of the monopile foundations that are most commonly used for offshore wind farms in Danish waters, there were differences in the distance at which animals were reported to be affected, and for how long. Harbour porpoises were reported to be affected at ranges of 8–25 km (Edrén et al., 2010, 2004; Russell et al., 2016; Skeate et al., 2012; Whyte et al., 2020). In some cases, the responses lasted only 6–8 hours, while they have been suggested to last 1–2 days in some studies (Brandt et al., 2011, 2016; Dähne et al., 2017; Nabe-Nielsen et al., 2018; Brandt et al., 2018; Rose et al., 2019; Thompson et al., 2020). Similar reactions to pile driving noise have been observed for seals, except perhaps even more variable. 1-3 days in the German Bight, by Horns reef and the Beatrice OWF within a < 3 km distance from the impact site (Brandt et al., 2018, 2011, 2016; Rose et al., 2019; Thompson et al., 2020). In addition, other studies calculated the return of harbour porpoises to be between 6-10 hours (Dähne et al., 2017; Nabe-Nielsen et al., 2018).

The consequences of operating wind farms are even less well studied for the three species we focus on here. While there is no indication that the animals are able to hear the operating wind turbines at distances exceeding a few hundred meters, at least one study points to a long-lasting negative effect of a wind farm on porpoises (Teilmann and Carstensen, 2012). This could be due to habitat alterations and reduced prey levels. In this study, the number of porpoise detections was reduced by approximately 10% for some years following construction. As such habitat alterations could also affect the less well studied seal species, we take a precautionary approach and operate with a consequence level of 10% for all three species and for all geographical regions.

The sensitivity is calculated as the consequence multiplied by relative population abundance. As consequence is constant and the same for all three species, the sensitivity is directly proportional to relative density. The relative density was calculated in earlier studies using habitat suitability modelling (as summarized in the Appendix; Fig. A1-A9), but the results of these analyses will not be discussed here. The sensitivity is calculated for one species and population at a time, and the cut-off limits between areas with the lowest, medium, and highest sensitivity are determined per population based on best available knowledge of the conservation status of the different populations. This ensures that vulnerable or declining populations can be characterized as relatively sensitive in larger areas than more robust populations (see discussion). This is reflected in the sensitivity maps (Figures 1–3).

## Harbour seal

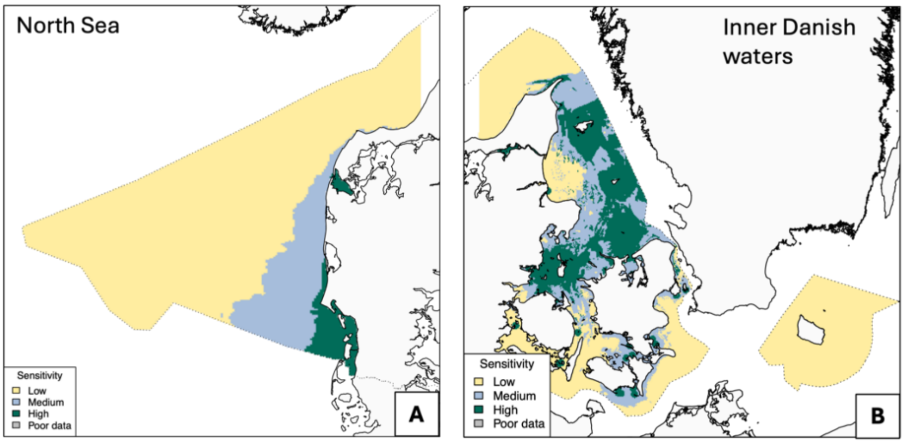



**Figure 1.** Sensitivity map of harbour seals, where the colors represent the level of sensitivity, bright yellow = lowest, bright blue = medium and dark green = highest. A) sensitivity map of the North Sea and B) sensitivity map of the Inner Danish waters.

## Grey seal

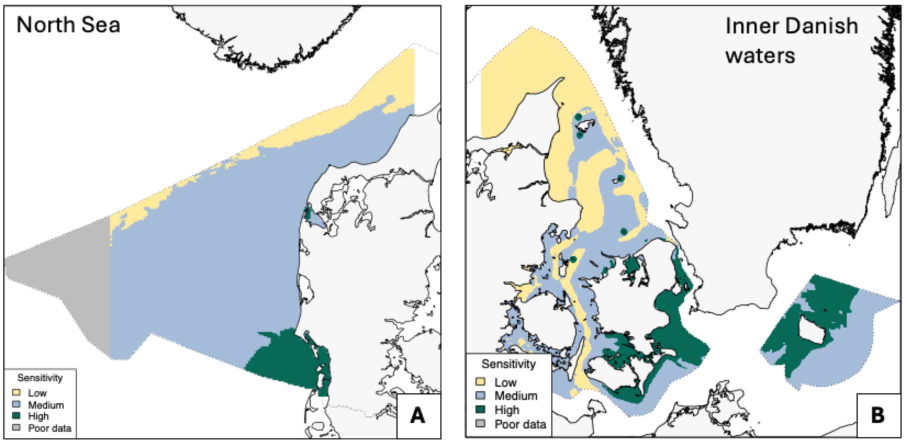
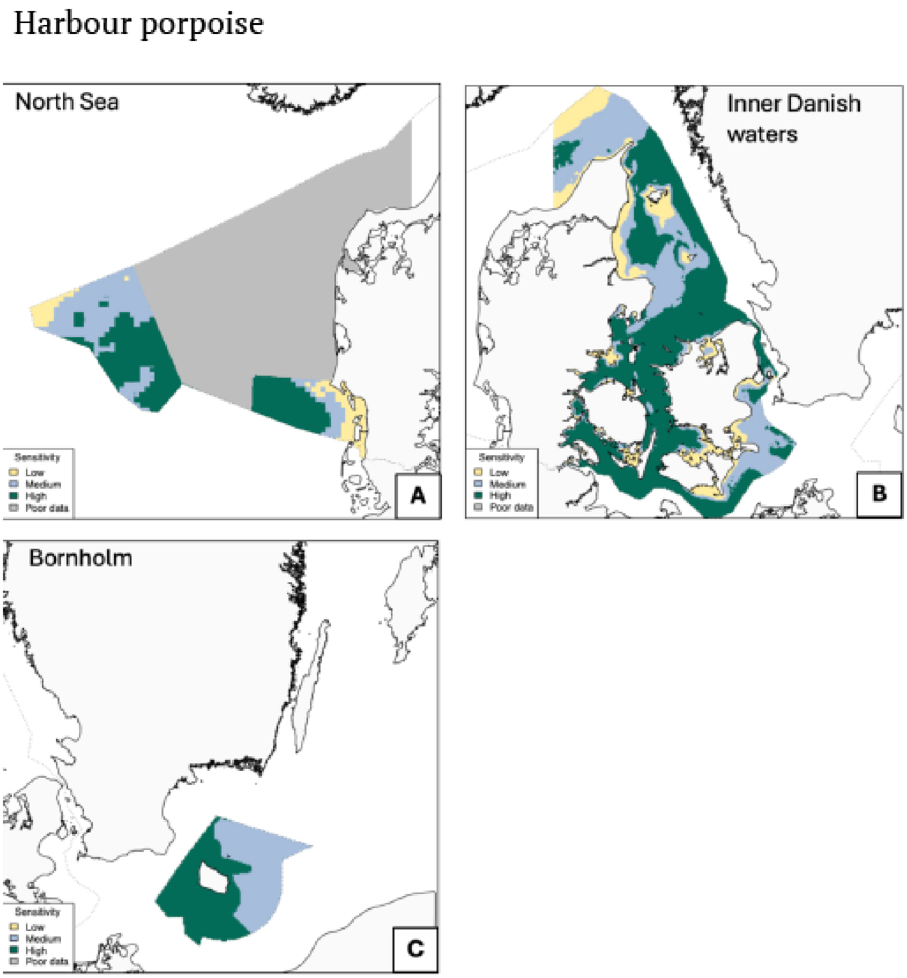



**Figure 2**. Sensitivity map of grey seals, where the colors represent the level of sensitivity; bright yellow = lowest, bright blue = medium, dark green = highest and grey = areas with too poor data coverage to conclude anything. A) sensitivity map of the North Sea and B) sensitivity map of the Inner Danish waters.

**Figure 3.** Sensitivity maps of harbour porpoises, where the colors represent the level of sensitivity; bright yellow = lowest, bright blue = medium, dark green = highest and grey = areas with too poor data coverage to conclude anything. A) sensitivity map of the North Sea, B) sensitivity map of the Inner Danish waters and C) sensitivity map of the waters surrounding Bornholm. The North Sea map will be updated in a future revision of this report.



# 5 Discussion

## 5.1 Sensitivity maps for seals and harbour porpoises

### Harbour seals

Harbour seals in the eastern North Sea are mainly distributed in the Danish, German and Dutch part of the Wadden Sea. Therefore, the highest sensitivity to offshore wind farms is predominantly found along the coastline in the southern Danish part of the North Sea (Fig. 1A). The sensitivity decreases with the distance from the shore, as harbour seals are dependent on hauling out at well-defined haul-out sites, particularly during the breeding and moulting season (Kyhn et al., 2024). The Wadden Sea haul-out sites are distributed south of Blåvandshuk. The other well-defined haul-out locality along the Danish west coast is the sand banks in the outer part of the Limfjord, east of Thyborøn, which are also marked as an area with relatively high sensitivity (Fig. 1A). This haul-out site, however, has relatively few pups during the breading season. Harbour seals should be considered sensitive to offshore wind developments in the entire Limfjord as harbour seals from two subpopulations (Central Limfjord and the Wadden Sea) are tightly connected to this area. The area with medium sensitivity along the west coast of Jutland signifies a band along the coast with medium population densities, further from haul-out sites (Fig. 1A). This band stretches from Hanstholm and all the way down along the Wadden Sea, where it extends further offshore in the southern part compared to the deeper northern part. The areas with the lowest sensitivity include the Skagerrak as well as the more offshore parts of the North Sea that are rarely visited by harbour seals (Fig. 1A-B).

The Inner Danish waters contain several areas that belong to the highest-sensitivity class close to the numerous haul-out sites in Kattegat, the Danish Straits and in the western part of the Baltic Sea (Fig. 1B). Due to the larger population sizes in the Kattegat region, larger areas are evaluated to be important and hence marked as belonging to the highest sensitivity class, based on the movements of satellite tracked harbour seals. These have been tagged at several locations including Anholt, the haul-out sites around Bosserne, Rødsand and Falsterbo, and are thus expected to be representative of harbour seals in the inner Danish waters. The medium sensitivity areas make up the remaining eastern part of the Danish Kattegat area except for the coastal area north of Djursland, which is evaluated to have a relatively low sensitivity due to the environmental conditions in this area, combined with long distance to nearest haul-out sites (Fig. 1B). A large part of the Belt Seas and the Western part of the Baltic is evaluated to be of relatively low importance due to the small number of harbour seals inhabiting these areas (Fig. 1B).

### Grey seals

Grey seals in the eastern North Sea are mainly distributed in the Danish, German and Dutch part of the Wadden Sea. Therefore, the highest sensitivity to offshore wind farms is predominantly distributed along the coastline in the southern Danish part of the North Sea, extending further offshore than for the harbour seals (Fig. 2A). Again, the sensitivity decreases with distance from the shore, although the medium sensitivity area for grey seal is considerably larger than the corresponding area for harbour seals (Fig. 1A). The reason for this is that grey seals move further away from haul-out sites and the shore than harbour seals do (Dietz et al., 2003, 2015; van Beest et al., 2022; Kyhn et al., 2024). Grey seals are dependent on hauling out at well-defined haul-out sites along the west coast of Jutland, particularly during the breeding and moulting seasons (Kyhn et al., 2024). The Wadden Sea haul-out sites are distributed south of Blåvandshuk. Grey seals resemble harbour seals in having well defined haul-out sites on the sand banks in the outer part of the Limfjord east of Thyborøn (marked as areas with relatively high sensitivity) (Fig. 1A). The remaining part of the Limfjord is rarely used by grey seals and should, hence, be regarded as of minor importance, corresponding to a relatively low sensitivity. The medium sensitivity area extends from Hirtshals and all the way down along the Wadden Sea, where it covers almost the entire part of the Danish North Sea (Fig. 1A). The area with relatively low sensitivity includes the deeper parts of the Skagerrak (Fig. 1B).

The Kattegat is less important for grey seals compared to the harbour seals, and areas belonging to the highest sensitivity class are predominately found close to the haul-out sites used by the grey seals. In Danish waters, grey seals only occur in larger numbers in the Baltic Sea, at the haul-outs at Rødsand and Ertholmene. The western part of the Baltic, including Rødsand and Ertholmene, is considered to be an area where grey seals are relatively sensitive to disturbances, as this is where most grey seals in Danish waters are found (Fig. 1B). The grey seals in the western Baltic are part of a larger population, which extends further north in the Baltic, and only very few grey seals give birth in Denmark, the great majority of these do so in the southwestern Baltic. The grey seals should therefore be considered vulnerable to disturbances until they establish a viable breeding stock. The medium and lowest sensitivity areas are large in the Kattegat area as well as the western Danish Straits (Fig. 1B). The area with highest sensitivity in the Isefjord is likely an artefact of the underlying species distribution model (Appendix: Fig. A7), which results from the favorable environmental conditions found in this area rather than the actual occurrence of seals (Fig. 1B).

### Harbour porpoises

The sensitivity mapping of harbour porpoises was done separately for the three Danish populations, 1) The North Sea population (covering the entire North Sea, Skagerrak and northern Kattegat), 2) the Belt Sea population (covering the southern Kattegat, the Danish straits and the western Baltic) and 3) the Baltic population (covering waters around Bornholm and eastwards) (Fig. 3). The sensitivity maps are based on habitat-based density models based on visual surveys in the North Sea (during summer), habitat suitability models based on satellite tracking in the Belt Sea (prediction for the summer months) and species distribution models in the form of "predicted probability of detection of harbour porpoises" based on passive acoustic monitoring around Bornholm (May-October).

In the North Sea, relative porpoise densities are obtained from Gilles et al. (2016) and used to construct a sensitivity map. A newer map including data from 2010-2020 was produced for the OSPAR QSR-2023 assessment (https://www.ospar.org/work-areas/cross-cutting-issues/qsr2023), but the GIS files were not available in time to be included in this report. Furthermore, the problem with sparse data in the central Danish North Sea remains in this newer map, as the QSR model only included data from the sporadic coverage of SCANS-III. Since 2020, a comprehensive amount of new survey data has been collated, e.g. during SCANS-IV (much better coverage than previous

SCANS surveys), during national aerial surveys, during the Energy Island project (covering the entire Danish North Sea in 2023) and the North Sea I project. However, to date these new data have not been used to produce a distribution model that could be used for sensitivity mapping. As a result, a large part of the North Sea is marked as "poor data" area, and only the Danish part of the Dogger Bank region and the south-eastern North Sea have sufficient coverage (Fig. 3A). However, the DEA and AU have agreed upon a new project on harbor porpoise habitat mapping for the North Sea, which will make it possible to obtain a high-resolution sensitivity map based on recent data for the parts of the North Sea that are currently marked as "poor data". This map will be presented in a revised version of this report. In Skagerrak, however, the eastern part is included in the habitat suitability model for the Belt Sea region based on satellite tracking data, which makes it possible to estimate sensitivity for this region (see Belt Sea section below for more information) (Fig 3B). The areas with relatively high sensitivity in the western part of the Danish North Sea (Fig 3A) coincide with the Dogger Bank region, where high porpoise densities have been reported in several other surveys (Geelhoed et al., 2014; Lacey et al., 2022; Kyhn et al., 2024). A decrease in sensitivity occurs in the south-eastern part of the Danish North Sea when approaching the coast of Jutland. However, it should be noted that harbour porpoises in the Wadden Sea may belong to a small separate population with relatively small home-ranges (Scheidat et al., 2024), and that it may therefore be more correct characterizing them as belonging to the highest sensitivity class for porpoises in the Wadden Sea region. In the Skagerrak (based on the habitat suitability map, Appendix: Fig. A9), the sensitivity is highest in the middle of the Danish waters, corresponding to the slopes of the Norwegian Trench, while decreasing closer to the coast and further offshore.

The Belt Sea consists of relatively narrow straits that are used by harbour porpoises to find food in the strong currents. According to the sensitivity maps (Fig. 3B), harbour porpoises are most sensitive in the Little Belt, Great Belt, the Sound, north of Zealand and along the Swedish marine border in Kattegat, which is consistent with earlier studies of this population (Unger et al., 2021). The lower sensitivity along the coast of Jutland north of Djursland and south of Læsø coincides with areas with shallow water. Porpoises also have relatively low sensitivity east of Stevns and Møn (Fig. 3B). In general, a large part of the Belt Sea population range is regarded highly sensitive, which corresponds with the newest HOLAS-III assessment map for harbour porpoises (Sveegaard et al., 2022). Recent population estimates for this population show a significant decline over the past 18 years, which is assumed to be caused by too high levels of bycatch, prey depletion and a general declining health of the marine environment (Owen et al., 2024). This increases the likelihood that the population would be further affected negatively by additional disturbances.

The harbour porpoise in the Baltic proper is listed as Critically Endangered (CR) by IUCN, Denmark and all the Baltic range states, with an estimated total population of around 500 individuals (Amundin et al., 2022). This population is therefore highly sensitive by definition, and any disturbance that may compromise the future fitness or survival of even a single individual should be avoided (Fig. 3C).

## 5.2 Uncertainties related to habitat suitability modelling

The sensitivity maps presented in this report are based on the assumption that disturbances have the largest population impact in areas where the population density is high (cf. (Gibbs and Browman, 2015)). In this report, we follow a common approach and use habitat suitability models for calculating the relative population density of the studied species, but these kind of models are associated with various uncertainties that need to be taken into account when interpreting the sensitivity maps.

One important assumption of habitat suitability models is that the likelihood that animals use a particular area is linked to the environmental conditions in that area, and that the animals are equally likely to use other areas with similar environmental conditions. This may not always be the case, particularly when extrapolating to areas far from where animals were observed. In some cases, our results have required such extrapolations. For example, almost all data for harbour seals derive from seals tagged at a few haul-out localities, namely Anholt, Rødsand and Falsterbo (Sweden) in the inner Danish waters and Thyborøn in the North Sea. Harbour seals mostly move over limited distances relative to their key haul-out site (Dietz et al., 2003, 2013, 2015). This is particularly the case for adult seals during the breeding period, whereas subadults may perform longer travels to explore new areas during the winter period (Dietz et al., 2013). This means that in the inner Danish waters, model output from areas more than 50 km away from the few haul-outs, where seals were tagged, are mostly extrapolations. The same is the case for grey seals, where almost all data derive from seals tagged at Rødsand, Falsterbo, Ertholmene and Thyborøn, although grey seals have larger home ranges than harbour seals (Dietz et al., 2015, 2003). This could pose a problem if the animals are, in fact, associated with fine-scale variations in prey availability, which may not be directly linked to the large-scale environmental variables used in the models. As the fish prey species of seals vary both spatially and temporally (Scharff-Olsen et al., 2019), extrapolations to other periods and areas are wrought with uncertainties. This may be particularly problematic for wide-ranging species such as grey seals, where the model was fitted on the basis that seals spent most of their time in the Northern Baltic area.

Another challenge with the habitat suitability models we use here is that they are partly based on old data and on relatively small sample sizes. The great majority of the harbour seal data from the inner Danish waters are more than ten years old, and animals may no longer be associated with the same habitats that they were back then. The model for the grey seal in the North Sea was based on more recent data, but the sample size was low, and as many of the tagged animals were juveniles, they may not be representative of the entire population (Kyhn et al., 2024). We attempted to also include grey seal tagging data from our colleagues in the Netherlands, but unfortunately this failed due to the time restrictions of this project. This is the reason for the exclusion of the westernmost part of the North Sea for the predictions for grey seal.

Another assumption of the habitat suitability models that form the core of the sensitivity maps is that they assume that the populations are in equilibrium. This is not the case for grey seals and harbour seals that are currently recovering from past culling campaigns (Olsen et al., 2018; Galatius et al., 2020, 2024b, 2024a), and grey seal recolonization is still in the early stages in Danish waters (Galatius et al., 2020, 2024b). If the grey seal population in the inner Danish waters continues to increase, it is likely to affect the harbour seal population negatively, which may make it more vulnerable to additional disturbances associated with construction of wind farms, thus necessitating an expansion of the areas where it should be considered highly sensitive.

One of the key challenges when assessing how sensitive marine species are to the development of offshore wind is that animals react to multiple pressures at the same time, and that the impact of these pressures are not necessarily constant in time and space. Several different methods have been used to account for the cumulative impacts of the different factors that affect animals by individual wind farms as well as cumulative pressures of multiple wind farms over large spatial scales (Masden et al., 2010; Goodale and Milman, 2019; Declerck et al., 2023), but as the impact of cumulative pressures was rarely discussed in the studies that this report is based on, our sensitivity assessment only implicitly takes these pressures into account.

The studies that we use for assessing consequences of individual wind farms are also limited in the sense that both the size of the individual turbines and the area covered by wind farms were small in comparison to the wind farms that are planned for the future. Future wind farms may, thus, influence the marine environment over areas far larger than those for which we have data, which calls for caution when assessing impacts of future wind farms based on how animals reacted to wind farms in the past. It is therefore essential to continuously monitor how populations develop under the operation of large wind turbines in order to be able to adapt management plans to unexpected population developments.

Although sensitivity maps like the ones we present here provide a useful tool for pinpointing areas that are particularly important for different species, they are not suited for determining the consequence of developing wind farms on populations. The calculated sensitivity values cannot be directly related to changes in population status, as this also depends on the life history of the studied species and the extent to which animals are able to exploit different parts of the landscape during a period where they are deterred from a wind farm development site. Long-lived, stationary animals are more likely to be affected by wind farm development than short lived species that can exploit many different habitats in different parts of the landscape. To more fully determine the consequences of wind farm developments on populations and ensure that populations have a favorable conservation status, it is necessary to use population models that account for these variations in life history traits. If such models are based on the fundamental processes that govern the dynamics of populations, such as animal energetics and movements, they are also more suitable for predicting impacts of future conditions than are simple statistical extrapolations of earlier findings. The aim of the next phase of the Screening project is to use such a process-based population model to assess the cumulative impacts of offshore wind on the harbour porpoise.

# 6 Recommendations

To improve the habitat suitability models, new seal tracking data from the Wadden Sea and throughout the inner Danish waters would increase the likelihood that the data match current habitat use that may have changed over the past decades. For grey seals, data from Kattegat are lacking. For both species of seals, the proportion of haul-out time provided by satellite telemetry should be updated as the populations approach a stable distribution and abundance throughout the Danish waters.

For harbour porpoises, the distribution map for the area around Bornholm is based on data that are relatively old (2011-2013) and the distribution may have changed since then. However, the SAMBAH-II project is running 2023-2026 and, thus, the basemap for this area should be updated, once new maps become available.

Likewise, the North Sea harbour porpoise distribution model is also based on old data (2005-2013), and for the majority of the Danish North Sea the effort is so poor that they could not be used to produce reliable sensitivity maps. However, more data are available covering a large part of the Danish North Sea. These include SCANS-III (2016), SCANS-IV (2022) as well as multiple smaller regional surveys from (2014-2024). These data will be used to develop an updated habitat suitability model for porpoises in the North Sea, which will be made available in an updated version of this report. Further, we recommend acquiring additional satellite telemetry data for porpoises in all Danish waters to ensure that these maps stay current.

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# 9 Appendix

## 9.1 Data maps

### North Sea

**Harbour seals – all filtered positions**

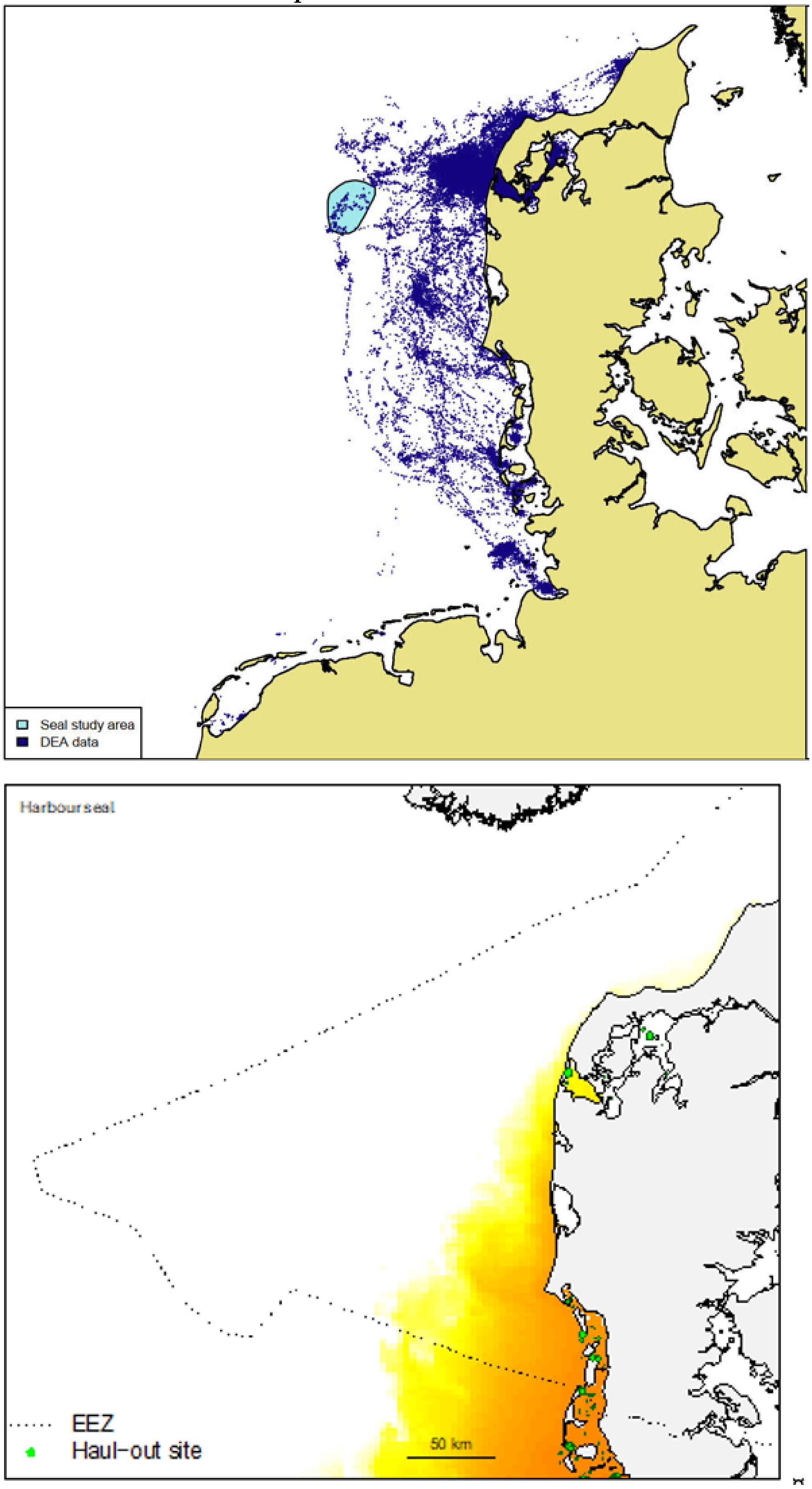
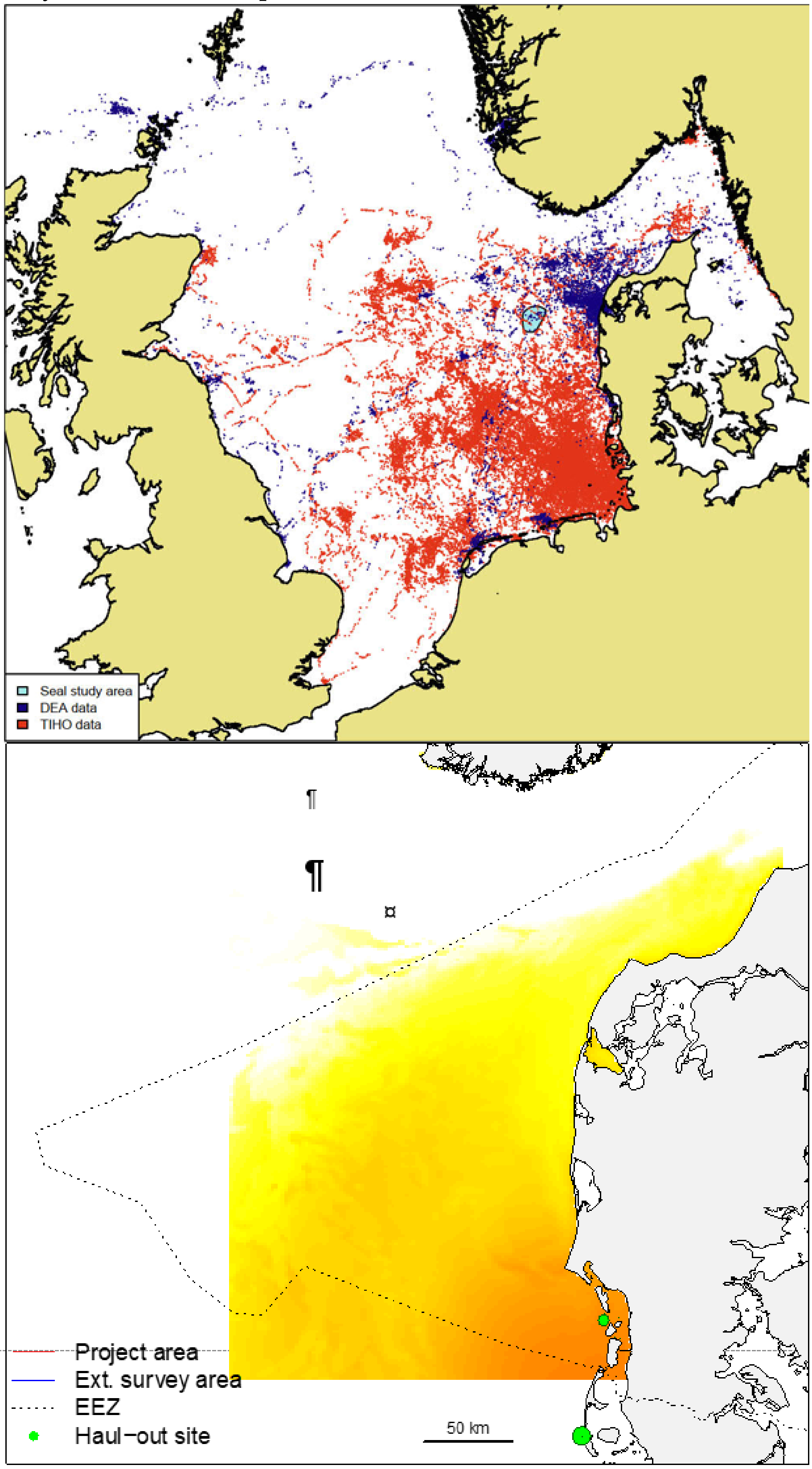



**Figure A1.** Left) Map of the GPS and ARGOS data from 27 harbour seals (n = 75,732). The blue dots represent the filtered positions of individuals tagged at Thyborøn between 2022-2023. The light blue “Seal study area” was the area previously considered for construction of an Energy Island. Right) Habitat suitability for harbour seals tagged at Thyborøn (Kyhn et al., 2024). The the dotted line defines the Danish Exclusive economic zone. Green dots are haul-out areas with seals counted in the moulting season (August 2021); the size of the dots is proportional to the number of seals. Not all German haul-out sites are shown. The color scale signifies the relative probability that an area is used by seals, with red-orange being high and white/yellow being low. The map uses the EPSG:3035 ETRS89 projection.

**Figure A2.** Maps of the GPS and ARGOS data from 48 grey seals (blue: 15 individuals, Thyborøn, n = 27,191 and red 33 individuals, Helgoland, n = 84,861) obtained throughout the Energy Island project (Kyhn et al., 2024). The blue dots represent the filtered positions of individuals tagged at Thyborøn between 2022-2023 and the red dots represent the filtered positions of individuals tagged at Helgoland between 2018-2022. The light blue "Seal study area" was the area previously considered for construction of an Energy Island. Right) Figure A6. Habitat suitability model for grey seals tagged at Thyborøn and Helgoland (Kyhn et al., 2024). The dotted line defines the Danish Exclusive economic zone. The green dots show haul-out sites where seals were counted in the moulting season of 2021, i.e., March–April; the size of the dots is proportional to the number of seals. Not all German haul-out sites are shown. No seals were counted at Thyborøn in 2021, but grey seals are known to haul out in that area. The color scale signifies the relative probability that an area is used by seals. The habitat suitability map was copied from the Energy Island report (Gilles et al., 2016), but superimposed with the North Sea Lot1 project area. The map uses the EPSG:3035 ETRS89 projection

**Grey seals – all filtered positions**



### Harbour porpoises

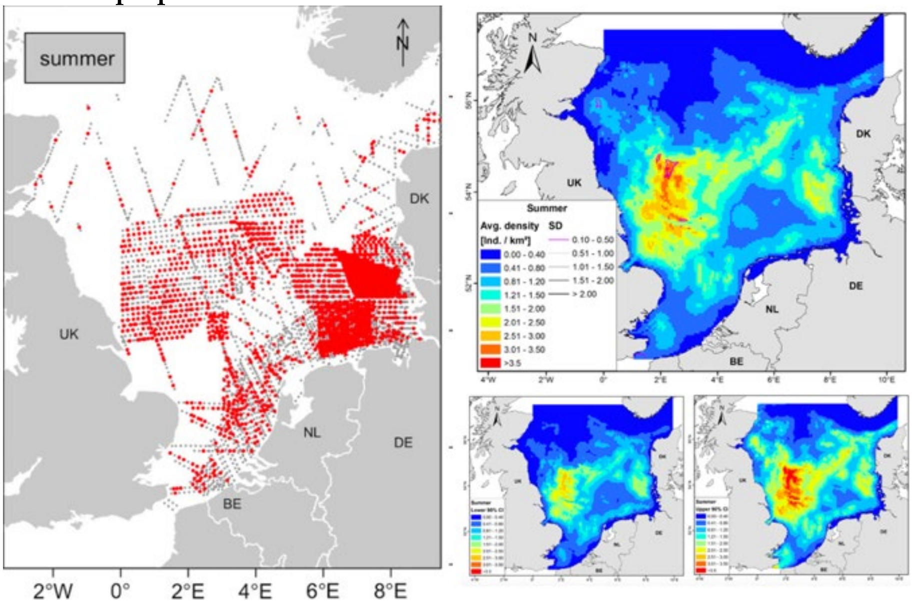



**Figure A3**. Left) Seasonal coverage of transect segments in 2005–2013, for summer (Jun.–Aug.). Effort segments are shown in gray, sighting positions in red (Gilles et al., 2016). Right) Predicted harbor porpoise densities in the North Sea in summer (Jun.–Aug.). Upper panel: The overlaid contours are associated jackknife standard deviations (SD). Lower panel: Lower and upper lognormal 90% confidence intervals (Lower 90% CI and Upper 90% CI) for the seasonal density based on the jackknife samples (Sveegaard et al., 2022)

## Inner Danish waters & southwestern Baltic Sea

### Harbour seals

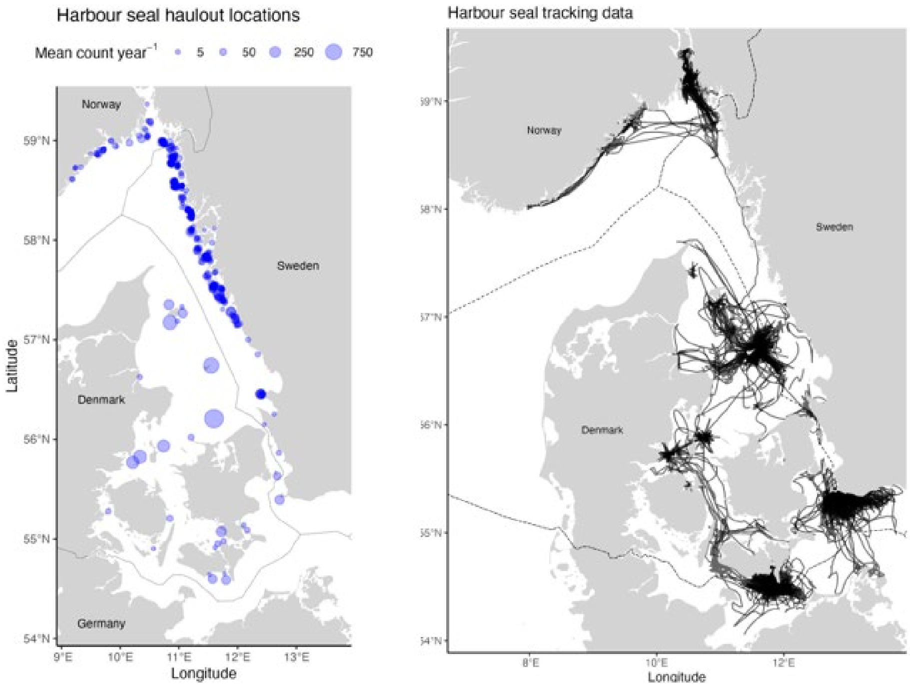
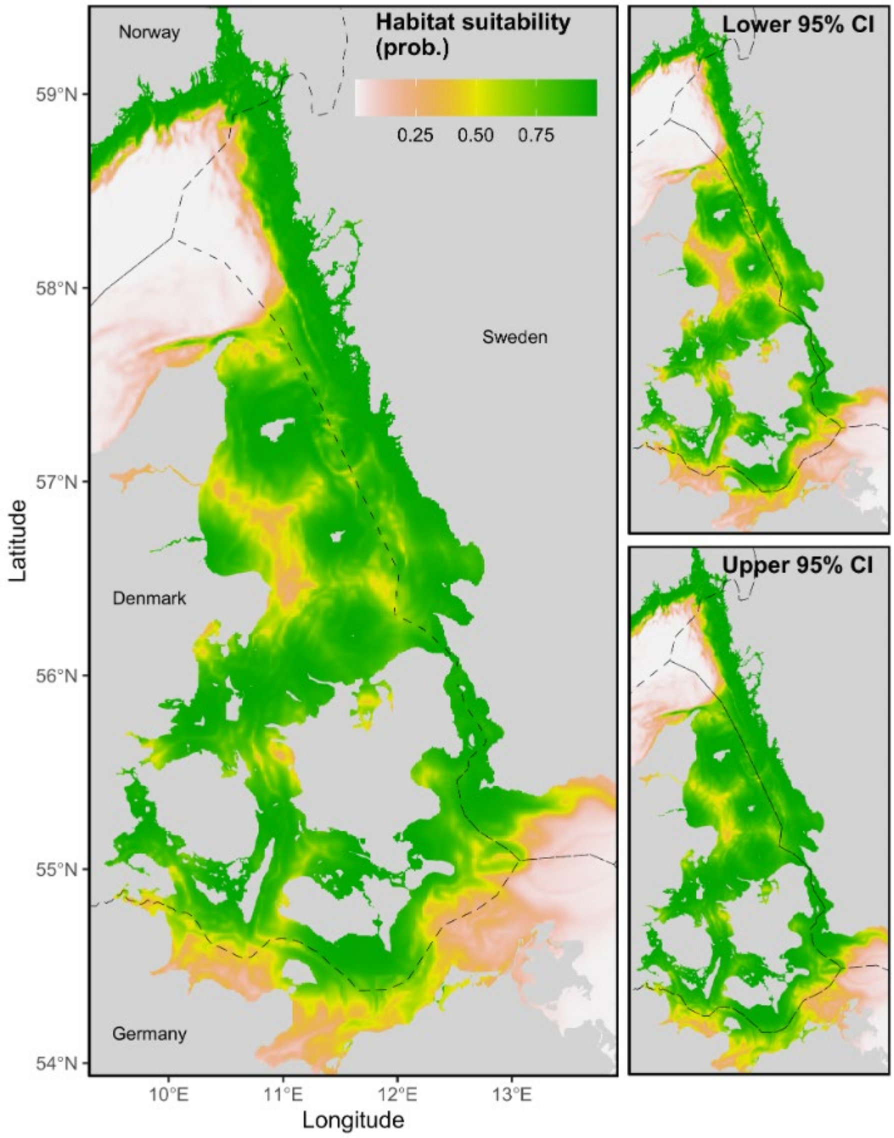



**Figure A4.** Map to the left shows the location of harbour seal haulout sites (blue) along the coast of Denmark, Sweden and Norway. The size of the dots (haulout sites) is proportional to the mean number of harbour seals counted during aerial surveys during 2018-2022. Map to the right shows the movement tracks of 67 harbour seals fitted with GPS or argos tags during the period 2001-2022 (Denmark (n=34), Sweden (n= 10), Norway (n=23)) with a total of 179,853 locations (Van Beest et al., in prep.).

**Figure A5.** Habitat suitability model for harbour seals based on tagging data collected during 2001-2022 from 67 individuals. The color scale signifies the relative probability that an area is used by harbour seals. The map uses the EPSG:3035 ETRS89 projection (Van Beest et al., in prep.).



## Grey seals

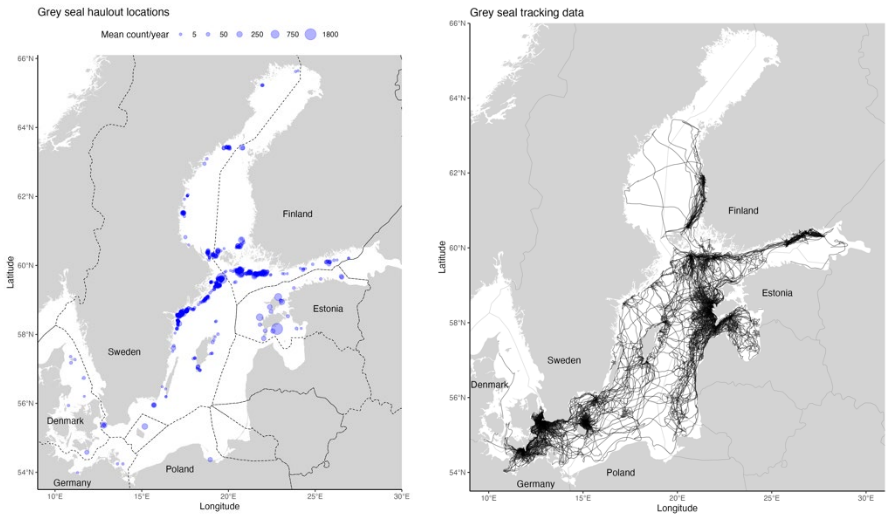



**Figure A6.** Map to the left shows the location of grey seal haulout sites (blue) across the Baltic Sea. The size of the dots (haulout sites) is proportional to the mean number of grey seals counted during aerial surveys during 2018-2022. Map to the right shows the movement tracks of 61 grey seals fitted with GPS or argos tags during the period 2000-2023 (Denmark (n=17), Sweden (n= 13), Estonia (n=18), Finland (n=13)) with a total of 315,013 locations. (Van Beest et al., in prep.).

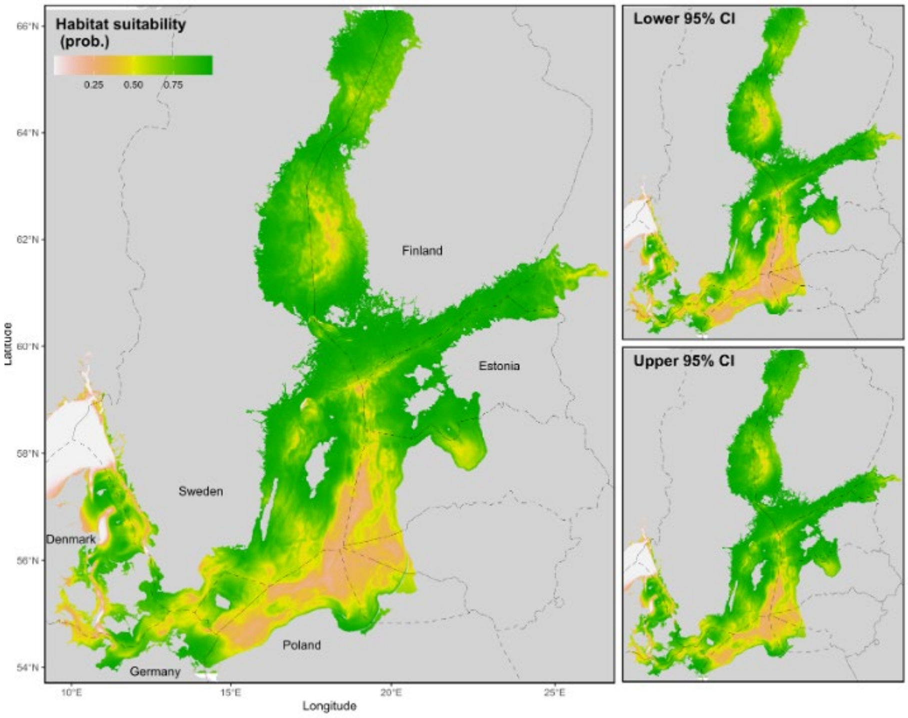



**Figure A7.** Habitat suitability model for grey seals based on tagging data collected during 2000-2023 from 61 individuals. The color scale signifies the relative probability that an area is used by grey seals. The map uses the EPSG:3035 ETRS89 projection (Van Beest et al., in prep.).

**Figure A8.** Map of seasonal movement tracks of 46 harbour porpoises fitted with argos tags during the period 2013-2022 with a total of 2,353 locations (Van Beest et al., in prep.).

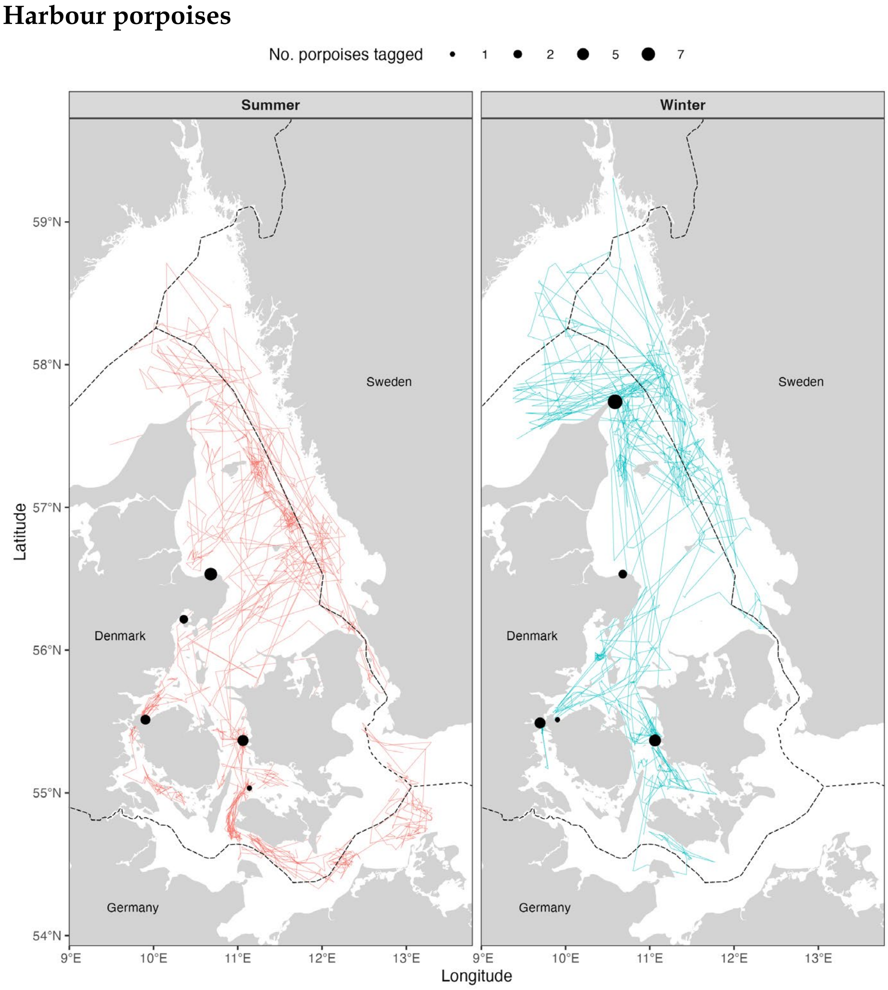
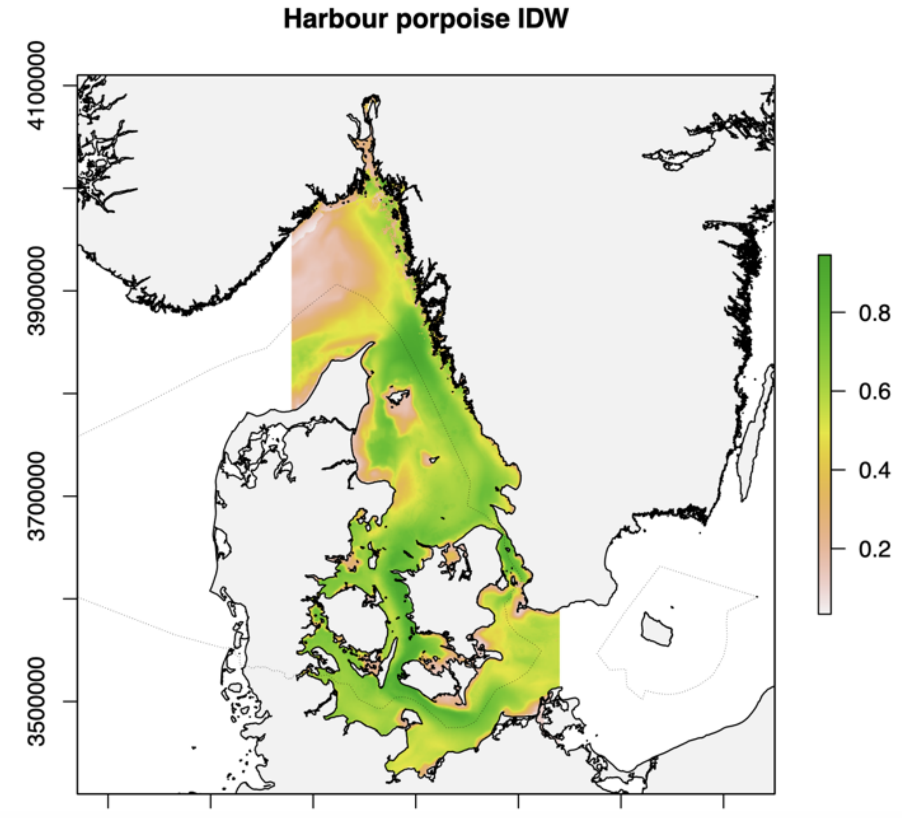


**Figure A9** Habitat suitability model for harbour porpoises based on MaxEnt analyses using location data collected during summer period of 2013-2022. The map uses the EPSG:3035 ETRS89 projection (Van Beest in prep.)



Bornholm area

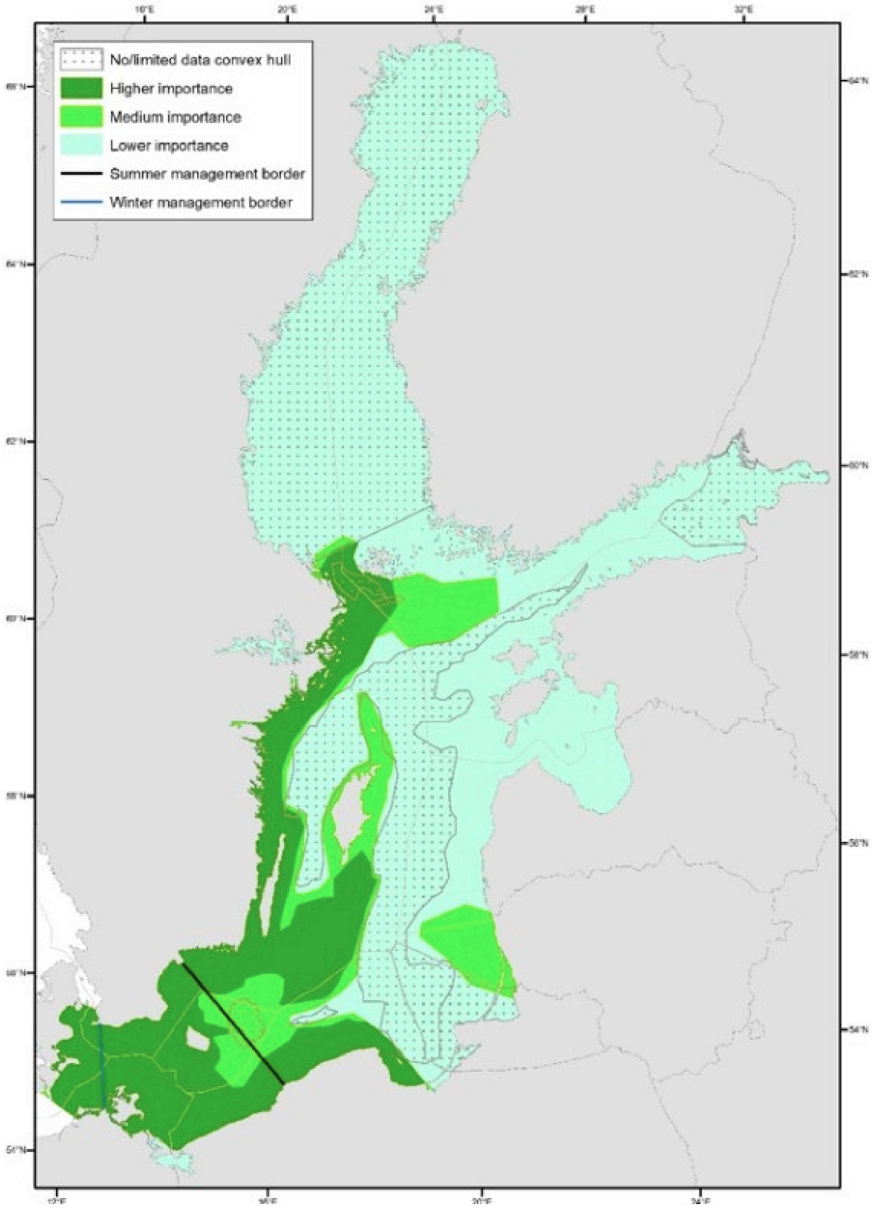



**Figure A10** Final map of importance for the Baltic Proper area based on SAMBAH data and national expert judgement. Note the Summer management borders for the Baltic Proper population. West of the boarders, the majority of porpoises will belong to the Belt Sea population (Sveegaard et al., 2022).

## 9.2 Sensitivity maps

### Harbour seals

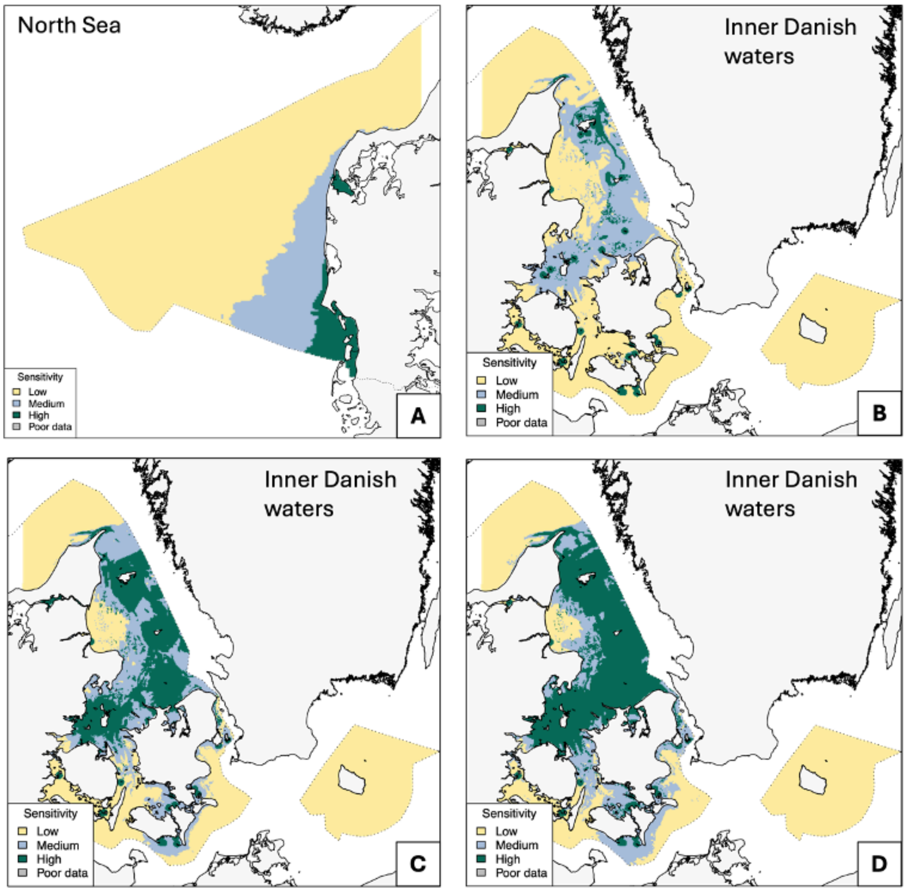
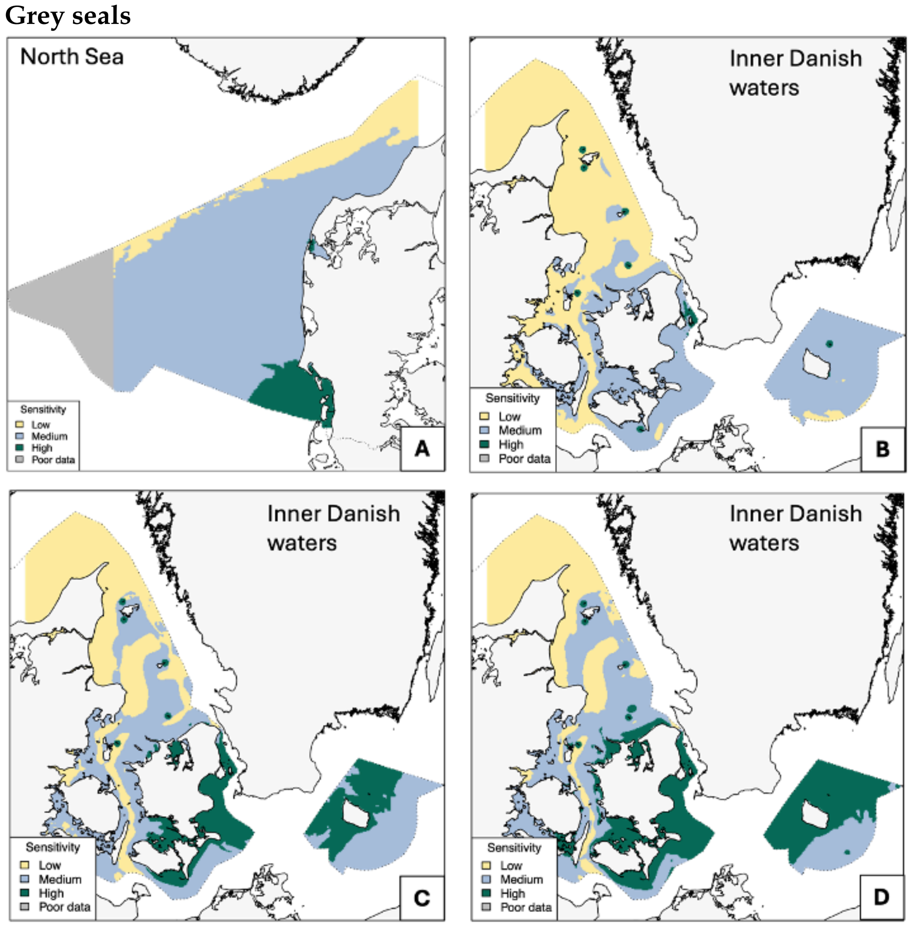



**Figure A11**. Sensitivity maps of harbour seals, where the colors represent the level of sensitivity (bright yellow = lowest, bright blue = medium, dark green = highest and grey represents areas of too poor data coverage to conclude anything. A) Sensitivity map of the North Sea with a consequence value of 0.1, B) sensitivity map of the Inner Danish waters with lowest sensitivity (consequence value 0.05), C) sensitivity map of the Inner Danish waters with medium sensitivity (consequence value 0.10), D) sensitivity map of the Inner Danish waters with highest sensitivity (consequence value 0.15).

**Figure A11**. Sensitivity maps of grey seals where the colors represent the level of sensitivity (bright yellow = lowest, bright blue = medium, dark green = highest and grey represents areas of too poor data coverage to conclude anything. A) Sensitivity map of the North Sea with a consequence value of 0.1, B) sensitivity map of the Inner Danish waters with lowest sensitivity (consequence value 0.05), C) sensitivity map of the Inner Danish waters with medium sensitivity (consequence value 0.10), D) sensitivity map of the Inner Danish waters with highest sensitivity (consequence value 0.15).



## Harbour porpoises

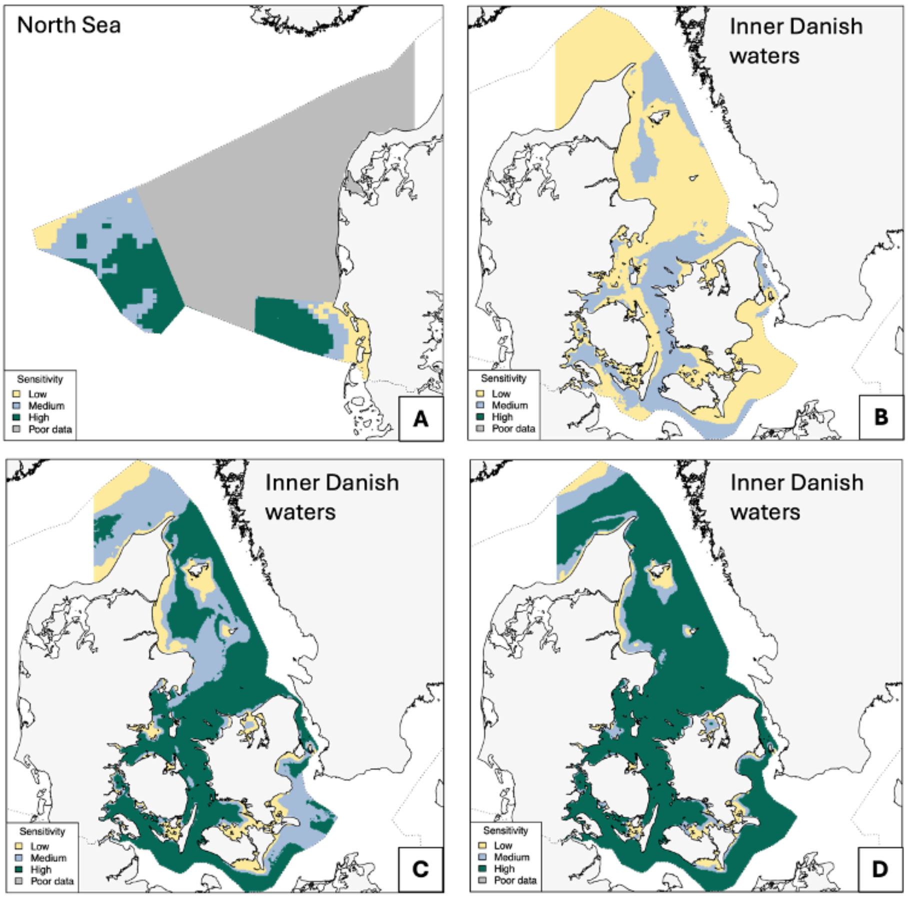



**Figure A12.** Sensitivity maps of harbour porpoises where the colors represent the level of sensitivity (bright yellow = lowest, bright blue = medium, dark green = highest and grey represents areas of too poor data coverage to conclude anything. A) Sensitivity map of the North Sea with a consequence value of 0.1, B) sensitivity map of the Inner Danish waters with the lowest sensitivity (consequence value 0.05), C) sensitivity map of the Inner Danish waters with medium sensitivity (consequence value 0.10), D) sensitivity map of the Inner Danish waters with highest sensitivity (consequence value 0.15).

**Table 5.** Data summary for the subject, along with status for each dataset. Included: Data that has been included in the analysis; Excluded: Data that has been professionally assessed as not useful, e.g., due to age or collection method; Unavailable: Data that could not be obtained, e.g. because they have not been stored or not ready within the timeframe of the project; Unauthorized: Data for which permission to use could not be obtained.

| Data description | Project | Time period | Geographical area | Data owner | Data status |
|---|---|---|---|---|---|
| Seal tagging data (grey seal and harbour seal) | North Sea Energy Island project (Project ID: 10412920) | 2022-2023 | Eastern North Sea | Danish Energy Agency | Included |
| Seal tagging data (grey seal) | North Sea Energy Island project (Project ID: 10412920) | 2018-2022 | Eastern North Sea | TIHO | Included |
| Seal haul-out counts | North Sea Energy Island project (Project ID: 10412920) | 2018-2022 | Denmark and Germany | DCE and TIHO | Unavailable |
| Seal haul-out counts | North Sea Energy Island project (Project ID: 10412920) | 2018-2022 | Netherlands | Wageningen | Unavailable |
| Harbour porpoise visual survey data | Numerous projects, national monitoring and SCANS, cf. Gilles et al. (2016) (https://doi.org/10.1002/ecs2.1367) | 2005-2013 | Entire North Sea | Multiple | Partly included |
| Harbour porpoise PAM data | SAMBAH (cf. figure 2.4 in HOLAS-III report; http://dce2.au.dk/pub/TR240.pdf) | 2011-2013 | Bornholm region | Unknown | Included |

| | | | | | |
|---|---|---|---|---|---|
| Seal tagging data (grey seal and harbour seal) | Crown Estate (uncertain) | 2009-2011 | Southwestern Baltic | Unknown | Included |
| Seal tagging data (harbour seal) | Et vindue til sælerne | Unknown | Kattegat | AU (uncertain) | Included |
| Seal tagging data (grey seal and harbour seal) | Nysted and Kriegers Flak Offshore Wind Farms | 2000-2013 | Southwestern Baltic | AU | Included |
| Seal tagging data (grey seal) | Forvaltning af skader forvoldt af sæler | 2013-2014 | Southwestern Baltic | AU | Included |
| Seal tagging data (grey seal) | EU Life MPA | 2007-2008 | Estonia | Pro Mare, Estonia | Partly included |
| Seal tagging data (grey seal) | Saarema Wind Energy | 2021-2022 | Estonia | Pro Mare, Estonia | Partly included |
| Seal tagging data (grey seal) | Gulf of Riga Wind Farms | 2023-2024 | Estonia | Pro Mare, Estonia | Partly included |
| Seal tagging data (grey seal) | Swedish Museum of Natural History Seal database | 2012-2020 | Sweden | Swedish Museum of Natural History | Partly included |
| Harbour porpoise | Running tagging program of harbour porpoises caught in pound nets | 1997-2024 | Inner Danish waters | AU | Included |

# SENSITIVITY MAPPING OF HARBOUR SEALS, GREY SEALS AND HARBOUR PORPOISES TO THE CONSTRUCTION AND OPERATION OF OFFSHORE WIND FARMS IN DANISH WATERS

We assessed the sensitivity of harbour seal (*Phoca vitulina)*, grey seal (*Halichoerus grypus*), and harbour porpoise (*Phocoena phocoena*) populations to offshore wind farms in Danish waters. Sensitivity was defined as the relative abundance of a species, multiplied by the consequence of constructing a wind farm in a given area, where we considered consequences across both construction and operation of the wind farms. Consequences were assessed based on published studies and expert knowledge. The division of the resulting sensitivity maps into high-, medium- and low sensitivity areas also reflects whether where the population is considered vulnerable.

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