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Scientific Report from DCE – Danish Centre for Environment and Energy No. 690 2026

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Abstract: This study assesses the cumulative effects of offshore wind farm (OWF) development and associated vessel traffic on harbour porpoise (*Phocoena phocoena*) populations in the North Sea and Inner Danish Waters. Using the DEPONS agent-based model, we simulated porpoise behaviour and survival under realistic OWF construction and operation scenarios from 2020 through 2031. Despite incorporating noise from pile-driving, vessel activity, and potential beneficial prey changes, no population-level impacts were detected. Porpoise abundance and distribution remained stable, with seasonal patterns driven by natural cycles. These findings suggest that, under current development trajectories and mitigation practices, OWF expansion is compatible with harbour porpoise conservation. However, ongoing declines in the Belt Sea harbour porpoise population and unmodeled stressors highlight the need for adaptive management and broader cumulative impact assessments.

Keywords: Strategic Cumulative Impact Assessment; Marine mammals; Harbour porpoise (*Phocoena phocoena*); Offshore wind farms; Marine spatial planning

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Contents

Preface

This report contributes to the project "Environmental mapping and screening of the offshore wind 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, DCE /Department of Ecoscience, Aarhus University 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 of areas for offshore wind 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 3: cumulative impact assessment. Specifically, it provides an assessment of how harbour porpoise populations are affected by the combined impacts of noise from offshore wind farms and commercial vessels in the Danish part of the North Sea and in the inner Danish waters (defined as southern Kattegat, the Belt Seas, the Sound, and the Western Baltic). The investigated impacts of offshore wind include both noise and altered prey availability in the vicinity of individual turbines.

The assessment presented in this report is based on a well-established modelling framework that has previously been used for assessing impacts of pile-driving noise and vessel noise, although the combined impacts of the two have not previously been studied. The model uses several kinds of realistic input data, and a full documentation of the available datasets is freely available online, as is the model and model documentation. No new data was obtained specifically for this report. It is important to recognise cumulative impact assessments as dynamic tools that should ideally be updated as new data becomes available.

The project management teams at both DCE / AU and NIRAS have contributed to the description of the background for the report in this Preface. The remainder of the report and the work contained within are solely the responsibility of the authors from DCE / AU.

Summary

This report evaluates the cumulative impacts of offshore wind farm (OWF) development and associated vessel traffic on harbour porpoise (*Phocoena phocoena*) populations in North Sea and inner Danish waters (here defined as southern Kattegat, the Belt Seas, the Sound, and the Western Baltic). Its purpose is to determine whether current and planned OWF construction could result in population-level effects on this protected species, providing evidence to guide strategic environmental planning and marine spatial management.

Harbour porpoises are potentially sensitive to underwater noise from pile-driving and vessel traffic, raising concerns about cumulative impacts as offshore wind expands. Using the DEPONS agent-based model, we simulated porpoise movements, energetics, and survival under realistic development scenarios for the North Sea and the inner Danish waters. Scenarios incorporated turbine installation noise, construction and maintenance vessel activity, commercial vessels (represented by AIS-recorded traffic), and potential prey enhancement near turbines. Control scenarios included only baseline prey and commercial traffic. Simulations ran for 26 years, comparing population trajectories under impact and control conditions.

Across all scenarios and spatial scales, no measurable population-level impacts were detected. Porpoise abundance and distribution remained stable in both regions, with seasonal fluctuations driven by natural cycles rather than anthropogenic stressors. Even within monitoring blocks surrounding Danish OWFs, no consistent displacement or demographic effects emerged. These results indicate that, under current development trajectories and mitigation practices, OWF construction and associated vessel traffic on their own are unlikely to cause population declines in harbour porpoises.

The findings provide a scientific basis for continued offshore wind development in Danish waters, provided that cumulative impacts are periodically reassessed. While encouraging, these results do not eliminate all risk. The model assumes effective noise mitigation and does not account for additional stressors such as contaminants, fisheries interactions (e.g. bycatch and food depletion), or climate-driven habitat shifts. Future assessments should refine prey modelling, incorporate a broader range of stressors, and explore multi-species frameworks to capture ecosystem-level effects. Additionally, the Belt Sea population of harbour porpoises inhabiting the inner Danish waters are currently undergoing a large-scale decline. Without understanding and addressing the drivers of these losses, it remains challenging to determine the added contribution of offshore wind development to cumulative impacts.

Under the conditions and assumptions tested, large-scale OWF development in Danish waters appears compatible with harbour porpoise conservation objectives. This supports ongoing planning and licensing decisions, while highlighting the need for adaptive management and updated cumulative impact assessments as offshore wind expands.

1 Introduction

The global shift toward renewable energy has gained unprecedented momentum in recent years, driven by the urgent need to mitigate climate change and reduce dependence on fossil fuels (IPCC, 2021, 2018; UNFCCC, 2015). Offshore wind farms (OWFs) play a central role in this transition, offering high-capacity, low-carbon electricity generation with minimal land use. The European Union has set ambitious targets for offshore wind deployment, aiming for 300 GW of installed capacity by 2050 (European Commission, 2020), with up to 212 GW projected for the North Sea alone (WindEurope, 2019). Denmark, a pioneer in offshore wind since the installation of the world's first offshore wind farm in 1991 (Vindeby), continues to lead in this sector.

While offshore wind development offers substantial climate and energy security benefits, it also introduces ecological challenges. Marine ecosystems, particularly those supporting top predators such as seabirds and marine mammals, face increased pressure from construction noise, vessel traffic, and habitat alteration (Dias et al., 2019; Garthe et al., 2023; Madsen et al., 2006). Pile-driving during turbine installation generates intense underwater noise that can disrupt foraging and communication in sensitive species (Dähne et al., 2013; Hastie et al., 2015). The development and ongoing maintenance of offshore wind farms involve considerable vessel traffic (Ren et al., 2021), which contributes to underwater noise and physical disturbance. Moreover, many offshore wind farm sites are situated in regions of intense maritime activity, such as the North Sea, where cumulative pressures from shipping and energy infrastructure may exacerbate ecological impacts (Pigeault et al., 2024). Additionally, the presence of turbines and associated infrastructure may lead to habitat displacement or attraction, depending on species-specific responses (Dierschke et al., 2016; Perrow, 2019).

The North Sea, already one of the most heavily industrialized marine regions globally (Halpern et al., 2015), is a focal point for offshore wind expansion. This development could impact sensitive marine species and may intensify existing pressures from shipping, fishing, and resource extraction, raising concerns about cumulative impacts on biodiversity and ecosystem functioning (Emeis et al., 2015). Nonetheless, offshore structures may also provide ecological benefits, such as reef-like habitat enhancement and increased fish biomass around turbine foundations (Bicknell et al., 2025; Birt et al., 2024; Clausen et al., 2021; De Mesel et al., 2015; Vandendriessche et al., 2015). While it remains uncertain whether these observations reflect true increases in biomass or instead shifts in spatial distribution, patchy aggregations of prey resources, as can occur around foundations, can support species at higher trophic levels (Benoit-Bird et al., 2013; Gallagher et al., 2022; Weller et al., *in prep*).

Marine mammals, particularly cetaceans such as the harbour porpoise (*Phocoena phocoena*), are recognized as particularly sensitive to these anthropogenic noise disturbances due to their reliance on acoustic signals for navigation, foraging, and communication (Dyndo et al., 2015; Lucke et al., 2009; Olesiuk et al., 2002; Thompson et al., 2013; Tougaard et al., 2009). The harbour porpoise is strictly protected under Annex II and IV of the EU Habitats Directive (European Union, 1992), and recent evidence indicates that the Belt Seas population of harbour porpoises is undergoing a significant decline (Owen et al., 2024). This trend raises additional concern because cumulative impacts from offshore wind development will interact with other pressures such as bycatch, prey depletion, and environmental change.

There is mounting evidence that harbour porpoises react to both pile-driving noise and passing vessels at fine temporal and spatial scales (Frankish et al., 2023; Graham et al., 2023, 2019). Pile-driving noise can elicit behavioural responses in porpoises at distances of at least 20 kilometres (Benhemma-Le Gall et al., 2021; Brandt et al., 2011; Carstensen et al., 2006), while ship noise has been shown to cause tagged harbour porpoises to stop foraging, change direction or dive deeper (Frankish et al., 2023; Wisniewska et al., 2018). These two noise sources differ in their acoustic characteristics and potential impacts: pile-driving is brief but intense, often triggering acute and temporary avoidance, whereas ship noise is lower in intensity but more persistent, potentially leading to chronic stress or long-term habitat displacement, with short-term displacement already documented on broad scales (Pigeault et al., 2024).

Disturbance-induced movements can cause animals to move away from important foraging areas, leading to short-term reductions in feeding opportunities. When such disturbances occur repeatedly or over extended periods, they can result in cumulative energetic costs that reduce the energy available for vital processes like growth and reproduction (National Research Council, 2005; Pirotta et al., 2018). These disruptions, if frequent or intense, may ultimately affect population dynamics by altering survival and reproductive success (Gallagher et al., 2021b; Nabe-Nielsen et al., 2018; Pirotta et al., 2018). Assessing and mitigating these population-level impacts is challenging, as behavioural responses and demographic consequences are often substantially separated in space and time. While reactions to noise may be brief, their effects can accumulate through changes in energy balance and body condition (Johnston et al., 2019; Pirotta et al., 2018). For long-lived, mobile species like harbour porpoises, directly linking behavioural responses to acoustic disturbance with changes in vital rates remains infeasible through empirical observation alone. Given their sensitivity to a range of anthropogenic disturbances, it is essential to evaluate the status of harbour porpoise populations by accounting for all relevant pressures across appropriate spatial and temporal scales.

Process-based models, particularly agent-based models (ABMs), offer a powerful approach to bridge this gap between individual mechanisms and population-level consequences (Boult and Evans, 2021; Johnston et al., 2019). ABMs can simulate how individual animals respond to environmental variation and disturbances, with population dynamics emerging from the interactions of autonomous individuals rather than being imposed by top-down demographic rates (Grimm and Railsback, 2005). In ABMs, individuals can be represented as discrete entities that differ from one another, interact locally with their environment and other individuals, and exhibit adaptive, fitness-seeking behaviour based on their internal state and environmental conditions (Grimm and Railsback, 2005). This approach allows population-level properties to emerge from the behaviour of, and interactions among, individual agents through time, making ABMs particularly useful when individual variation, local interactions, adaptive behaviour, or heterogeneous environments are assumed to influence population-level responses to disturbance (Railsback and Harvey, 2020; Speakman et al., 2025).

The core principles of ABMs align well with the need to assess cumulative impacts of multiple stressors on marine mammal populations. By building models that incorporate the fundamental processes determining animal fitness, such as the balance between energy intake and expenditure for maintenance, movement, growth, and reproduction, ABMs are likely to maintain predictive power across a wider range of environmental conditions than correlative statistical models (Stillman et al., 2015; Urban et al., 2016). This is particularly important for forecasting responses to novel conditions or combinations of stressors, where statistical relationships derived from past observations may not hold. The integration of energetics into ABMs provides a mechanistic link between disturbance and population consequences: disturbances affect behaviour (such as displacement from foraging areas), which affects energy acquisition and use, which in turn influences body condition, survival, and reproduction (Sibly et al., 2013; Speakman et al., 2025). Since many non-lethal disturbances, including those related to noise exposure, have impacts on energy acquisition or use, models that account for animal energetics can help quantify the impacts of multiple stressors on wildlife populations (Speakman et al., 2025). The use of ABMs to integrate energetics and mechanistic disturbance pathways aligns with the EU's Marine Spatial Planning Directive (2014/89/EU), which mandates ecosystem-based planning and thorough cumulative impact assessments to support sustainable marine development across temporal and spatial scales.

To ensure these models are sufficiently realistic to be applied to their intended purpose, it is important that they can reproduce characteristic patterns observed in nature. Models that capture such higher-level or landscape-scale patterns are more likely to provide credible assessments of disturbance scenarios (Grimm, 2005). The strategy of pattern-oriented modelling (POM) has proven particularly valuable for developing and validating ABMs of real ecological systems (Gallagher et al., 2021a; Grimm, 2005). This approach uses multiple observed patterns, at different scales and at both individual and system levels, to guide model design, parameterization, and testing. Patterns indicate internal organization of the system, and by ensuring that models can reproduce characteristic patterns observed in nature, modelers increase the structural realism and mechanistic richness of their representations (Gallagher et al., 2021a).

DEPONS is an ABM developed specifically to assess the effects of underwater noise on harbour porpoise populations by simulating individual movements, energetics, and survival in realistic landscapes (Nabe-Nielsen et al., 2023, 2018). In DEPONS, population impacts arise from individuals' tendency to move away from noise sources, which reduces their foraging efficiency, causes energy levels to decline, and ultimately influences reproduction and survival. Animals move through the landscape according to a combination of correlated random walk movements and movements guided by a spatial memory of previously visited foraging patches, allowing them to optimize foraging behaviour and produce movements that closely resemble those of real animals (Nabe-Nielsen et al., 2013). Their dose-response relationships to noise have been calibrated using POM to ensure that simulated foraging movements and reactions to noise mimic behavioural patterns observed in nature (Nabe-Nielsen et al., 2023, 2018).

Previous studies have demonstrated that pile-driving noise from offshore wind farm construction can have localized but temporary effects on harbour porpoise distributions (Dähne et al., 2017; Nabe-Nielsen et al., 2018), with animals typically returning to construction areas within hours after pile-driving ceases. When incorporating similar responses in DEPONS, this did not result in discernible population-level impacts from wind farm construction when animals responded to noise at distances consistent with observations from the Gemini Wind Park (approximately 9 km), although population impacts became detectable when response distances were assumed to exceed 20-50 km (Nabe-Nielsen et al., 2023, 2018). Under such extreme conditions population effects were influenced by the order in which wind farms were built. This illustrates how the spatially explicit nature of ABMs makes it possible to assess the population impacts of different construction scenarios, which renders them ideal for marine spatial planning aimed at minimizing the impacts of offshore wind.

However, most previous studies have focused only on noise associated with turbine installation and often examined single wind farms in isolation. In reality, offshore wind development is occurring simultaneously across multiple sites, and porpoises are exposed to multiple overlapping stressors, including vessel traffic and habitat changes. This underscores the urgent need for cumulative impact assessments that evaluate the population-level effects of multiple stressors (Pirotta et al., 2022), including the combined influence of multiple OWFs and associated activities across time and space.

In the recent expansion of DEPONS to version 3.0+, ships have been incorporated as sources of impact with noise source levels (calculated for the decidecade band centred at 16 kHz) related to vessel speed, length, and type (Frankish et al., 2025; MacGillivray and de Jong, 2021). The model now enables simulation of realistic vessel movements using Automatic Identification System (AIS) data and includes calibrated harbour porpoise responses to ship noise based on GPS-tracked animals' behavioural reactions. Ship noise propagation is modelled using sound propagation models that account for environmental characteristics, and simulated porpoises react probabilistically to received sound levels, with the probability and magnitude of deterrence depending on noise level, distance to the vessel, and time of day (following results of Frankish et al., 2023). This enhanced capability allows for assessment of the combined effects of pile-driving and vessel traffic on harbour porpoise space use and population dynamics.

Here we applied DEPONS to evaluate the cumulative impacts of all offshore wind farms constructed or planned to be constructed between 2020 and 2031 on harbour porpoise populations in the North Sea and inner Danish waters (here defined as southern Kattegat, the Belt Seas, the Sound, and the Western Baltic). The evaluation period extended through 2031 to accommodate wind farms with construction start dates in 2030, ensuring their full construction phase is included. The assessment integrates multiple stressors: noise from turbine installation, vessel traffic (commercial, construction, and service vessels), and a potential benefit through localized increases in prey availability in the vicinity of individual turbines. By simulating harbour porpoise responses across realistic spatial and temporal scales, the study aims to inform mitigation strategies and support ecologically responsible offshore wind development.

2 Methods

To assess the cumulative impacts of offshore wind farm (OWF) development and vessel traffic on harbour porpoise populations in the North Sea (NS) and inner Danish waters (IDW), we constructed spatially and temporally explicit simulation scenarios using the DEPONS model (Nabe-Nielsen et al., 2023, 2018). These scenarios incorporated turbine installation noise, construction and service vessel activity, and changes in prey availability. All inputs were prepared using a combination of spatial data processed in R and QGIS (QGIS Development Team, 2025; R Core Team, 2024), supplemented by external datasets including AIS records, wind farm metadata, and habitat suitability maps.

2.1 The DEPONS Model

2.1.1 General Overview

The model used in this study is based on version 3.2 of the DEPONS agent-based framework, which simulates harbour porpoise population dynamics in response to anthropogenic pressures. Model documentation follows the structure of the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2020, 2006), with full documentation available in the TRACE report for version 3.0 (Nabe-Nielsen et al., 2023). Updates beyond version 3.0 are described in the present text.

2.1.2 Purpose

This model is designed to explore how harbour porpoise populations respond to multiple stressors and a potential benefit, in terms of increased prey availability, associated with offshore wind farm development. Specifically, it evaluates the effects of underwater noise from pile-driving during turbine installation, vessel traffic, and changes in prey availability near turbines. Individual reproduction and survival are determined by energy balance, which is influenced by noise-induced disruptions to foraging behaviour. The model aims to replicate natural population dynamics by ensuring that movement, habitat use, and behavioural responses to noise are ecologically realistic.

2.1.3 Entities, State Variables, and Scales

The simulation includes six core entity types: harbour porpoises, wind turbines, vessels, hydrophones (which can potentially be used to measure received sound from vessels within the model), grid cells, and cell groups. Porpoises are modelled as super-individuals (Scheffer et al., 1995), each representing multiple female animals. Their attributes include spatial position, movement speed and direction, age, maturity status, energy reserves, reproductive state (pregnancy and lactation), and movement mode.

Ships are defined by their name, type, length, speed, and assigned route. Hydrophones are static and characterized solely by their location. Wind turbines are represented by their coordinates, construction noise levels, and the temporal window during which pile-driving occurs.

The model operates across two spatial domains: the North Sea and inner Danish waters (Fig. 2.1). The North Sea landscape spans 982 km × 830 km and is divided into 2455 × 2075 grid cells, each measuring 400 m × 400 m. This domain is larger than in previous DEPONS versions and includes interpolated monthly maps derived from earlier seasonal datasets. The inner Danish waters landscape covers a 240 km × 400 km area and consists of 600 × 1000 grid cells of the same resolution. In both landscapes, grid cells are grouped into larger 2 km × 2 km cell groups to support large-scale navigation, allowing porpoises to return to previously visited areas. While cell sizes were chosen arbitrarily, they are sufficient to capture fine-scale movements and habitat use.

Grid cells are assigned environmental attributes including coordinates, bathymetry, salinity, proximity to land, sediment type, and food availability. Only designated food patches, comprising 1.6% of the water area, contain prey resources, and each patch occupies a single grid cell. Food levels in non-patch cells are zero. The spatial distribution of food patches mirrors that used in earlier studies (Nabe-Nielsen et al., 2014, 2013). The number of patches is sufficient to support realistic movement and foraging behaviour. The only temporal environmental variable is the time of year.

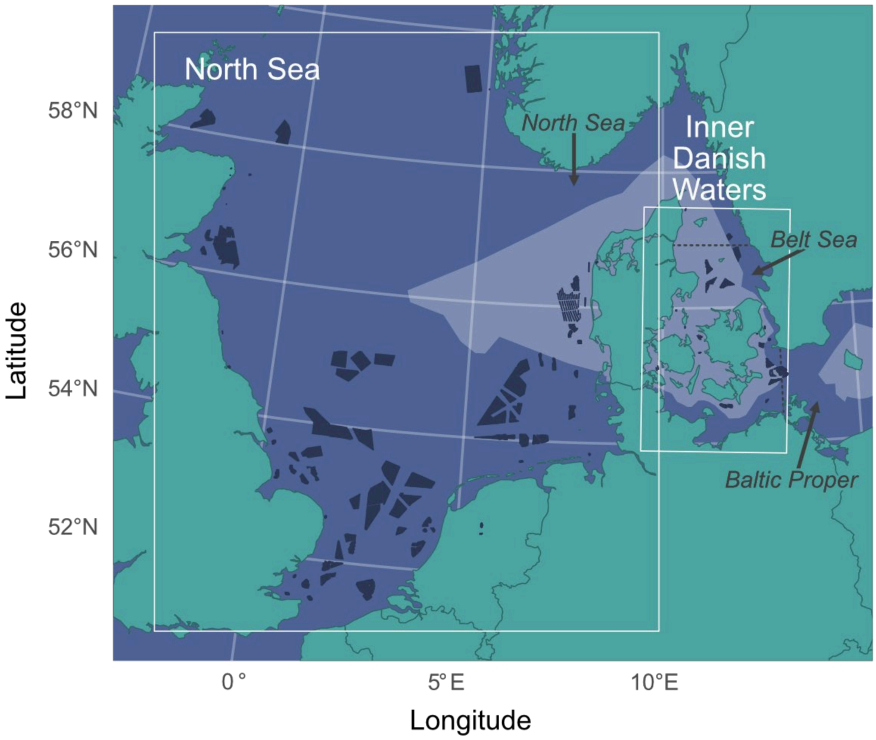


Figure 2.1. Geographic extent of the two modelled scenarios in the North Sea and inner Danish waters (in white). Water bodies are shown in blue, land in green, and wind turbine locations in dark blue. The Danish Exclusive Economic Zone (EEZ) is in light blue. The three harbour porpoise populations occurring in Danish waters, the North Sea, Belt Sea, and Baltic Proper, are denoted in grey, with dashed grey lines indicating their population boundaries.

2.1.4 Process Overview and Scheduling

Simulations proceed in 30-minute intervals and typically cover a total of 20–50 years, including a 15-year burn-in period to reach equilibrium followed by the impact scenarios. At each time step, harbour porpoises assess acoustic conditions, detecting noise from active pile-driving and nearby vessels. Detection is based on the source level, propagation loss, and a behavioural threshold below which animals do not respond.

Harbour porpoise movement is governed by a combination of correlated random walk (CRW) behaviour (Turchin, 1998), memory-guided navigation toward known food patches, and avoidance of noise sources. CRW dominates when energy intake is sufficient; otherwise, animals increasingly rely on memory to locate previously profitable areas (Nabe-Nielsen et al., 2013). Movement slows and redirects when approaching land. Noise avoidance is modulated by received sound levels, and responses to vessels vary with distance and time of day.

From DEPONS version 3.1 onward, vessel speeds can vary dynamically. Movement parameters were recalibrated for the inner Danish waters region using simulations with realistic ship densities. Behavioural responses to ship noise above ambient levels were informed by GPS tracking data (Frankish et al., 2023). In version 3.2, harbour porpoise reactions to pile-driving in the presence of construction vessels were further refined using data from the Gemini wind farm.

Energy dynamics are central to individual survival. Energy levels range on a scale from 0 to 20 and increase when animals feed in food patches but decrease with movement. As energy levels rise above 10, food consumption becomes less efficient, reflecting physiological limits to energy storage. Seasonal variation and lactation status influence energy expenditure. Mortality risk increases with declining energy, and lactating females may abandon calves rather than die. Energy budgets follow principles from physiological ecology (Sibly et al., 2013).

Harbour porpoises move sequentially, with movement order randomized at each time step. Porpoises consume prey as they pass through food cells without stopping. The proportion of food consumed decreases as their energy levels rise from 10 to 20, reflecting reduced foraging effort when energy needs are lower. Individuals experiencing prolonged energy deficits switch from fine-scale to large-scale movements, targeting more favourable regions (i.e. cell groups).

Food availability is restricted to the food patches, which are randomly distributed across the landscape. The amount of resources within each food patch is determined by underlying resource maps, ensuring spatial variability in food abundance. In the North Sea, food levels are based on a single annual map of harbour porpoise density, while in the Kattegat, four seasonal maps were used and interpolated to generate monthly food availability (see Section 2.1.6). These maps are updated every 30 days, assuming a uniform month length. Within each patch, food levels regenerate daily through logistic growth after being depleted by foraging, with full replenishment typically occurring within two days.

At the end of each simulation day, life-history events are processed. Harbour porpoises may die upon reaching their maximum age, mate depending on season and age, give birth if pregnant, or wean calves. Weaning results in the creation of new female individuals. Male porpoises are not explicitly modelled, as their abundance is not considered limiting for reproduction. Mating dates are recalculated annually.

2.1.5 Input Data

The model incorporates seven spatial background layers (Nabe-Nielsen et al., 2023): bathymetry, food availability, discrete food patches, monitoring zones (called blocks; see 2.2.4 for details), sediment grain size, salinity gradients, and proximity to the coastline. For the scenarios presented here, only the food availability maps were updated. The two landscapes used in the simulations are based on different projected coordinate systems: EPSG:3035 (Europe-wide) for the North Sea and EPSG:25832 (UTM zone for Denmark) for the inner Danish waters. For consistency, all figures are shown in WGS84, a global standard for latitude and longitude.

2.1.6 Base Food Availability

Updated habitat maps were used to represent prey availability for harbour porpoises. For the North Sea, a single distribution map was used across all months (Figure A3 in Stokholm et al., 2025) (Fig. 2.2), as recent data were insufficient to develop seasonal maps for this region. For the inner Danish waters, four seasonal maps (winter, spring, summer, autumn) based on van Beest et al., (2025) were interpolated to monthly maps using the *interpolate.maps* function from the 'DEPONS2R' R package (Nabe-Nielsen et al., 2025) (Fig. 2.3).

To ensure compatibility with DEPONS, which requires complete raster coverage, missing values were identified using bathymetry as a template and filled using the *Fill NoData* tool (GDAL) in QGIS. All maps were masked to retain only valid marine areas by resampling bathymetry to match the resolution of the habitat maps and applying a spatial mask, using the 'terra' package in R (Hijmans et al., 2025).

Each raster was then normalized to a [0, 1] scale and rescaled to a consistent mean value of 0.38592, matching previously used food levels in DEPONS simulations (Nabe-Nielsen et al., 2018). Final rasters were exported in ASCII format with a NAflag = -9999 for DEPONS input.

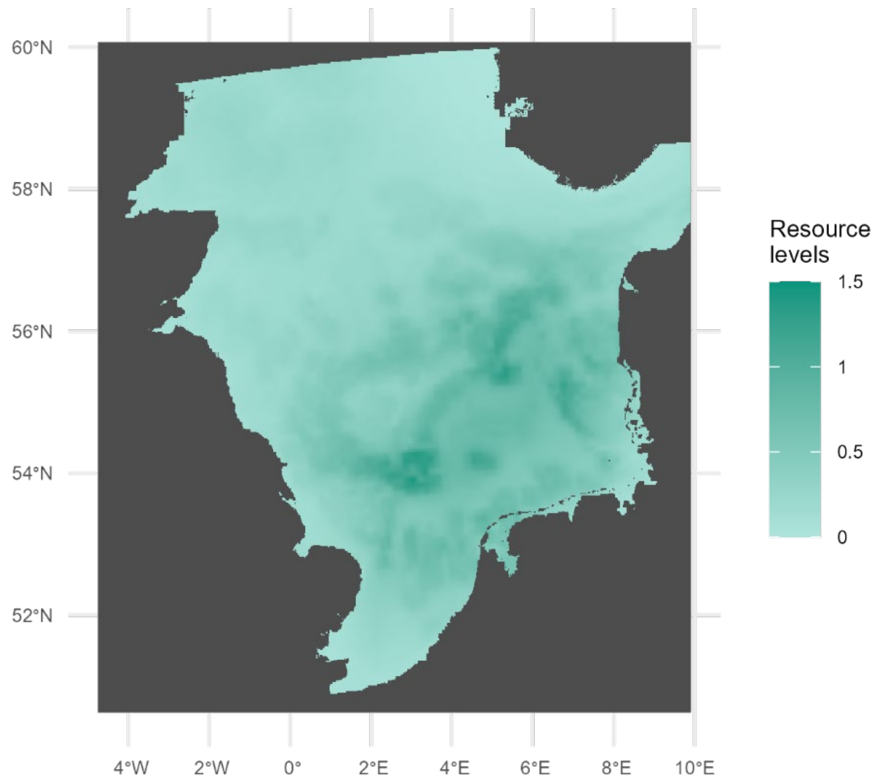


Figure 2.2. North Sea resource density map based on harbour porpoise distribution data from Stokholm et al., 2025.

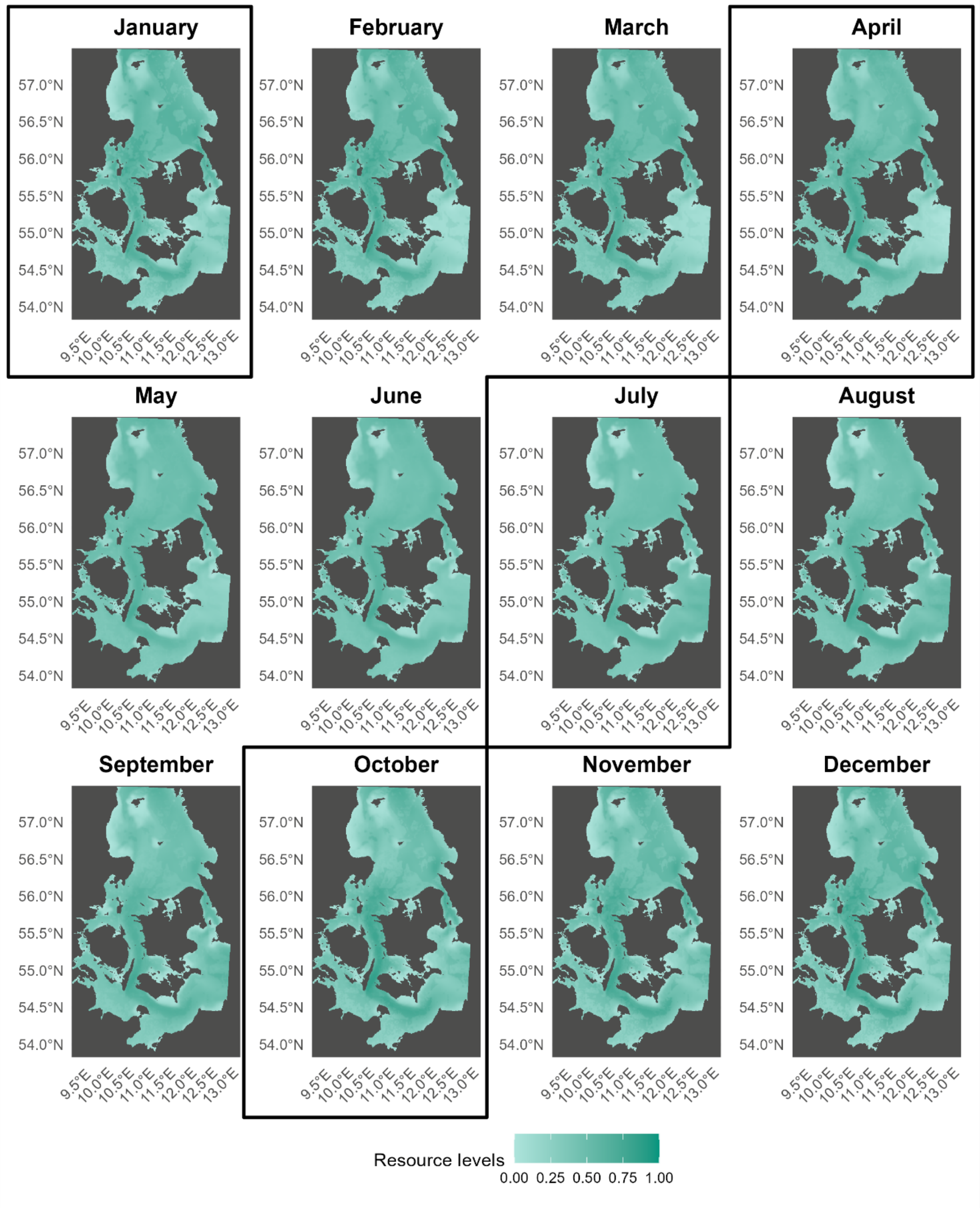


Figure 2.3. Monthly resource distribution maps for the inner Danish waters, based on seasonal harbour porpoise density maps (van Beest et al., 2025). Values for intermediate months were interpolated between the original seasonal maps (highlighted with black boxes) using a sine function.

2.2 Wind Farm Construction Input Data

2.2.1 Turbine, Piling, and Acoustic Parameters

Turbine locations were obtained from the Danish Technical University (DTU), and wind farm boundaries were sourced from the 4C Offshore Windfarm Database (www.4coffshore.com). Each simulation included the piling of 8,010 individual turbines in the North Sea landscape or 665 individual turbines in the inner Danish waters landscape. Within each wind farm, the order of turbine piling was randomized.

Table 2.1 summarizes the key physical and acoustic parameters used in construction and sound propagation modelling. Turbine capacity was set at 15 MW, reflecting current trends in large-scale offshore wind development. Pile dimensions for turbines of this size were drawn from Gaertner et al., (2020), which were used to determine piling source levels for unmitigated installations, while piling duration and rest intervals between piling events were standardized based on typical operational practices.

Acoustic modelling incorporated both unmitigated and mitigated source levels for pile-driving, measured at a distance of 1 meter from the source, with mitigation represented through a reduced source level (based on recommendations in KEC 5.0 report (Heinis et al., 2025)). Underwater sound transmission was simulated using the beta-log transmission loss model (Bellmann et al., 2020), with propagation coefficients α and β applied as follows:

$$Received\ level = Source\ level - (\beta \times log_{10}(r) + \alpha \times r)$$

where r is the distance from the source in meters, $\alpha = 0.00027$, and $\beta = 14.72$. Source levels were derived from sound measurements at 750 meters (Bellmann et al., (2020) for unmitigated and Heinis et al., (2025) for mitigated piling) and back-calculated to 1 meter using the propagation model. The strength of the harbour porpoise response was determined by comparing the received sound level to a response threshold for turbine installation noise, and to ambient noise levels in the case of vessel-related sound. For pile-driving, this response threshold was calibrated using patterns in the recovery of harbour porpoise densities after piling events observed during construction of the Gemini wind farm (Nabe-Nielsen et al., 2018). For vessel noise, ambient sound pressure levels (SPL) were assigned a value of 80 dB re 1 µPa @ 1 m (Frankish et al., *in prep*). Ship noise source levels were estimated based on vessel speed, length, and type following the JOMOPANS-ECHO source model (MacGillivray and de Jong, 2021) and for the decidecade band centred at 16 kHz (measurable frequency in tagged porpoises (Wisniewska et al., 2018)). Noise propagation was modelled using a range-independent version of the Weston flux integral method, which here was dependent on the water depth (assumed constant between a ship and a porpoise), sediment properties (density, sound speed and attenuation rate) and water properties (density, sound speed and attenuation rate) at the source location as well as the distance between the source (i.e. a ship) and the receiver (i.e. a porpoise; Weston 1959). Finally, simulated harbour porpoises were assumed to react to ship noise by being deterred (i.e. moving away) and the probability and magnitude (distance moved) of the deterrence in DEPONS is dependent on the loudest noise received per time step, the distance between a porpoise and the vessel from which this noise originated and on the period of the day (Frankish et al., 2023).

Noise mitigation measures for pile-driving, such as the use of bubble curtains, were assumed to be in place in the North Sea for Germany, Denmark, Belgium, and the Netherlands, in accordance with regional regulatory practices (following Heinis et al., 2025), as well as for all installations in the inner Danish waters scenario.

Table 2.1. Summary of turbine specifications and acoustic parameters used in construction and sound propagation modelling.

Parameter name	Value	Units	Source
Turbine capacity	15	MW	Danish Energy Agency
Pile diameter	10	m	Gaertner et al., 2020
Piling duration	6	hours	-
Breaks between piling	18	hours	-
Piling source level (SELss) (unmitigated)	224	dB re 1 μPa²s @ 1 m	Bellmann et al., 2020
Piling source level (SELss) (mitigated)	203	dB re 1 μPa²s @ 1 m	Heinis et al., 2025
Pile-driving sound propagation (Beta)	14.72	-	Danish Energy Agency, 2016
Pile-driving sound propagation (alpha)	0.00027	dB/m	Danish Energy Agency, 2016
Ambient noise levels (SPL; used for vessels)	80	dB re 1 μPa @ 1 m	Frankish et al., *in prep*

2.2.2 Construction Scheduling

For OWFs that were in operation in 2025, construction start dates were obtained directly from 4C Offshore. For OWFs not yet built, start dates were assigned by randomly selecting a construction month from the distribution of known construction months among existing OWFs, a start year between 2026 and 2030, and a day within the selected month, resulting in a fully randomized start date (Fig. 2.4). Detailed and consistent start dates for all planned OWFs are not publicly available in a standardized format, making randomization necessary to reflect uncertainty and variability in future development timelines.

To ensure spatial realism, each wind farm was assigned its nearest port using centroid-based proximity calculations (*st_nearest_feature*) in the 'sf' package (Pebesma et al., 2025). This port assignment informed the simulation of vessel movements during both construction and maintenance phases.

Construction was modelled as a year-round activity, with turbine installation sequences randomized within each wind farm.

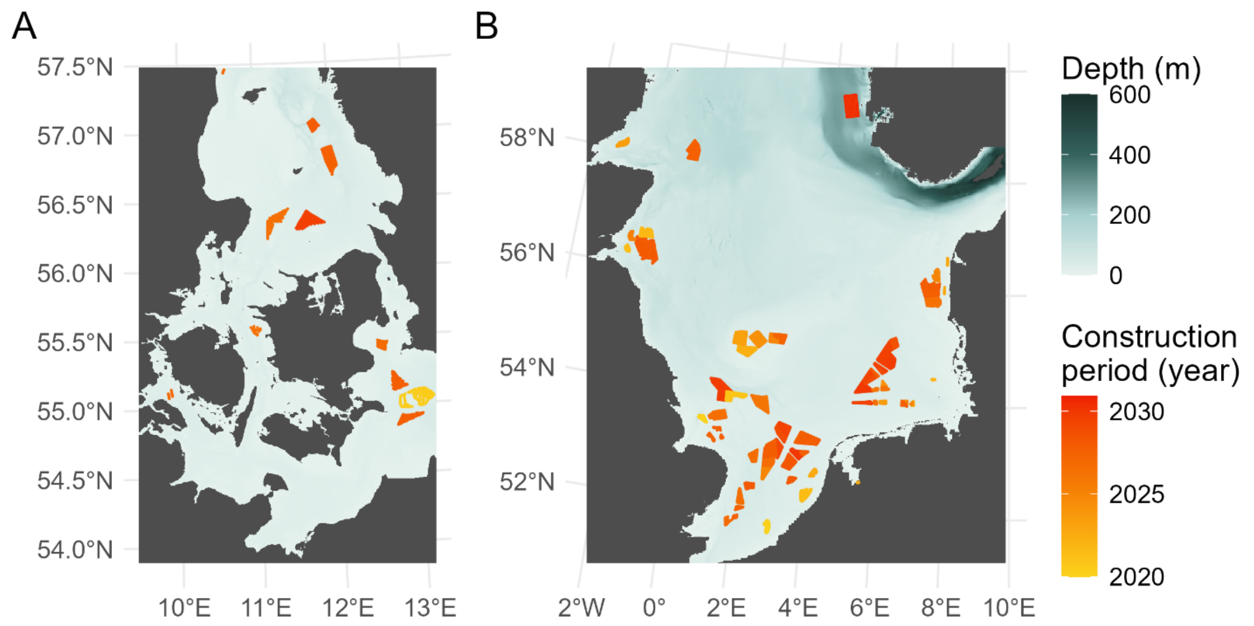


Figure 2.4. Start dates for offshore wind farm (OWF) turbine construction, with some projects extending beyond 2030 for completion. Only OWFs initiated from 2020 onward are shown. Bathymetry shown for context.

2.2.3 Vessel Activity Modelling

Commercial Vessels

Commercial vessels were included to represent background maritime traffic present in the study areas during the reference periods, based on AIS data. These vessels represent routine commercial and other AIS-equipped traffic and form the baseline noise and disturbance environment, onto which simulated construction and maintenance vessel activity was added.

Commercial vessel traffic was modelled using AIS data from two reference periods: a one-day snapshot for the North Sea (July 1, 2020; 3,398 vessels) and a two-week period for the inner Danish waters (June 1–15, 2020; 2,553 vessels). These datasets represent complete AIS-based traffic patterns for the observed periods, with vessel characteristics (speed, length, type) sourced from the Danish Maritime Authority (dma.dk) and MarineTraffic (marinetraffic.com). To prepare AIS data for use in DEPONS, the following steps were applied: (1) cropped to the landscape extent (Fig. 2.1), (2) retained only records with 9-character MMSI (Maritime Mobile Service Identity) numbers, as these uniquely identify individual vessels and allow reliable ship type classification, (3) removed duplicate entries and sailing vessels, (4) excluded positions with speeds >50 or <0.1 knots, and (5) retained only ships with ≥60 minutes of data and at least 10 positions to ensure at least one movement in DEPONS (Frankish et al., 2023). Average vessel speeds were approximately 5.7 knots in the North Sea and 8.35 knots in the inner Danish waters, with mean vessel lengths of 86.6 m and 99.8 m, respectively.

To ensure compatibility with DEPONS, commercial vessel tracks were formatted as .json files and repeated across the simulation period. Each vessel was assigned a unique identifier, and timestamps were standardized to match DEPONS input requirements.

Construction Vessels

Construction vessel activity was simulated using AIS data from the heavy lift vessel *Les Alizés* (MMSI: 253726000; www.jandenul.com/fleet/heavy-lift-vessels), which operated as the principal installation vessel at the Thor offshore wind farm. AIS records were downloaded daily from the Danish Maritime Authority for the period April 29 to July 5, 2025, and filtered to retain only positions associated with the target vessel.

Spatial filtering was applied to identify vessel behaviour in two zones:

- A 10–20 km ring around turbines to characterize transit behaviour.

- A 150 m buffer around turbines to identify installation activity.

From these zones, the following metrics were extracted:

- Transit speed: Mean speed over ground (SOG) in the 10–20 km ring around the wind farm, estimated at an average of 9.2 knots.

- Trip structure: Installation trips were defined by gaps of >48 hours between turbine visits, with visits defined by periods of at least 30 minutes spent within 150 m of a turbine. On average, each trip installed ~3 turbines (range: 1-5), with ~8 hours between installations.

- Ship characteristics: Length was set to 236 m, and ship type was categorized as "Other" (specifically a heavy lift vessel).

These metrics were used to generate synthetic construction vessel tracks for all wind farms with simulated construction dates from 2020 onward. The final output was a dataset of construction vessel tracks annotated with timestamps, spatial coordinates, vessel states (e.g. transit, installing), and metadata such as ship type and ID. These tracks were formatted for DEPONS input and used to simulate noise exposure from construction activities across both the North Sea and inner Danish waters.

Maintenance Vessels

Service vessel activity was characterized using full-year AIS data from 2023, accessed via the Danish Maritime Authority (dma.dk). The analysis focused on two reference wind farms: Anholt and Horns Rev 1. AIS records were downloaded monthly and filtered to exclude irrelevant vessel types (e.g. fishing, pleasure, sailing, law enforcement, SAR). Spatial filtering was applied to retain only vessel positions within a 20 km buffer around turbine locations, grouped by wind farm.

To identify service vessels, AIS points were further filtered to those occurring within a 1.5 km buffer around turbines and exhibiting low speeds. Vessels were classified as service vessels if they spent more than 30 minutes within the turbine buffer and had an average speed below 5 knots during those visits.

For each identified service vessel, the following metrics were calculated:

- Transit speed: Mean and standard deviation of speed over ground (SOG) in the 10–20 km ring around the wind farm.

- Visit frequency: Number of distinct turbine visits per vessel per day.

- Dwell time: Total and average time spent near turbines.

- Breaks between visits: Average time between successive visits.

- Ship characteristics: Length, type, and MMSI were extracted from AIS metadata.

These metrics were aggregated into a summary dataset (ServiceShipOutputs.csv) to assess distributions of visit frequency, dwell time, vessel speed, and ship type.

To model service vessel activity across wind farms of varying sizes, daily vessel visit counts were aggregated and linked to turbine count. A negative binomial regression was fitted to predict daily service vessel visits as a function of turbine number (Fig. 2.5). The model accounts for overdispersion and adjusts the maximum number of ship visits based on turbine size, allowing realistic tail behaviour in the predicted distributions. For modelling purposes, we assume that maintenance vessel activity remains constant over the simulation period and does not vary with platform age or lifecycle stage.

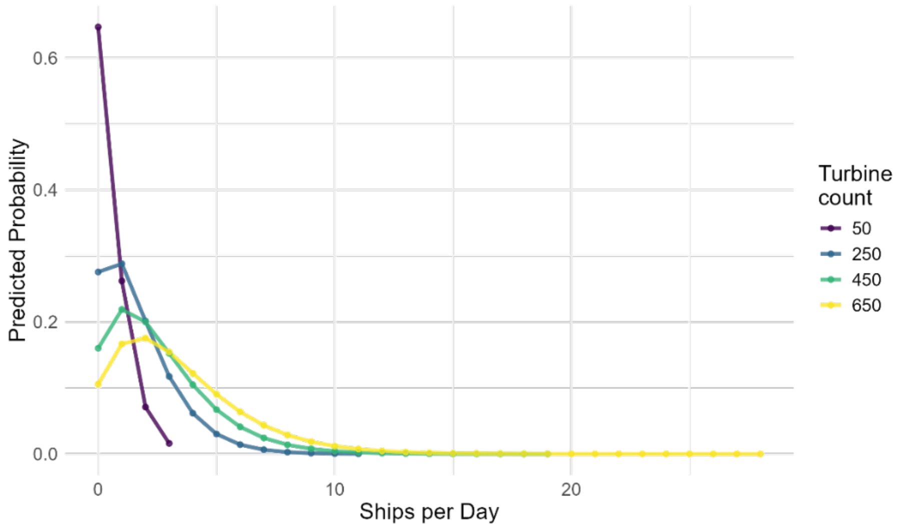


Figure 2.5. Probability distribution of daily maintenance vessel deployments as a function of windfarm size (number of turbines).

This modelling approach enables scalable prediction of service vessel traffic for unbuilt wind farms and supports realistic simulation of maintenance-related noise exposure in DEPONS. This activity was only simulated for OWFs constructed from 2020 onward and therefore does not overlap with vessel traffic captured in the commercial vessels dataset (above).

Vessel Track Simulation and Integration

To simulate realistic vessel movements for both construction and maintenance activities, spatially explicit tracks were generated using custom R functions that interpolate paths between ports and turbine locations at 30-minute intervals. For each wind farm, the nearest port was identified using spatial proximity calculations, and turbine installation or service visits were scheduled based on wind farm-specific construction timelines or post-construction periods.

Construction vessel tracks were simulated using the trip parameters derived from AIS data for *Les Alizés*, including average transit speed and number of turbines installed per trip (see section Construction Vessels). Each trip included outbound transit, sequential turbine installations, intra-field movements, return transit, and port pauses. The number of turbines installed per trip was sampled from the empirical range and installation durations and breaks between piling events followed routine industrial practices (Table 2.1).

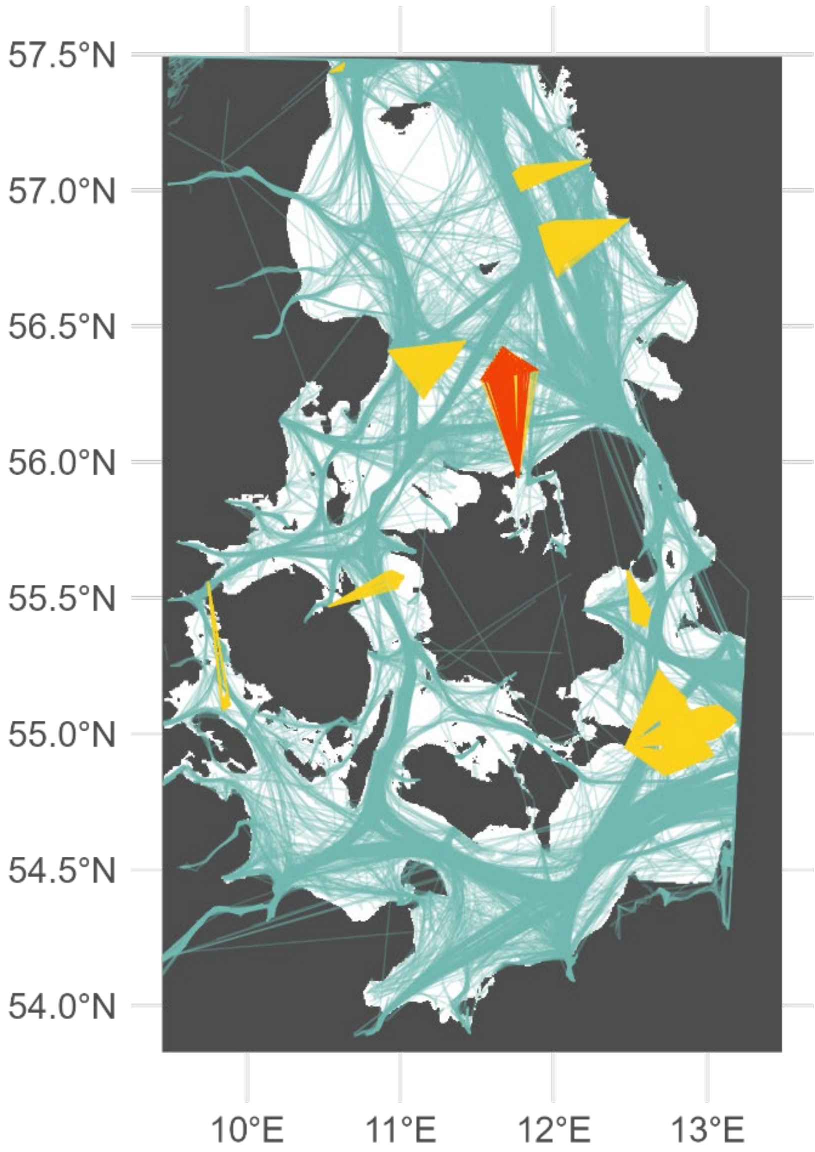
Maintenance vessel tracks were generated using the negative binomial model based on turbine count to estimate the number of maintenance vessels on a particular day, and vessel characteristics (type, length, speed, dwell time) were sampled from observed distributions. Each simulated maintenance vessel performed transit to the wind farm, visited multiple turbines with defined dwell durations, and returned to port.

To prepare vessel movement data for DEPONS simulations, tracks from construction, maintenance, and commercial vessels were combined and formatted into annual .json files using the 'DEPONS2R' package. For each simulation year (2020–2031), vessel tracks were filtered by timestamp and region (North Sea or inner Danish waters), and spatial coordinates were transformed to match the landscape-specific coordinate reference system. Timestamps were standardized to DEPONS format, and each vessel was assigned a unique ID.

Simulated construction and maintenance vessels were converted to DeponsShips objects using the *ais.to.DeponsShips* function in the 'DEPONS2R' package (Nabe-Nielsen et al., 2025). By default, DEPONS treats only moving vessels as noise sources, based on their current speed. To account for periods when vessels were stationary but still emitting noise, such as when using dynamic positioning systems, relevant instances were identified using *make.stationary.ships* and incorporated into the final dataset. Quality checks and formatting corrections were applied using *check.DeponsShips* and *set.ship.type*.

Finally, all vessel routes and metadata were merged with commercial vessel traffic data and exported as landscape-specific .json files for use in DEPONS simulations (Fig. 2.6).

Figure 2.6. Example year of vessel traffic in the inner Danish waters (simulation year 2030), showing commercial vessel traffic (in blue; two weeks of traffic repeated throughout simulation year), maintenance vessels (in yellow), and construction vessels (in red).



2.2.4 Food Resource Changes

To simulate localized increases in prey availability due to reef effects or altered oceanographic conditions and fishing activity within wind farms, we applied a 3× increase in resource levels (in the base food availability maps; section 2.1.6) within a 150 m buffer around turbines that had been constructed at least two years prior to the simulation year (Bicknell et al., 2025). This represents a simplified assumption of food availability near turbines, following the approach used in the PrePARED project (Weller et al., *in prep*), where a descending curve was applied from 3× at the pile to 1× at 500 m away. These increases in prey availability were only represented in the model when a food cell overlapped with the 150 m turbine area. Because food cells are not present in all grid cells, localized increases were not applied to all turbines.

Turbine locations and commissioning years were extracted from spatial datasets and joined with wind farm boundaries. For each simulation year from 2020 to 2031, turbines in OWFs older than two years were buffered, and the corresponding raster maps were modified by tripling the food values within the buffered areas, though as food cells themselves are randomly placed in the landscape (Nabe-Nielsen et al., 2014, 2013), this increase only affects food cells occurring within this 150 m zone.

This process was repeated for each region and year to generate final prey maps included in impact scenarios.

2.2.5 Spatial Analysis

The North Sea was divided into three spatial monitoring blocks for impact assessment (Fig. 2.7):

- 1° geographic buffer (WGS84) around OWFs in the Danish EEZ (Block 1)
- Danish EEZ (Block 2)
- All other North Sea waters (Block 3)

Danish EEZ boundaries were obtained from MarineRegions.org (Version 4, 2024-10-10). A 1° buffer was applied around Danish wind farms to capture localized effects. Blocks were not applied in the inner Danish waters, where effects were observed across the full region.

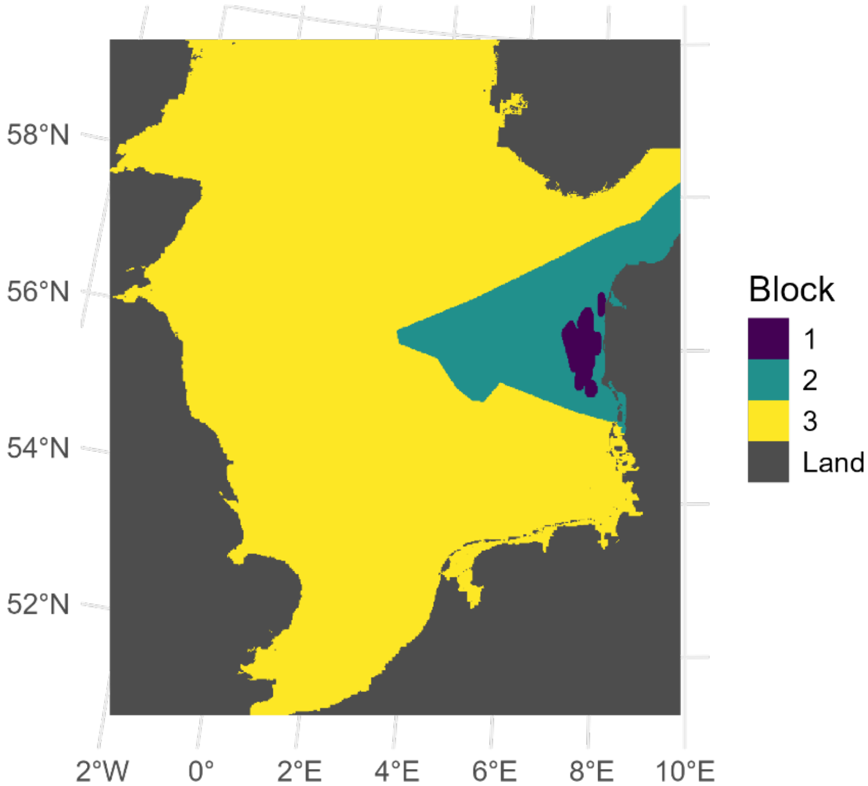


Figure 2.7. Monitoring blocks used in the North Sea scenario.

2.3 Simulation Scenarios

Two scenarios were run, each with and without a control: one for the inner Danish waters and one for the North Sea, as these represent two distinct harbour porpoise sub-populations (NAMMCO and IMR, 2019; Sveegaard et al., 2015). Each scenario incorporated all relevant turbine positions, commercial vessels, construction vessel activity, maintenance vessel traffic, and localized changes in prey availability, according to their predefined spatial and temporal schedules. These scenarios reflect realistic development timelines and vessel behaviour derived from AIS data and simulation outputs.

To isolate the effects of these alterations, control scenarios were also run for each region. These included only commercial vessel traffic and baseline prey maps, allowing for comparative assessment of population-level impacts.

All scenarios were run from 2004 to 2031, with the first 15 years (2004–2019) designated as a burn-in period to allow porpoise populations to stabilize. This period was excluded from analysis. The simulation end year of 2031 was chosen to accommodate wind farms with construction start dates in 2030, ensuring full representation of their construction impacts. Thirty simulation replicates were run for each scenario.

2.4 Analysis of Impacts

Simulation outputs were evaluated by tracking the number of harbour porpoise agents present within predefined spatial blocks throughout the simulation period. These blocks were designed to capture both local effects (e.g. displacement from wind farm areas) and regional population dynamics.

To ensure results reflected stable population dynamics, all data from the burn-in period (2004–2019) were excluded from analysis. Impacts were quantified by comparing harbour porpoise abundance in each block between impact scenarios and their respective controls.

Changes in block-level abundance were interpreted as indicators of altered space use and energetic stress (e.g. avoidance behaviour), while changes in total population size reflected broader demographic effects, including shifts in reproduction and mortality. This dual-scale approach allowed for assessment of both behavioural displacement and fitness-related consequences of offshore wind development. Impacts were identified by inspecting whether abundance values in impact scenarios consistently deviated above or below the control means over time, indicating potential shifts in space use or population dynamics.

3 Results

North Sea

Across the full North Sea, no detectable differences were observed between the impact and control scenarios (Fig. 3.1). Population dynamics remained stable throughout the impact period, with variation closely resembling that of the control simulations. Seasonal fluctuations in mean population size were primarily driven by natural cycles in reproduction and intra-specific competition, rather than by anthropogenic impacts. After the initial equilibration period, the population maintained a stable trajectory under both scenarios, indicating that the simulated offshore wind farm construction did not result in measurable population-level effects at the basin scale.

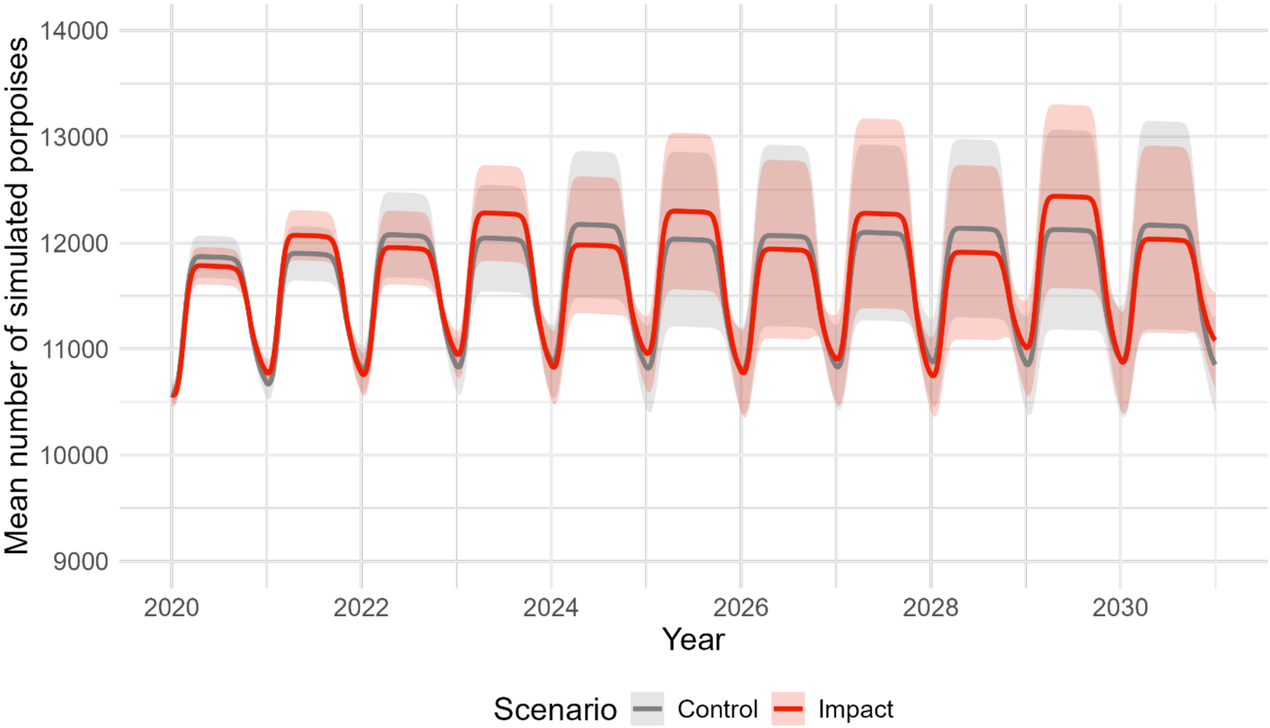


Figure 3.1. Mean daily population size of simulated harbour porpoises in the full North Sea from 2020 to 2031. Solid lines represent the mean across 30 replicates for control scenarios (grey; baseline resource maps and commercial vessels only) and full impact scenarios (red). Shaded areas indicate ±1 standard deviation from the mean.

When examining effects on harbour porpoises within geographical subregions in the North Sea, no detectable differences were observed between control and impact scenarios (Fig. 3.2). Notably, the region which includes areas directly surrounding Danish offshore wind farms in the North Sea (Block 1), showed a gradual increase in abundance throughout the impact period, and this trend persisted under both scenarios. Across all subregions, seasonal fluctuations and overall variation were similar between treatments, indicating that population dynamics at this finer spatial scale were again driven primarily by natural processes rather than simulated construction impacts.

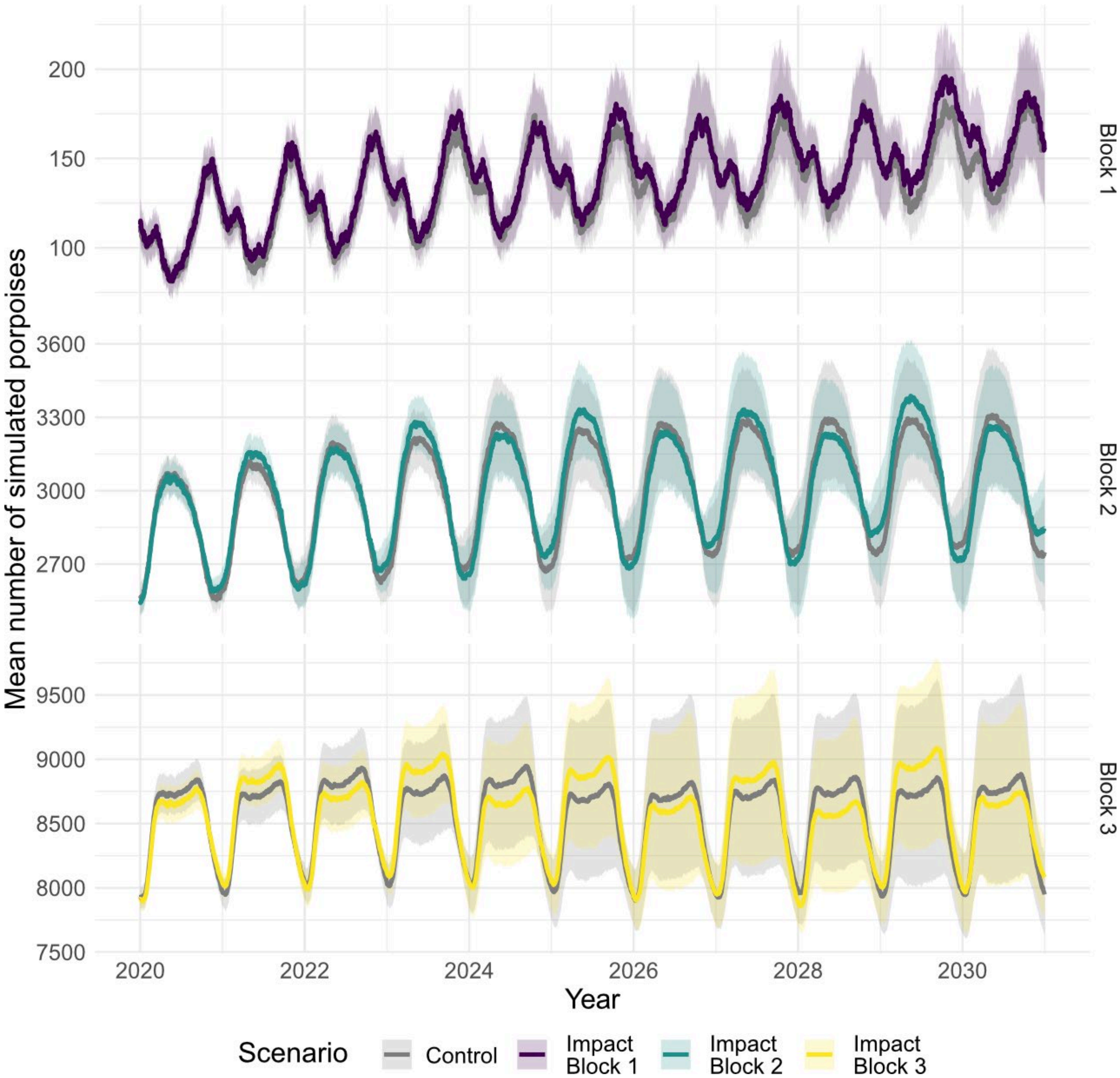


Figure 3.2. Mean daily population size of simulated harbour porpoises within three North Sea geographical subregions from 2020 to 2031. Solid lines represent the mean across 30 replicates for control scenarios (grey; baseline resource maps and commercial vessels only) and full impact scenarios (coloured by block). Block 1 represents a 1° buffer around offshore wind farms within the Danish EEZ, Block 2 covers the remainder of the Danish EEZ, and Block 3 includes all other North Sea waters (see Fig. 2.7 for map). Shaded areas indicate ±1 standard deviation from the mean.

Inner Danish Waters

For the inner Danish waters scenario, no detectable differences were observed between impact and control simulations (Fig. 3.3). A slight tendency toward higher mean population sizes under impact scenarios was noted during the construction period, however, these values consistently fell within the variability of the control simulations.

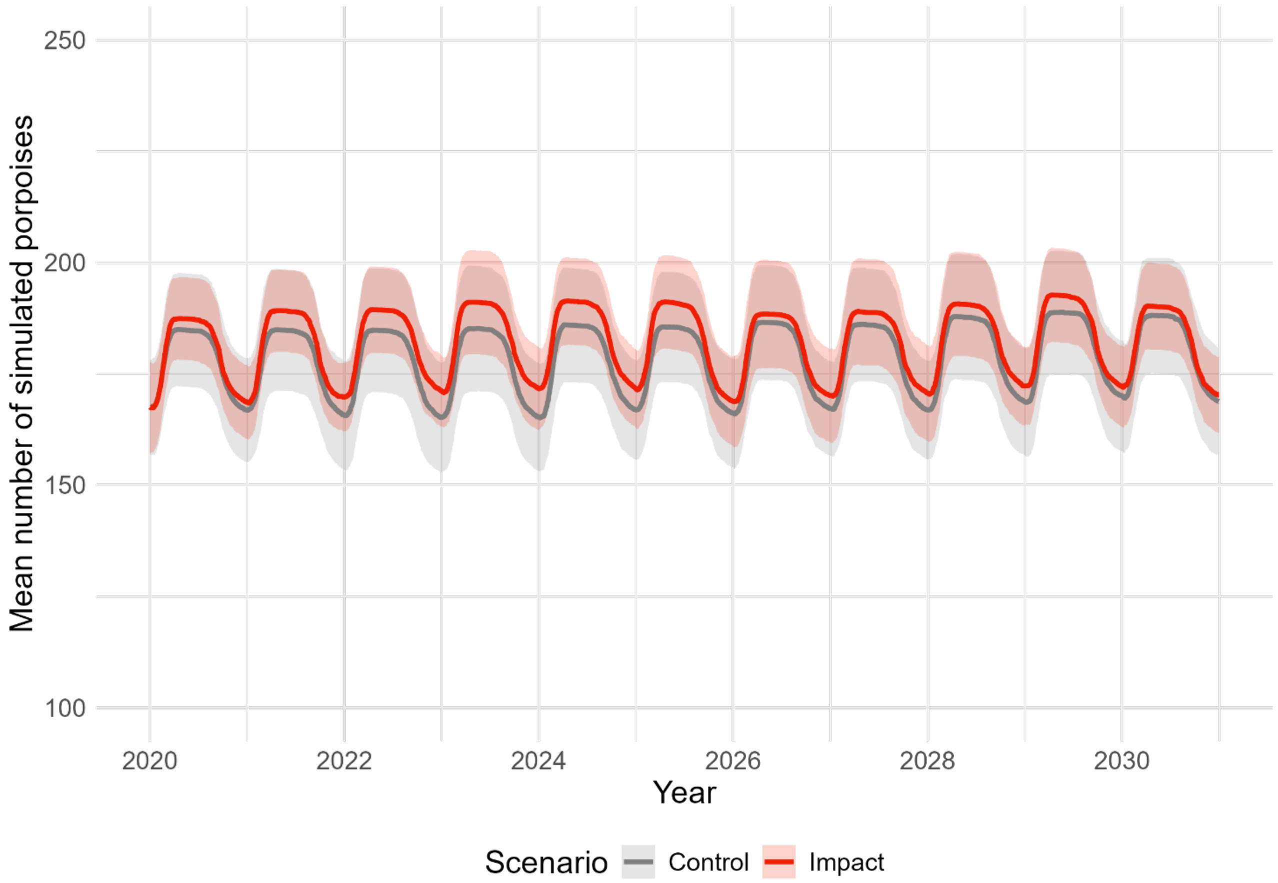


Figure 3.3. Mean daily population size of simulated harbour porpoises in the inner Danish waters from 2020 to 2031. Solid lines represent the mean across 30 replicates for control scenarios (grey; baseline resource maps and commercial vessels only) and full impact scenarios (red). Shaded areas indicate ±1 standard deviation from the mean.

4 Discussion

This study applied the DEPONS agent-based model to evaluate the cumulative impacts of offshore wind farm development and associated vessel traffic on harbour porpoise populations in the North Sea and inner Danish waters. The model incorporated multiple stressors, including commercial vessels, underwater noise from pile-driving, construction and maintenance vessel activity, as well as localized increases in prey availability near turbines. Despite accounting for additional pressures and assessing broad-scale, contemporaneous development activity, no population-level effects were detected in either scenario. Harbour porpoise abundance, across broader regions as well as within the three predefined spatial monitoring blocks (Fig. 2.7), remained stable across all impact simulations, suggesting that the modelled anthropogenic activities did not result in measurable demographic consequences under the simulated development trajectories. While these blocks do not capture fine-scale spatial distribution, temporal trends in density within each region provide insight into broader patterns of space use over time. Even in the one area where local abundance increased over the simulation period, near Danish OWFs in the North Sea (Block 1; see Fig. 3.2), the increase was comparable between control and impact scenarios, indicating that the increase is not a result of the increased prey availability around the turbines. This observed increase may instead reflect a slow, large-scale redistribution process, potentially linked to inherited and gradually refined optimal foraging movement patterns (knowledge of food intake in different parts of the landscape passed from mothers to calves) within the North Sea (Nabe-Nielsen et al., 2018).

The absence of detectable impacts may reflect a combination of biological resilience and effective noise mitigation, represented here by a reduction in sound source levels from piling activities in the relevant countries (following Heinis et al., 2025). Harbour porpoises are known to exhibit short-term behavioural responses to underwater noise, including displacement and cessation of foraging (Frankish et al., 2023; Wisniewska et al., 2018). However, the simulations suggest that displacement and the reduced food intake associated with being scared away from wind farm areas did not produce sufficient energetic deficits to induce demographic changes at the population level under the spatial and temporal conditions modelled here. This outcome is consistent with previous DEPONS studies, which found that population-level effects only emerged under extreme assumptions, such as response distances to pile driving exceeding 20–50 km (Nabe-Nielsen et al., 2018). However, these earlier studies did not account for maintenance vessel traffic, which could potentially influence animals in the wind farm areas for beyond the construction period. In the present study, animal responses to different types of disturbances were calibrated using empirical data and vessel movements were simulated using realistic AIS-derived tracks. The simulation results therefore reflect changes in the most important pressures related to construction and operation of offshore wind farms.

Two factors were not included in the DEPONS model due to the lack of comprehensive data across the study area. First, vessels without AIS, which may contribute significantly to underwater noise in coastal areas such as the inner Danish waters (e.g. Hermannsen et al., 2019). Second, the use of ultra-short baseline (USBL) devices, which are used almost continuously by geophysical survey vessels, underwater construction vessels, and fishing trawlers to position subsea equipment (Michaelsen et al. 2025). These high-intensity sound sources are widely used and have recently been shown to triple the time between harbour porpoise encounters when deployed in the North Sea.

Additionally, mitigation measures implemented in several countries substantially reduced modelled sound exposure distances during pile-driving. Although mitigation measures, such as bubble curtains, were not explicitly simulated in DEPONS, theoretical reductions in source levels were applied to represent their effect, assuming the same dose-response behaviour from calibration to Gemini OWF (Nabe-Nielsen et al., 2018). For example, under mitigated conditions, the modelled range at which received levels exceeded the behavioural response threshold decreased from ~26 km to 2.6 km, reflecting a tenfold reduction in impact radius. This illustrates the potential effectiveness of mitigation in reducing noise exposure, though observed impact distances vary considerably across wind farms, environmental conditions, and due to associated activities such as the use of 'seal scarers' (e.g. Dähne et al., 2017).

While widespread, the spatial and temporal heterogeneity of stressors likely allowed porpoises to maintain access to foraging areas. Pile-driving noise, being brief and high-intensity, may have prompted temporary avoidance, but their short duration can enable animals to resume foraging nearby. More persistent stressors, like service vessel noise or localized prey enhancement, tended to affect smaller areas and did not appear to affect population-level patterns. As a flexible and opportunistic species (Kastelein et al., 2019; Stedt et al., 2024), the harbour porpoise may be able to compensate for energy losses caused by disturbances during wind farm construction, provided that sufficient prey resources are available. The inclusion of prey enhancement near turbines may have additionally contributed to the overall stability of population dynamics. However, the representation of these effects was intentionally simplified, and further work is needed to assess the potential for turbine structures to attract porpoise prey species and whether porpoises are actually using this food resource.

Simulations in both the North Sea and the inner Danish waters exhibited similar outcomes, despite differences in landscape structure, vessel density, and wind farm clustering. The North Sea, with its greater spatial extent may allow harbour porpoises to better navigate around disturbances and exploit alternative foraging areas, but even in the inner Danish waters the harbour porpoises remained unaffected by wind farm construction. This may be due to the relatively low number of wind farms in this area. Within the North Sea, no consistent patterns of displacement were observed in the predefined monitoring blocks, including those surrounding Danish wind farms. This suggests that even localized construction activity did not produce sustained avoidance or demographic effects, although it is worth noting that these blocks still represent relatively large spatial scales compared to the areas directly impacted.

These findings have important implications for cumulative impact assessment (CIA) and marine spatial planning (Judd et al., 2015). While individual-level responses to noise are well documented, translating these into population-level effects requires mechanistic models that integrate movement, energetics, and disturbance exposure (Gallagher et al., 2021b; Speakman et al., 2025). DEPONS provides such a framework, and its application here suggests that current OWF development trajectories may be compatible with harbour porpoise conservation goals, at least under the assumptions and conditions modelled. However, the absence of effects should not be interpreted as a guarantee of safety. CIA must remain precautionary, particularly as OWF development intensifies and expands into new regions (Caine, 2020; Hague et al., 2022; Willsteed et al., 2018). Coordinated construction schedules, noise mitigation, and strategic siting remain essential tools for minimizing risk. Models like DEPONS can also support marine spatial planning by simulating population-level impacts under hypothetical or extreme scenarios, helping to identify strategies that reduce cumulative pressures from OWFs and other human activities. The results also underscore the importance of modelling combined stressors, as cumulative exposure may lead to non-linear or emergent outcomes not captured by single-stressor assessments (National Academies of Sciences, Engineering, and Medicine, 2017; Pirotta et al., 2022).

Despite the strengths of this assessment, several limitations should be considered when interpreting the results. The model assumes that populations operate near equilibrium carrying capacity throughout the impact period. This simplifies demographic processes but does not reflect current trends in all regions. Notably, the Belt Sea population of harbour porpoises inhabiting the inner Danish waters is undergoing a significant decline (Owen et al., 2024). This context is critical because the model does not incorporate the underlying drivers of this decline, such as bycatch, prey depletion, or disease. Additionally, because the model has not yet been applied to the waters of the Baltic Proper, we were unable to assess potential impacts on the harbour porpoise population inhabiting that region, a population classified as "Critically Endangered" (Hammond et al., 2008). While the absence of additional impacts from offshore wind development under the tested scenarios is encouraging, these findings should be interpreted with caution. In populations already under stress, cumulative effects may be amplified when multiple pressures interact.

Other uncertainties relate to behavioural responses to noise and prey distribution. The representation of prey enhancement near turbines was highly simplified, and empirical data on reef effects and fish redistribution remain limited. Recent findings from a project monitoring Horns Rev III did not support an increase in harbour porpoise presence near turbines, though this lack of evidence for a "reef effect" was not statistically significant (Sveegaard et al., 2025). However, a separate study focusing on oil rigs found seasonal use of offshore structures by porpoises (Clausen et al., 2021). More detailed modelling is needed, particularly given the potential influence of fishing restrictions and local oceanographic changes on prey availability, as does knowledge on how porpoises may use this resource. Additionally, prey availability in the model was based on harbour porpoise distribution maps, which may not directly reflect prey density. However, given the species' dependence on elevated foraging rates (Wisniewska et al., 2018) and strong variability in their associations with environmental conditions (van Beest et al., 2025), this remains the most ecologically grounded proxy currently available. Similarly, sound propagation was modelled using a relatively simple approach that did not account for depth variation, wind speed, or ambient noise fluctuations, all factors that can affect received sound levels (Brekhovskikh and Lysanov, 1991) and, therefore, animal behavioural responses (Tougaard, 2021). Nonetheless, comparisons with a more complex model and empirical data suggest the simplified approach performs reasonably well under most conditions (Frankish et al., *in prep*), and sensitivity analyses could help evaluate whether such simplifications affect population-level outcomes. Simulated construction activity was modelled to resemble operations of *Les Alizés*, a modern purpose-built and relatively independent heavy-lift vessel (www.jandenul.com/fleet/heavy-lift-vessels), which may reflect forwardlooking scenarios but does not capture the diversity of construction strategies or the presence of additional support vessels such as cable layers, crew transfer vessels, and dredgers (Support Offshore Wind, 2025). In combination with vessel without AIS and vessels using USBL units, as mentioned above, this likely leads to an underestimation of overall sound inputs in the model. Maintenance activity was assumed to be constant over time, without accounting for lifecycle variation or evolving operational practices, although in reality it is likely to be dynamic and complex (Ren et al., 2021). Additionally, the model does not include physiological stress responses, disease, predation and displacement from killer whales, bottlenose dolphin and grey seals (Cosentino, 2015; Filatova et al., 2025; van Neer et al., 2020), or behavioural changes beyond movement and foraging efficiency, which could influence survival and reproduction in ways not captured by energetics alone (El-Dairi et al., 2024; Wright et al., 2007). Finally, harbour porpoises exhibit considerable individual and contextual variation in their responses to disturbance, and the underlying drivers of this variability remain poorly understood (van Beest et al., 2018), highlighting the need for further empirical data to improve impact assessments.

Nevertheless, while the limitations of this study warrant careful consideration, the absence of observed population-level impacts remains encouraging, particularly given the scale and comprehensiveness of this assessment. The DEPONS model's capacity to integrate multiple stressors, empirically grounded vessel movements, and spatially explicit prey dynamics, alongside the extensive scenario testing, positions this application as one of the most detailed cumulative impact assessments conducted to date for any marine species. However, even such a robust approach captures only part of the broader ecological picture. To advance ecologically responsible offshore wind development, future research must address key gaps in our understanding of marine mammal biology and ecology, especially regarding energetics and resilience to disturbance (e.g. McHuron et al., 2022). In parallel, more refined modelling of prey abundance and redistribution is needed, particularly in response to changing fishing regulations and oceanographic conditions (Barbut et al., 2020; Daewel et al., 2022), as well as long-term climate shifts. This is especially important given the long operational lifespans of offshore wind farms, which will remain in place as marine ecosystems undergo potentially profound changes. Expanding assessments to include additional stressors, such as contaminants, fisheries interactions, and climate-driven habitat shifts, as well as other sensitive species like other cetaceans, seals, and seabirds and associated competitive interactions, would contribute to a more comprehensive understanding of cumulative impacts of offshore wind. Ultimately, integrating these elements into ecosystem models or multi-species agent-based frameworks could help capture indirect effects and trophic interactions, supporting a more holistic and informed approach to marine spatial planning.

Despite limitations provided by any model, our results suggest that under the conditions and scenarios assessed, current offshore wind development in Danish waters is unlikely to cause population-level impacts on harbour porpoises. This provides a scientifically grounded basis for continued development based on this context, provided that cumulative impacts are regularly reassessed and emerging ecological knowledge is integrated into future evaluations. However, for populations already in decline, such as the one in the Belt Seas, precautionary management and integrated assessments remain essential to ensure that cumulative pressures do not exacerbate existing trends.

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CUMULATIVE IMPACTS OF OFFSHORE WIND AND COMMERCIAL VESSELS ON HARBOUR PORPOISE POPULATIONS IN DANISH WATERS

This study assesses the cumulative effects of offshore wind farm (OWF) development and associated vessel traffic on harbour porpoise (*Phocoena phocoena*) populations in the North Sea and Inner Danish Waters. Using the DEPONS agent-based model, we simulated porpoise behaviour and survival under realistic OWF construction and operation scenarios from 2020 through 2031. Despite incorporating noise from pile-driving, vessel activity, and potential beneficial prey changes, no population-level impacts were detected. Porpoise abundance and distribution remained stable, with seasonal patterns driven by natural cycles. These findings suggest that, under current development trajectories and mitigation practices, OWF expansion is compatible with harbour porpoise conservation. However, ongoing declines in the Belt Sea harbour porpoise population and unmodeled stressors highlight the need for adaptive management and broader cumulative impact assessments.

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