PrePARED Report No. 010

HARBOUR PORPOISE POPULATON RESPONSE TO WINDFARM CONSTRUCTION, SERVICE TRAFFIC, AND CHANGES IN PREY AVAILABILITY

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Predators + Prey Around Renewable Energy Developments

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Summary

The harbour porpoise (*Phocoena phocoena*) is known to be affected by noise generated during the construction of offshore windfarms, and estimates of the effects of such disturbances on populations on the scale of years or decades are crucial for the establishment of suitable mitigation and protection measures. We used the DEPONS agent-based model to simulate the response of harbour porpoise populations at different spatial scales to the noise from piling operations and service ship traffic at the Moray Firth offshore windfarm. DEPONS simulates the individual movements and survival of thousands of virtual porpoises in a dynamic landscape and implements the responses of porpoises to noise from piling and ship sources. We hypothesised that at the decadal scale, the North Sea population would not be affected by the wind farm-related noise disturbance, but that impacts on the regional population in the Moray Firth might be observed.

We investigated three scenarios: a control scenario with no added disturbance; a construction scenario featuring the piling schedules and ship traffic recorded during

the construction period, as well as ongoing service traffic created for the forecast period; and an increased food scenario that added the effects of enhanced food availability from fish around turbine foundations to the piling scenario, at a decreasing percentage out to a radius of 500 m (based on fish surveys at the windfarm). Simulations were run for a duration of 60 years and with 100 replicates for each scenario.

The simulation results suggest that, as hypothesised, noise disturbance from piling and ship traffic had minimal impact on the dynamics of the wider North Sea harbour porpoise population. Contrary to expectations, localized analyses for the windfarm area similarly show no population decreases in response to windfarm-related noise disturbance, and differences among scenarios were small in comparison to variability among replicate simulations. Further, population responses in the disturbance scenario featuring increased food biomass did not indicate any definite positive impact of the implemented enhanced food availability.

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1. Introduction

The continuing increase in the number of offshore wind developments in Europe and worldwide affects marine mammals in various ways. While some effects, such as avoidance of the noise pulses generated from pile-driving, are limited in time and space, they form part of the cumulative impact of offshore construction activities that may have longer-lasting consequences at both local and larger scales (Benhemma-Le Gall et al., 2021). Construction and operation of windfarms may influence the foraging behaviour of some species, which can ultimately affect their populations (Madsen et al., 2006; Bailey et al., 2010). Such population effects are difficult to determine through field observations, particularly for highly mobile and long-lived species like the harbour porpoise (*Phocoena phocoena*). Harbour porpoises, a protected species in European waters, have been shown to flee from piling noise (Brandt et al., 2009; Dähne et al., 2017; Graham et al., 2019, 2023) and also show avoidance of noise from shipping traffic (Benhemma-Le Gall et al., 2023; Frankish et al., 2023), which accompanies windfarm construction. At the same time, the installation of turbine foundations causes more permanent alterations of porpoise habitat, such as changes in the composition and biomass of food fish species that form part of the demersal fauna near turbine foundations (Reubens et al., 2014; Gimpel et al., 2023; Bicknell et al., 2025).

One of the aims of the PrePARED (Predators and Prey Around Renewable Energy Developments) project has been to develop and inform modelling frameworks that can be used to predict responses of porpoise populations to these multiple impacts. Spatially explicit ABMs (agent-based models) represent a powerful tool to investigate such scenarios due to their ability to directly incorporate the low-level mechanisms that determine dynamics of populations (Grimm & Railsback, 2005; McLane et al., 2011; Stillman et al., 2015). In these models, the interactions among simulated individual animals result in an emergent population response to environmental and behavioural variables. Simulation studies using ABMs can thus offer insights by integrating a great variety of factors into predictions of future population developments. We employed the DEPONS model (Nabe-Nielsen et al., 2018; Frankish et al., 2026), a purpose-built agent-based model in which simulated porpoises react realistically to noise disturbance from windfarm construction and moving vessels by altering their movement patterns, and to changes in prey fish distributions by adapting their choice of foraging location. Changes in population dynamics emerge over the course of the simulation from the balance between reproduction and mortality related to competition for food. In this study, we extended the geographic scope of DEPONS to simulate population responses to wind farm construction and operation in the Moray Firth, NE Scotland. We then created model scenarios to represent the changes in noise disturbance and prey fish biomass through the construction and operation of the three commercial wind farms that were built within the Moray Firth between 2017 and 2024. Using directly observed patterns of pile driving and vessel movements during the course of these developments, we investigated the long-term (annual to decadal) effects of these combined factors on local population densities near the windfarm and on the North Sea population scale.

We hypothesized that on the annual to decadal time scale, noise from construction and service of windfarms in the Moray Firth would have minimal effect at the North Sea spatial scale, but that it could potentially have a negative impact on the local population in the Moray Firth area. However, we also hypothesised that increases in prey densities around turbine foundations similar to those locally observed in the PrePARED project (Bicknell et al., 2025) could to some extent offset these negative impacts.

2. Model

2.1 Model description

This section provides an overview of the DEPONS model version 3.2, based on components of the updated ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2010, 2020). Only the first elements of the ODD are provided here; the rest is available as part of the TRACE document for model version 3.2 (Frankish et al., 2026).

2.1.1 Purpose

The model simulates how harbour porpoise population dynamics are affected by pile-driving noise emitted during construction of offshore wind farms, by noise emitted from ships, and by variation in prey availability in the vicinity of wind turbines. The animals' survival is directly related to their energy levels, and the population dynamics are affected by noise through its impact on the animals' foraging behaviour. By ensuring that the animals' movement patterns, space use and reactions to noise are realistic, the population dynamics should have the same causal drivers in the model as in nature.

2.1.2 Entities, state variables, and scales

The model includes six kinds of entities: porpoises, wind turbines, ships, hydrophones, landscape grid cells and cell groups. The porpoise agents are characterized by their location, speed, movement direction, age, age of maturity, energy level, pregnancy status, lactation status and movement mode. Each porpoise agent is a 'super individual' (Scheffer et al., 1995) representing several real-world female porpoises. Ships are characterized by their name, speed, type, length, and transit route. Hydrophones (not used in this simulation) are characterized by their location. Wind turbine agents are characterized by their location, noise source level, and start and end times of pile installation.

Simulations are by default based on a 982 km × 830 km landscape covering the North Sea. This landscape extends further north than landscapes used prior to DEPONS 3.2. It is divided into 2,455 × 2,075 grid cells, each covering 400 m × 400 m, and into cell groups covering 2 km × 2 km. The choice of cell size was arbitrary. Cell groups do not have state variables but are characterized exclusively by their location. They enable porpoises to navigate back to areas where they have been before when using large-scale movements. Grid cells are characterized by their coordinates, water depth, sea surface salinity, food level, maximum food level, distance to land, sediment grain size, and by whether they contain food or not. The default landscape includes land (40.0%) and water (Figure 1). Food patches cover 1.6% of the water and each food patch covers one grid cell. The food level is always zero for grid cells that are not used as food patches. The distribution of food patches is random and identical to the one used by Nabe-Nielsen et al. (2013, 2014). The employed number of food patches is arbitrary, and movement parameters of simulated porpoises were calibrated to develop realistic movement patterns based on the selected patch density. The only other environmental parameter in the model is the time of year.

2.1.3 Process overview and scheduling

The model proceeds in half-hour time steps. At the beginning of each time step, porpoises detect noise originating from active pile-driving operations and ships. This permits animals within a certain radius from the noise source to know where the noise comes from and the received sound level. The radius depends on the sound source level, propagation loss and a threshold sound level below which they do not react to noise.

The animals' fine-scale movements are controlled by a combination of correlated random walk (CRW) behaviour (Turchin, 1998), their ability to move towards known food patches (directed by a spatial memory) and the extent to which they are deterred by noise. CRW movements dominate as long as energy intake is high, else animals gradually become more directed towards patches where they have previously found food (Nabe-Nielsen et al., 2013). The animals turn and slow down if there is land ahead. Animals are deterred by noise, and the strength of the bias away from the noise source depends on the received sound level. Deterrence from ships also depends on the distance to the ships and the period of the day (day or night). The noise level affects only direction but not the speed of porpoises' fine-scale movements. In DEPONS 3.1 and later, ship speeds can change during a simulation, and parameters controlling porpoise movements were recalibrated for the Kattegat landscape based on simulations including a realistic number of ships, where porpoises reacted to ship noise above the ambient noise level. The magnitude of the reaction, and the probability that they reacted, were obtained from GPS tracked animals (Frankish et al., 2023). In DEPONS 3.2, porpoise response to pile-driving noise in the presence of windfarm construction ships was recalibrated based on data from the Gemini windfarm (see section 3.5).

The animals' energy levels and mortality are tightly coupled in the model. An animal's energy level (scaled to lie in the range 0–20) increases when it encounters food in a food patch but decreases with every move. Animals consume a decreasing fraction of the food as their energy levels increase from 10 to 20, assuming that there is a limit to how much energy they can store. Consumption of food causes their energy levels to increase equivalently. Their energy expenditure per time step depends on the season and whether they are lactating. The lower their energy levels, the higher their risk of dying. However, lactating animals with low energy levels do not die, but instead abandon their calves Individual energy budgets were constructed following established principles of physiological ecology (Sibly et al., 2013). The animals move one at a time in an order that is randomized after each half-hour time step. Animals whose energy levels have been decreasing for some time stop using fine-scale movements and start using large-scale movements to move towards more profitable areas (cell groups).

The maximum amount of food (energy) in the landscape varies by location and season. It is derived from seasonal maps of the relative porpoise densities in the North Sea (Figure 2; Gilles et al., 2016; Geelhoed et al., 2022), assuming that porpoises are only observed in areas with sufficient food. The food distribution map is updated monthly, i.e., on day 30, 60, …, and 330 (the model assumes 30 days per month). The actual amount of food in the patches changes dynamically: When a porpoise visits a patch, it consumes all or part of the food found there, but afterwards the food level increases logistically until reaching the maximum potential level for the patch. The updating of patch energy levels, i.e. replenishment of food, takes place at the end of every simulation day, after porpoises have moved and consumed the food they encountered.

At the end of each day, a number of life-history processes take place: Porpoises die if they reach their maximum age. They may mate, depending on the time of the year and their age. If they are already pregnant, they may give birth. If accompanied by a lactating calf they may wean the calf, which results in the creation of a new, independent individual in the model (if the calf is a female). Independent male porpoises are not included in the model, as the number of males was not considered a limiting factor for reproduction. The number of males is therefore not expected to affect population dynamics. Once every year, new mating dates are calculated.

The different variables in the model are updated asynchronously, i.e., immediately after a process has been executed.

3. Input data

3.1 Map data

Seven different kinds of background maps are employed in the model (Frankish et al., 2026): bathymetry, broad-scale prey distribution (food), fine-scale prey distribution (food patches), monitoring blocks, sediment grain size, salinity, and distance to coast. All North Sea maps were expanded or updated for use with the PrePARED scenarios in DEPONS 3.2. The ETRS89 projection (EPSG:3035) was used.

3.1.1 Bathymetry

The northern extent of all maps was increased by 112 km beyond that used in previous model versions, from 3,995,583 N to 4,107,600 N, just beyond Fair Isle (Figure 1). This extension is expected to prevent boundary effects on porpoise agents in the Moray Firth, whose movements might otherwise be affected by the proximity of the northern boundary of the simulation area. To avoid presenting agents with an additional small-scale, highly complex coastline, the Orkney Islands are treated as connected to the mainland (i.e. the Pentland Firth is closed) and the western extent of the map roughly follows the east coast of the Orkney Islands. The bathymetry map, which governs the areas of simulation space accessible to porpoise agents by restricting them from waters shallower than a specified minimum depth, was set to these boundaries. Bathymetry data were downloaded from the European Marine Observation and Data Network's digital terrain model[1]. All other maps were then cropped based on the bathymetry map.

[1] https://emodnet.ec.europa.eu/en

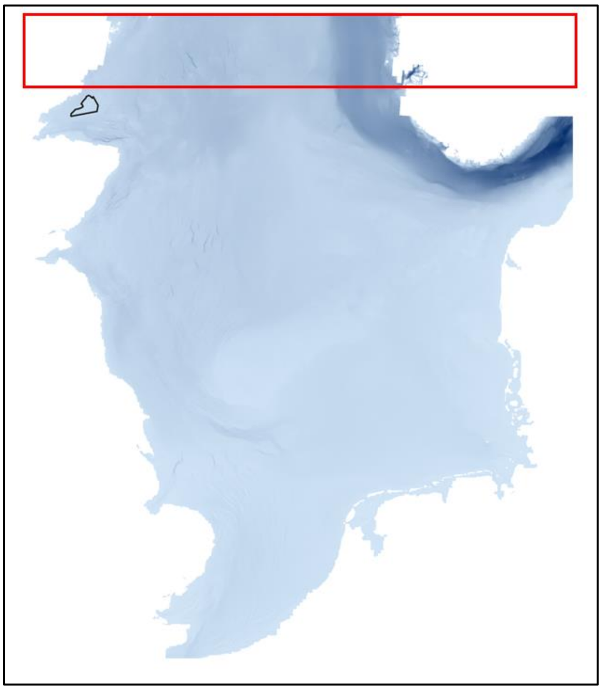

Figure 1. Bathymetry map of simulation area. Northern extension is indicated by red outline and windfarm area by black outline. Depth range (light to dark blue), 0–689 m

3.1.2 Food

The maximum amount of food in each food patch was derived from seasonal maps (spring, summer and autumn) of porpoise densities in the different parts of the North Sea (Frankish et al., 2026; see Gilles et al. [2016] for details). For the PrePARED scenarios, these maps were extended with additional data for the northern expansion, and individual monthly maps were created by interpolation.

We employed a version of the existing maps that had been enhanced with cross-survey porpoise density estimates for the Moray Firth area only (Moray Offshore Wind Farm (East) Limited, 2012). Map data for the expanded northern area during the summer (July) were sourced from the most recent OSPAR quality status report (Geelhoed et al., 2022, Figure k; data provided by Anita Gilles). Those estimates were based on observations for the period 2005–2020, while the existing maps were based on data from 2005–2013. The mean value in the northern area was calibrated to the mean of the existing map, corresponding to the mean food level previously used in simulations of the population in the inner Danish waters (Nabe-Nielsen et al., 2014), to calibrate food levels across the entire map. For each of the three seasons, the boundary of the northern area was extended southwards to create a 32-km overlap zone, then map values were blended across this strip using a buffer that retained values from the existing map at the southern limit of the strip and from the northern area at the northern limit, with a gradual blend of values in between.

The resulting three seasonal extended maps (Figure 2 d, g, j) were used for the months April, July, and October, respectively. Map values for the other nine months were interpolated from these data assuming cyclical dynamics for food values (Figure 2). This was done for each cell separately using a function of the form $\alpha \sin(x) + \beta \cos(x)$, where x is the map value, and α and β are estimated from the existing seasonal values using a linear model (implemented as function *interpolate.maps* in the R package

DEPONS2R [2]). Figure 3 shows close-up maps of the Moray Firth area for April, July, and October.

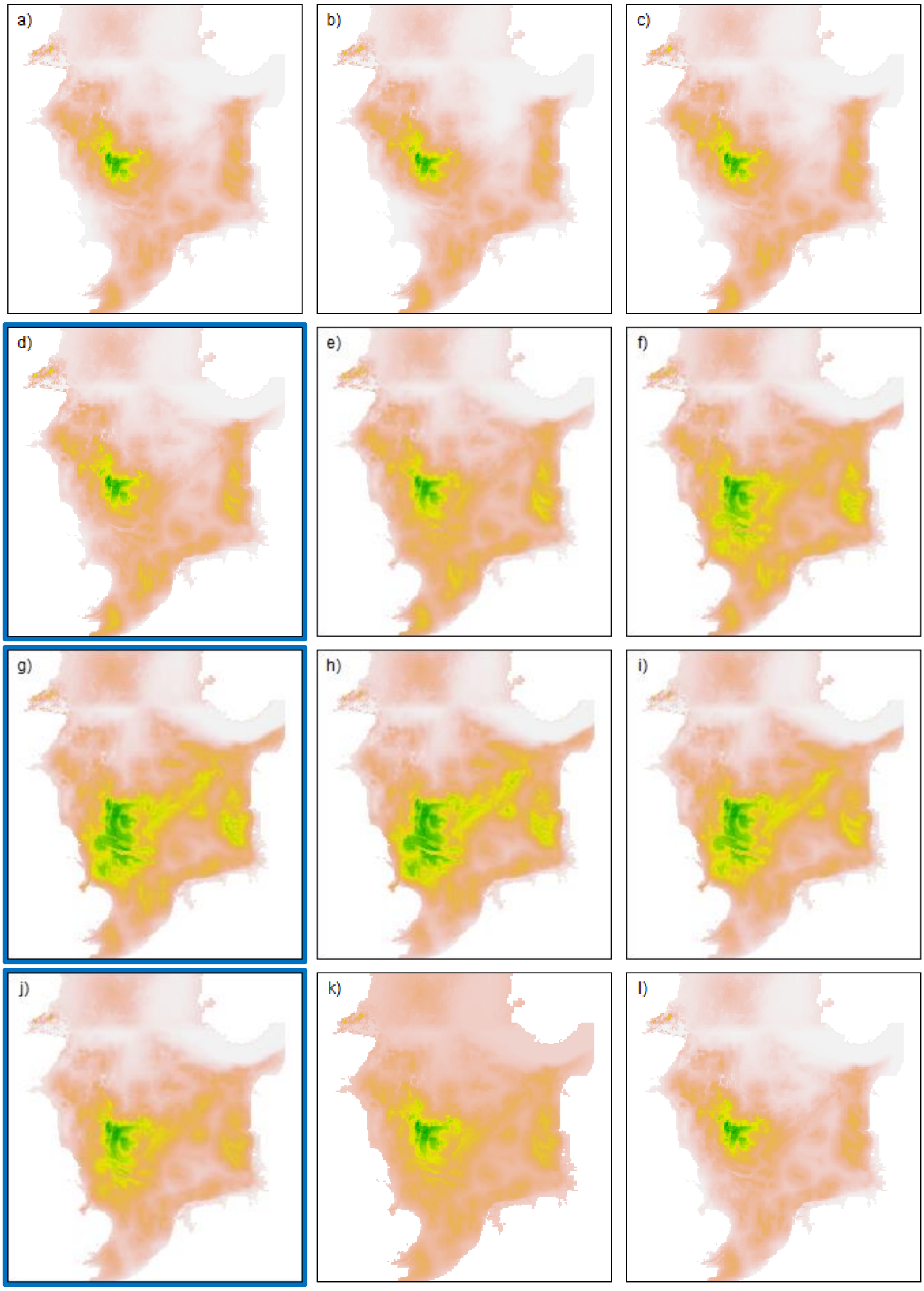

Figure 2. Monthly food distribution maps (January to December) derived from seasonal maps of porpoise densities in the North Sea (Gilles et al., 2016; Geelhoed et al., 2022). Map values for additional months were interpolated between the original seasonal maps (in blue)

[2] https://CRAN.R-project.org/package=DEPONS2R

using a sine function. Green shows areas with high porpoise densities, grey shows low densities and white indicates land or missing data.

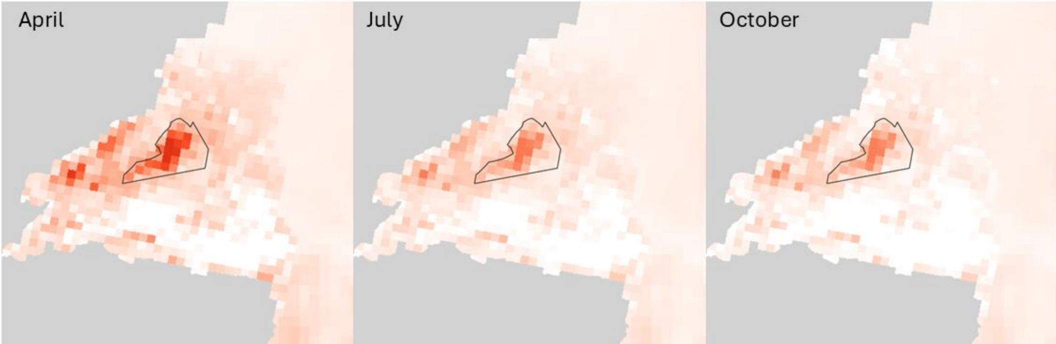

Figure 3. Close-up monthly food distribution maps for the Moray Firth area for April, July and October (corresponding to Figure 2 d, g, j), based on a cross-survey map of porpoise density estimates for the area (Moray Offshore Wind Farm (East) Limited, 2012). Red to white shading indicates high to low porpoise density, grey indicates land, and black outline indicates the windfarm area.

3.1.3 Food patches

The random food patch map was expanded into the northwards extension while maintaining the spatial distribution of patches found elsewhere in the landscape.

3.1.4 Monitoring blocks

Monitoring blocks enable the model to record porpoise numbers in different, non-overlapping map regions during the simulation. Blocks for the PrePARED scenarios consisted of a windfarm block for the combined area of the three windfarm developments (Beatrice, Moray East, and Moray West), one block for the remaining Moray Firth area (100 km radius from centre of the windfarm block), and one block for the remaining North Sea area (Figure 4). In the analysis, local population density for the Moray Firth block was measured as the sum of densities in the windfarm and Moray Firth blocks, and density for the entire North Sea as the sum of all three blocks.

3.1.5 Sediment grain size

This map is used to model the propagation of ship noise. Median sediment grain size data were derived from an extension of Bockelmann et al. (2018)'s map which was created by establishing a relationship between median grain size and the Folk classification scheme (Folk, 1954). Data for the northern map extension were sourced from the data prepared for the original maps (Appendix 1 of Frankish et al. (2026), Figure S2).

3.1.6 Salinity

Salinity levels are used by agents for navigation during fine-scale movements (van Beest et al., 2018). Monthly salinity data for the new extended maps were downloaded from the Copernicus Marine Environment Monitoring Service and derived from the Atlantic-European North West Shelf-Ocean Physics Reanalysis model (NWSHELF_MULTIYEAR_PHY_004_009) (CMEMS, 2026). Data from 2021 were used to maintain consistency with previous maps.

3.1.7 Distance to coast

This map allows agents to turn when approaching land. It was created by applying a proximity buffer to the bathymetry map.

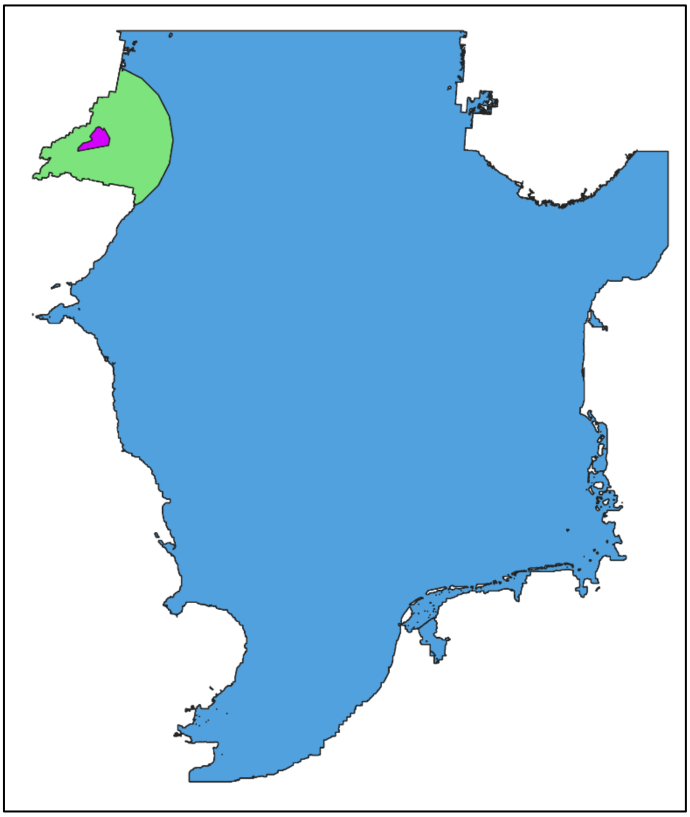

Figure 4. Monitoring blocks used in the PrePARED scenarios. Blue, North Sea block; green, Moray Firth block; purple, windfarm block.

3.2 Windfarm and piling data

Piling operations at the Beatrice, Moray East, and Moray West windfarm developments were represented in the model using data on the timing of each piling event, which were provided to PrePARED by developers (Table 1). For purposes of scenario construction, the period from the first day of the first month of Beatrice piling (04/2017) to the last day of the last month of Moray West piling (04/2024) was treated as the "piling period".

Piling at seven turbine locations (three at Beatrice, three at Moray East, and one at Moray West) was removed from the data because the piling work occurred on dates not accommodated in the model (the model year has 360 days and skips 29 February and 31 May/July/August/October/December). Ship traffic for these days was also omitted.

Including offshore substation platforms and transformer modules, piling during the simulation period occurred at 83 locations in the Beatrice development, at 100 locations in Moray East, and at 61 locations in Moray West (245 in total). Start and end times of piling events (mean duration 143 min) were rounded to 30-min intervals to conform to the model's time step.

The response of DEPONS porpoise agents to piling noise was calibrated under the assumption that acoustic deterrent devices (ADDs) are in use before each piling event, and periods of ADD use are therefore not separately represented in the simulation. As ADDs were employed before most piling events during construction in the Moray Firth (eg. Graham et al. 2019; 2023), all events were treated as including this component. Vibro-piling was used in some instances at Moray West (while omitting ADDs), but this was not considered in the simulations.

The sound source level of impact piling events was set to 221.5 dB re 1 µPa SEL @1 m, based on a mean received sound level of 179 dB re 1 µPa SEL @750 m recorded at Moray West (Moray Offshore Windfarm (West) Limited, 2025). This constitutes a worst case scenario in that noise levels during impact piling at Beatrice and Moray East were presumably lower due to the use of smaller pin piles, as opposed to the larger-diameter monopiles used at Moray West (Benhemma-Le Gall et al., 2023, 2024). The source level was calculated assuming a spreading loss factor (called '*beta_hat'* in DEPONS) of 14.72 and an absorption coefficient (*alpha_hat*) of 0.00027, which was considered appropriate for depths of up to 50 m in the North Sea (Danish Energy Agency, 2016; Bellmann et al., 2020).

Table 1. Characteristics of impact piling operations in the Moray Firth.

Development	Piling operations start	Piling operations end	Locations (in model)	ADD use
Beatrice	02/04/2017	02/12/2017	86 (83)	95%
Moray East	20/05/2019	27/02/2020	103 (100)	97%
Moray West	04/10/2023	13/04/2024	62 (61)	44% *

* remaining locations used vibro-piling

3.3 Ship data

Vessel activity within the Moray Firth study area was characterised using AIS records from 2017–2025. Ship traffic for the complete 60-year scenarios was then simulated using these observed AIS data from the Moray Firth and a single day of AIS data for the whole Noth Sea had been used in earlier phases of DEPONS development (see below). All AIS records were processed with functions included in the R package DEPONS2R (Nabe-Nielsen et al., 2025), most importantly *ais.to.DeponsShips*, which converts AIS positions into DEPONS vessel tracks. AIS data with a temporal resolution of 1 or 5 min were converted to positions at 30-min intervals for use in DEPONS. Where necessary during processing, details of individual ships (such as type and length) were obtained from Marine Traffic[3].

The base ship data set covering the entire North Sea simulation area was an expansion (for the added northern area) and revision of the set used in previous DEPONS versions and included 3,398 ships. It represented a single day of records previously used in DEPONS development (01/07/2020) that was replicated for every day of the simulation.

For the period containing the complete piling operations in the Moray Firth (04/2017–04/2024) and the following period containing the records used to derive ongoing

[3] www.marinetraffic.com

service traffic (05/2024–11/2025), these data were supplemented with AIS records specific to the Moray Firth. Data were sourced from Astra Paging, Anatec and FleetMon [now Marine Traffic] and Marine Traffic Kpler, and covered a rectangular area slightly smaller than the Moray Firth sampling block (Figure S1, Appendix). In 2022, data for the months of January–March and October–December (6 months) were missing, and data from the same months in 2021 were substituted. That year was chosen in preference of 2023 because it contained no piling activity at any development and thus did not inflate the occurrence of piling-related traffic in the data set. Data from 11/2025 were duplicated to 12/2025 to make up a complete year required for data handling in the model.

Both original AIS data sets were first filtered using the following exclusion criteria: a) unsuitable vessel types (~80% of exclusions), including sailing ships (no engine noise), immobile (platforms, etc.), or vessels otherwise not considered by the model (drones, seaplanes, etc.); b) no or uncertain identification (no MMSI number, or contradictory information in online records); c) no length information available; d) total track duration less than 30 min; and e) more than one instance of a speed > 150% of expected maximum speed for the vessel class (single instances were repaired by setting to expected speed). The final base data set consisted of 2,981 vessels and the Moray Firth data set of 5,340 vessels.

The Moray Firth ship data were then merged with the base data set after excising existing records for the overlapping area and time period (Moray Firth on 01/07/2020) from the Moray Firth set. Further, two offshore supply vessels and one survey vessel that were engaged in stationary work (see below) in the Beatrice area on 01/07/2020 were removed from the base set to avoid daily presence of such traffic outside the piling period.

The combined data were processed to implement the simulation of stationary active ships. This was intended to represent ships using their engines to hold position, such as a crew transfer vessel (CTVs) performing a bollard push against a turbine pile, or an offshore supply vessel (OSV) using a dynamic positioning system (DPS). Under these circumstances, the ship could emit noise that could affect porpoise agents. Other than this, only moving ships are considered to emit noise in DEPONS. Candidate ships were identified by the following criteria:

a) classifiable as type “Other” or “Government/Research” using the scheme of MacGillivray & De Jong (2021), which is implemented in DEPONS to govern noise emission by ship type. These two types contain the survey, construction and crew transfer ships that would be expected to make up the majority of applicable cases. Passenger, recreational, fishing and cargo vessels were assumed to not or rarely use DPS and were omitted
b) immobile for two or more consecutive time steps
c) not in a cell (400 × 400 m) adjacent to land, to exclude berthed ships
d) not in a cell adjacent to the map boundary, or in the first or last position of the ship’s track, as ships that leave and later re-enter the simulation area are also considered to be “pausing” by the model

For purposes of noise emission, the speed value of identified candidates was set to 7.4 knots for “Other” ships and to 8 knots for “Government/Research” ships, using the reference speeds in MacGillivray & de Jong (2021). This functionality was implemented as function *make.stationary.ships* in DEPONS2R. A total of 577 ships were identified as using one or more active pause periods (413 of which in the Moray Firth).

After the end of piling activities, windfarm installations are expected to receive further installation work (such as wind turbine and jacket foundation installation; final turbine installation in the Moray Firth was on 15/11/2024 at Moray West) and then be visited by regular service ship traffic. Such traffic was covered by the available records up to 11/2025 (15 months after the end of piling at Moray West). To represent ongoing service traffic in every year for the remainder of the simulation, we extracted selected ship tracks from the processed Moray Firth data set to construct artificial service traffic data.

We used data from the latest available 12-months period (12/2024–11/2025) as the source for one year's worth of service traffic, which was intended to accommodate seasonal differences in traffic volume and composition. The first month of this period (12/2024) was transposed to serve as the missing last month (12/2025) to make up a complete year for data handling in the model. Ships in the "Other" category (containing CTVs, OSVs, and construction vessels) that entered the area of the windfarm during that period were identified as candidates. Of these ships, we retained a total of 30 vessels (20 of which were CTVs) that were present in the "Construction and heavy maintenance vessel" and "Service vessel" databases maintained by 4C Offshore[4], which provide an updated list of vessels recorded as associated with windfarm construction and maintenance (Table S1, Appendix). The extracted tracks of these vessels were processed as above and merged with the single-day base ship data to create the ship data used during the post-piling simulation period.

Volume of windfarm-related ship traffic by ship hours spent in the windfarm area for the piling and post-piling periods is shown in Table S2 (Appendix).

3.4 Fish biomass data

We implemented a representation of potential enhanced prey fish biomass around locations of installed turbines. This was based on findings from baited remote underwater video (BRUV) monitoring at Beatrice and Moray East in August 2022 and at Beatrice in August 2024. It was found that 6 years after the end of piling at Beatrice and 4 years after end of piling at Moray East, haddock and flatfish abundance and biomass were significantly increased at sites in close proximity (~30 m) to Beatrice locations, compared to sites > 500 m from turbines. This was also the case for haddock at Moray East locations (Bicknell et al., 2025). This increase in biomass can be broadly estimated as a 3-fold increase in available food energy for harbour porpoises at the turbine pile compared to fish densities at sites > 500 m from the turbines. Sampling at higher resolution at Beatrice in 2024 found a 1.5-fold increase in demersal fish biomass at 30 m distance from piles compared to samples taken at 240 m distance (Bicknell et al., in review). Taken together, these findings suggest an increase in demersal fish biomass form 1-fold (background level) at 500 m distance to 2-fold at 240 m and roughly 3-fold at the pile location.

We implemented this change in food biomass within the radius of 500 m as a simplified linear formula $y = 3 – (x / 250)$, where x is distance in meters from the pile and y is the resultant biomass multiplier. This only influenced food levels in food patches falling within the radii around each pile. Out of the 59 food patches within the windfarm area,

[4] https://www.4coffshore.com

39 were unaffected, six had a biomass increase of 0.1–10%, 13 of 10–75%, and three of 100–188%, for a total biomass increase in the windfarm area of 16.1% (Figure 5).

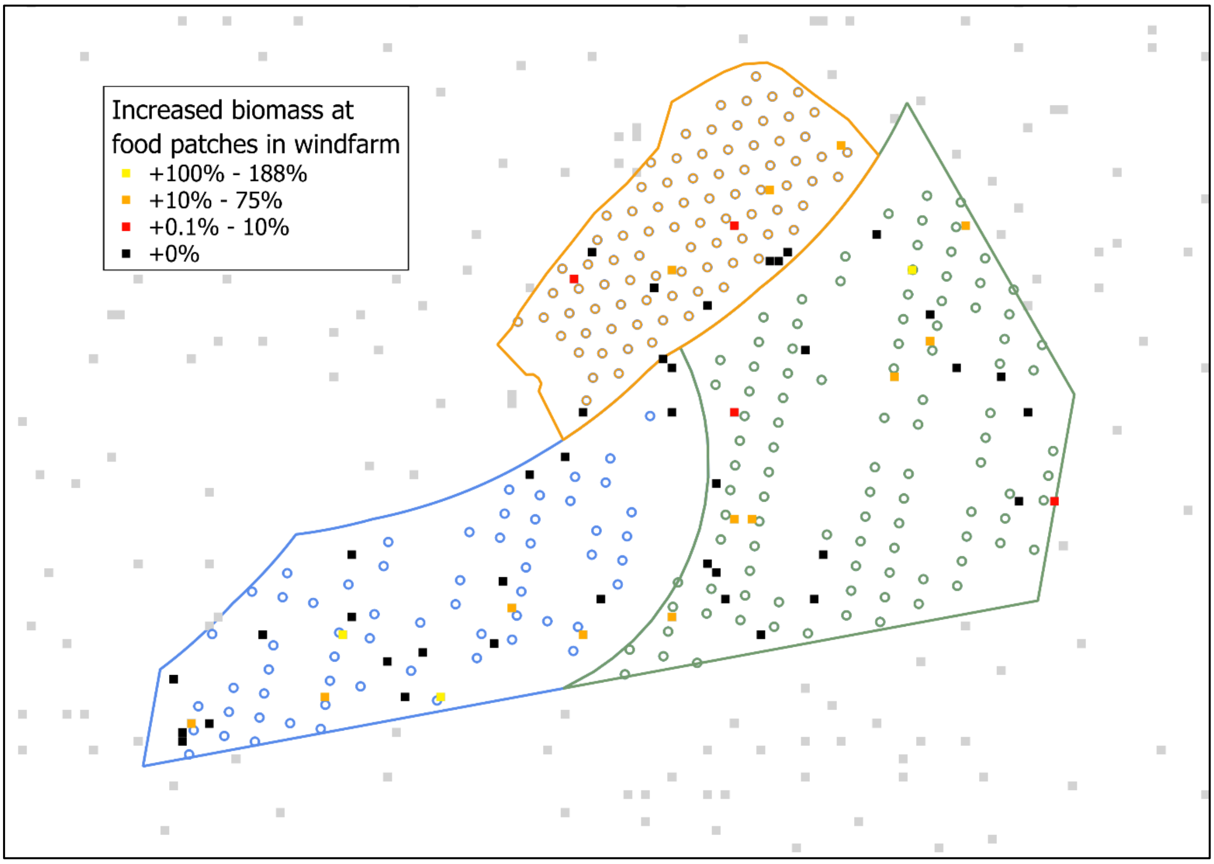

Figure 5. Scenario with increased food biomass around turbine locations. Coloured circles show turbine locations (orange: Beatrice; green: Moray East; blue: Moray West); grey squares show food patches outside windfarm area; black / red / orange / yellow squares, food patches inside windfarm area, in ascending order of additional biomass based on proximity to turbines

3.5 Recalibration of response to windfarm construction

Porpoises are expected to be deterred from the vicinity of piling events, but to gradually return to the area after the noise has ended. In previous DEPONS versions, porpoise movement parameters were calibrated to make recovery of simulated porpoise densities after piling events resemble those observed during construction of the Dutch Gemini wind farm[5] (Nabe-Nielsen et al., 2018). However, those simulations did not feature ship noise, although ship traffic was present during the Gemini operations. Since ship noise is included in the baseline scenarios of later model versions, and would also be expected to influence the patterns of porpoise response to piling noise in the same area, we recalibrated the model to more realistically represent porpoise movements in the PrePARED scenarios (which contain both piling and ship noise sources).

The ship traffic that was added to the calibration scenario consisted of a representation of windfarm construction-related traffic only (~4 months of the 2-year scenario duration). Since the ships involved in the construction of Gemini were not known,

[5] https://www.geminiwindpark.nl/

construction traffic was generated based on ships identified during the piling period at Moray East (05/2019–02/2020). We identified 13 ships of suitable type (9 CTV, 3 OSV, 1 dive support vessel) that were active at piling locations in at least 5 of the 10 months of this period, and calculated the mean amount of time each spent immobile at turbines. We then created artificial schedules for these ships between the nearest port of suitable size (Eemshaven) and each Gemini piling location according to the piling schedule. Ships were routed between port and turbines at a constant speed of 7.4 +/- 0.2 knots (see section 3.3) such that each ship spent its specific (noise-generating) pause time at the turbine, bracketing the time of the piling event. Then it attempted to return to port to wait for the next piling; or failing that, returned partway towards port before turning around; or remained in the windfarm area continuously if this was indicated by records. Each ship attended each foundation installation and spent the remaining time in port. This functionality was implemented as function *make.construction.ships* in DEPONS2R.

Furthermore, the sound pressure level above which porpoises are deterred by ship noise (i.e., the background noise threshold; *Tships*) was raised from the 70 dB re 1 µPa value previously used in DEPONS to 80 dB, based on results from the JOMOPANS project that were considered to be broadly applicable to North Sea locations (Frankish et al. in prep.). This mandated additional calibrations of parameters related to agent's fine-scale and large-scale movements, which were carried out against movement records of satellite-tracked animals.

We calibrated the following parameters: *T* (dB SEL), which determines the maximum distance at which porpoise movements are influenced by noise from a pile-driving event; *c* (unitless), which determines the strength of that response; *rR* and *rS* and (unitless), which respectively determine reference and satiation memory decay; *PSM_dist* (km), which determines distance to the movement target when initiating large-scale moves; *PSM_angle* (degrees), which determines maximum turning angle after each such move; and *ddisp* (km), which determines the distance moved. We used pattern-oriented modelling (Grimm et al., 2005) to test scenarios with different combinations of parameters, with the aim of minimizing the sum of squared differences (SSD) between field and simulated data. For details see Frankish et al. (2026) (sections 1.9.3–1.9.5).

A list of all user-definable parameters used in the PrePARED scenarios, including the parameter values determined in the above calibrations, is shown in Table S3 (Appendix).

4. Scenarios

We employed different scenarios to investigate the response of the porpoise population to the combined effects of piling noise, ship noise, and changes in food biomass at turbines (Figure 6). Scenarios were initiated with a starting population of 10,000 agents (each a super-individual representing multiple female porpoises), which was known to be close to an eventual equilibrium North Sea population size, and had a total duration of 60 years. Scenarios were divided into 4 periods: burn-in, pre-piling, piling, and post-piling.

With a starting population of 10,000 agents, the model generated a relatively stable population of ~9,000 individuals after 25 years. The first 25 years where therefore designated as a **burn-in period** that was excised from the results before interpretation. The **pre-piling period** was taken as representative of population dynamics at a stable population size in absence of piling operations and related traffic in the Moray Firth. It constituted “normal” disturbance conditions without increased pressure from windfarm developments, and had a duration of 7 years to approximate the length of the piling period (Figure 6). The **piling period** covered the 8 years during which piling operations were carried out at the Moray Firth windfarm developments (2017–2024). The **post-piling period** started at the end of piling operations and continued for another 20 years to allow forecasts of future population development under conditions where turbine construction was completed but windfarm maintenance-related ship traffic remained stable. Based on the fixed dates of the piling schedule, the dates for the simulation periods were set as follows: 1985–2009, burn-in (25 years); 2010–2016, pre-piling (7 years); 2017–2024, piling (8 years); 2025–2045, post-piling (20 years).

Three different scenarios were developed: **control**, **construction**, and **construction + increased food biomass**. The control scenario served as baseline and used the base food map and base ship traffic (recurring 1-day records) throughout. The **construction scenario** implemented piling events following the recorded schedule and added recorded ship traffic for the Moray Firth during that period. In the post-piling period, it implemented ongoing service traffic in the Moray Firth. Base biomass was used throughout. The **construction + increased food scenario** was set up equivalently to the construction scenario but added increased prey fish biomass around turbines, based on the estimated decreasing curve out to a radius of 500 m. Biomass increases came into effect 24 months after the end of piling operations (01/2019) at Beatrice, and somewhat earlier for Moray East (after 22 months; 01/2022) and Moray West (after 19 months; 01/2026) due to the necessity of maintaining units of full years for data handling. Enhanced biomass was then maintained for the rest of the simulation.

Each scenario was replicated 100 times.

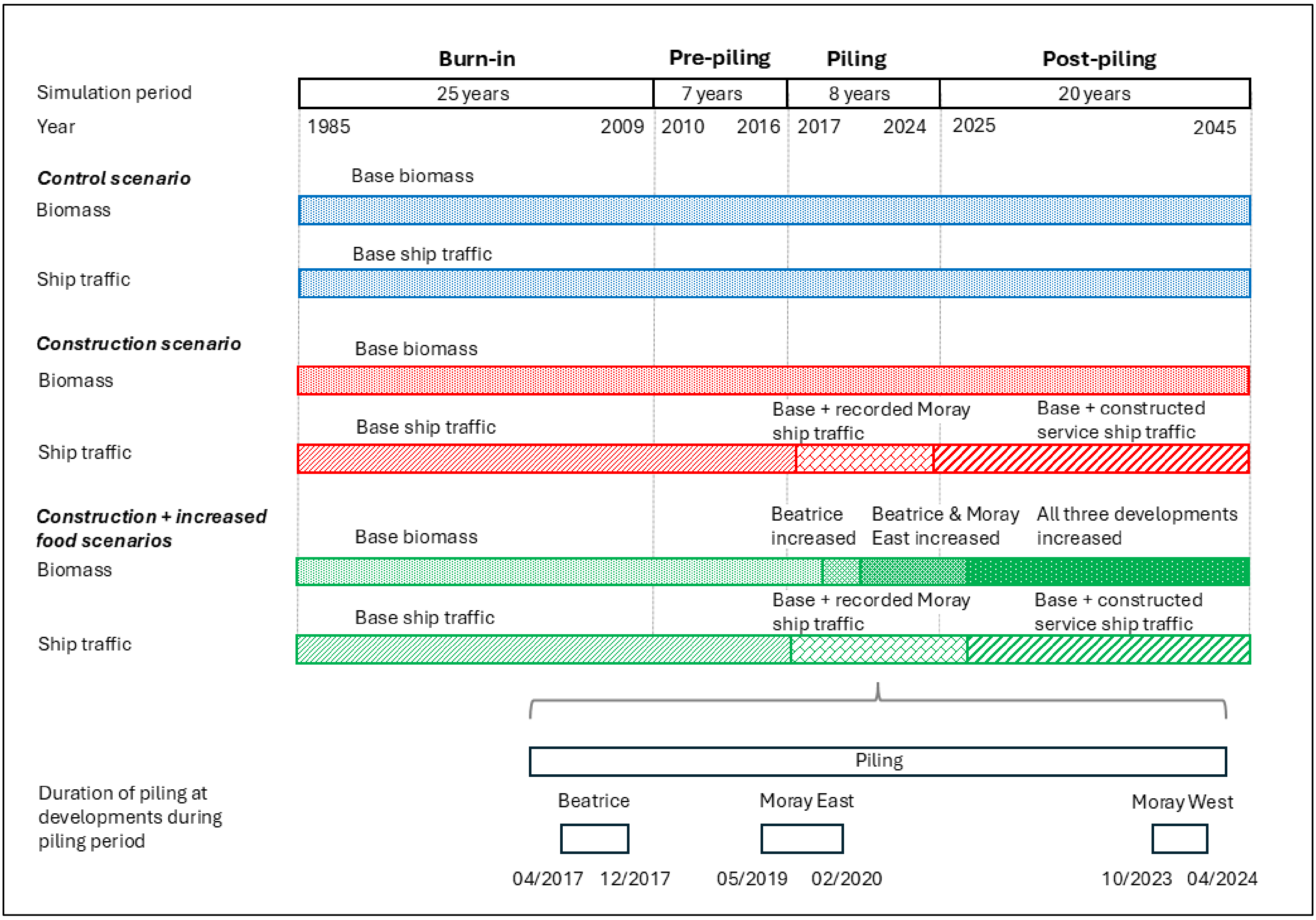

Figure 6. Timeline and data (food biomass and ship traffic) used in simulation scenarios. All three scenarios use base biomass and base ship traffic during the burn-in and pre-piling periods; these are modified for the construction and construction + increased food scenarios in later years. For details see text. The bottom timeline shows the duration (first to last record) of piling operations at the three windfarm developments during the piling period of the simulation

5. Analysis

The analysed output consisted of the number of porpoise agents recorded in the specified monitoring blocks over the course of the simulation. Before analysis, data from the burn-in period were excised from the output. '

To reduce the depiction of cyclical annual dynamics, at the North Sea scale, only the values for midnight of 1 January of each year are shown (Figure 7). At the Moray Firth and wind farm scale, agent presence was too infrequent to follow the same approach. Instead, we constructed rolling means across 13 months (to access 6 months each side of the centre) of population size values of the first day of each month. To more clearly depict differences between scenarios, values were then standardized relative to the mean of the control scenario during the pre-piling period, which represents the background disturbance regime.

Rather than assuming normally distributed results, confidence intervals (CIs) were generated using Efron's percentile method (a non-parametric bootstrap approach; Manly, 1997). For each scenario and monitoring block, a percentage of replicate data series with respectively the lowest and highest overall means were identified and removed from the data, and the lowest and highest remaining data value at each time point were treated as respectively the lower and upper CI boundaries. Due to high stochastic variability among replicates, we constructed a 50% CI by removing the 50/100 replicates with the greatest deviation from the mean from the CI boundary data. In the figures illustrating change in the number of porpoise agents over time for each scenario-monitoring block combination (Figures 7, 8 and 9), CIs are only shown at the North Sea scale; at smaller spatial scales (windfarm area and Moray Firth monitoring blocks), CI ranges were too large relative to mean population size to include in the figures.

6. Results

At the scale of the complete North Sea population there was no discernible difference between scenario outcomes (Figure 7). Mean population numbers remained closely similar throughout the simulation and seem more strongly affected by emergent stochastic fluctuations than by disturbances.

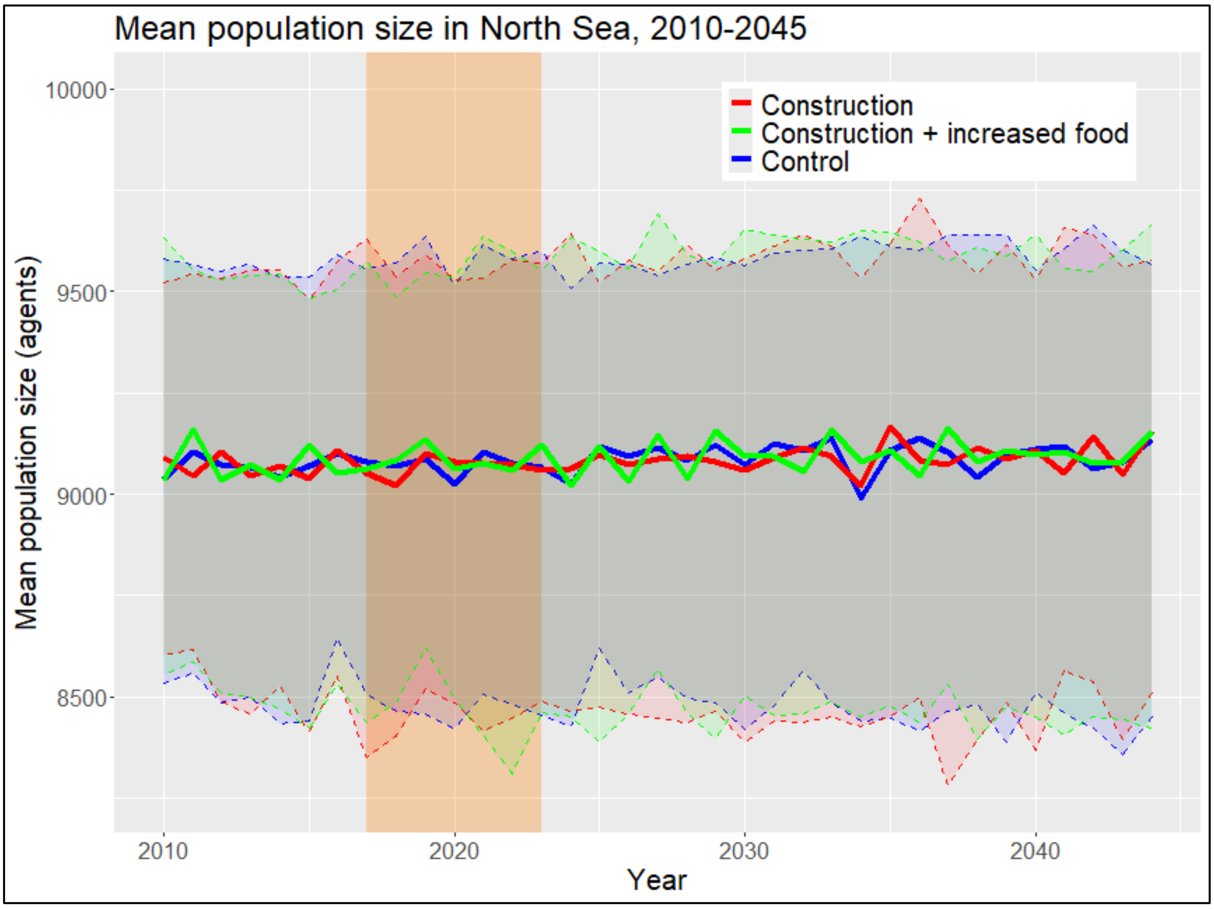

Figure 7. Mean population size of simulated porpoises in the complete North Sea area, for the period 2010–2045 (pre-piling to end of simulation), showing the first record (1 January) of each year. Solid lines show means across 100 replicates, shaded areas show 50% confidence intervals. The orange rectangle shows duration of piling period.

At the scale of the windfarm area, very low porpoise numbers were present, with the majority of simulation replicates not registering any agents at any given time point. We addressed this with high replicate numbers and by evaluating population sizes as relative to the mean of the control scenario during the pre-piling period, based on a 13-month rolling mean (Figure 8). Mean outcomes for the control, construction and construction + increased food scenarios did not differ substantially from each other throughout most of the simulation period. Apparent differences between scenarios at this scale are strongly driven by stochasticity — e.g., note that all three scenarios used the same food and disturbance input data prior to 2017. During the periods of increased disturbance in the construction scenarios, porpoise numbers were not visibly reduced below those in the control scenario.

At the scale of the Moray Firth, porpoise numbers were slightly larger yet still strongly influenced by stochasticity (Figure 9). Dynamics mirror those seen at the windfarm scale. The apparent divergence between scenarios during pre-piling is absent but that towards the end of the simulation period remains, suggesting that the ranking of outcomes at this point (control > disturbance scenarios) may be driven by stochasticity to a lesser degree.

For all scenarios at the smaller spatial scales, the difference in population size among replicate simulations was large compared to differences in mean population size between scenarios (coefficient of variation during piling period at wind farm scale: 142.6, 205.8, and 232.6 for control, construction, and construction + increased food scenarios, respectively; 38.9, 49.8, and 50.1, respectively, at Moray Firth scale; 0.27, 0.27, and 0.39, respectively, at North Sea scale).

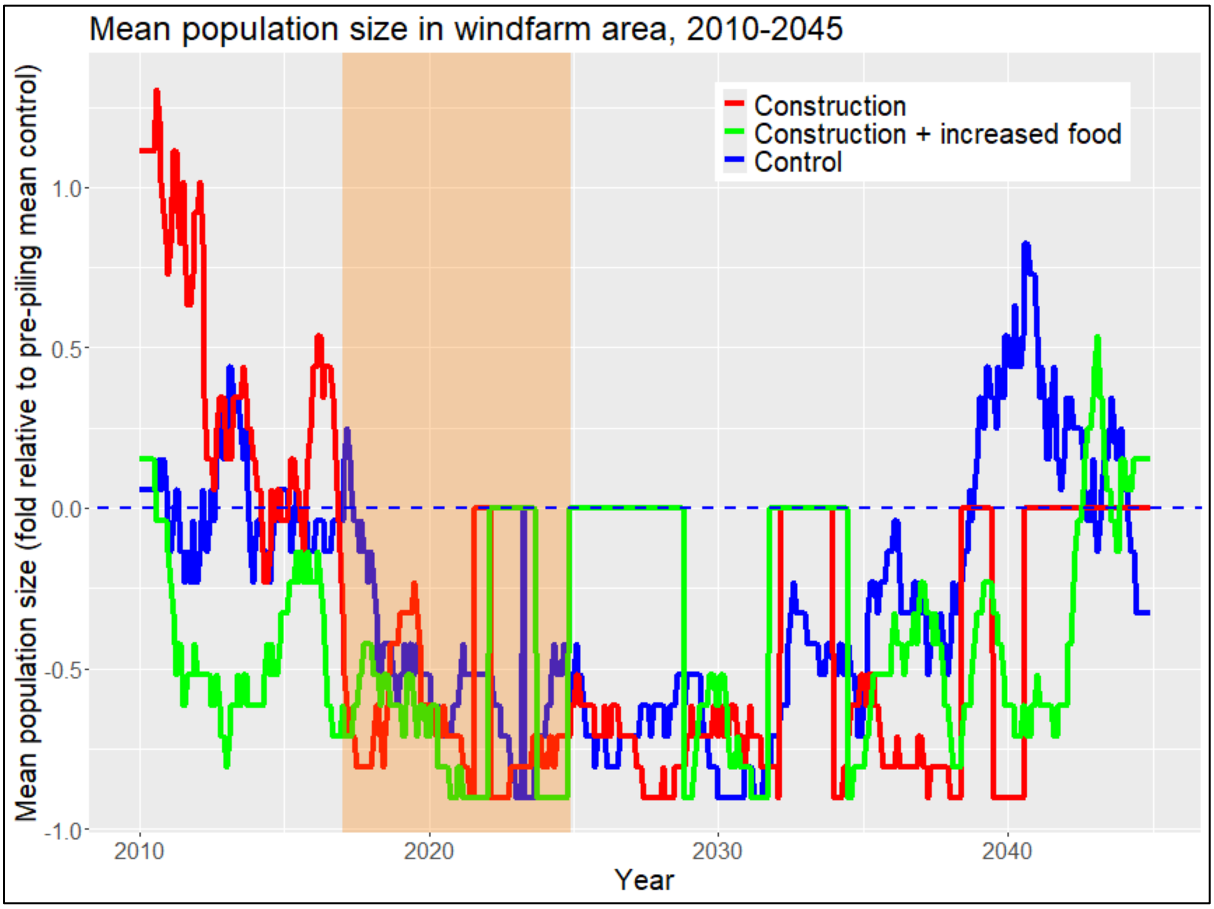

Figure 8. Mean population size of simulated porpoises in the windfarm area, for the period 2010–2045 (pre-piling to end of simulation), standardized relative to the mean of pre-piling control (blue dashed line). Values shown are rolling means over 13 months (100 replicates). The orange rectangle shows duration of piling period.

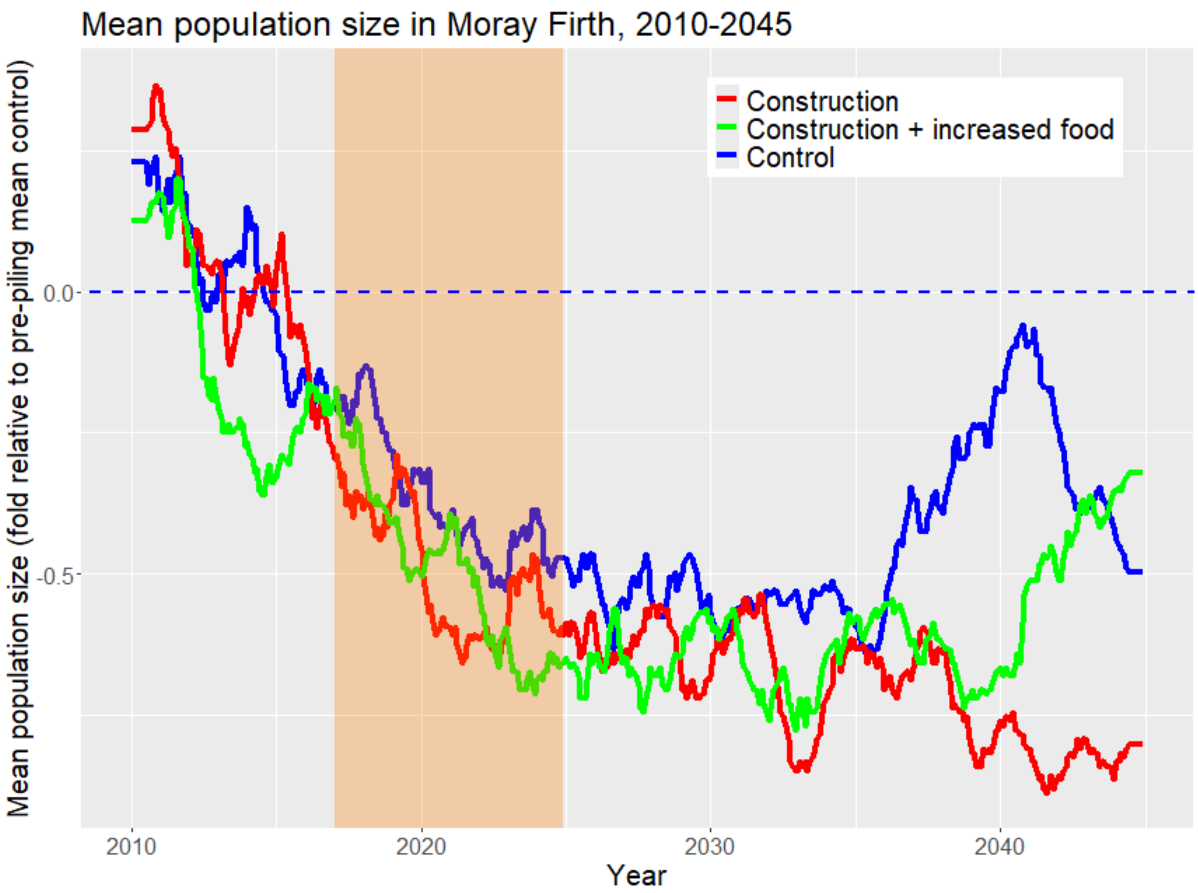

Figure 9. Mean population size of simulated porpoises in the Moray Firth area (100 km radius around windfarm), for the period 2010–2045 (pre-piling to end of simulation), standardized relative to the mean of pre-piling control (blue dashed line). Values shown are rolling means over 13 months (100 replicates). The orange rectangle shows duration of piling period.

7. Discussion

The simulated scenarios represented reported and potential changes in noise disturbance and prey fish biomass during and after the piling operations in the Moray Firth windfarm developments. We hypothesized that on the decadal scale, i) noise from piling as well as construction and service traffic would not affect the wider North Sea population, but ii) would have a negative effect on the regional population in the Moray Firth area, which might be offset to some extent by different levels of increases in prey densities. Our findings provided support for hypothesis i) but not for hypothesis ii), i.e. no regional negative effect was predicted.

The original environmental impact assessments for the Moray Firth offshore developments (Beatrice Offshore Windfarm Ltd, 2012; Moray Offshore Renewables Ltd., 2012; Moray Offshore Wind Farm (West) Ltd., 2018) concluded that it was unlikely that there would be any long-term deterrence effects on the harbour porpoise population, despite the expected short-term response to disturbance. These predictions were based on the separate evaluation of noise from impact piling, off-shore construction, and associated ship traffic. In the present analysis, we employed a more integrative method that accounts for cumulative impacts of these disturbances and increased food availability. This analysis similarly did not demonstrate a long-term impact of the modeled disturbances.

The model results indicate that the harbour porpoise population at larger spatial scales than that of the Moray Firth is unlikely to be affected by noise disturbance from piling and ships that was implemented in our simulations. The overall population size in the North Sea did not change in response to piling at the modeled Moray Firth sites, and an increase in food availability at those sites did not result in an increase in the population size. This is not unexpected, as the implemented changes affected only a very small percentage of the total population and similarly represented a very small increment in the disturbance amount and food availability in the total area.

For the majority of the simulation period, the local population size in the Moray Firth windfarm area also did not vary discernibly among the control, construction, and construction + increased food scenarios. At this spatial scale, porpoise numbers across all scenarios declined throughout the first half of the simulation period (post burn-in). This indicates that regional equilibrium population sizes took longer to establish than that at the full North Sea scale, where a stable population mean was present at the end of the burn-in period. However, during the periods featuring piling, construction, or service traffic noise in the disturbance scenarios, regional population size did not decrease further relative to the control scenario. This suggests that the noise disturbance was too localized and intermittent to cause simulated porpoises to consistently avoid the area. Exposure to underwater noise has been shown to disrupt foraging in harbour porpoises and cause short-term behavioural responses such as evasive movements, changes in dive behaviour, and displacement (Wisniewska et al., 2018; Frankish et al., 2023). Previous studies using DEPONS have indicated that pile-driving noise alone is unlikely to give rise to population level effects (Nabe-Nielsen et al., 2018; Van Geel et al., 2025), presumably due to the transient nature of the disturbance. However, this is the first time this ABM has been used to investigate the long-term impacts of recurrent service vessel operations.

Towards the end of the forecasting period (10+ years after the end of construction), the apparent divergence of population sizes by scenario at the smaller spatial scales would agree with the expected ranking by disturbance magnitude: lowest porpoise numbers in the construction scenario, higher numbers due to greater food biomass in the construction + increased food scenario, and greatest numbers in the absence of ongoing service traffic in the control scenario. The presence of similar dynamics at the scales of both the windfarm and Moray Firth monitoring blocks lends greater weight to a non-stochastic interpretation. However, high random variation among replicates (note coefficients of variation, above) must still be considered a dominant driver of porpoise numbers, and none of the scenario means fell outside the range of variation of the others. Note also, e.g., the downwards dynamics in porpoise numbers of control simulations in the final five years of simulation (Figures 8 and 9), for which no scenario-based cause exists. Overall, the simulations offer no convincing indication that the modeled disturbance and food differences between scenarios would lead to long-term differences in population development at regional and smaller spatial scales.

While there are currently no observational data that support post-construction alterations in porpoise presence in the Firth region, previous studies in the North Sea have reported that structures like oil and gas platforms (Clausen et al., 2021) and the Beatrice demonstrator turbines (Fernandez-Betelu et al., 2022) can be attractive to porpoises. The importance of enhanced foraging opportunities around structure foundations would, however, presumably depend on both the maturity of the ecosystem and the difference in spatial configuration between individual large, complex “islands” (platforms), and arrays of simpler turbine foundations. It should also be emphasized that the implementation of enhanced foraging opportunities in the scenarios is based on a rough approximation. The available BRUV analyses provide some empirical data points with which to model the expected drop-off in fish biomass with distance from turbine piles, but extrapolation across most of the range remains speculative, especially between 240 m and 500 m (Bicknell et al., 2025; Bicknell et al., in review). Further, the implemented 3-fold biomass at the pile location assumes that the observed increase in haddock biomass translates directly into an equal increase in food availability to harbour porpoises, which is unlikely because Gadidae make up only a proportion (albeit often substantial) of porpoise diet (Wisniewska et al., 2016; Andreasen et al., 2017) and the fish assemblages observed in August might not be representative for the entire year. It was also assumed that all increases represented newly produced biomass rather than a redistribution of existing fish populations, a distinction that Bicknell et al. (2025) could not make from their observations. On the other hand, the model did not take into account any potential further increases in fish habitat attractiveness as the hard substrate ecosystem at the sites matures in later years. Overall, however, it seems more likely that the effect implemented in the model overestimated the real impacts to some extent, while still failing to measurably affect porpoise densities.

It is unknown whether the increase in fish density observed at the Moray Firth sites may have been partly caused by a decreased presence of fisheries vessels, as fishermen might wish to avoid snagging their gear on cables and obstacles on the seafloor around turbines. Similar fish biomass increases were reported around an operational oil and gas platform in the North Sea, but as a permanent 500-m fisheries exclusion zone was in effect at that location, the relative importance of fisheries exclusion was not clear in that study either (Ibanez-Erquiaga et al., 2024, 2025). It would have been desirable to model changes relative to pre-piling traffic in the presence of fishing vessel (and the resulting noise disturbance) around turbine sites during and after piling operations, but no relevant data were available.

The variability in porpoise numbers recorded in the Moray Firth area within DEPONS arises from stochasticity in how porpoises move in their search for food. This is influenced by their memory of where food has been abundant in the past, as it is expected to be the case for porpoises in nature (Nabe-Nielsen et al., 2013). Such complex interactions between food availability, competition and spatial memory can drive high variability in poropise numbers at small spatial scales. As this is likely to be the case in both the present simulation results and in reality, it underscores the importance of understanding the mechanisms that govern impacts of disturbances on populations, rather than focusing on temporary changes in population sizes in a single study site. As an example, porpoises may be more easily deterred from areas where the population density is low, and where food is presumably scarce (New et al., 2020). The outcomes of population surveys at such times could be interpreted as a sign of large population impacts of offshore windfarm construction. However, at larger temporal scales the population may in fact be unaffected by offshore windfarms, as the area can be easily repopulated through immigration from areas with higher population densities after a disturbance ends. As marine mammal population densities are rarely measured for long periods after the end of wind farm construction, such measurements would not reflect the true population impact of construction-related acoustic disturbance. When long-term field data are unavailable, mechanistic simulation models like ABMs may thus provide a more faithful picture of long-term population consequences of disturbance than short-term observations alone.

However, one caveat with using ABMs for predicting effects of disturbances in small areas is that they may be especially sensitive to how realistically fine-scale variations in food availability and their effect on animal behaviour are represented. As there are no indications that the porpoise population foraging in the Moray Firth is philopatric (as opposed to, e.g., the population in the inner Danish waters and Kattegat), it cannot be modeled at a regional spatial scale over generational time scales, but must be allowed access to the wider North Sea habitat to enable realistic population dynamics to emerge from model simulations. In the present study, on average less than two out of 100 replicate simulations registered a single porpoise in the windfarm block at any point during the pre-piling period. While it is important to remember that each simulated animal represents several real-world animals, this trend likely reflects that the number of food patches in any map area the size of the Moray Firth study site is very low. To utilize the area the animals need to discover the food patches, but afterwards they will be able to navigate back to them repeatedly using a spatial memory. The combination of few simulated animals entering the Moray Firth site and their dependency on a small number of food patches in this area cause model outcomes to be strongly influenced by stochasticity.

While ABMs are subject to limitations such as these scale-dependent effects, they are still among the best available tools for predicting the long-term impacts of multiple stressors and changes in the environment on marine animals. For long-term predictions in novel or changing conditions, classical correlation-based approaches are likely to be unreliable (Stillman et al., 2015; Urban et al., 2016), making process-based models the only viable approach. ABMs are well suited to handle sparse and uncertain ecological data due to their ability to integrate and buffer processes across space and time (Grimm & Railsback, 2005; McLane et al., 2011), and to model combinations of stressors that may yield emergent results (Pirotta et al., 2022). The DEPONS model represents one of the most comprehensive tools for cumulative impact assessments in marine mammals. In this simulation study, we informed the model with the best available data to realistically represent both porpoise movements and population dynamics, and anthropogenic disturbances in the Moray Firth and the wider North Sea area. This simulation's main outcome — the absence of any long-term effects of wind farm construction on the porpoise population at either regional or North Sea scale — agrees with previous DEPONS studies that found no effect of realistically parameterized piling noise on harbour porpoises at larger spatial scales and/or annual or longer time frames (Nabe-Nielsen et al., 2018). We therefore conclude that the results of the simulation can be considered reliable.

However, it must be kept in mind that modeling of the response of harbour porpoises to environmental and man-made pressures in the North Sea still remains incomplete in several important respects. These include the poorly understood impacts of sources of underwater noise such as acoustic positioning systems used by geophysical survey ships and large fishing vessels (Nørholm et al., 2025), the physiological and population-level effects of environmental contaminants (HELCOM, 2023), and mortality from fisheries bycatch (Kindt-Larsen et al., 2023). As information on these pressures continues to become available, they can be readily integrated into DEPONS and form part of further explorations of the cumulative impact of present or planned wind farm developments in the North Sea. Perhaps most importantly, potential future large-scale changes in fish distribution driven by climate change may have much larger impacts on porpoise populations than the effects we have been able to document here. The dependence of harbour popoise populations on the distribution, abundance and biomass of prey fish is challenging to model because current information on porpoise abundance (which in DEPONS is used as a proxy for presence of prey fish) has poor correspondence with the estimated distribution of expected prey species (Gilles et al., 2016; Geelhoed et al., 2022). This is probably a function of variability in, and fragmentary information on, porpoise diet choices, and the fact that fisheries-derived data on fish distributions may not reflect the prey individuals or assemblages that porpoises exploit. We are currently exploring the creation of a multi-species, spatially explicit prey distribution index that may enable linking forecasts of porpoise population dynamics directly with estimates of future climate-driven changes in fish distributions (Gordó-Vilaseca et al., 2024). Creating comprehensive and reliable forecasts of the population responses of harbour porpoises and marine mammals in general will likely depend on integrating this and similar factors into ABMs and wider ecosystem models.

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9. Supplementary Material

Table S1. Constructed service ship traffic in the model. Details and presence of the 30 vessels identified as active in post-piling service traffic at the Moray windfarm developments during the period 12/2024–11/2025, and whose tracks were used to construct a repeating 12-month data set of ongoing service traffic for later years. The 12/2024 data were transposed to the end of the set (12/2025, column "Dec") to make up one full year for data handling. CTV, crew transfer vessel; OSV, offshore supply vessel

MMSI	Vessel type	Vessel length	Presence											
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
219029786	Jack-up vessel	161	X											X
219464000	Tender (SWATH)	25	X	X										X
232013230	CTV	27	X	X	X	X	X	X	X	X	X			X
232029215	CTV	24	X	X	X	X	X	X	X	X	X	X	X	X
232031394	CTV	24	X	X	X	X	X	X	X	X	X			X
232036844	CTV	24	X	X	X	X	X	X	X	X	X	X	X	X
232046092	CTV	27	X	X	X	X	X	X	X	X	X	X	X	X
232049709	CTV	27	X	X	X	X	X	X	X	X	X	X	X	X
232050960	CTV	27	X		X	X								X
257584000	Commissioning service operations vessel	89	X	X										X
232039877	CTV	28	X	X	X	X	X	X	X	X	X	X	X	
235088132	Utility vessel (Multicat)	26	X		X									
235085842	CTV	18		X		X	X	X	X	X				
232040984	CTV	27			X	X					X	X	X	
235090347	CTV	22			X	X	X	X	X	X	X	X		
235107284	CTV	24			X	X	X	X						
311034300	Jack-up vessel	76			X	X								

232025959	CTV	27					X	X						
235108461	CTV	18					X							
253586000	Jack-up vessel	89					X	X						
257974000	OSV	96					X	X						
235089035	CTV	26					X							X
215644000	Jack-up vessel	115						X	X	X				
232006483	CTV	27						X						
232007444	CTV	27						X						
232047798	CTV	24						X	X	X	X	X	X	
232048134	CTV	27						X						
219019814	Search and rescue vessel	8								X	X	X	X	
235083968	CTV	18									X			
232004102	Mooring vessel	41										X	X	

Table S2. Windfarm area ship traffic in the model. Table shows active (noise-generating) ship hours in the windfarm area during the piling period (2017–2024) and one year of post-piling traffic (2025; both of these periods consisting of records), and the remaining 19 years of the simulation (2026–2045) consisting of constructed ongoing service traffic extracted from data for the period 12/2024–11/2025. Records from 11/2025 were doubled to 12/2025 due to absence of 12/2025 records, and extracted data from 12/2024 were transposed to 12/2025 to make up one full year for data handling.

Year	Active ship hours in windfarm area											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	99	108	732	1823	2308	2200	3127	3579	2531	1425	3240	2791
2018	2213	3012	2760	2983	3083	3079	4534	6095	3845	2362	942	1163
2019	983	882	1584	2650	4106	4277	4612	3967	2500	2296	1374	1788
2020	1692	1466	2008	2047	2176	2110	495	4983	5110	6483	4869	4356
2021	4535	4233	2047	2176	2110	6664	5743	4531	3882	4946	4609	4535
2022	4233	6664	5098	3330	2446	745	68	2622	3116	2698	3545	2780
2023	1607	1655	1491	1818	1755	2969	2641	2628	2100	2041	2438	2281
2024	2308	3149	3770	5432	5360	5901	6568	6589	5339	3613	2786	2009
2025 (after end of piling)	2175	1469	2152	2386	3567	3935	3586	2878	1648	1698	1433	1433
2026+ (ongoing service traffic extracted from 2024/2025)	1244	1337	753	1287	1395	1819	2050	1457	1215	651	940	866

Table S3. Model parameters used in the PrePARED scenarios. The names shown are those used in the model GUI and batch files. For details on parameter functions see Frankish et al. (2026). Normally distributed ranges are indicated by “N(<mean>; <standard deviation>)”.

Parameter	Description	Value
a0	Autoregressive coefficient for log10(d/100), where d is distance per CRW move [unitless]	0.35
a1	Coefficient indicating effect of water depth on log10(d/100) [unitless]	0.0005
a2	Coefficient indicating effect of salinity on log10(d/100) [unitless]	-0.02
alpha_hat	Absorption coefficient for pile-driving sound	0.00027
b0	Autoregressive coefficient for turning angles in CRW [unitless]	-0.024
b1	Coefficient indicating effect of water depth on turning angles in CRW [unitless]	-0.008
b2	Coefficient indicating effect of salinity on turning angles in CRW [unitless]	0.93
b3	Intercept from regression of turning angle on salinity and bathymetry [unitless]	-14
beta	Survival probability constant [unitless]	0.4
beta_hat	Spreading loss factor for pile-driving sound	14.72
bycatchProb	Randomly selected proportion of the population to remove each year [unitless]	0
c	Deterrence coefficient [unitless]	0.012
cship_dist_day	Coefficient of ship distance on magnitude of deterrence during day [unitless]	-0.0355541
cship_dist_night	Coefficient of ship distance on magnitude of deterrence during night [unitless]	0.0284629
cship_dist_x_noise_day	Interaction of ship noise and distance on magnitude of deterrence during day [unitless]	0
cship_dist_x_noise_night	Interaction of ship noise and distance on magnitude of deterrence during night [unitless]	0
cship_int_day	Intercept of ship noise and distance on magnitude of deterrence during day [unitless]	2.9647996

cship_int_night	Intercept of ship noise and distance on magnitude of deterrence during night [unitless]	2.7543376
cship_noise_day	Coefficient of ship noise on magnitude of deterrence during day [unitless]	0.0472709
cship_noise_night	Coefficient of ship noise on magnitude of deterrence during night [unitless]	0
ddisp	Distance moved per time step while using large-scale movements [km]	2
dispersal	Type of large-scale movements	PSM-Type2
dmax_deter	Maximum deterrence distance [km]	1000
dmax_mov	Maximum value of log10(d/100) while using fine-scale moves, where d is distance moved per time step [m]	1.73
dmin_deter_ships	Minimum deterrence distance [km]	0.1
Einit	Initial energy level for porpoises [relative unit]	N(10.0;1)
Elact	Energy use multiplier for lactating mammals [unitless]	1.4
Euse	Energy use per 30-min step [relative unit]	4.5 × 10-3
Ewarm	Energy use multiplier in warm water [unitless]	1.3
h	Probability that adult females become pregnant	0.68
k	Inertia constant; the animal's tendency to keep moving using CRW irrespective of foraging success [unitless]	0.001
landscape	Simulation landscape	Expanded North Sea map
porpoiseCount	Number of porpoise agents in the simulation when initiated	10000
pship_dist_day	Coefficient of ship distance on probability of deterrence during day [unitless]	-0.130388
pship_dist_night	Coefficient of ship distance on probability of deterrence during night [unitless]	0.085242
pship_dist_x_noise_day	Interaction of ship noise and distance on probability of deterrence during day [unitless]	0.0293443
pship_dist_x_noise_night	Interaction of ship noise and distance on probability of deterrence during night [unitless]	0

pship_int_day	Intercept of ship noise and distance on probability of deterrence during day [unitless]	-3.0569351
pship_int_night	Intercept of ship noise and distance on probability of deterrence during night [unitless]	-3.233771
pship_noise_day	Coefficient of ship noise on probability of deterrence during day [unitless]	0.2172813
pship_noise_night	Coefficient of ship noise on probability of deterrence during night [unitless]	0
Psi_deter	Deterrence decay constant; decrease in deterrence per time step after noise has stopped [percent]	50
PSM_angle	Maximum absolute turning angle after each persistent spatial memory (PSM) large-scale move [degrees]	40
PSM_dist	Distance to target when initiating PSM moves [km]	N(350;100)
PSM_log	Parameter controlling logistic increase in turning angle during large-scale movement [unitless]	0.6
PSM_tol	Tolerance band within which the target cell group is selected (PSM_dist±PSM_tol) when initializing PSM behaviour [km]	5
R1	Mean and standard deviation in log10(d/100), where d is distance moved per time step [m]	N(1.25;0.15)
R2	Variation in turning angle between steps [degrees]	N(0;4)
rR	Reference memory decay rate [unitless]	0.03
rS	Satiation memory decay rate [unitless]	0.03
T	Response threshold (piling): received sound pressure level above which porpoises get deterred by piling noise [dB re 1 μPa]	152
rU	Food replenishment rate; the rate that food recovers after being eaten [unitless]	0.1
simYears	Simulation duration	50
tdeter	Residual deterrence time; number of time steps the deterrence effect lasts when the animal is no longer exposed to noise [time steps]	0

tdisp	Time before onset of large-scale movement [days]	3
tgest	Gestation time [days]	300
tmating	Mating day [day of year]	N(225;20)
tmature	Age of maturity [years]	3.44
tmaxage	Maximum age of porpoises [years]	30
tnurs	Nursing time [days]	240
Tships	Response threshold (ships): received sound pressure level above which porpoises are deterred by ships [dB re 1 μPa]	80
turbines	Piling schedule	Moray piling (2017-2024)
Umin	Minimum food level in a patch; the starting value for logistic replenishment of the food [relative unit]	0.001
wdisp	Minimum water depth while using large-scale movement [m]	4
wmin	Minimum water depth required by porpoises [m]	1

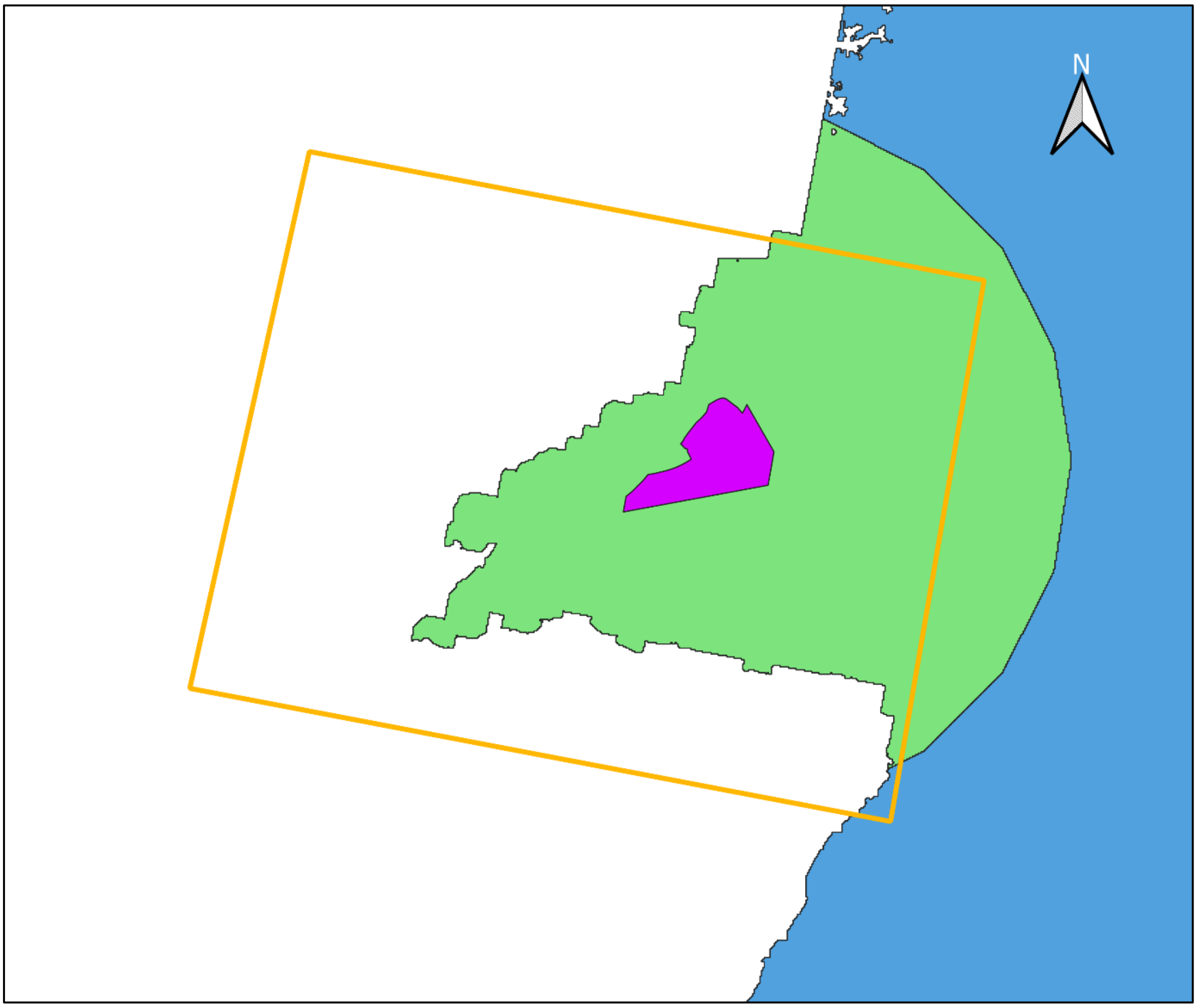

Figure S1. Scope of AIS data used for Moray Firth traffic (orange outline). Blue, North Sea monitoring block; green, Moray Firth monitoring block; purple, windfarm monitoring block.