CALIBRATION OF DEPONS 4.0

Scientific Report from DCE – Danish Centre for Environment and Energy   No. 705   2026

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Data sheet

Abstract: This report presents the calibration of the newest version of DEPONS (v4.0) with the aim of ensuring that simulated harbour porpoise movements resemble those observed from ARGOS satellite-tracked porpoises. DEPONS 4.0 includes a more detailed energetics sub-model than previous versions, representing individual energy intake and energetic costs throughout the life of each porpoise. Updates also include a revised food patch map in which food patches now cover 5% of the landscape instead of 1.6% as in earlier versions. This increase was implemented to allow assessment of fine-scale changes in food availability around offshore wind turbines. The calibration focused on parameters controlling energetics and survival ($IR2EA$ and $beta$), memory decay (r_R and r_S), large-scale movement behaviour (PSM_dist, PSM_angle and $ddisp$), and behavioural responses to pile-driving noise (T and c). A pattern-oriented modelling approach was used to test multiple parameter combinations and identify those that minimized discrepancies between simulated outputs and empirical observations.

Contents

Preface

Harbour porpoises are deterred by various kinds of underwater noise, including sounds emitted from vessels and from construction of offshore wind farms. These disturbances influence porpoise movements, food intake and, ultimately, their survival and population dynamics. This population response can be simulated using the DEPONS model, but to make the latest version produce realistic predictions, it is important to calibrate movements so that they closely resemble those of real animals.

By contract of 12 November 2025, Rijkswaterstaat Water, Transport and Environment, The Netherlands, requested the Danish Centre for Environment and Energy (DCE) to calibrate the most recent version of DEPONS (v. 4.0) to make it suitable for simulating population consequences of disturbances as realistically as possible. It was identified that this could be done by updating seven different model parameters.

Summary

In this report, we calibrated the newest version of DEPONS (v4.0) to ensure that simulated movements resemble those observed in real harbour porpoises. DEPONS 4.0 includes a detailed energetics sub-model representing individual energetic costs and energy intake throughout the porpoise life. Compared to previous versions, key updates include the introduction of a new parameter, *IR2EA*, which converts ingested food into energy (joules), and an updated food patch map in which patches now occupy 5% of the landscape, compared to 1.6% in earlier versions. This change in food patches proportion was made to make it possible to assess fine-scale changes in food availability in the vicinity of offshore wind turbines.

The following parameters were calibrated: *IR2EA* and *beta*, which control energy conversion and survival probability, respectively; r_R and r_S, which respectively determine reference and satiation memory decay; *PSM_dist*, *PSM_angle* and *ddisp*, which define the distance and directional characteristics of large-scale movements; and *T* and *c*, which respectively determine the threshold and strength of behavioural responses to pile-driving noise. We used pattern-oriented modelling to test simulations with different combinations of parameters, with the aim of minimizing the difference between field and simulated data.

Sammenfatning

I denne rapport kalibrerede vi den nyeste version af DEPONS (v4.0) for at sikre, at de simulerede bevægelsesmønstre svarer til dem, der observeres hos rigtige marsvin. DEPONS 4.0 omfatter en detaljeret energi-delmodel, som beskriver individuelle energiforbrug og indtag gennem hele marsvinets liv. Vigtige opdateringer sammenlignet med tidligere versioner omfatter introduktionen af en ny parameter, *IR2EA*, som konverterer indtaget føde til energi (joule), samt et opdateret fødepatch-kort, hvor patches nu udgør 5 % af landskabet mod 1.6 % i tidligere versioner. Denne ændring i andelen af fødepatches blev gennemført for at gøre det muligt at vurdere fin-skala ændringer i fødetilgængeligheden i nærheden af havvindmøller.

Følgende parametre blev kalibreret: *IR2EA* og *beta*, som henholdsvis styrer konvertering af enhed for energi og overlevelsessandsynlighed; r_R og r_S, som styrer hvor hurtigt reference- og mæthedshukommelse aftager; *PSM_dist*, *PSM_angle* og *ddisp*, som definerer afstands- og retning når dyrene bruger storskala bevægelser; samt *T* (dB SEL) og *c*, som henholdsvis bestemmer tærsklen for og styrken af adfærdsmæssige reaktioner på pæleramningsstøj. Vi anvendte 'pattern-oriented modelling' til at teste simulationer med forskellige parameterkombinationer med det formål at minimere forskellen mellem feltdata og simulerede data.

1   Introduction

Harbour porpoises (*Phocoena phocoena*) are small cetaceans found in coastal waters in the northern hemisphere. They use sound for communication and navigation, which makes them particularly sensitive to underwater noise (Tougaard et al., 2009). Human activities, such as vessel traffic and offshore wind farm construction, generate acoustic disturbances that can cause porpoises to abandon critical foraging grounds (Dähne et al., 2013, 2017; Frankish et al., 2023; Nabe-Nielsen et al., 2014). For wind farm construction, this can happen at distances up to more than 20 km (Tougaard et al., 2009), while vessel noise affects animals up to more than 2 km (Frankish et al., 2023). Such displacement may compromise the animals' energetic balance by reducing access to important foraging areas, potentially leading to calf abandonment and higher mortality rates (Nabe-Nielsen et al., 2014, 2018) with long-term implications for population conservation. Harbour porpoises are protected under European law, which obliges member states to ensure that populations are maintained or restored to a favourable conservation status (European Union, 1992). It is therefore necessary to assess whether noise from anthropogenic activities influences the population.

Agent-based models (ABMs) offer a robust approach for assessing the impact of anthropogenic disturbances on porpoise populations. ABMs can simulate individual animals (agents) and their interaction with the environment and with each other in realistic landscapes. This allows population dynamics to emerge from the simulated animals' ability to find food, survive and reproduce (Grimm & Railsback, 2005). This means that population dynamic outcomes in the simulation result from the same ecological processes that also determine their dynamics in nature (Nabe-Nielsen et al., 2013, 2014; Watkins & Rose, 2017). Because ABMs rely on fundamental biological and ecological processes rather than statistical correlations, they are likely to maintain their predictive power under changing environmental conditions (Stillman et al., 2015).

DEPONS is an open-source ABM that was developed to simulate how wind farm construction noise affects the North Sea harbour porpoise population (Nabe-Nielsen et al., 2018). The latest version, DEPONS v4.0, introduces a new level of physiological realism by incorporating more detailed energetics in simulated porpoises, allowing porpoises' population dynamics to reflect temporal variations in the animals' energetic requirements (Gallagher et al., 2021). Since porpoise movement is closely tied to energetic status, the previous movement calibration used in DEPONS v3.2 was not expected to remain valid in the new version. The aim of this project was, therefore, to re-calibrate important movement parameters using satellite-tracked animals to ensure that the model produces realistic movement patterns. Five movement-related parameters were calibrated: the reference memory decay rate (r_R), the satiation memory decay rate (r_S), distance to the target cell group (*PSM_dist*), the maximum turning angle after each persistent spatial memory (*PSM_angle*) and the dispersal distance per 30 minutes during large-scale movements (*ddisp*) (see text below for details). In addition, two nonmovement parameters, the survival probability constant (*beta*) and the ingested food to energy conversion factor (*IR2EA*), were calibrated to ensure that energy intake and starvation processes generate realistic population dynamics.

2   Model description

DEPONS is a process-based ABM that simulates the movements of individual animals and their change in behaviour and energetics when they are exposed to noise. DEPONS was initially parametrized to simulate how porpoise population dynamics are impacted by pile driving noise (Nabe-Nielsen et al., 2018) and has later been updated to simulate impacts of vessel noise (DEPONS v3.2; Frankish et al. in prep.). In DEPONS v4.0, the energetics sub-model was substantially improved to more accurately reflect the real-world energy budget of porpoises (Gallagher et al., 2021). Furthermore, food patches now occupy 5% of the water (Fig. 2.1; 1.6% in previous versions). Increasing the number of food patches involves redistribution of the same amount of food across a larger number of foraging locations. This modelling choice was made to avoid unrealistically long distances between places where animals can find food and to make it possible to simulate increases in food availability in the immediate vicinity of offshore wind turbines (Bicknell et al., 2025; Gimpel et al., 2023; Reubens et al., 2013).

These updates were expected to influence both fine-scale and large-scale movement behaviours in simulated porpoises. Fine-scale movements refer to periods lasting days or weeks, during which animals remain in confined areas and follow slow, tortuous paths indicative of foraging. In the model, these behaviours are driven by reference memory, which causes porpoises to revisit areas where they have previously found food. This spatial memory decays over time and is regulated by the parameter r_R (reference memory decay rate). Additionally, r_S (satiation memory decay rate) allows animals to remember how much food they consumed in the recent past and determines how profitable it is to move using a correlated random walk. Large-scale movements are characterized by relatively fast and more directed travel between foraging grounds. In DEPONS, this behaviour is controlled by the persistent spatial memory (PSM)-related parameters *PSM_dist* and *PSM_angle* in the North Sea and user-defined landscapes. In the Kattegat, a specific type of large-scale movements enables porpoises to navigate through narrow straits. Common to the North Sea and Kattegat, the distance covered during these movements is represented by the parameter *ddisp*, defined as the average distance travelled during 30-minute intervals. More details on those parameters and the model can be found in the TRACE document for DEPONS v3.2 (https://github.com/jacobnabe/DEPONS/blob/master/DE-PONS%203.2%20TRACE-2026-02-05.pdf).
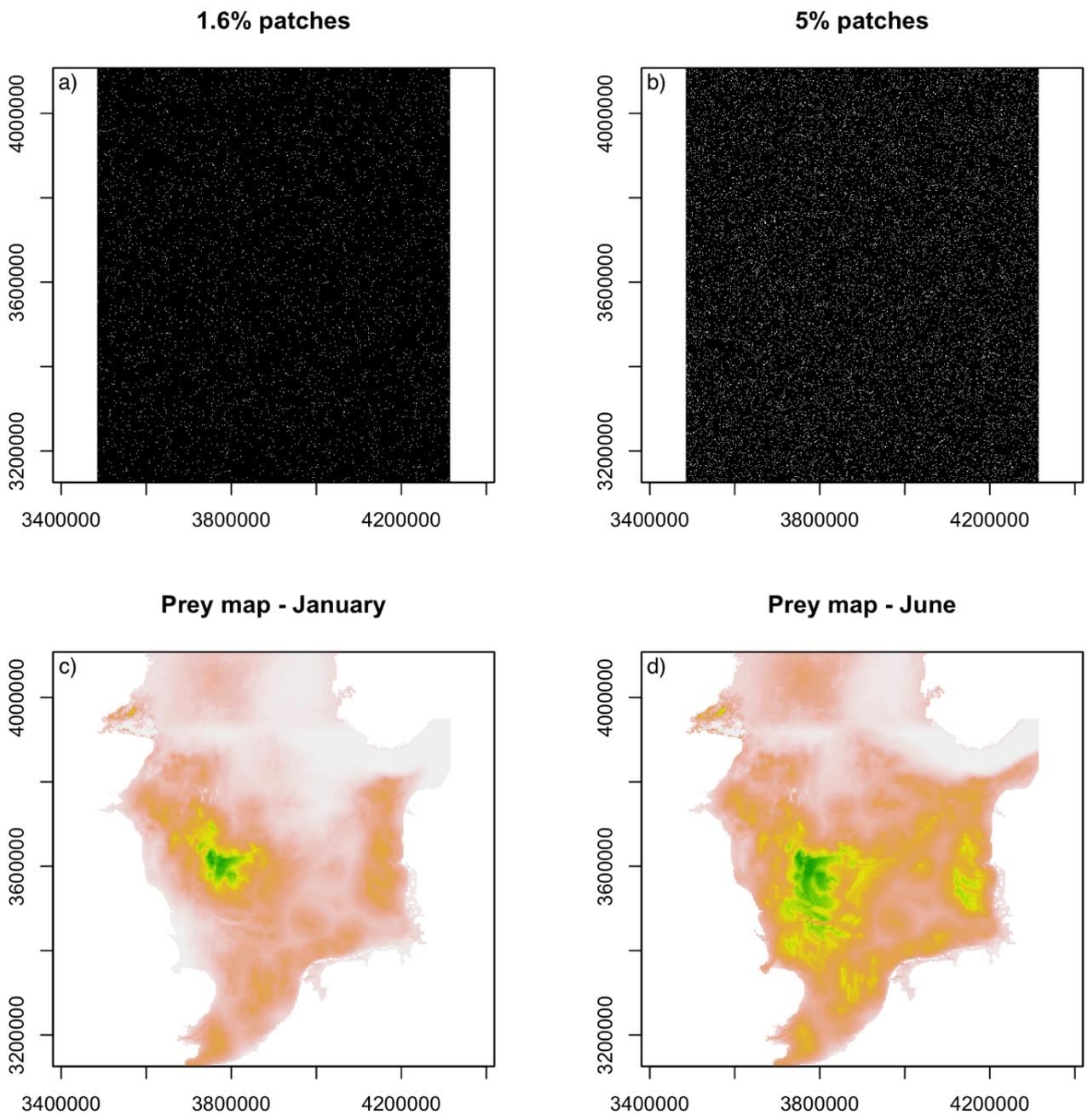
Figure 2.1. Prey availability for simulated porpoises in DEPONS (a); Distribution of prey patches in DEPONS 3.2 (1.6% of total area) and (b) in DEPONS 4.0 (5%). White shows presence of food, black indicates absence of food patches. (c) Prey map showing amount of food in the prey patches in January before food is exploited by porpoises and (d) equivalent map for June. Monthly prey maps (January to December) are derived from seasonal maps of porpoise densities in the North Sea (Geelhoed et al., 2022; Gilles et al., 2016). Green shows areas with high porpoise densities, grey shows low densities and white indicates land or missing data.

3   Calibration process

As the patches map was updated and more food patches are now available to porpoises, animals will now encounter and consume food more often, requiring *IR2EA* to be adjusted to allow the population to stabilise at a carrying capacity of approx. 15,000 agents, as a larger number of agents would cause the model to run inconveniently slowly. This stabilised carrying capacity reflects the equilibrium population dynamics observed for harbour porpoises in the North Sea (Gilles et al., 2023). After an initial adjustment of *IR2EA* to approximate the desired carrying capacity, the calibration proceeded in the same order as for earlier versions of the model: fine-scale movements (r_R and r_S), response to piling parameters (*c* and *T*), large-scale movements (*ddisp*, *PSM_dist* and *PSM_angle*) and *IR2EA* and *beta* for a final stabilisation of the population at carrying capacity. Along the calibration process, we used a pattern-oriented modelling approach (Grimm et al., 2005), in which empirical patterns (here, movement metrics, response to piling and equilibrium population dynamics) are used to calibrate and validate agent-based models. Parameters were calibrated based on data for satellite-tracked animals (r_R, r_S, *PSM_dist*, *PSM_angle* and *ddisp*) from passive acoustic monitoring around the Gemini wind farm (for *c* and *T*) and with the aim of having a stabilised population (*IR2EA* and *beta*). All computations were carried out in R (R Core Team, 2025).

3.1   Data for wild harbour porpoises

Movement data were obtained using ARGOS satellite telemetry for porpoises tagged in the North Sea and Kattegat (Sveegaard et al., 2011; Teilmann et al., 2007). Due to irregular time intervals between recorded positions, a Bayesian state-space switching model (SSM) was fitted to (1) interpolate and standardize the data with one position a day (finer temporal resolution was considered but not retained due to occasional long gaps in ARGOS transmissions) and (2) detect switches in movement behaviours, using an approach similar to Stalder et al (2020) and identical to previous versions of DEPONS. The model classifies movement segments into either transient (i.e. large-scale movement) or area-restricted search (i.e. fine-scale movement) states (Jonsen et al., 2005). We analysed the data using the package bsam (Jonsen, 2016), where movement modes (chains) are fitted and estimated for all individuals based on variation in speed and turning angles. We allowed a burn-in of 60,000 iterations per chain and generated 40,000 posterior iterations. To reduce autocorrelation, every 20th iteration was retained, resulting in 2,000 posterior samples per chain. The resulting behavioural classifications enabled us to extract specific track segments for calculating movement metrics used to calibrate model parameters related to fine- and large-scale movement behaviour. The interpolation was not constrained by land and could generate occasional over-land segments (Fig. 3.5) and potentially bias fine-scale movement metrics in coastal/strait areas (i.e. mainly in the Kattegat landscape). Movement tracks were used for calibration of fine-scale movements when animals had been classified as using this behaviour for 30 consecutive days. Large-scale movement tracks included 100 days independently of movement behaviour. Movement metrics were calculated using the function *calib_02* from the DEPONS2R package (Nabe-Nielsen et al., 2025). For fine-scale calibration, metrics included home range size (km²), mean net squared displacement (km²) and residence time (days). For the large-scale calibration, the metrics included home range size (km²), max net squared displacement (km²), sinuosity index and cumulated distance moved (km).

The kernel home range size was calculated using the *href* smoothing method as implemented in the adehabitatHR package. In the North Sea, the default *href* bandwidth (determined by the spatial variance of the data) was used. In the Inner Danish Waters, the bandwidth was limited to 15 km to prevent excessive smoothing across narrow straits. Net squared displacement (NSD) was calculated for each track as the squared distance between each location and the starting location. For fine-scale tracks, the mean NSD (km²) within the track was used, whereas for large-scale tracks, the maximum NSD (km²) within the track was retained. Residence time (days) was calculated by taking the mean time spent in a circle with a radius of 5 km across all locations of that track (Barraquand & Benhamou, 2008; Nabe-Nielsen et al., 2013). Sinuosity was calculated from step lengths and turning angles using the formulation of Benhamou (2004). The cumulative distance moved was calculated as the sum of step lengths between successive locations along each movement track.

3.2 Initial stabilisation of the population (*IR2EA*)

IR2EA, the ingested food to energy conversion factor, needed to be adjusted following the increase in food patch density in both the North Sea and Kattegat landscapes. The value of 113,750,000 calibrated in Gallagher et al. (2021) under a 1.6% food-patch configuration resulted in a sustained increase in population size without stabilising when applied to the updated 5% patch map. This initial calibration step was therefore primarily intended to bring the population to a stable state, so that porpoise movements could be calibrated for a population that had reached carrying capacity, which happened after individuals had explored the landscape and developed spatial memory of profitable patches. The calibration consisted of 5 replicates of 25 simulation years, initialised at 10,000 (North Sea) and 200 (Kattegat) individuals and using movement parameters from DEPONS v3.2. *IR2EA* values ranged from 88,750,000 to 94,000,000. The *IR2EA* value that produced a stabilised population was 90,000,000 in the North Sea and 91,420,000 in the Kattegat.
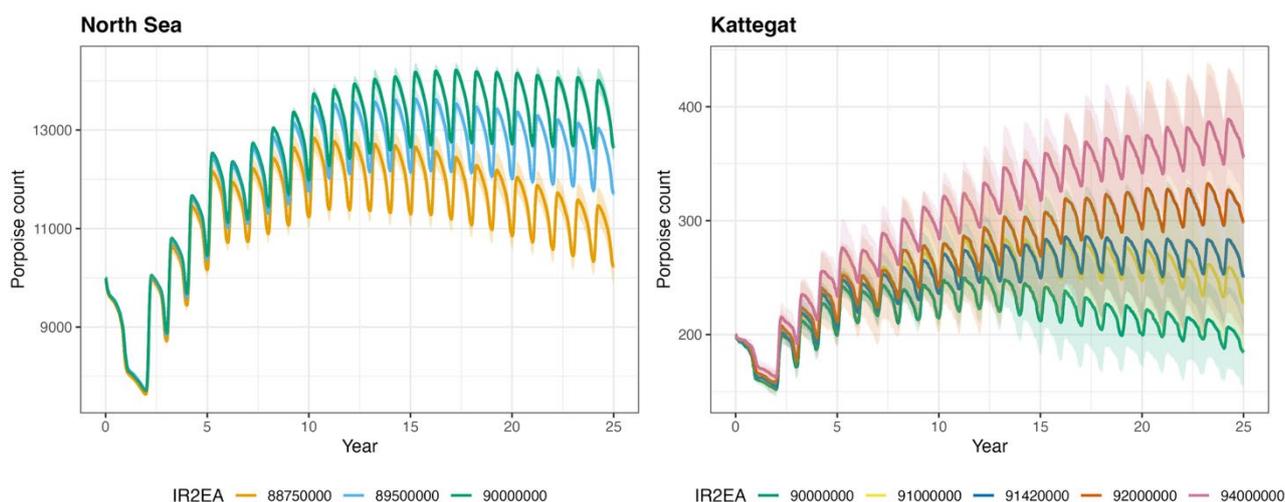

Figure 3.1. Population dynamics over 25 years given various *IR2EA* values in the North Sea (left) and the Kattegat (right).

3.3 Fine-scale movements calibration (r_R and r_S)

Next, parameters controlling spatial memory (r_R and r_S) were recalibrated. Simulations were run in the North Sea and in the Kattegat, with a population starting at 10,000 and 200, respectively, using the previously determined *IR2EA* values. As the population appeared to stabilise roughly after year 15

(Fig. 3.1), porpoises were tracked from that time onward. Simulated animals were tracked from starting points located near the places where the real animals were tagged. A range of r_R and r_S combinations were tested, with the constraint that r_S was equal to or higher than r_R (Nabe-Nielsen et al. 2013). Since r_S controls how fast animals forget profitable food patches, and r_R controls how fast animals get hungry again, r_R cannot be higher than r_S, i.e. animals cannot forget profitable food patches faster than they become hungry again.

The movement metrics resulting from each combination of r_S and r_R were compared to the metrics from the observed data to ensure that simulated animals developed movement tracks that resembled those of ARGOS satellite-tracked porpoises (24 in the North Sea and 17 in the Kattegat). The patterns that were compared were (1) home range size (km2), (2) mean net squared displacement (km2; mean within each track) and (3) residence time (days) (Figs. 3 and 5). For each pattern, the median metric value of the simulated individuals was compared to the median metric value of the observed individuals. Movement data for the tagged and simulated porpoises consisted of one location per day for 30 days (Figs. 4 and 6), and the parts of the track that were characterized as large-scale movements were removed prior to the analyses. Movement metrics were calculated using the function *calib_02* from the DEPONS2R package, identical to the way ARGOS satellite data were analysed.

Outputs were evaluated using global ranking (Chion et al. 2011), which quantifies deviations between model outputs and empirical patterns. The parameter combination that produced the closest match (i.e. the lowest ranking value) was chosen. For both the North Sea and the Kattegat, those were r_R = 0.1 and r_S = 0.2. With these new values, food replenishment (r_U) happens at the same rate as r_R, meaning that food has time to partly replenish in exploited patches before animals forget their location.
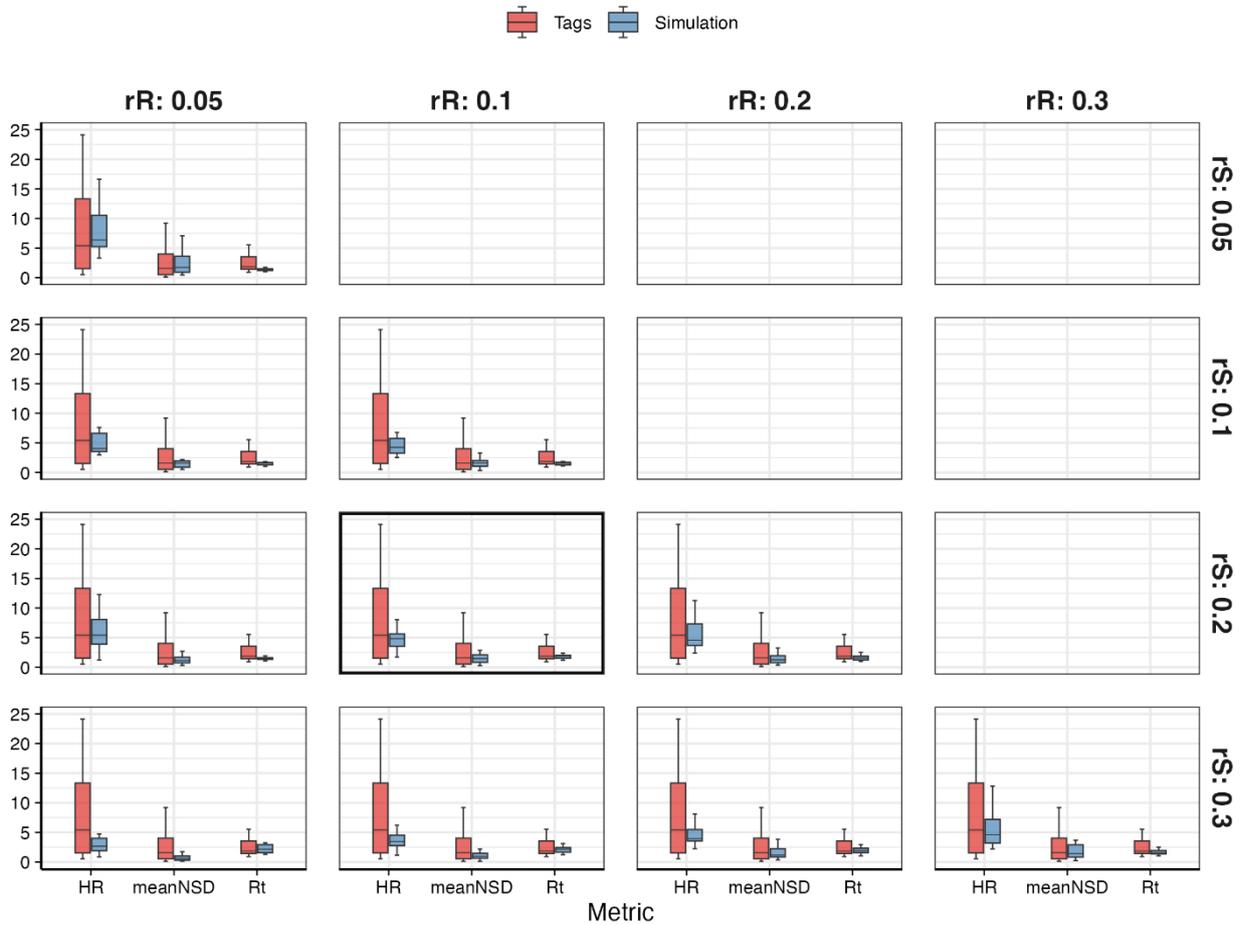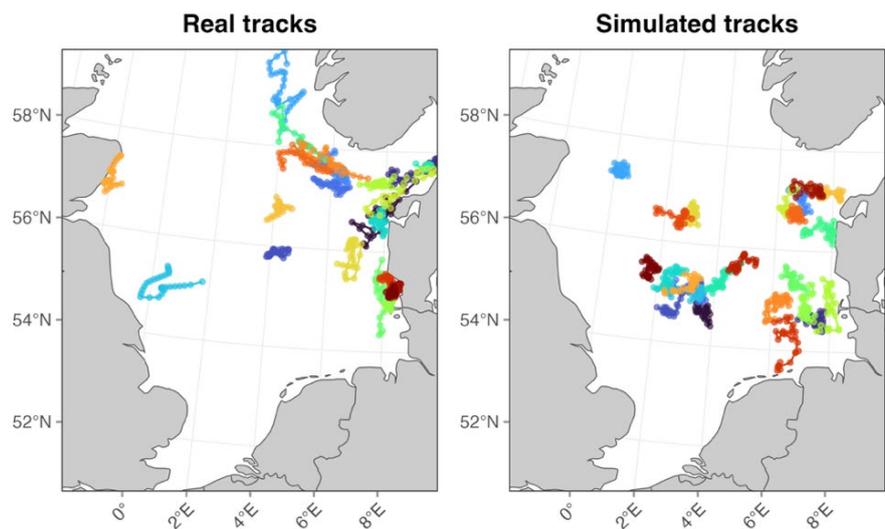
Figure 3.2. Parameterization of spatial memory components of fine-scale movements (parameters r_R and r_S) in the North Sea landscape. The y-axis shows home range size (HR; km^2 / 1000), net squared displacement (NSD; km^2 / 1000) and residence time (Rt; days) for real and simulated animals (N = 24 for each group). The bold rectangle shows the combination of r_R and r_S values that produced patterns that most resembled those based on real animals. Only a subset of all tested combinations of r_R and r_S is shown.

Figure 3.3. Fine-scale movement tracks of free-ranging porpoises equipped with ARGOS satellite tags (left) and simulated animals (right) in the North Sea (N = 24). Tracks were interpolated using a state-space model and each consist of 30 positions (one per day).
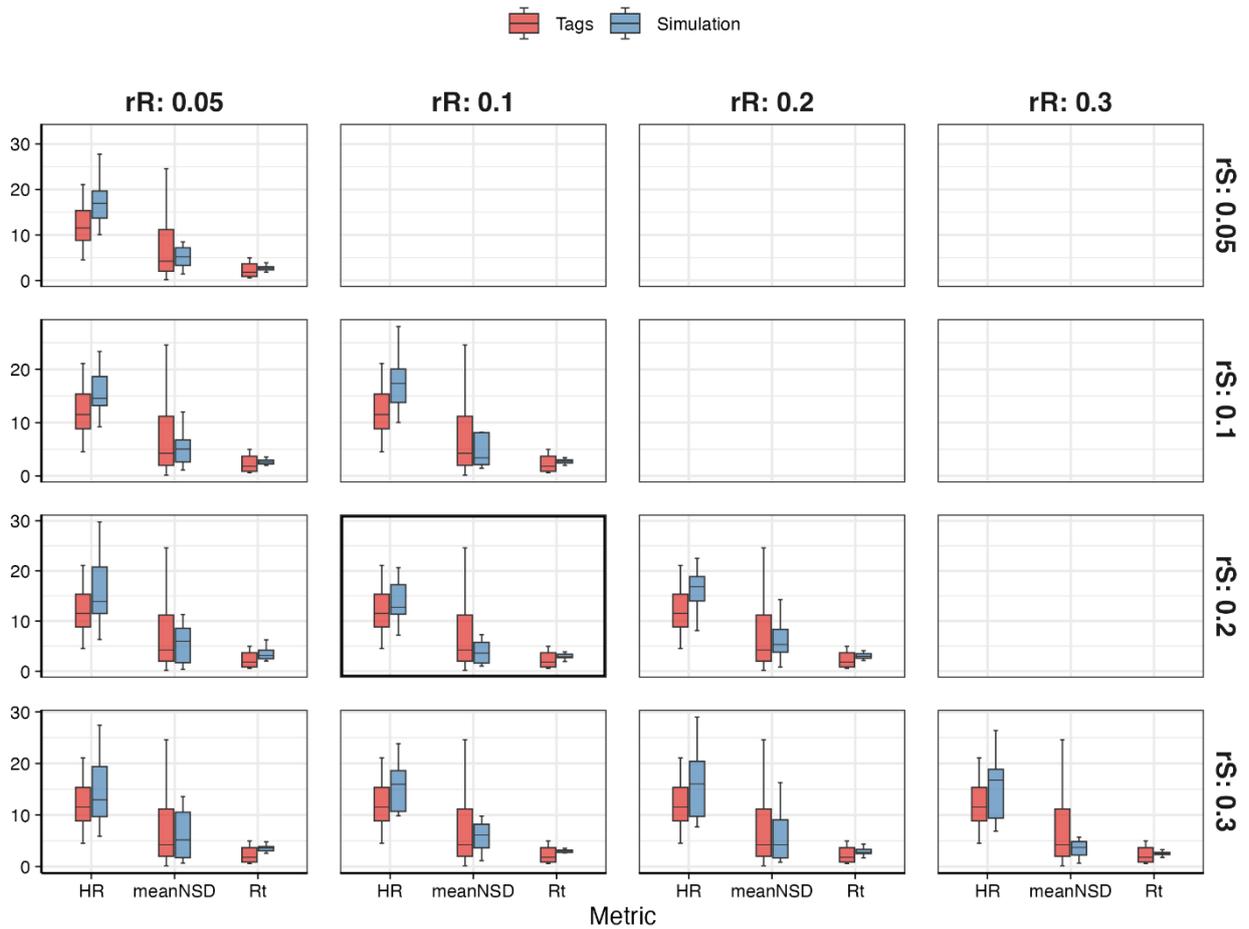
Figure 3.4. Parametrization of the spatial memory component of fine-scale movements (parameters r_R and r_S) in the Kattegat. The y-axis shows home range size (HR; km^2 /1000), mean net squared displacement (NSD; km^2 /1000) and residence time (days) for real ('Tags') and simulated ('Simulation') animals (N = 17 for each group). The bold rectangle shows the combination of r_R and r_S values that produced patterns (mean and standard deviation) that most resembled those based on real animals. Only a subset of all tested combinations of r_R and r_S is shown.

Figure 3.5. Fine-scale movement tracks of free-ranging porpoises equipped with ARGOS satellite tags (left) and simulated animals (right) in the Kattegat (N = 17). Tracks were interpolated using a state-space model and include 30 positions (one per day).
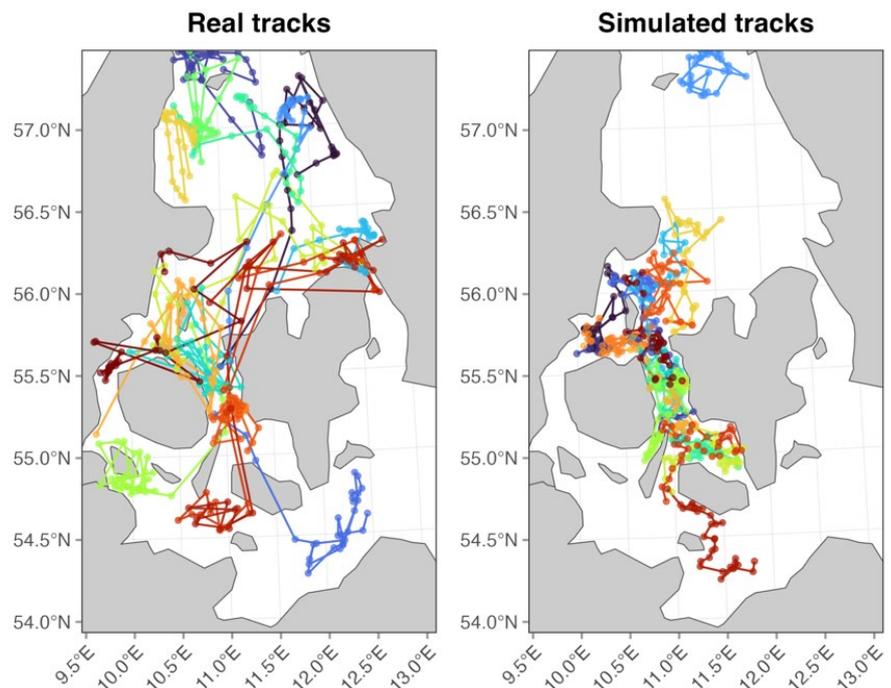
3.4 Response to piling (c and T)

Piling events are expected to reduce local porpoise densities during construction, followed by a gradual increase in densities over time after piling stops. Porpoise movement parameters were calibrated to make the recovery of simulated porpoise densities after piling events resemble those observed during construction of the Gemini wind farm. No sound mitigation measures were used during construction of the Gemini wind farm. The scenario included 160 pilings at the same location, using the same sound source levels and following the same piling order as the real construction event. Sound source levels were 234 dB re 1 µPa²s for 152 pilings and 228 dB re 1 µPa²s for 8 pilings. These simulations did not include ships.

Parameters controlling the response to noise are c (unitless), the deterrence coefficient and T (dB SEL), the response threshold. Here, T is the received sound level above which porpoises start getting deterred by piling noise, and c determines the strength of that response. Assuming sound-transmission loss parameters $\hat{\beta}$ = 14.72 and $\hat{\alpha}$ = 0.00027 (Bellmann et al., 2020), T and c were adjusted so that the simulated recovery pattern matched that observed during Gemini construction. In the field, porpoise densities were measured using Cetacean & Porpoise Detectors (C-PODs) that recorded the clicks emitted by echo-locating porpoises. Simulations were based on a landscape that included virtual C-PODs (each covering 2 × 2 cells, equivalent to 800 × 800 m) placed in the exact same positions as those used in the field. The simulations used pile-driving events that occurred on the same schedule and produced the same sound source levels as the real ones.

We simulated the wind farm construction in the purpose-built small-scale Gemini landscape (160 km × 160 km) with an initial population of 155 individuals over 2 years, then discarded the 1.5 years before wind farm construction started, allowing animals to build up a spatial memory of profitable patches. Due to the limited size of the landscape, large-scale movements were turned off. A blocks map representing C-PODs at the original locations was used to record the number of porpoises in the vicinity of the Gemini wind farm construction site. We ran simulations using a range of parameter combinations (c in the range 0.03–0.11 and T in the range 165–173 in increments of 1). The simulated porpoise densities were standardized to obtain the same overall mean and variance as observed in the field. The aim was to find the values of c and T that minimized the sum of squared differences (SSD) between field and simulated data at different distances from the nearest pile-driving event. The optimal values of c and T were therefore the ones that yielded the smallest SSD across all distances. The smallest value of SSD was obtained for T = 170 dB re 1 µPa²s and c = 0.07 (Fig. 3.6).
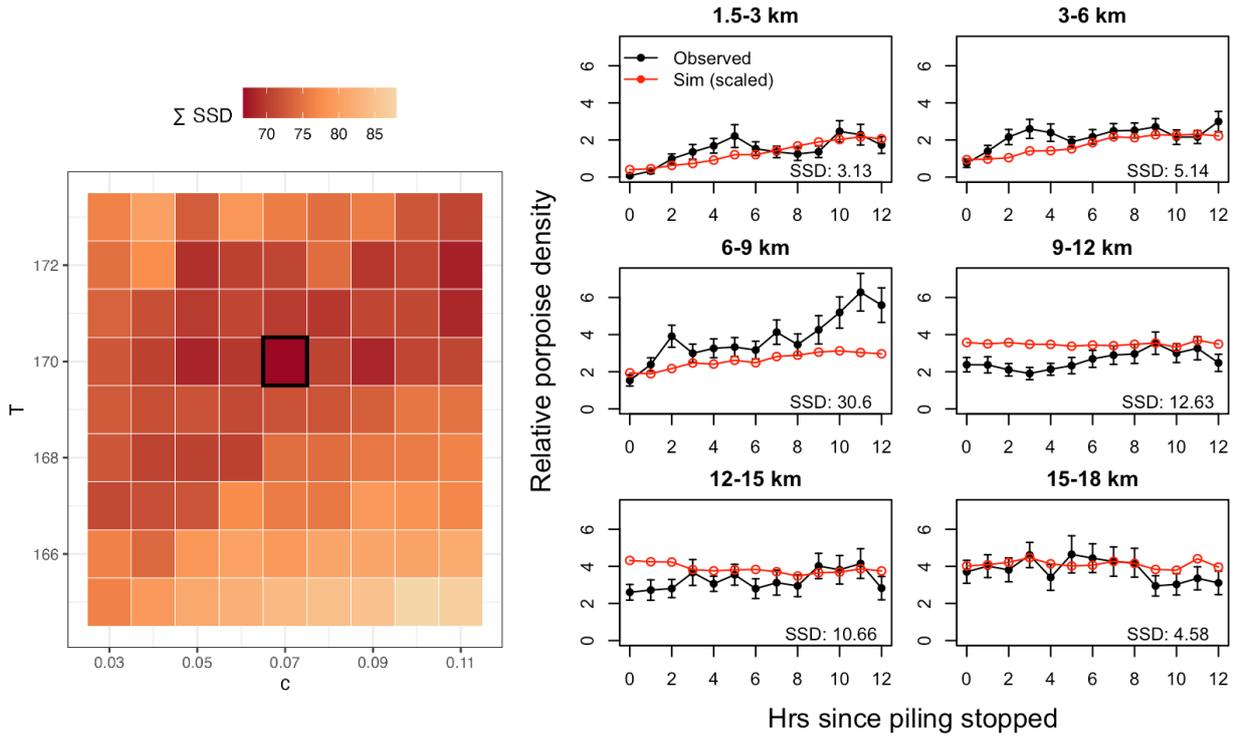
Figure 3.6. Parametrization of response to piling parameters *c* and *T*. SSD is the sum of squared differences of porpoise counts in simulated and real data. The best combination was *T* = 170 and *c* = 0.07.

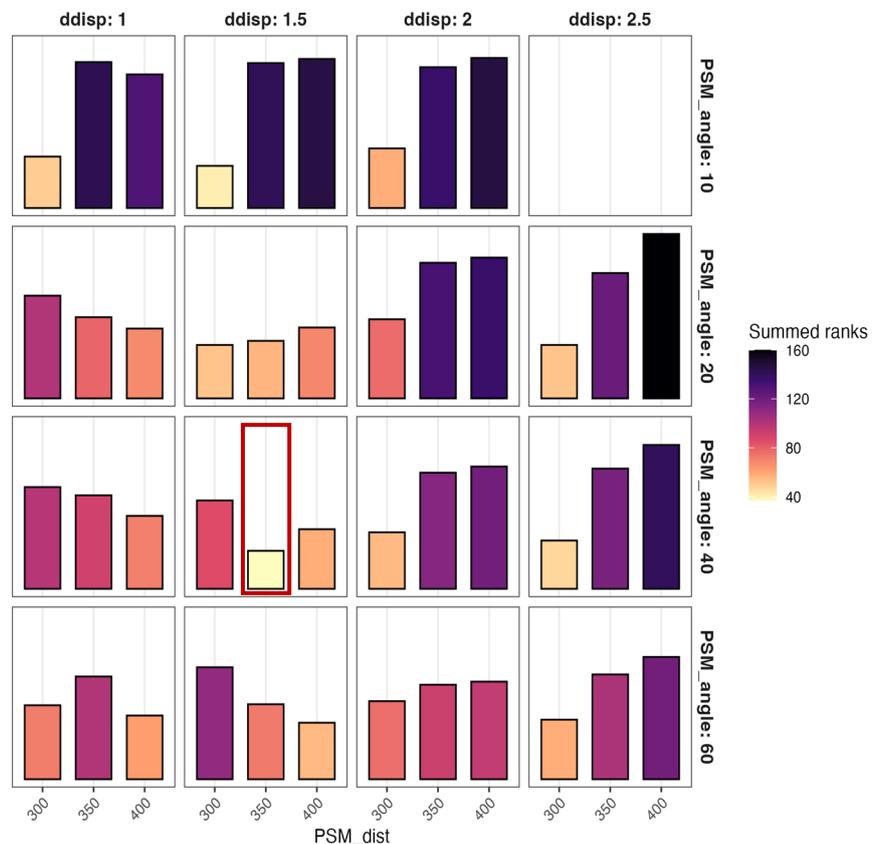## 3.5 Large-scale movements (*PSM_dist*, *PSM_angle* and *ddisp*)

In both the North Sea and the Kattegat, large-scale movements consist of steps of length *ddisp*. In the North Sea, these movements are based on a persistent spatial memory (PSM) behavior that enables animals to move back towards the most profitable (i.e. highest energy intake) 2 × 2 km cell group at their preferred distance (*PSM_dist*), with turning angles increasing up to a maximum set by *PSM_angle*. In the Kattegat, large-scale movements are instead based on a specific behaviour (*InnerDanishWaters*) designed to allow them to navigate through the narrow straits in this area. PSM-related parameters were thus calibrated in the North Sea only, along with *ddisp*. The value for parameter *ddisp* from the North Sea calibration was used in the Kattegat landscape, as too few ARGOS-tracked animals (N = 7) were available in the Kattegat for a continuous 100-day period to calibrate *ddisp* robustly. We furthermore assume that *ddisp* is primarily a physiological parameter and that it therefore should not vary across landscapes.

For calibrating *PSM_angle*, *PSM_dist* and *ddisp*, ARGOS satellite tracks from the North Sea (19 harbour porpoises) were filtered to have one position per day for 100 days regardless of their movement modes (as opposed to using only parts of the tracks that were identified as fine-scale movements in the fine-scale calibration). Four metrics were calculated from ARGOS tracks: (1) home range size (km²), (2) maximum net squared displacement (NSD; km²), (3) sinuosity (Benhamou et al, 2004) over a 100-day period and (4) cumulated distance (km). For each movement metric, the median across ARGOS-tracked individuals was compared to the median across simulated porpoises initiated from the same locations as the ARGOS-tracked animals (Fig. 9). Standardization of simulated movement tracks to one position per day was done to match the ARGOS data resolution.

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Simulations were run in the North Sea landscape. The population was initialized at 10,000 individuals and was simulated over a 16-year period, with the first 15 years used as a burn-in period. All porpoises were tracked from year 15, starting as close as possible to the locations where animals were tagged. Because the population had already spent 15 years exploring the landscape and aggregating in areas of higher food availability, some tagging locations could not be matched exactly, as no simulated individuals were present there at the start of the tracking period. We used the updated values of r_R and r_S following the fine-scale calibration, along with the value of *IR2EA* from the initial calibration. We tested values for *ddisp* ranging from 1 km to 2.5 km in 0.5 km increments, for *PSM_dist* ranging from 300 km to 400 km in 50-km increments, and for *PSM_angle* of 10º, 20º, 40º or 60º.

Outputs were evaluated using global ranking (Chion et al. 2011). The parameter combination producing the best (lowest) ranking was PSM_dist = N(350;100) [i.e. normally distributed with a mean of 350 km and a standard deviation of 100 km], *PSM_angle* = 40º and *ddisp* = 1.5 km (Figs. 8, 9 and 10).

Figure 3.7. Parameterization of *PSM_dist*, *PSM_angle* and *ddisp* (part of PSM-Type2 long-distance movement behaviour). The figure is based on tracks simulated with the standard deviation of *PSM_dist* set to 100. The best correspondence (highlighted by the red rectangle) between tracks of simulated and recorded animals was obtained for *ddisp* = 1.5 km, *PSM_dist* = 350 km and *PSM_angle* = 40° (lowest summed ranks).

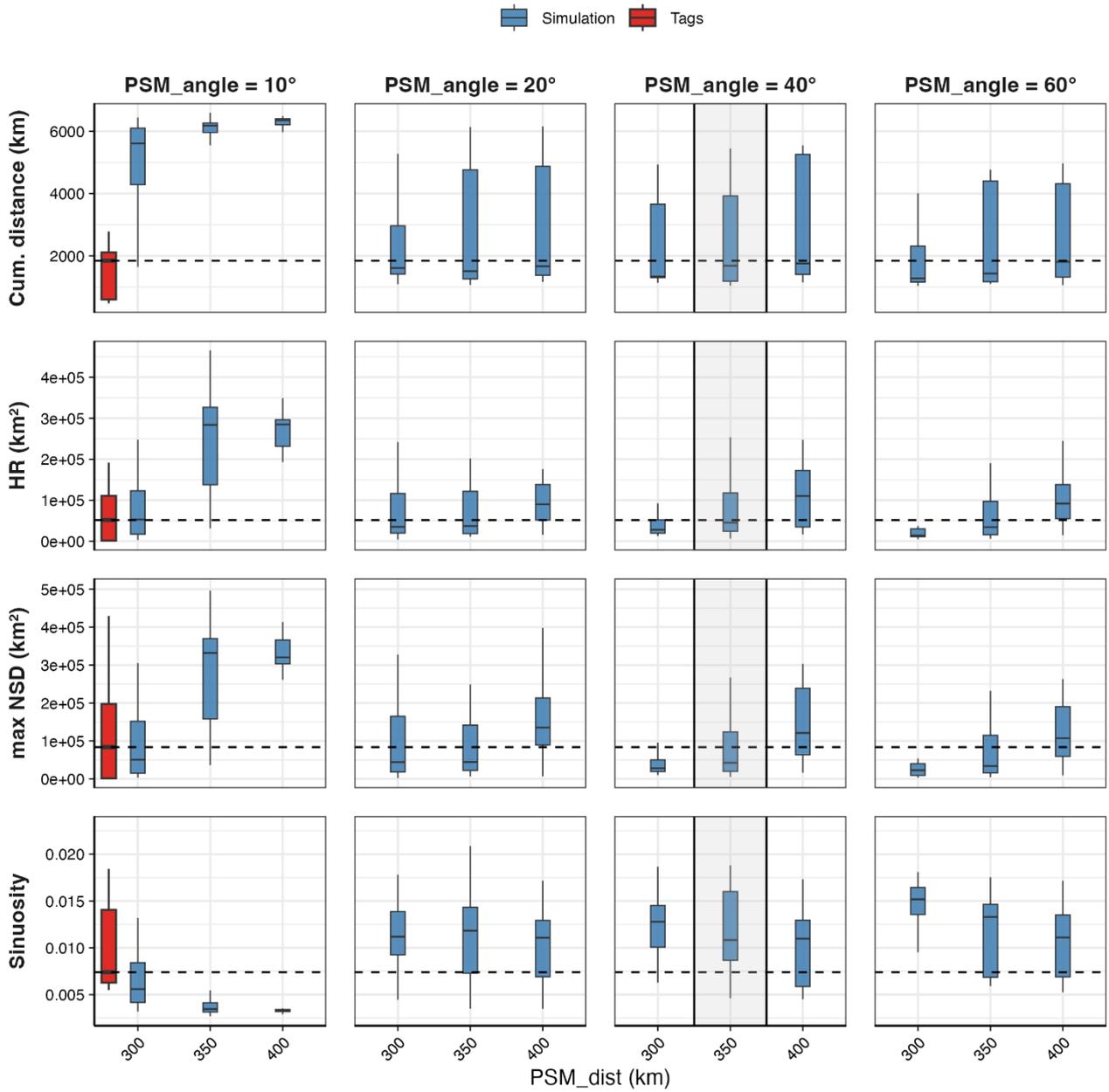**Figure 3.8.** Large-scale movement metrics fit across values of *PSM_dist* (x-axis) and *PSM_angle* (columns), for *ddisp* = 1.5 km, comparing simulated and ARGOS-tracked animals in the North Sea landscape (N = 18 in each group). The ARGOS data (i.e. from tagged animals) is shown as red boxplots in the leftmost column, and the ARGOS median is shown as a dashed line across all panels. The best combination is highlighted in grey.

Figure 3.9. Tracks of free-ranging porpoises equipped with AR-GOS satellite tags and simulated animals tracked resulting in the best combination of large-scale parameters in the North Sea (N = 18 of each). Tracks were interpolated using a state-space model and include both large-scale and fine-scale movements over 100 positions (one per day).

Real tracks   **Simulated tracks**
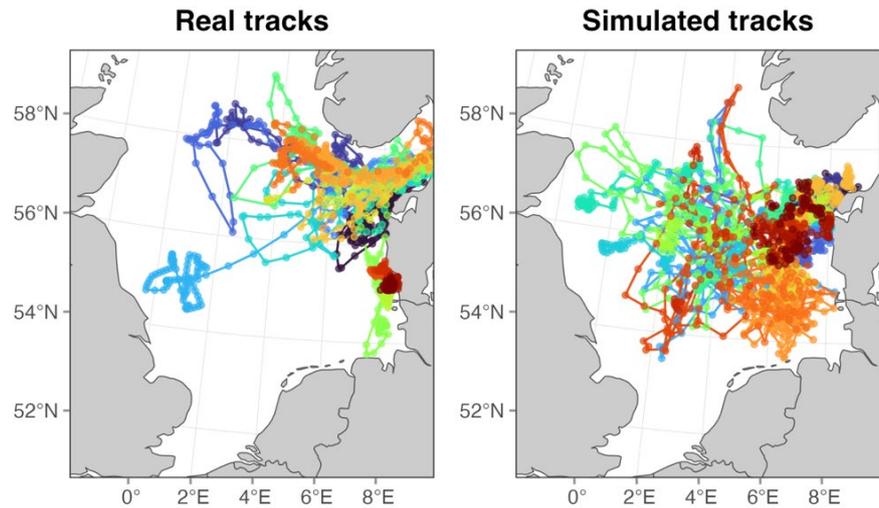
3.6   Final stabilisation of the population (*IR2EA* and *beta*)

The final step of the calibration process was to ensure that the population stabilises at the carrying capacity as early as possible and at a population size that is reasonable from a computation point of view. Because parameters controlling population levels may be affected by changes in parameters controlling movement, initial results of the calibration may not be valid at this final stage. Different combinations of *IR2EA* (ingested food to energy conversion factor; unitless) and *beta* (survival probability constant; unitless) were evaluated in simulations run over 50 years. The parameter *beta* determines the relationship between storage level and probability of surviving, so animals with lower storage levels have a higher probability of dying. The objective was to identify values leading to long-term population stability. We tested *beta* values of 11.5, 13.5 and 15.5, *IR2EA* was adjusted iteratively across successive simulations rather than in fixed increments, and we ultimately test values within the range 89,000,000-93,000,000. In the North Sea landscape, it was found that *beta* had minimal effects on population levels and it was therefore retained at the original value of 13.5. The *IR2EA* value that resulted in a stabilisation of the population carrying capacity was 92,000,000, corresponding to a population size stabilising at on average 16,036 ± 502 individuals from year 25. In the Kattegat landscape, the combination of *beta* = 15.5 and *IR2EA* = 93,000,000 resulted in the stabilisation of the population, with an average population size of 321 ± 12 individuals from year 20 (Fig. 3.10). Stabilisation occurring from year 25 in the North Sea and 20 in the Kattegat produced the most consistent long-term equilibrium, as earlier apparent stabilisation using lower *IR2EA* values tended to be followed by a subsequent population decline (Fig. 3.10). The change in values from the initial *IR2EA* calibration was considered too small to impact movements. Furthermore, movement calibration was performed on a stabilised population at carrying capacity and, thus, remains valid following this final adjustment.
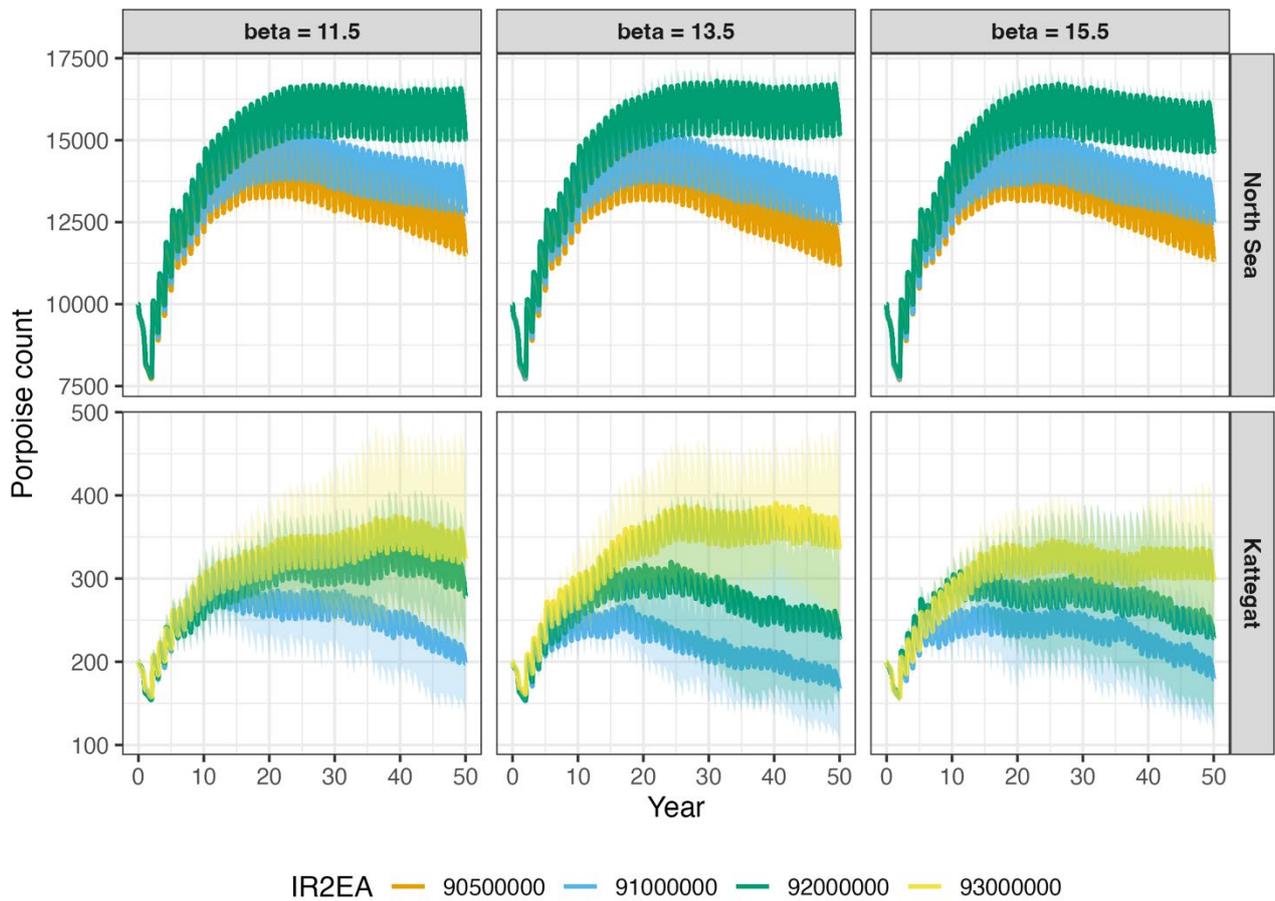
Figure 3.10. Final calibration of the *IR2EA* and *beta* in the North Sea and the Kattegat (each parameter combination has 5 replicates). The selected parameter values were the ones leading to the long-term stabilization of the population. Only a subset of the tested parameter combinations is shown.

4 Discussion

DEPONS v4.0 required recalibration because the dynamics of simulated porpoises were affected by two important alterations to the model: a more detailed and realistic energetics sub-model, and a revised spatial representation of prey, in which food was redistributed across a larger proportion of the landscape. Increasing the proportion of food patches improves the model's ability to represent fine-scale changes in prey availability, which is important for accurately testing wind-farm impact scenarios. The calibrated parameters (Table 1) produced movement patterns consistent with empirical observations, although the simulations did not fully reproduce the observed variability in fine- and large-scale movements. This mismatch may highlight limitations in the behavioural processes currently represented in the model. For example, we could not reproduce movements of porpoises along the Norwegian Trench, which may be influenced by large-scale oceanographic features (e.g. currents and water-mass structure) that are not explicitly included in DEPONS.

Fine-scale movement parameters were robust across landscapes, suggesting that the underlying spatial memory processes operate similarly in both the North Sea and the Kattegat. The increase in r_R and r_S relative to the previous DEPONS version (v3.2) likely reflects the updated food patch configuration. With a higher density of food patches, faster memory decay rates are required to reproduce observed movement metrics.

Large-scale movement parameters, namely the distance to target cell group (*PSM_dist*) and maximum turning angle during persistent spatial memory (*PSM_angle),* remained unchanged from the previous version. However, the parameter controlling the average distance moved per time-step (*ddisp*) decreased from 2 to 1.5 km. For a 30-minute time-step, the distance moved corresponds to an average swimming speed of approximately 0.83 m s^{-1}. This value is considered realistic and rather on the conservative side based on the reported average speed of 5.3 km h^{-1} (corresponding to 1.47 m s^{-1}) in the area (Sveegaard et al., 2011).

The response-to-piling parameter *T* increased relative to earlier DEPONS versions prior to v3.2 because the sound propagation parameterisation was updated in v3.2 ($\hat{\beta}$ = 14.72; $\hat{\alpha}$ = 0.00027) compared to the earlier settings ($\hat{\beta}$ = 20; $\hat{\alpha}$ = 0). Under the updated propagation model, received levels attenuate less rapidly with distance, which would otherwise trigger avoidance responses at unrealistically large ranges. *T* was therefore increased to maintain a realistic deterrence range. With the calibrated response threshold (170 dB re 1 µPa^{2}s), simulated animals are deterred up to 13.45 km from piling. This closely matches the observed avoidance response of up to 12 km during the Gemini construction (Fig. 3.6), while being smaller than other reported deterrence distances (Tougaard et al., 2009).

Finally, the calibration of *IR2EA* after movement parameters were calibrated allowed the population to reach a stabilised carrying capacity after 25 years in the North Sea at ~16,000 individuals. In the Kattegat, the population reached a stable carrying capacity of ~320 individuals after 20 years. The increased carrying capacity from 10,000 (v3.2 in the North Sea landscape) to ~16,000 and from 200 (v3.2 in the Kattegat landscape) to ~320 individuals (~50% increase) is most likely attributable to the higher proportion of food

patches in the landscape, resulting in more frequent food encounters and consumption. This new setup (i.e. higher proportion of food patches) allows to better capture the local effects of small-scale changes in food availability near individual wind farms. Combined with the more detailed energetics submodel, DEPONS v4.0 allows for a more realistic simulation of population-level responses.

Table 4.1. Summary of results from the DEPONS 4.0 calibration. The names shown are those used in the model GUI and batch files. Normally distributed ranges are indicated as "N(<mean>; <standard deviation>)".

Parameter	Description	DEPONS 3.2 value	DEPONS 4.0 value
IR2EA	Ingested food to energy conversion factor [unitless]	NA	92,000,000 (93,000,000 in the Kattegat)
beta	Survival probability constant [unitless]	0.4 (0.7 in the Kattegat)	13.5 (15.5 in the Kattegat)
r_R	Reference memory decay rate [unitless]	0.03 (0.04 in the Kattegat)	0.1
r_S	Satiation memory decay rate [unitless]	0.03 (0.05 in the Kattegat)	0.2
PSM_dist	Distance to target when initiating PSM moves [km]	N(350;100)	N(350;100)
PSM_angle	Maximum absolute turning angle after each persistent spatial memory (PSM) large-scale move [degrees]	40	40
ddisp	Distance moved per time step while using large-scale movements [km]	2	1.5
c	Deterrence coefficient [unitless]	0.08	0.07
T	Response threshold: received sound level above which porpoises start getting deterred by piling noise [dB SEL; sound exposure level]	172	170

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CALIBRATION OF DEPONS 4.0

This report presents the calibration of the newest version of DEPONS (v4.0) with the aim of ensuring that simulated harbour porpoise movements resemble those observed from ARGOS satellite-tracked porpoises. DEPONS 4.0 includes a more detailed energetics sub-model than previous versions, representing individual energy intake and energetic costs throughout the life of each porpoise. Updates also include a revised food patch map in which food patches now cover 5% of the landscape instead of 1.6% as in earlier versions. This increase was implemented to allow assessment of fine-scale changes in food avail-ability around offshore wind turbines. The calibration focused on parameters controlling energetics and survival (*IR2EA* and *beta*), memory decay (r_R and r_S), large-scale movement behaviour (*PSM_dist*, *PSM_angle* and *ddisp*), and behavioural responses to pile-driving noise (*T* and *c*). A pattern-oriented modelling approach was used to test multiple parameter combinations and identify those that minimized discrepancies between simulated outputs and empirical observations.