DISTURBANCE EFFECTS ON THE HARBOUR POR-POISE POPULATION IN THE NORTH SEA (DEPONS): STATUS REPORT ON MODEL DEVELOPMENT

Scientific Report from DCE – Danish Centre for Environment and Energy No. 140 2015

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

DEPONS

[Blank page]

DISTURBANCE EFFECTS ON THE HARBOUR PORPOISE POPULATION IN THE NORTH SEA (DEPONS): STATUS REPORT ON MODEL DEVELOPMENT

Scientific Report from DCE – Danish Centre for Environment and Energy No. 140 2015

Floris M. van Beest
Jacob Nabe-Nielsen
Jacob Carstensen
Jonas Teilmann
Jakob Tougaard

Aarhus University, Department of Bioscience

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

DEPONS

Data sheet

Series title and no.:	Scientific Report from DCE – Danish Centre for Environment and Energy No. 140
Title:	Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS): Status report on model development
Authors:	Floris M. van Beest, Jacob Nabe-Nielsen, Jacob Carstensen, Jonas Teilmann, Jakob Tougaard
Institution:	Aarhus University, Department of Bioscience
Publisher:	Aarhus University, DCE – Danish Centre for Environment and Energy ©
URL:	http://dce.au.dk/en
Year of publication:	February 2015
Editing completed:	February 2015
Referee:	Frank Rigét
Quality assurance, DCE:	Jesper R. Fredshavn
Financial support:	Vattenfall, Forewind, Eneco Luchterduinen, SMart Wind & East Anglia Offshore Wind
Please cite as:	van Beest, F.M, Nabe-Nielsen, J., Carstensen, J., Teilmann, J. & Tougaard, J. 2015: Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS): Status report on model development. Aarhus University, DCE – Danish Centre for Environment and Energy, 43 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 140 http://dce2.au.dk/pub/SR140.pdf
	Reproduction permitted provided the source is explicitly acknowledged

Abstract:	The goal of this report is to provide a status update of an individual-based model (IBM) that is being developed to evaluate the impact of pile-driving noise from offshore wind farm construction on the harbour porpoise (*Phocoena phocoena*) population in the North Sea (DEPONS model). We considered five different porpoise movement and dispersal strategies in combination with three hypothetical pile-driving scenarios ranging from no noise to a realistic but worst case piling scenario. We compared the average simulated porpoise population sizes and dynamics across movement/dispersal models and pile-driving scenarios. Although the results should be considered preliminary, the patterns generated by the current version of the DEPONS model did not suggest any clear, long-lasting effects of pile-driving noise on the average porpoise population size and dynamics in the North Sea. We discuss several model components that need to be investigated in more detail so as to replace certain underlying assumptions in the model with a direct data driven parameterization approach.

Keywords:	agent-based model; construction, harbour porpoise; individual-based model; management model; movement ecology; *Phocoena phocoena*; pile driving; wind turbines; wind farms.
Layout:	Anne van Acker
Drawings:	The authors
Front page photo:	Monopole installation at DanTysk wind farm. Photo: Bjarke Laubek
ISBN:	978-87-7156-127-2
ISSN (electronic):	2245-0203
Number of pages:	43
Internet version:	The report is available in electronic format (pdf) at http://dce2.au.dk/pub/SR140.pdf

Contents

Summary

There is mounting scientific evidence that anthropogenic disturbances, such as offshore wind farm construction, affect the behaviour of harbour porpoises (*Phocoena phocoena*) and other marine mammals. The impact of noise generated through human activities on porpoise population dynamics has, so far, only been evaluated for the inner Danish waters (IDW) population. As part of the Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS) project, the main goal of this report is to demonstrate how the individual-based model (IBM) that was developed to simulate the cumulative impacts of different kinds of disturbances on the porpoise population in the IDW can be extended for evaluating the impact of pile-driving noise from offshore wind farm construction on the porpoise population in the North Sea (DEPONS model). The focus of this status report is on model parameterization and the types of processes included in the DEPONS model. The presented results are only indicative of the kinds of effects to be expected in the final model simulations. Although the results based partly on parameters for the IDW can give a first indication of the impact of different wind farm construction scenarios on the porpoise population in the North Sea, the DEPONS model output will become more accurate as the behaviour of the simulated porpoises is refined to resemble North Sea porpoises more closely. Porpoise deterrence behaviour in relation to pile-driving noise was parameterised based on empirical data showing reductions in porpoise density at different distances from the construction site before and during pile-driving events as collected around the DanTysk wind farm in the North Sea. We considered five different porpoise movement and dispersal strategies, which were either derived from theoretical movement models or from behaviour observed in the IDW. We used the movement/dispersal models in combination with three hypothetical pile-driving scenarios ranging from no noise to a realistic but worst case piling scenario. We compared the average simulated porpoise population sizes and dynamics across movement/dispersal models and pile-driving scenarios. Although the results should be considered preliminary, the patterns generated by the current version of the DEPONS model did not suggest any clear, long-lasting effects of pile-driving noise on the average porpoise population size and dynamics in the North Sea. The movement/dispersal strategy employed by the simulated porpoises had a far greater impact on the population size and whether population dynamics stabilized over time. To improve the DEPONS model further and enhance model inference, we highlight and discuss several model components that need to be investigated in more detail so as to replace certain underlying assumptions in the model with a direct data driven parameterization approach. Most importantly, empirical data on porpoise movement behaviour and dispersal strategies from the North Sea are required to better parameterize the model. Most of the data deficiencies in the current parameterization will be addressed during the remainder of the DEPONS project. The preliminary results presented here do indicate that the DEPONS model can ultimately become a valuable and powerful modelling platform for use in informing offshore wind farm construction planning.

Sammenfatning

Der er i stigende grad videnskabelig dokumentation for at menneskeskabte forstyrrelser, såsom konstruktion af havmølleparker, påvirker adfærden hos marsvin (*Phocoena phocoena*) og andre havpattedyr. Betydningen af menneskeskabt støj for marsvins populationsdynamik er indtil nu kun blevet evalueret for populationen i de indre danske farvande. Målet med denne rapport, som indgår i projektet "Disturbance Effects on the Harbour Porpoise Population in the North Sea" (DEPONS), er at vise, hvordan den individbaserede model (IBM), som blev udviklet med henblik på at simulere kumulative effekter af forskellige former af forstyrrelser på marsvinepopulationen i de indre danske farvande, kan udvides til at vurdere populationseffekten af støj fra pælenedramninger i forbindelse med byggeri af havmølleparker i Nordsøen (DEPONS-modellen). Formålet med denne statusrapport er at beskrive parametrisering og typer af processer, som er inkluderet i DEPONS-modellen. Selvom resultaterne baseret på parametre fra de indre danske farvande giver en indikation på, hvor stor effekt konstruktionen af vindmølleparker kan have på marsvinepopulationen i Nordsøen, kan forudsigelserne forventes at blive mere nøjagtige efterhånden som bevægelsesmønstrene for de simulerede marsvin bliver tilpasset, så de i højere grad kommer til at svare til dem, som marsvin har i Nordsøen. Marsvinenes reaktion på ramningsstøj blev parameteriseret baseret på empiriske data, der viser reduktioner i marsvine-tætheden i forskellige afstande fra pæleramninger før og under konstruktionen af DanTysk vindmølleparken i Nordsøen. Vi undersøgte effekten af marsvinenes spredningsmønstre på baggrund af fem forskellige bevægelses- og spredningsstrategier, som enten stammede fra teoretiske bevægelsesmodeller eller fra adfærd observeret i de indre danske farvande. Vi brugte disse bevægelses- og spredningsmodeller i kombination med tre ramningsscenarier, som spændte fra ingen støj til et realistisk worst case scenarie. Populationsdynamikken og den gennemsnitlige populationsstørrelse blev herefter sammenlignet på tværs af bevægelses- og spredningsmodeller samt ramningsscenarier. Selvom resultaterne bør betragtes som foreløbige, var der intet ved de mønstre, som den individ-baserede model genererede, der tydede på, at der er en længerevarende effekt af støj fra pælenedramninger på marsvinepopulationens dynamik eller gennemsnitlige størrelse. Valget af bevægelses- og spredningsstrategi havde en langt større betydning for populationsstørrelsen og på, om populationsdynamikken stabiliseredes over tid. For at forbedre IBM'en yderligere og for at gøre forudsigelserne endnu mere robuste fremhæver vi en række modelkomponenter, der skal undersøges nærmere for at erstatte visse antagelser i modellen med en direkte data-genereret parametrisering. Først og fremmest er empiriske data om marsvins bevægelsesmønstre og spredningsstrategier i Nordsøen nødvendige for at sikre en bedre parametrisering af modellen. De fleste af de parametre, der i øjeblikket mangler data for, kommer der bedre estimater for i løbet af DEPONS projektet. De foreløbige resultater, som er præsenteret her, viser, at DEPONS-modellen i sidste ende vil resultere i en værdifuld og stærk modelleringsplatform, som kan bruges i forbindelse med planlægning af offshore vindmølleparker.

1 Introduction

Anthropogenic disturbances can affect the behaviour and survival of individual harbour porpoises (*Phocoena phocoena*), but their impact on porpoise populations has not been investigated until recently (*Nabe-Nielsen et al. 2013a*; *Nabe-Nielsen et al. 2014*). Such understanding of how disturbances and habitat changes jointly affect the long-term survival of populations is integral to the protection of endangered species in Europe (*EU 1992*). As part of the Disturbance Effects on the Harbour Porpoise Population in the North Sea (DEPONS) project the main goal of this status report is to demonstrate how the individual-based population model that was developed by *Nabe-Nielsen et al. (2014)* to simulate the cumulative impacts of different kinds of disturbances on the porpoise population in the inner Danish waters (IDW) can be used to evaluate the impact of pile-driving noise from wind farm construction on the porpoise population in the North Sea (DEPONS model).

The model that was developed for simulating porpoise population dynamics in the IDW is an individual-based model (IBM, also called an agent-based model), where the movements and life history of each individual depend on the environmental conditions they encounter when moving around in the landscape, their internal state and on the way they adapt their behaviour based on what they have experienced in the past (*Grimm & Railsback 2005*). In such models the population dynamics and spatial distribution of individuals are emergent properties (*DeAngelis & Mooij 2005*). The IDW model was based on extensive knowledge of porpoise movement patterns in these waters, and on their response to disturbances. A crucial aspect of the DEPONS project is to obtain data from the North Sea, which are needed for parameterizing the DEPONS model. To do so the DEPONS project consists of 7 related subprojects (SPs). A brief description and a timeline (start-end year) for each subproject are provided below as we refer to them throughout the report.

SP 1 Obtain data on the behavioural responses of porpoises to airgun noise producing a frequency spectrum comparable to pile-driving noise (2012-2015).

SP 2 Obtain data on the spatiotemporal distribution of porpoise prey in the North Sea (2013-2014).

SP 3 Obtain data on movement patterns of porpoises in the North Sea (2013-2016).

SP 4 Obtain data on local population densities before, during and after pile-driving events by the DanTysk wind farm in the North Sea (2012-2014).

SP 5 Development and sensitivity analyses of the DEPONS model using data obtained through the other subprojects; analysis of model simulation results and reporting (2012-2015).

SP 6 Annual DEPONS workshops to communicate and discuss project findings among project partners and stakeholders (2013-2015).

SP 7 Obtain data on large-scale movement and dispersal patterns of porpoises in the North Sea (2014-2017).

Because SP 3 and 7 are on-going and data are still being collected, the simulation results provided in this report build on the assumption that the movement patterns and life history parameters are the same in the IDW and the North Sea. This is clearly a crude assumption, and the results presented here are therefore preliminary.

The dynamics of the North Sea porpoise population are likely to be particularly strongly influenced by the animals' ability to disperse among areas with high prey densities and by their ability to forage efficiently in these areas. Animal populations are often more fragile if they consist of subpopulations with limited dispersal between them (*Turner 2005*). In the study *by Nabe-Nielsen et al. (2013a; 2014*), the dispersal patterns of the simulated animals were calibrated to resemble those of satellite-tracked animals by adjusting the modelled animals' ranges and dispersal speeds. The porpoises' dispersal patterns in the North Sea are likely to differ from the ones in the IDW where movements are more bounded by land, and it is therefore important to recalibrate the model for the North Sea. The satellite tracking data needed for conducting this calibration are currently being collected under two different DEPONS subprojects (SP 3 and SP 7), and season specific maps of important foraging areas in the North Sea are produced under SP 2 based on aerial survey data of porpoise observations. In order to compensate for the scarcity of data on dispersal, we present model predictions corresponding to a range of dispersal types in this report. This allowed us to test how sensitive the population effects of different wind farm construction scenarios are to the way dispersal is modelled.

The modelled population effects of wind farm construction are also strongly affected by the animals' exact response to noise in the simulation model. When animals are displaced from an area where a wind farm is constructed it prevents them from foraging there. This may cause their energy levels to decrease, which in turn can lead to increased mortality. The model for the IDW (*Nabe-Nielsen et al. 2013a*; *Nabe-Nielsen et al. 2014*) built on the assumption that porpoises were deterred by noisy objects, and that their tendency to turn away from these was stronger the more noise they experienced. This was simulated as a biased correlated random walk (*Barton et al. 2009*). The model was calibrated to ensure that the population densities at different distances from simulated wind farms resembled the ones observed around a real wind farm (see details in *Nabe-Nielsen et al. 2011*). The same pattern-oriented modelling approach (*Kramer-Schadt et al. 2007*) was used in this report, but here the porpoises deterrence behaviour was calibrated based on passive acoustic monitoring data from a wind farm under construction rather than on data from the post-construction phase (data collected by the DanTysk wind farm construction site; SP 4). The animals' exact behavioural response to pile-driving noise may later be re-calibrated based on data collected under SP 1. In this subproject the fine-scale movements of porpoises are recorded using GPS tags before, during and after exposure to simulated pile-driving noise.

The life history parameters and fine-scale movement behaviour is exactly the same in the current version of the DEPONS model as in the model used in the IDW (*Nabe-Nielsen et al. 2013b*; *Nabe-Nielsen et al. 2014*), but the simulations were done in a new simulation framework in order to be able to run the simulations for the much larger North Sea landscape. This re-implementation also served as an independent validation of the model code (conducted under SP 5). Although the results based on the parameters for the IDW can give a first indication of the impact of different wind farm construction scenarios on the porpoise population in the North Sea, the model predictions can be expected to become more accurate as the behaviour of the simulated porpoises is refined to resemble real animals more closely.

2 Methods

2.1 Building the North Sea IBM in Repast

All simulations presented here were executed in the software package Repast Simphony 2.1. Repast is a free, open source agent-based modelling platform that can be downloaded from http://repast.sourceforge.net. The Repast model (henceforth called the DEPONS model) was created based on the harbour porpoise IBM developed in the software application NetLogo as described by *Nabe-Nielsen et al. (2011, 2013b; 2014)*. The DEPONS model was thoroughly tested to ensure that the new implementation of the model produced the exact same movement behaviours and population dynamics as the NetLogo model. Although the NetLogo model concentrates on porpoise movements and population dynamics in the inner Danish waters explicitly, it is the ideal model to extend to use for simulating porpoise population dynamics in the North Sea. The choice of porting the model to Repast as a simulation platform was due to Repast's greater speed of running long-term, complex simulations (e.g. 2 weeks [NetLogo] versus 7 hours [Repast] to complete 5 simulations of 40 yrs. using 200 porpoise agents in the inner Danish waters) and its ability to handle larger landscapes.

The first step in building the DEPONS model was to translate the NetLogo model-code into Java (Version 7 is required to run the IBM successfully), which is the language used in Repast. As part of DEPONS SP 5, code translation and Repast model development were performed in collaboration with Aragost Trifork AG, a private consulting firm based in Zurich, Switzerland (http://aragost.com). The second step was to ensure that the simulation output produced with Repast was identical to NetLogo output (i.e. a one-to-one model translation). This was verified by reproducing all results and figures presented in *Nabe-Nielsen et al. (2013b; 2014)* for porpoise movements and population dynamics in the inner Danish waters as well as movement tracks for individual porpoises. Once the results were identical, the Repast model was extended by creating new landscapes, including one that just represented the DanTysk wind farm construction site and one that included the entire North Sea, and by introducing new pile-driving scenarios and dispersal types.

2.2 Calibration of porpoise deterrence behaviour to pile-driving noise

There is increasing evidence that porpoises react to pile-driving noise (*Tougaard et al. 2012*; *Dåhne et al. 2013*), but detailed estimates of how this affects their movements and subsequently population dynamics are currently lacking. Clearly, pile driving generates very high sound pressure levels, which can be detected many kilometres from the noise source (*Bailey et al. 2010*). Following *Nabe-Nielsen et al, (2014)*, we assume that porpoises react to noise by turning away from the sound-emitting objects, and that their tendency to turn increases with the amount of noise they are exposed to (*Fig. 1*). Deterrence behaviour of simulated porpoises in the IBM is controlled by four parameters: deterrence distance (d_{deter}), deterrence coefficient (*c*), deterrence time (t_{deter}) and the impact factor. The impact (proportional to sound pressure level) of the sound-emitting object together with d_{deter} determine the radius in which porpoises are deterred, while *c* and the impact jointly determine the strength of deterrence behaviour within the deterrence radius. The deterrence is greatest close to the sound-emitting object and declines gradually further from the noise-emitting object. The number of time steps the deterrence effect lasts after the noise has disappeared is set by t_{deter} but the intensity of the deterrence is halved with each time step. *Nabe-Nielsen et al. (2014)* calibrated the values for d_{deter} and *c* to ensure that relative porpoise densities in the model matched those around an established wind farm (i.e. with operational noise only). Here the impact factor was arbitrarily set to 1. Sound pressures during pile-driving events are many times higher and likely deter porpoises more strongly and at further distances, requiring us to recalibrate the deterrence behaviour.

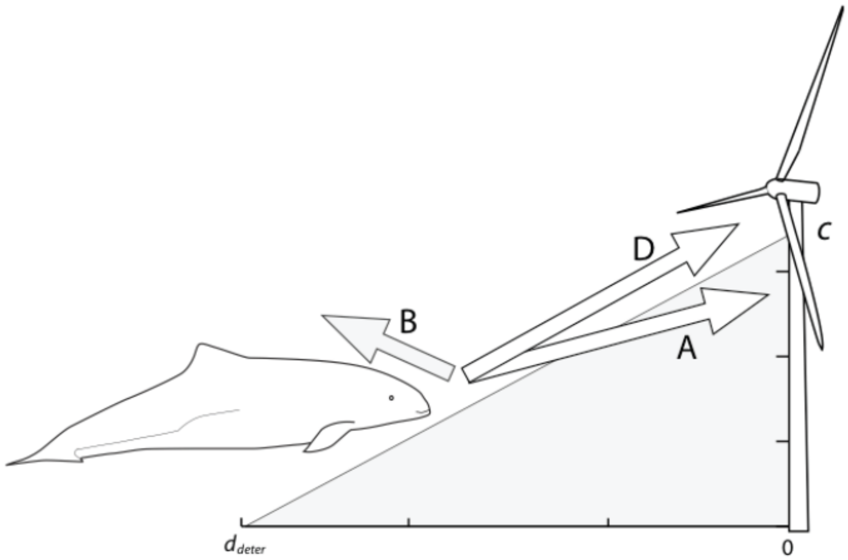
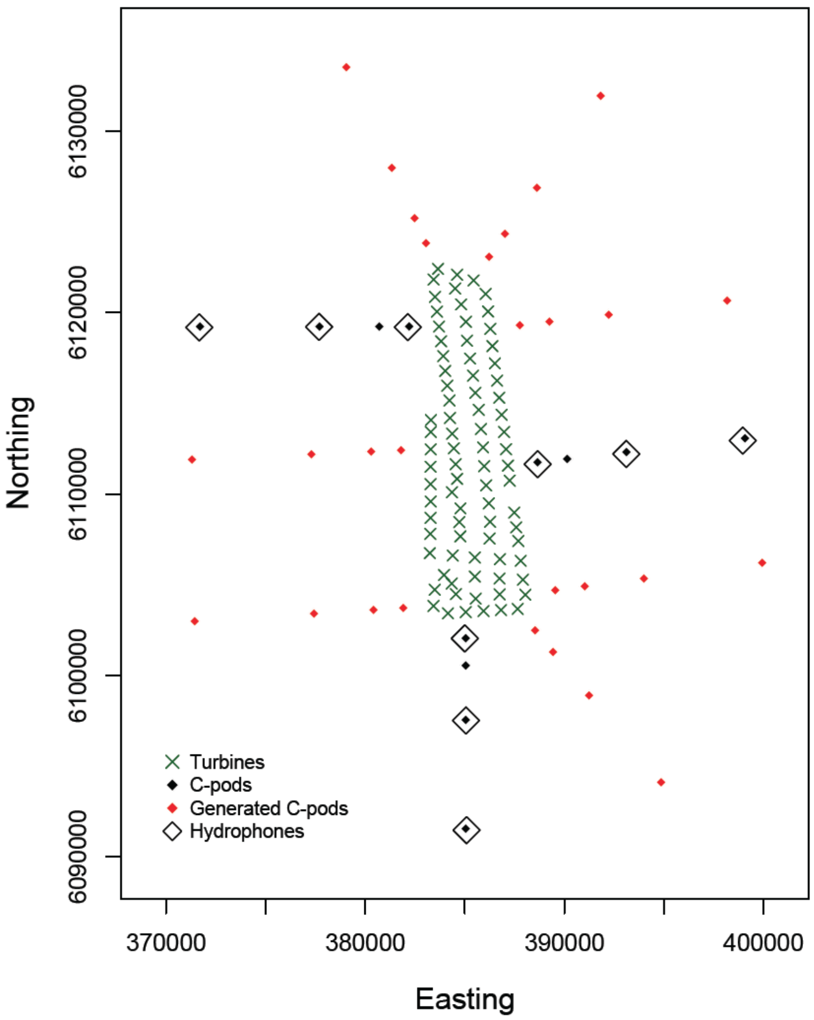


Figure 1. Schematic overview of the effects of noise (e.g. pile driving) on porpoise movement in the DEPONS model. The vector A shows the movement step as it should be in the absence of noise. The vector B shows the movement step the porpoise should take if it was determined exclusively by its reaction to the noise-emitting object. The length of B is proportional to the noise level, which decreases as a function of distance from the noise-emitting object (shaded grey area). d_{deter} is the maximum distance at which a noise-emitting object with impact factor = 1 deters porpoises, *c* is the deterrence coefficient and D is the actual movement step taken in the presence of noise. Figure is taken from *Nabe-Nielsen et al. (2014)*.

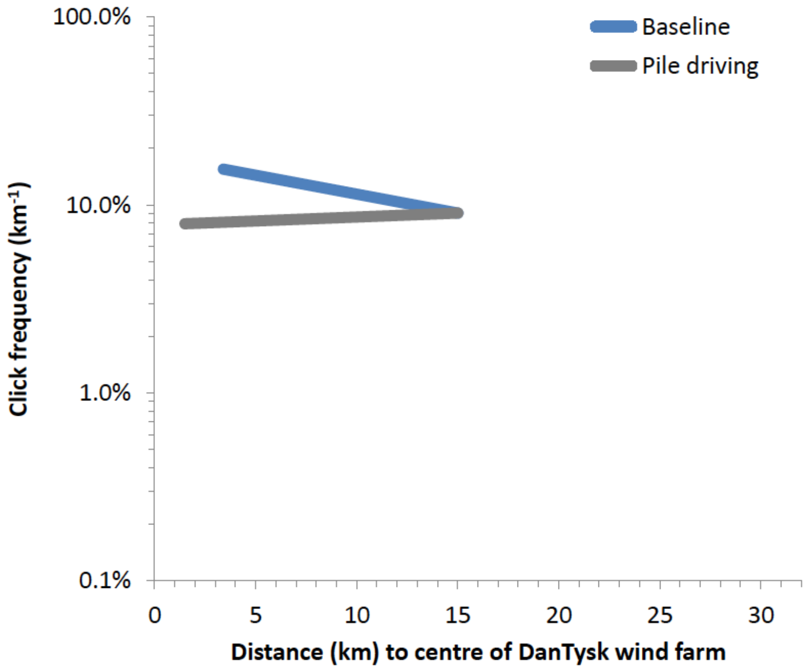
In the first step towards calibrating porpoise deterrence behaviour due to pile-driving noise, we employed data on porpoise click frequency collected with acoustic data loggers (C-PODs) around the DanTysk wind farm, both before and while it was constructed (*Fig. 2*). This unpublished dataset was collected as part of the DEPONS SP 4 (Tougaard et al., in prep.). In this project, C-PODs were deployed at 12 different sites (4 C-PODs across 3 transects) around the DanTysk wind farm at different distances from the closest turbine (1.5, 3, 6, and 12 km, respectively). C-PODs were active and continuously recording porpoise clicks both before (baseline data) and during pile-driving events, making it possible to detect any effect of pile driving on click frequency.

Figure 2. Overview of the DanTysk wind farm area showing the locations of C-pods (black dots; N = 12) and hydrophones (diamonds; N = 9) along 3 transects. C-pods were used to quantify the effect of pile driving on click frequency and hydrophones were used to quantify the sound pressure level (dB peak-peak) at the same positions. In addition, the locations of artificially generated sampling stations (N = 28) are shown in red. These were created to increase the number of points to measure changes in density as a function of distance from the centre of the wind farm in the DEPONS model simulations.



Log-transformed click frequency as a function of distance to the sound source was analysed using linear regression for both the baseline and pile-driving periods. Here the centre of the DanTysk wind farm was set as the source of the sound. Using the location of each individual monopile as the source of the sound resulted in too few data points in the DEPONS model simulations (porpoise counts per 30 minute step) to calibrate deterrence behaviour accurately. The overall effect of pile driving on log-transformed click frequency as a function of distance to the noise source can be quantified by the difference in slope between the baseline ($\beta_{baseline}$ = -0.0464) and the pile-driving periods (β_{piling} = 0.0097). The difference between slopes was 0.0561 (*Fig. 3*) and suggests a 56 % decrease in relative porpoise click frequency (km^{-1}) close (< 1 m) to the turbines during pile driving as compared to the baseline period. At 15 km from the sound source, click frequency during pile-driving events was indistinguishable from the frequency in the baseline period (as identified by the intersect of the regression lines in *Fig. 3*). Because porpoise click frequency is known to be correlated with porpoise densities (*Kyhn et al. 2012*), observed changes in click frequency due to pile-driving noise can be used directly to calibrate deterrence behaviour of simulated porpoises so as to obtain realistic changes in porpoise numbers as a function of distance from the noise source.

Figure 3. Plot showing the difference in click frequency (km^{-1}) of porpoises at increasing distances (km) from the centre of DanTysk wind farm during the baseline period (blue line, prior to pile driving) and during the pile-driving period (grey line). Figure is based on unpublished data collected for DEPONS SP 4.



To determine the noise level at the source of each piling event during the DanTysk construction phase, we recorded the sound pressure level during pile-driving events using hydrophones (*Fig. 2*). Here we also used linear regressions to predict the sound pressure at 1 m (the source) from each pile separately. Seal scarers, porpoise pingers and bubble curtains were employed before and during all piling events at DanTysk and these were included in the sound pressure analysis. The calculated noise source levels for the different piling events, which were subsequently used as the impact factors in the simulations used for calibrating d_{deter} and *c*, therefore took the employed noise mitigation into account. The mean source sound pressure of all piling events was 238 dB (range: 224-249 dB). The turbine specific impact values were subsequently included in the data file controlling where, when and how many turbines were constructed in the DanTysk landscape simulations.

With the DanTysk piling scenario in place, the next step involved creating the DanTysk landscape in the DEPONS model. We constructed a 160 km × 160 km area around the DanTysk wind farm, composed of 160,000 cells of 400 m × 400 m (default cell size for all landscapes). For each cell we extracted data on bathymetry and distance to coast. Food patches in the DanTysk landscape were randomly distributed throughout the landscape as in *Nabe-Nielsen et al. (2014)* and all contained the same amount of food (energy), which was season independent. As such, the DanTysk landscape was a homogeneous landscape, which ensured that porpoises were evenly distributed throughout the landscape, except along the coast (*Fig. 4*).

Preliminary simulation runs with the DanTysk landscape yielded a carrying capacity of 130 porpoises in the baseline scenario (i.e. no pile-driving noise), which we subsequently used as the number of porpoises at the start of each simulation. Each of these porpoise agents represents several female porpoises in the real world. We generated 40 sample blocks in the DanTysk landscape to track porpoise abundance at different distances from the centre of the wind farm. Of these sample blocks, 12 corresponded to the actual C-POD locations around the wind farm, and we generated an additional 28 sample blocks using the same spacing as for the C-PODs to increase sample size (*Fig. 2*). Each sample block covered 800 m × 800 m, and the total number of porpoises within a sample block within each 30 minute interval was used for model calibration.

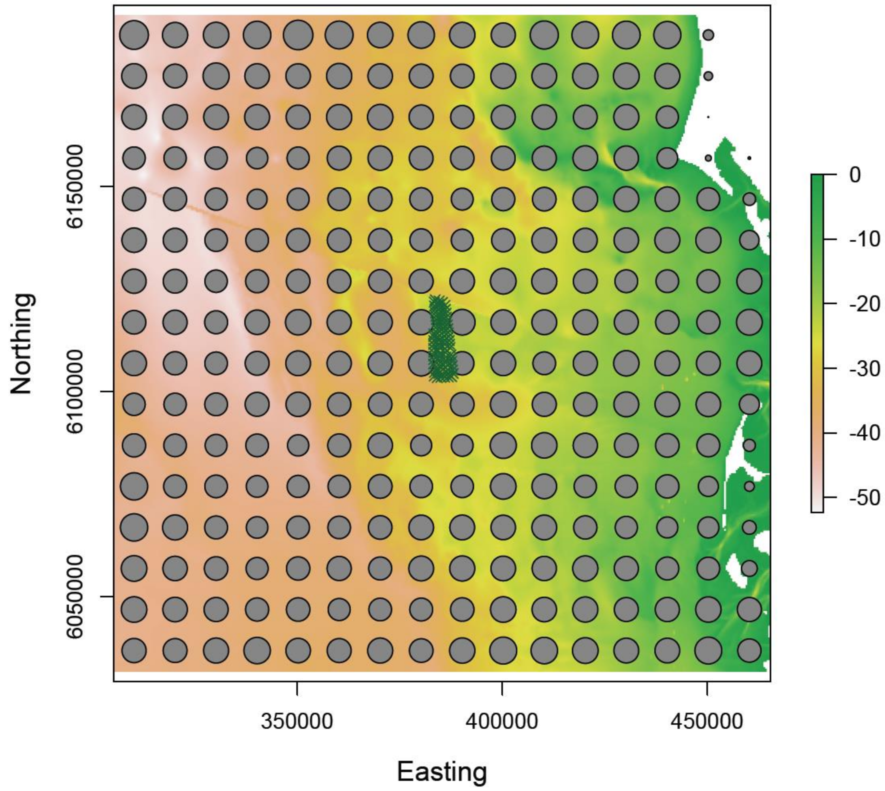


Figure 4. The DanTysk landscape as created for the IBM simulations to calibrate porpoise deterrence behaviour. The map shows the location of the DanTysk wind farm (dark green area in the middle of the plot) and bathymetry (m) for the whole landscape. The grey dots indicate the relative abundance of porpoises in a 100 km^2 block over a two-year period without any pile-driving noise. Smaller dots along the coast indicate lower overall abundance compared to larger dots in open water.

When the DanTysk landscape and the piling scenario were completed, the final step in calibrating deterrence behaviour of simulated porpoises in the DEPONS model was to replicate the observed changes in porpoise density around the DanTysk wind farm due to pile-driving (*Fig. 2*), but instead of changes in log-transformed click frequency we used changes in log-transformed number of simulated porpoises as a function of distance from the sound source. We did so using Pattern Oriented Modelling (POM), which is a common and powerful approach to replicate ecological processes in population-level models such as IBMs (*Grimm et al. 1996*; *Kramer-Schadt et al. 2007*). All simulations in our POM procedure covered two simulation years and were replicated 100 times. The data collected in the first simulation year were discarded as this was considered a burn-in period to allow the model to reach a stable carrying capacity (see *Appendix 1* for an example). We first simulated the baseline (no noise) scenario. For each of the 100 runs we computed the log-transformed number of porpoises in each sampling block (N = 40). Using linear regression we then quantified the baseline slope ($\beta_{baseline}$) of log-transformed porpoises with increasing distance from the centre of the DanTysk wind farm. The result was: $\beta_{baseline}$ = -0.008, SD = 0.005 ($F_{1,38}$ = 2.807, P = 0.1021). Our main interest was to calibrate porpoise deterrence behaviour in such a way that the difference in slopes of the baseline scenario model and the piling scenario model was 0.0561, so as to reproduce the observed 57 % decrease in porpoise click frequency (km^{-1}) close (< 1 m) to turbines during construction. As such, we were looking for a linear regression with a pile-driving slope (β_{piling}) of 0.048. In addition, the regression line for the pile-driving scenario should ideally intersect the baseline regression line at 15 km from the centre of the DanTysk wind farm like in *Fig. 3*. Our POM analysis consisted of many different simulations and we highlight 16 of these here. Each simulation used a unique combination of deterrence distance (d_{deter}) and deterrence coefficient (c). The parameter deterrence time (t_{deter}) was kept constant at 5 (i.e. animals remembered the location of the sound-emitting object for 5 time steps [150 minutes] after the sound had disappeared) as in *Nabe-Nielsen et al. (2014).* Here we show the results of 4 different values for d_{deter} (40, 50, 51 and 60 m) and 4 different values of c (0.0001, 0.001, 0.01 and 0.1). A combination of d_{deter} = 0.001 and c = 0.001 provided the best deterrence pattern with a β_{piling} of -0.048 and an intersect slightly larger than 15 km (*Fig. 5*). These values for d_{deter} and c were used in all subsequent simulations for the North Sea that included piling events.

2.3 Simulating porpoise dispersal behaviour

Movement is one of the defining characteristics of life. Nearly all animals move actively. As a result, it is often argued that most processes in ecology are directly related to movement. For example, two fundamental processes in population dynamics: survival and successful reproduction are, to a large extent, the outcome of movements made to successfully acquire food (*Turchin 1998*).

Animal movement is generally considered to be the result of a complex interplay between the focal individual and its environment (*Börger et al. 2008; Nathan et al. 2008*). Components that influence movement of the focal individual include its internal state (e.g. age, sex, reproductive status, energy-level), its motion capacity (e.g. physical ability to move) and its navigation capacity (e.g. cognitive abilities/memory of its environment).

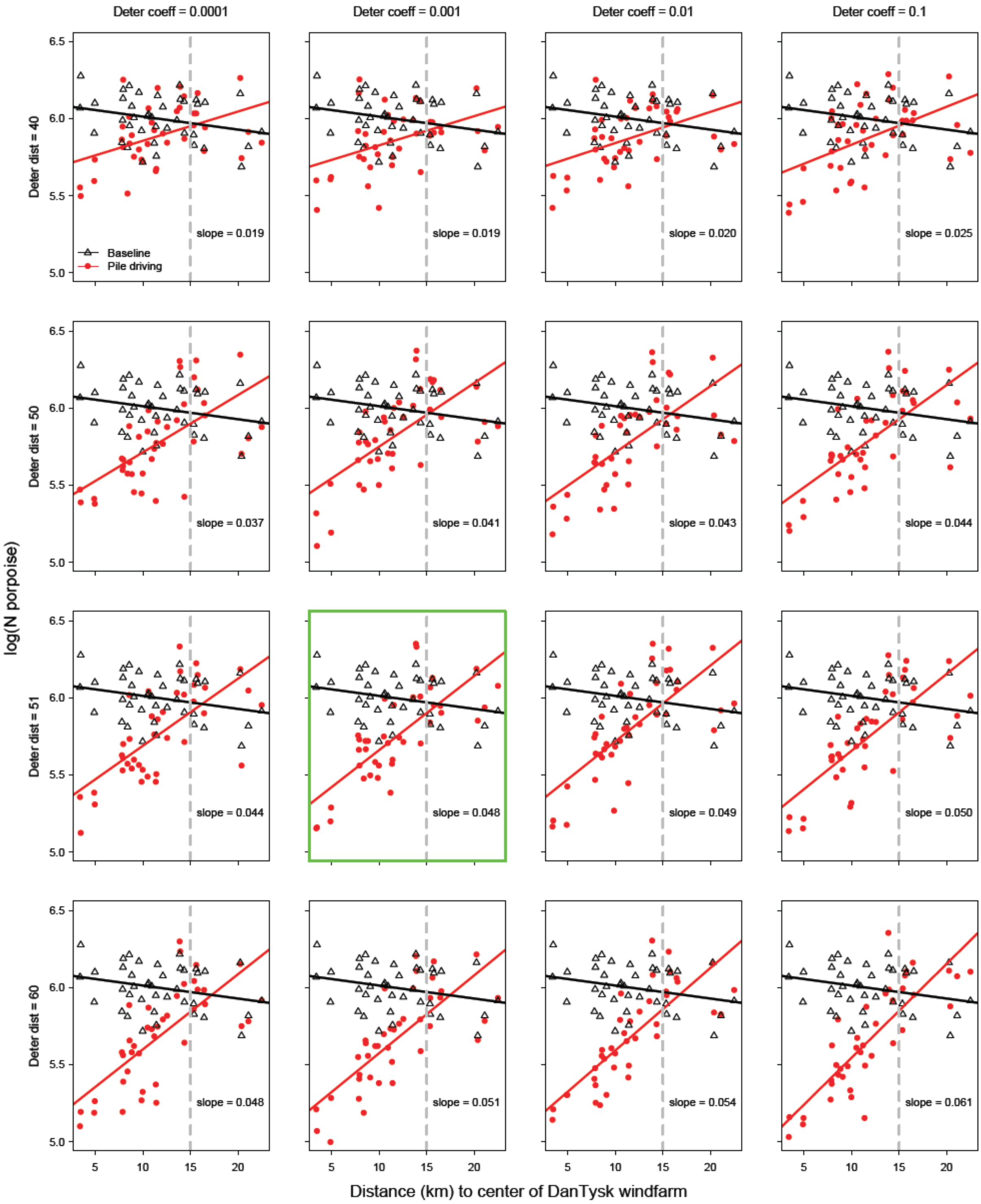


Figure 5. The results of the POM analysis showing the effect of piling noise on simulated log-transformed porpoise abundances at different distances from the centre of the DanTysk wind farm. Each panel shows the result (regression line and sampling block values) of the baseline (no piling) scenario (in black) and the result of the piling scenario (in red) for a particular deterrence distance and deterrence coefficient value. The dashed grey vertical line indicates 15 km from the centre of DanTysk wind farm to highlight where regression lines should ideally intersect based on data from SP 2. The slope of the pile-driving scenario (β_{piling}) is provided in each panel with the target slope being 0.048 based on data from SP 2. The panel outlined in green shows the deterrence values that best replicated the pattern in *Fig. 3*.

Environmental components that influence movement of the focal individual include a wide range of biotic and abiotic external factors such as forage availability, temperature, anthropogenic activity, etc. As the focal individual moves, its internal state and environment change leading to so-called scale-dependent movements (*Börger et al. 2008*). Decades of research have shown that variation in animal movement is enormous, both within and between species or individuals (*Skellam 1951*; *Hawkes 2009*; *Galanthay & Flaxman 2012*; *Avgar et al. 2013*). Most species, including porpoises in the inner Danish waters (*Nabe-Nielsen et al. 2013b*), remain in one and the same area for an extended period of time. This area is termed the home range. When an animal experiences decreasing energy levels related to declining food availability in the home range, it may choose to disperse or migrate to another area with higher levels of food/energy. Indeed, reduced forage intake within an area and a subsequent drop in energy level are often the primary driver of migratory or dispersal behaviour in mammals (*Dobson & Jones 1985*; *Fryxell & Sinclair 1988*). While many species display home range behaviour with occasional dispersal or migratory movements to an entirely different part of the individual's or population's range, some species rarely stay within a limited area for an extended period of time and move/disperse continuously (nomads; *Schwarzkopf & Alford 2002*; *Fryxell et al. 2004*).

There are limited empirical data on movement and dispersal behaviour of harbour porpoises, especially within the North Sea. DEPONS SP 3 and 7 are expected to greatly increase our understanding of porpoise movement and dispersal behaviour in the North Sea. This data will be collected and analysed during 2015/2016. For now, movement and dispersal models of porpoises in the North Sea incorporated into the DEPONS model are based on knowledge of porpoise movements in the inner Danish waters (*Nabe-Nielsen et al. 2013b*; *Nabe-Nielsen et al. 2014*), basic energetic principles of animal movement (*Sibly et al. 2013*), and theoretical movement models (*Turchin 1998*; *Morales et al. 2004*; *Bunnefeld et al. 2011*). We incorporated 5 different movement models that differ in *i*) the range over which animals can move and *ii*) the strategy employed to find food and maintain energy levels. An overview of each movement model is provided in *Table 1* with accompanying examples of the resulting movement paths in *Figure 6*. We also briefly explain each movement model below.

A common theoretic model to study animal movements is the Correlated Random Walk (CRW). CRW models are helpful to study the fine-scale movements of animals, especially for species living in homogeneous environments (*Turchin 1998*; *Morales et al. 2004*). However, classic CRW models are often less accurate when applied to animals living in heterogeneous landscapes and, moreover, classic CRW models do not incorporate cognitive abilities (spatial memory) of animals. Here we considered two types of CRW models in which varying levels of spatial memory (termed reference memory: r_R) were incorporated (*sensu Nabe-Nielsen et al. 2013b*). Movement model 1 in the DEPONS model is a very basic model that does not consider long-distance dispersal movements of porpoises, and the spatial memory of previously visited food patches decays rapidly. Movement model 2 is similar to model 1 but here the porpoise has a spatial memory decay rate that allows realistic home range sizes to emerge, using r_R as determined by *Nabe-Nielsen et al. (2013b)*.

As mentioned, dispersal or migratory movements often occur when local food resources (start to) deplete. When an animal has no prior knowledge of where in the landscape food availability is highest, a reasonable assumption is that the animal disperses away from its current location until food is encountered. Such a dispersal strategy is similar to that of nomadic species (*Olson et al. 2010*). We included this strategy into the DEPONS model as dispersal type 3.

Most species, however, do have some level of knowledge of where in the landscape food availability is highest at different times of the year. Well-known examples include the large-scale, seasonal migrations of grazing herbivores in savannah ecosystems (*Fryxell & Sinclair 1988*) and whales (*Clapham et al. 1993*). Here animals do not disperse away from areas with low food levels but instead disperse or move towards areas with high(er) expected food availability. We included this strategy into the DEPONS model as dispersal types 4 and 5. The main difference between these models is that in model 4 we allowed the porpoises to disperse towards any area in the entire North Sea landscape and as such the dispersal was unrestricted. In dispersal model 5 we restricted the maximum dispersal distance to 200 km, which is approximately the same size as animals can disperse in the inner Danish waters. This dispersal scenario may be more realistic for animals that have high energetic costs associated with migration and that are likely to encounter sufficient food by dispersing less. In models 4 and 5, the fine scale movements were simulated as a CRW as described for model 2.

Table 1. A description of the five different movement/dispersal models considered in the current version of the DEPONS model.

Movement/dispersal model	Description
1: CRW – low spatial memory	No long-distance dispersal. The porpoises move in a correlated random walk pattern and their memory of the locations of previously visited food patches (reference memory) is low and decays rapidly (r_R = 0.3). The fine-scale behaviour is calibrated to resemble one animal observed in the inner Danish waters.
2: CRW – high spatial memory	Similar to movement type 1, but here the individual's memory of the locations of previously visited food patches (reference memory) decays slowly (r_R = 0.1), and is calibrated to yield realistic home range sizes. The fine-scale behaviour is kept as in movement model 1.
3: Dispersal away	In this dispersal type, a porpoise moves away from the area where it started dispersing. The trigger to start dispersing is based on the energy level of the porpoise. If the energy level of the porpoise has been dropping for three consecutive days (the porpoise is now hungry and is starting to lose weight [*J. Teilmann pers. obs*.]), dispersal is initiated. In this dispersal mode, porpoises do not have prior knowledge of where food levels are high at different times of the year. As such, the porpoise will keep moving away from the location where it entered the dispersal mode until it dies or finds food. There is no restriction on the length of dispersal distance. Once food is found, the porpoise returns to correlated random walk movement behaviour with high spatial memory (type 2 above). This dispersal mode can be considered a nomadism type of behaviour.
4: Dispersal towards, unrestricted search	This dispersal type incorporates parameters that yielded realistic harbour porpoise dispersal in the inner Danish waters (*Nabe-Nielsen et al. 2014*). In this dispersal type, a porpoise moves towards an area where food availability is likely to be higher than in the area it foraged the last 3 days. The trigger to enter this dispersal mode is also based on the energy level of the porpoise

	(as in type 3: dispersal away above). If the energy level of the porpoise has been dropping for three consecutive days, dispersal is initiated. In this dispersal mode, porpoises have prior knowledge of where food levels are high at different times of the year. As such, the porpoise will disperse towards any 40 km x 40 km block selected at random from the 12 blocks with the highest average maximum food level present in the complete landscape. As such, the search radius/total length of dispersal distance is unrestricted. When the porpoise approaches the dispersal target, it moves along the coast at an approximately constant water depth until food is found (called back-tracking). Once food is found, the porpoise will return to correlated random walk movement behaviour with spatial memory (type 2 above). This dispersal type can be considered an unconstrained migratory type of behaviour.
5: Dispersal towards, restricted search	This dispersal type is a spatially restricted version of type 4. Here the porpoise will disperse towards a 40 km x 40 km block selected at random from the 12 blocks with the highest average maximum food level present within 200 km from the location where the porpoise entered the dispersal mode. As such, the search radius/total length of dispersal distance is restricted. The 200 km restriction distance was chosen as it covers approximately the size of the inner Danish waters landscape, a distance that porpoises regularly disperse without dying of starvation. Again, when a porpoise approaches the dispersal target, it moves along the coast at an approximately constant water depth until food is found (called back-tracking). Once food is found, the porpoise returns to correlated random walk movement behaviour with spatial memory (type 2 above).

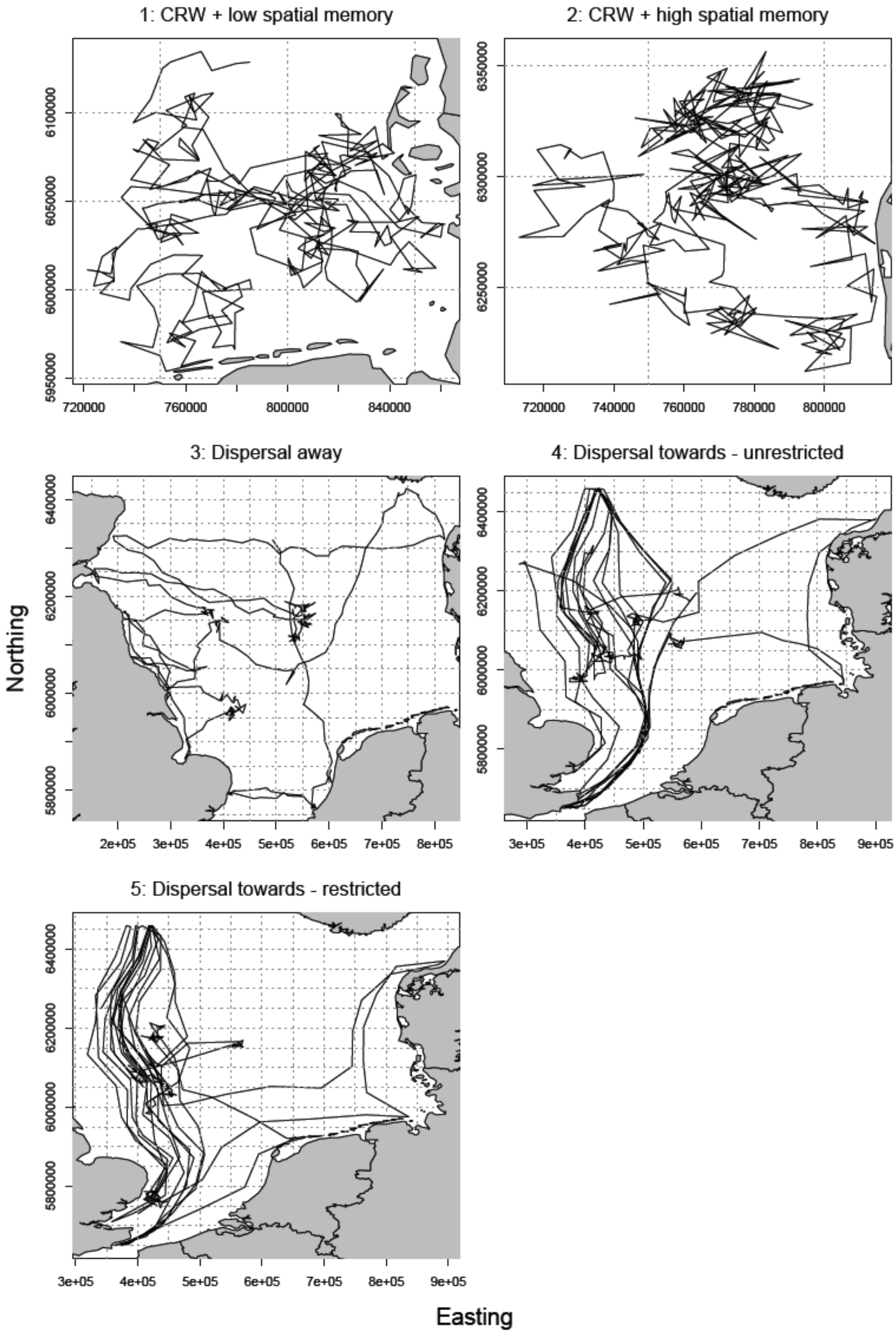


Figure 6. Movement tracks of simulated porpoises with different movement/dispersal strategies as implemented in the DEPONS model (*Table 1*). Tracks are made using one position per day for a period of one year, without pile-driving noise present. For reference, the outline of countries bordering the North Sea is shown in grey and the grey dotted squares in the panels indicate 50 km × 50 km blocks.

2.4 Pile-driving scenarios

To start building an understanding of how pile-driving noise associated with construction of offshore wind farms can affect population size and dynamics of harbour porpoises in the North Sea, we considered 2 different pile-driving scenarios in the DEPONS model. We also considered a noise-free baseline scenario in order to determine if there was any effect of pile driving on the average population size and population dynamics. Both pile-driving scenarios were developed and provided to us by the commissioners of the current report. Both scenarios were applied for each of the 5 dispersal models described previously. Both piling scenarios considered a 6-year period construction phase (2015-2020) in which only monopiles were built with a sound pressure level of 255 dB.

The scenarios differed in the number of wind farms and turbines to be built and their construction location (*Tables 2 & 3*; *Figs. 7 & 8*). Assuming a name-plate capacity of 6 MW/turbine, the maximum capacity in scenario 1 is 8.2 GW of power. This scenario was suggested to represent a most likely minimum development case. Scenario 2 has a maximum capacity of 12.4 GW of power and was suggested to represent a realistic worst-case scenario for the modelled timeframe.

To incorporate each piling scenario into the DEPONS model, we created two pile-construction text files (one for each scenario). In these files we listed the id and coordinates of each turbine to be constructed. We converted the date and time for the start of each piling event into a tick number, which is a numeric value that represents a 30-minute period (the length of one time step in the DEPONS model). Because all simulations in the DEPONS model start on 1st January (i.e. tick 1) and we included a 10-year burn-in period to allow the population to stabilize (see *Appendix 1*) before any disturbance effects (as in *Nabe-Nielsen et al. 2014*), we added 175680 ticks (1 simulation year is 17280 ticks) to the start of the first piling event (1st March 2015) and so on. As such, all North Sea simulations started on 1st January 2005. Piling events lasted for 2 hours (*Table 2*) so the end tick for a piling event was the start tick + 4. The impact value or the sound pressure level (dB peak-peak) at the source (1 m from turbine) was set at 255 for all turbines. This value was calculated based on a peak pressure of 200 dB re. 1 uPa as estimated for a 6 m pile in 30 m of water, at a distance of 750 m from the monopile (following details in *Betke & Schult-von Glahn 2008*). Assuming no noise mitigation measures are applied (e.g. seal scarers, bubble curtains, porpoise pingers), a transmission loss of 17 log r, and an additional 6 dB is added to convert from peak level to peak-peak level an estimated source level of 255 dB is obtained. This impact value is higher than the maximum impact value used in the DanTysk construction site (249 dB), which is realistic as noise mitigation measures were applied during pile-driving events in DanTysk construction.

Table 2. An overview of the generic wind farm construction details, the number of turbines to be built in each park, country, and scenario, their individual and combined capacity, and installation start and end for each pile-driving scenario. Blanks in the installation end column indicate that the wind park construction will be completed in the same year as installation start.

Turbine (MW)	Foundation diameter (m)	No. strikes/ 30 min	Hammer energy/ strike (kj)	Piling time (hrs.)	Time between pilings (hrs.)	Piling depth (m)
6	5-7	1200	2300	2	48	15-40
Scenario	**Wind farm**	**Country**	**No of turbines**	**Capacity (MW)**	**Installation start (yr.)**	**Installation end (yr.)**
1 & 2	1	UK	100	600	2016	
1 & 2	2	UK	100	600	2018	
1 & 2	3	UK	200	1200	2019	2020
1 & 2	4	DE	50	300	2015	
1 & 2	5	DE	50	300	2016	
1 & 2	6	DE	50	300	2017	
1 & 2	7	DE	50	300	2018	
1 & 2	8	DE	50	300	2019	
1 & 2	9	DE	50	300	2020	
1 & 2	10	DE	50	300	2015	
1 & 2	11	DE	50	300	2016	
1 & 2	12	DE	50	300	2017	
1 & 2	13	DE	50	300	2018	
1 & 2	14	NL	60	360	2015	
1 & 2	15	NL	60	360	2016	
1 & 2	16	NL	60	360	2017	
1 & 2	17	NL	60	360	2018	
1 & 2	18	BEL	55	330	2017	
1 & 2	19	BEL	55	330	2018	
1 & 2	20	BEL	55	330	2019	
1 & 2	21	DK	67	402	2018	
2	22	UK	200	1200	2018	2019
2	23	DE	50	300	2016	
2	24	DE	50	300	2017	
2	25	DE	50	300	2018	
2	26	DE	50	300	2019	
2	27	DE	50	300	2020	
2	28	NL	60	360	2019	
2	29	NL	60	360	2020	
2	30	BEL	55	330	2018	
2	31	DK	67	402	2020	

Figure 7. Overview of the spatial location of modelled wind farm parks in the North Sea for each pile-driving scenario. The underlying map shows porpoise densities (individuals/km^2) during summer (Gilles et al. in prep.). The location of wind farms in both scenarios is fictive but scenario 1 can be considered a most likely minimum development case while scenario 2 is a realistic worst case scenario.

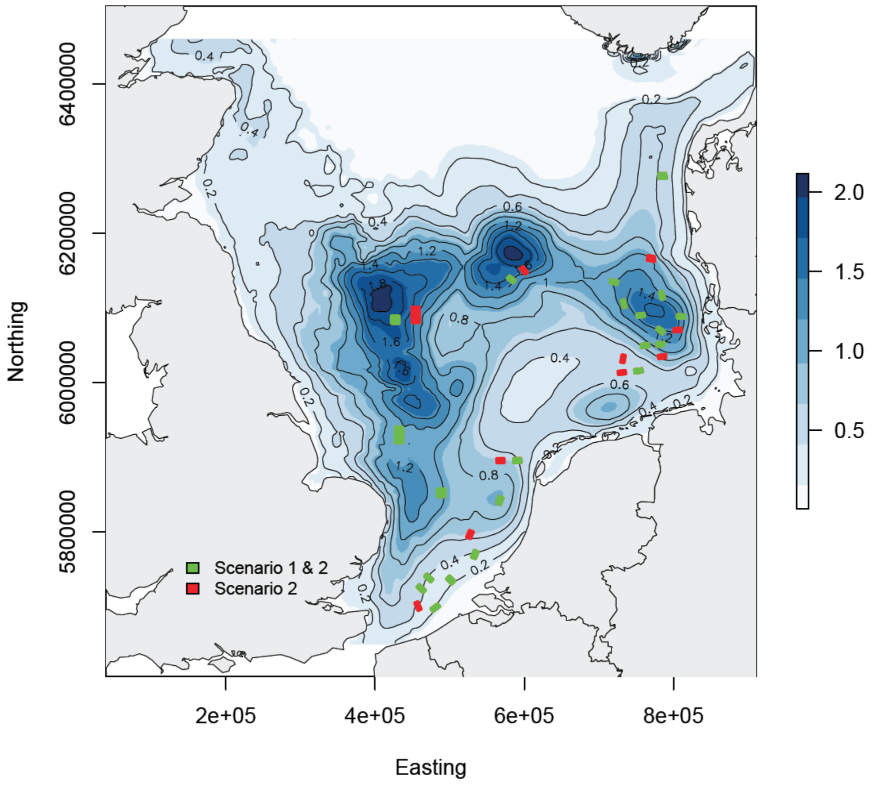
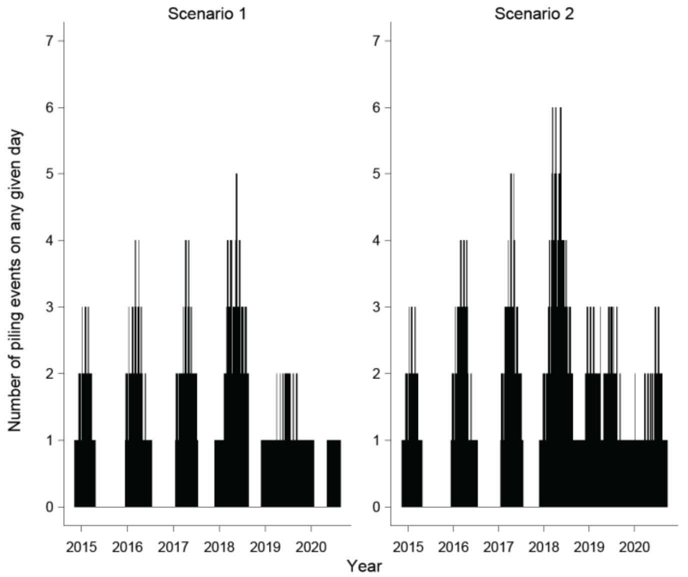


Table 3. An overview of the main differences in piling scenario characteristics.

Characteristic	Scenario 1	Scenario 2
No. of turbines constructed	1372	2064
No. of wind farm parks constructed	21	31
Date of first piling	01 Mar. 2015	01 Mar. 2015
Date of last piling	11 Nov. 2020	12 Dec. 2020
Hours between piling events within park	48	48
Mean number of pilings/day	1.56	1.81
Max. number of pilings/day	5	6
Piling intensity (no. turbines/available days)	0.66	0.97

Figure 8. Number of piling events per day for the total construction period for both scenarios. Scenario 1 can be considered a most likely minimum development case, scenario 2 can be considered a realistic worst-case.



2.5 Food availability

Both survival and reproductive success of porpoises in the DEPONS model are directly related to the energetic status of each individual. An individual porpoise maintains or increases its energy level by foraging. Detailed knowledge and reliable data of food (prey) availability and diet composition of harbour porpoises in the North Sea are currently absent. At present, the DEPONS model uses porpoise density/abundance as a proxy for food availability based on the assumption that where porpoise densities are high or low during a given time of the year, food availability should also be high or low. Although this is a reasonable assumption, density is difficult to estimate, especially over large areas. A more direct mechanistic approach is much more robust in, for example, studies of the long-term consequences of different management actions, where climate change or variations in fishing intensities may influence porpoise population dynamics through changes in food availability. As such, quantifying porpoise prey availability in the North Sea and using food (prey) availability or primary production maps directly in the DEPONS model remain key issues for future development of the model (see section 4.3 in the Discussion).

In the DEPONS model, the location and number of food patches in the North Sea landscape were distributed randomly (see section 2.6 below) and the estimated porpoise density determined the potential amount of food in each food patch (each food patch covers 1 cell of 400 m × 400 m). Seasonal porpoise density maps were created as part of DEPONS SP 2. The North Sea porpoise density maps were computed based on dedicated aerial cetacean assessment surveys from Denmark, UK, Germany and the Netherlands and analysed using generalized additive models. No survey data were available for winter, so we used the autumn density map for the winter season as well. The analyses to predict spatiotemporal variation in porpoise density are ongoing and the shown density maps should therefore be considered a preliminary product, which was used mainly to demonstrate how the DEPONS model is developed and operates (the main goal of this report).

Before uploading the seasonal density maps into the DEPONS model, we changed the pixel (cell) size of the maps to 400 m × 400 m, which is the required pixel size for any underlying map in the DEPONS model. Due to this conversion, some cells/pixels along the coastline did not have density values. Because all cells reflecting water need a density value before the DEPONS model can run, we replaced no data values in the density maps with a low value of 0.05 porpoises km^{-2}, which is similar to the values observed along most of the coastline. We then rescaled and standardized the density values across the landscape as in *Nabe-Nielsen et al. (2014)* to ensure that the potential total amount of food in the landscape stayed constant. We did so by dividing each density value (one cell/pixel in the map) by the sum of the density values across the landscape (all cells/pixels) and multiplied this by the sum of the density values across the landscape in autumn (reference level as in *Nabe-Nielsen et al. [2014]*). Using another season as the reference level would change the porpoise population size in the DEPONS model but would not change the population dynamics or behaviour.

Preliminary runs of the DEPONS model including the seasonal density maps revealed that the porpoise population size increased to such levels in some of the dispersal scenarios that a 40-year simulation would be completed in approximately 1 week. Due to time constraints and to shorten the duration of the simulations, we divided all density values by 1.5. This is not expected to influence the relative impacts of different dispersal and disturbance scenarios, as long as the food levels are sufficiently high to maintain a population in all parts of the simulation landscape where porpoises are known to occur in nature. The porpoise density maps as uploaded into the DEPONS model are provided in *Figure 8*.

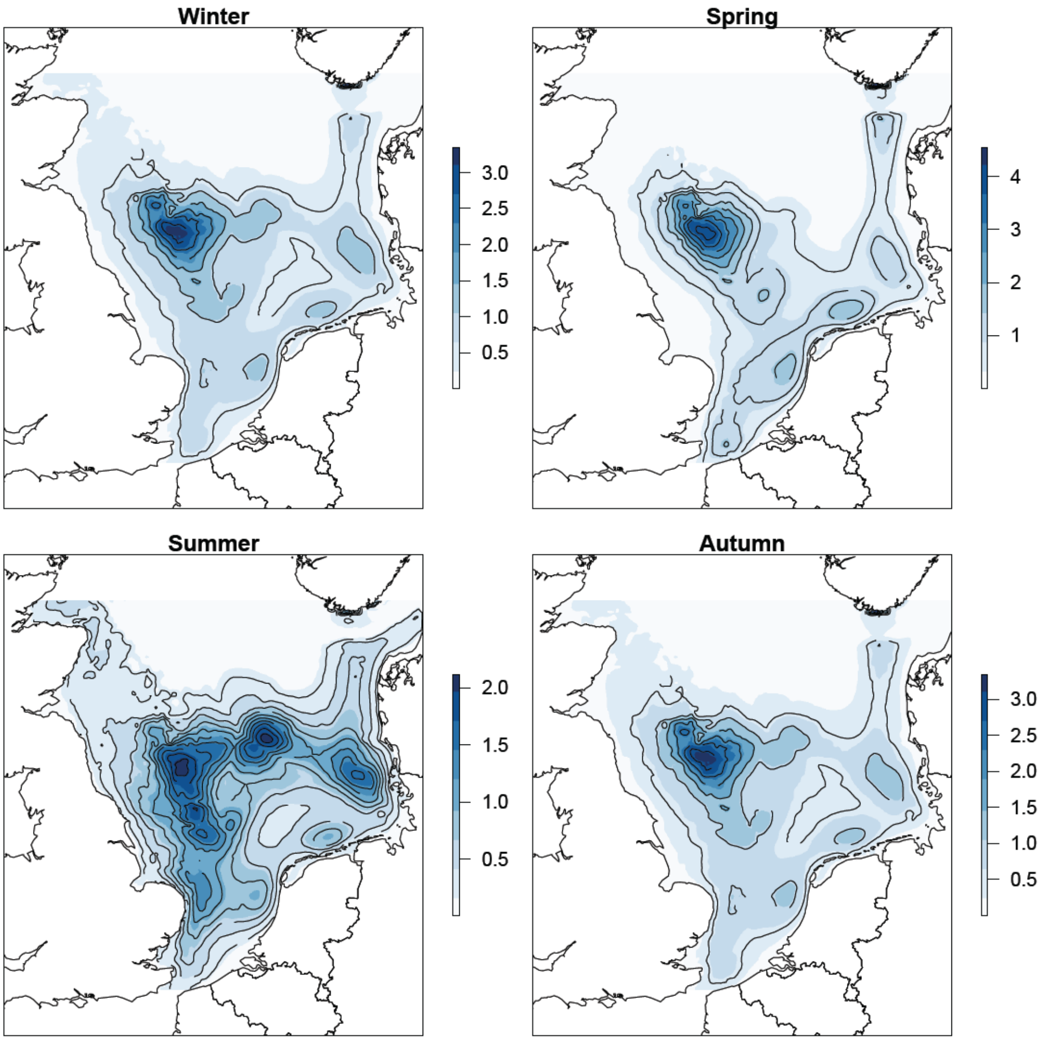


Figure 8. Seasonal maps of predicted harbour porpoise density (individuals km^2) in the North Sea. Maps are produced based on dedicated aerial cetacean assessment surveys from Denmark, UK, Germany and the Netherlands. The analyses to predict spatiotemporal variation in porpoise density are on-going and the shown maps should therefore be considered a preliminary product. Moreover, due to limited observation data during the non-summer seasons in the northern part of the North Sea, the density of porpoises reflected on the maps may be lower than in reality. Density maps were used as a proxy for food availability in the DEPONS model. Note that the density maps were rescaled and standardized using winter and autumn densities (identical) as reference.

2.6 North Sea landscape

The North Sea landscape in the DEPONS model consisted of a 810 km × 871 km area including all areas north of the English channel and all areas south of the southern tip of Norway (*Fig. 9*). The size of the area was largely determined by the extent of the seasonal harbour porpoise density maps presented in *Figure 8*. The landscape is comprised of 451 square blocks of 40 km × 40 km and holds 40553 randomly distributed food patches (*Fig. 9*). The average potential food level was calculated for the food patches in each square block, using porpoise density as a proxy, as explained in section 2.5. The landscape was further built up by 2025 × 2178 grid cells, each covering 400 m × 400 m (the default cell size for the DEPONS model).

The landscape includes land (57.18 %), water with food (0.92 %) and water without food (41.9 %). Several water bodies bordering the North Sea are unlikely to be occupied by porpoises or were closed off by a dam. We therefore masked these water bodies in the DEPONS model as land (< 1 % of the total landscape) to make sure that simulated porpoises could not move into these waters. Besides the block number and food availability, each cell was characterised by bathymetry (water depth) and distance to land (*Fig. 9*).

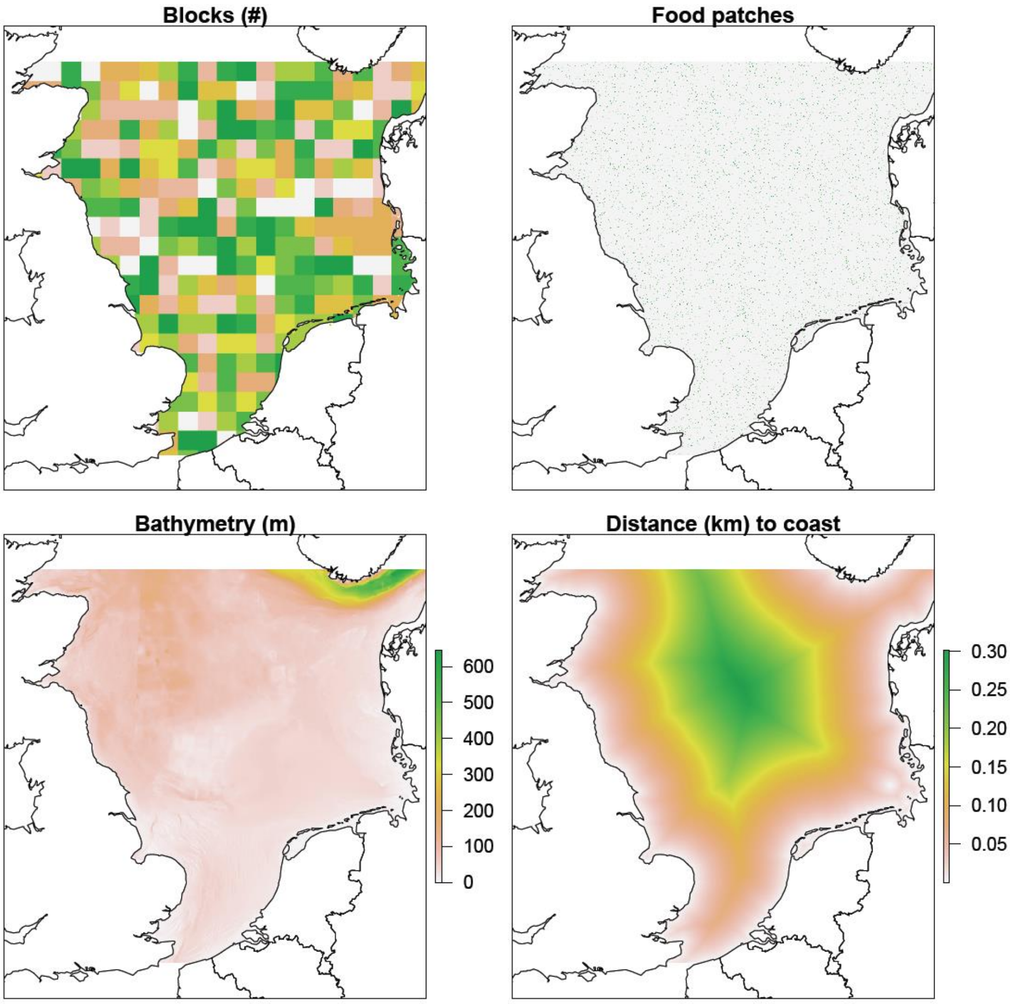


Figure 9. Overview of the underlying data maps of the North Sea used to control harbour porpoise movement in the DEPONS model. The seasonal porpoise density maps as shown in *Fig. 8* are also incorporated and used to calculate the average potential food level in each 40 km × 40 km block. The colours in the 'Blocks (#)' figure are arbitrary, and in the 'Food patches' figure the distribution of 400 m × 400 m food patches are shown in green. Note that the legend of the bathymetry map is in absolute values.

2.7 Initiating simulations in the DEPONS model

To initiate simulations in the DEPONS model, the user needs to specify values for a number of parameters that inform the model about the duration of the simulations, porpoise movement and dispersal types, the strength of noise deterrence behaviour, pile-driving activity, etc. To make it possible to replicate the main results of this report for the North Sea landscape, the values for each parameter are given and briefly explained in *Table 4*.

Table 4. Overview of the DEPONS model parameter settings used in the North Sea landscape simulations of this report.

Parameter	**Value(s)**	**Description**
Simulation years	40	Length (yrs.) of simulation run. Output was analysed for the last 30 years of each simulation.
Landscape	North Sea	Landscape to use in simulation.
Porpoise count	4000	No. of porpoise agents at the start of each simulation (randomly distributed across landscape). Each porpoise agent is a super individual representing several real-world female porpoises, which is an approach commonly used in individual-based modelling to avoid the long computation times associated with large numbers of agents (*Scheffer et al. 1995*). The starting value was chosen as it provided a stable carrying capacity of the porpoise population within 10 simulation years for the most realistic movement/dispersal models (4 & 5).
Dispersal	Off, 3, 4, 5	Movement/dispersal type to use in simulation (numbers correspond to models in *Table 1*). If movement models 1 or 2 are used, dispersal is off.
Max-disp-dist	0, 200	Maximum dispersal distance (km). Should be set to 200 for dispersal model 5, else 0 (indicating unrestricted search).
D_{disp}	1.6	Dispersal distance (km) per time step (30 min.) (J. Teilmann, unpublished satellite data).
Turbines	Off, scenario 1, 2	Pile-driving scenario to use in simulation. Off will run a baseline (no noise) simulation. Scenarios 1-2 are described in *Tables 2* & *3*.
c	0.001	Deterrence coefficient (unit less). Value calibrated using POM (*Fig. 5*).
D_{deter}	51	Standard deterrence distance (m). Value calibrated using POM (*Fig. 5*).
T_{deter}	5	Deterrence time or the number of 30 min. steps the deterrence effect lasts (*Nabe-Nielsen et al. 2014*).
E_{use}	4.5	Energy use/step (30 min.) in May-September (*Nabe-Nielsen et al. 2014*).
H	0.68	Probability of becoming pregnant (*Read and Hohn 1995*).
Q	12	Number of potential dispersal targets = 40 km × 40 km blocks (*Nabe-Nielsen et al. 2014*).
R_U	0.1	Food replenishment rate (unit less) (*Nabe-Nielsen et al. 2013b*).
r_R	0.1, 0.3	Reference memory decay rate (unit less). Determines how fast the animal forgets previously visited food patches (*Nabe-Nielsen et al. 2013b*). Values of 0.1 and 0.3 were used in dispersal models 1 and 2, respectively (*Table 1*).
R_S	0.2	Satiation memory decay rate (unit less). Determines how fast a porpoise agent gets hungry after eating (*Nabe-Nielsen et al 2013b*).
U_{max}	1	Maximum energy content in a food patch (*Nabe-Nielsen et al. 2014*).
W_{disp}	4	Min. water depth (m) when dispersing (*Nabe-Nielsen et al. 2014*).
W_{min}	1	Min. water depth (m) required by porpoises (J. Tougaard, pers. obs.)
Beta	0.4	Survival probability (*Nabe-Nielsen et al. 2014*).

Running simulations in the DEPONS model can be done in two ways. First, the user can load the Repast User Interface (UI). This method loads a window with a tab called “Parameters”. Once the values for each parameter are provided (following *Table 4*), the simulation can be initiated (power button) and a new tab called “PorpoiseSim Display with depth” appears (*Fig. 10*). By starting the simulation (play button) the user can visually follow the porpoise movements. The agents (porpoises) are shown as arrows and change colour depending on their energy level (green = optimal, yellow/orange = low, red = near death). If turbines, and as such pile-driving noise, are present in the landscape, porpoises that are close to turbines are deterred and change colour (purple: *Fig. 11*). Running simulations in the UI is helpful for visual calibration of the model and to verify that the model works as expected (*Fig. 11*). The UI also provides many other types of graphical output, including energy level, number of births and deaths, porpoise population size and age distribution. These panels are continuously updated as the simulation runs.

The second approach to initiate and run simulations is to launch the Batch mode. The main advantage of the Batch mode is that several simulations can be performed simultaneously and it runs at a greater speed compared to the UI simulations. All simulations for this report were performed in batch mode. Parameter values for each simulation should be provided in the Batch Parameter tab (*Fig. 12*) before starting the batch run.

A complete and more detailed documentation concerning the installation of Repast software, how to import the source code of the DEPONS model, and run simulations can be obtained by contacting the authors of this report.

2.8 Analysis of simulation output

Based on 3 different pile-driving scenarios (2 with noise and 1 baseline without noise) and 5 different movement/dispersal models, a total of 15 different simulations were performed in the DEPONS model. Each simulation was replicated 5 times. The first 10 years of all simulations were considered a burn-in period (to allow the population dynamics to stabilize, see *Appendix 1*) and as such discarded from any statistical analyses.

To quantify potential, temporary effects of the different pile-driving scenarios on the harbour porpoise population size, we used generalised least squares (GLS) regressions. We fitted a GLS regression for each movement model separately but only if the population dynamics stabilised within the first 10 years of the simulation (burn-in period). We calculated the annual population size, on day 180 of each simulation year for the 6-year period in which pile driving occurred, for each simulation replicate and for each of the 15 simulations (Nobs = 450). Annual population size was subsequently included as the dependent variable in the GLS models. The independent variable in each statistical model was the pile-driving scenario (3-level factor). To account for any autocorrelation in population size, we incorporated simulation year as a temporal autoregressive correlation structure (corAR1). The statistical analyses were done in R 3.0.2 (*R Development Core Team 2013*).

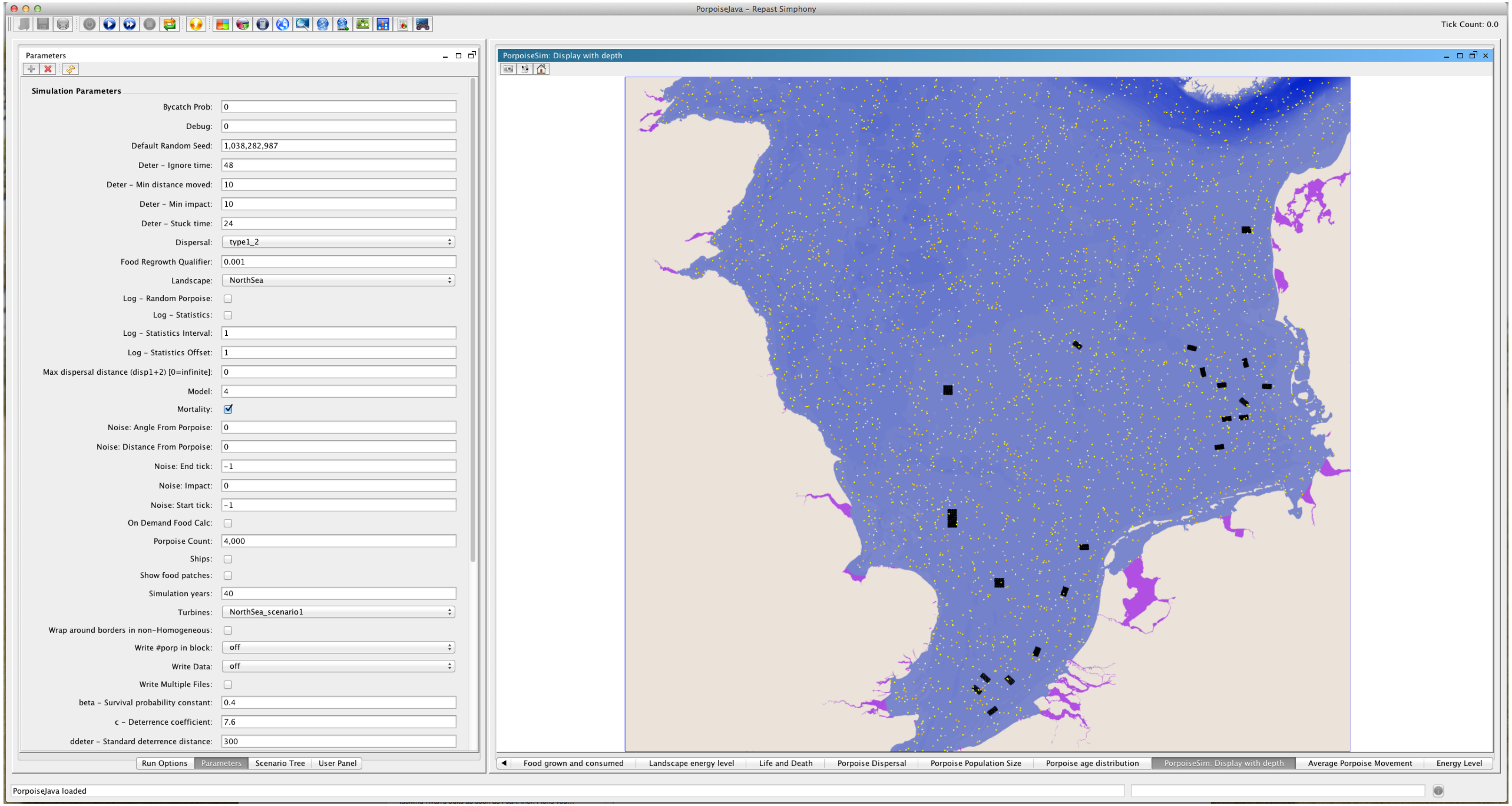


Figure 10. The Repast User Interface (UI) of the current version of the DEPONS model. The panel on the left shows the Parameter tab. The panel on the right shows the North Sea landscape, including bathymetry (m), 4000 porpoises distributed at random (yellow/orange dots), all wind farm parks from scenario 1 (black shapes), as well as the coastline of the UK, the Netherlands, Denmark, Germany and Belgium. Purple areas are masked/closed off water bodies that simulated porpoises cannot enter.

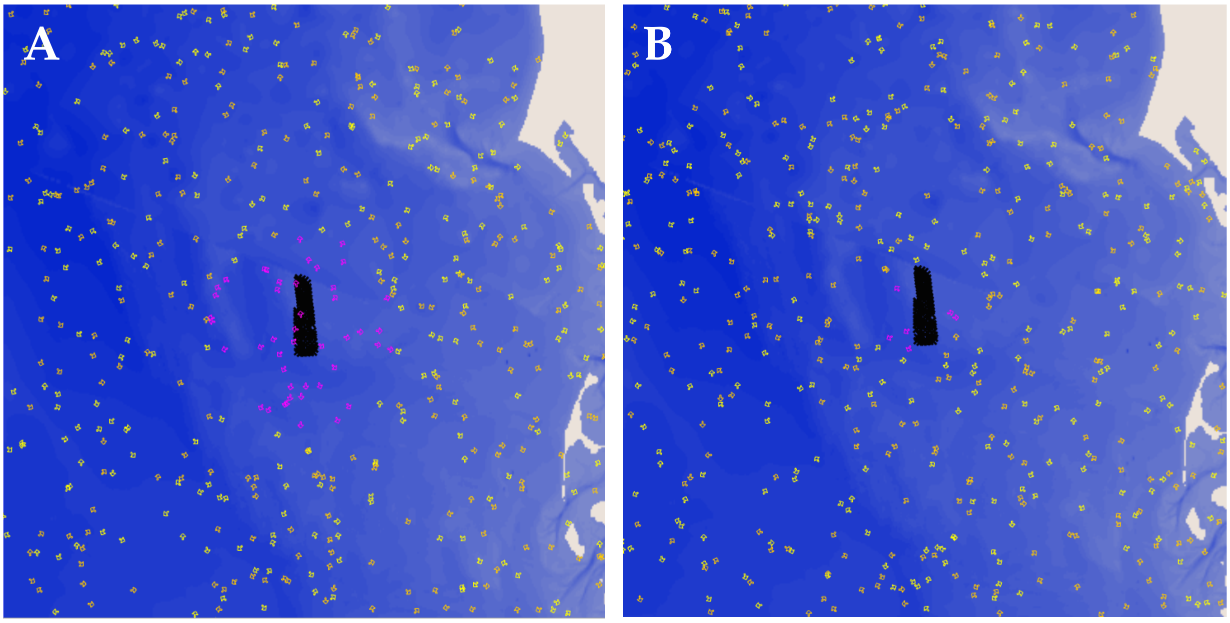
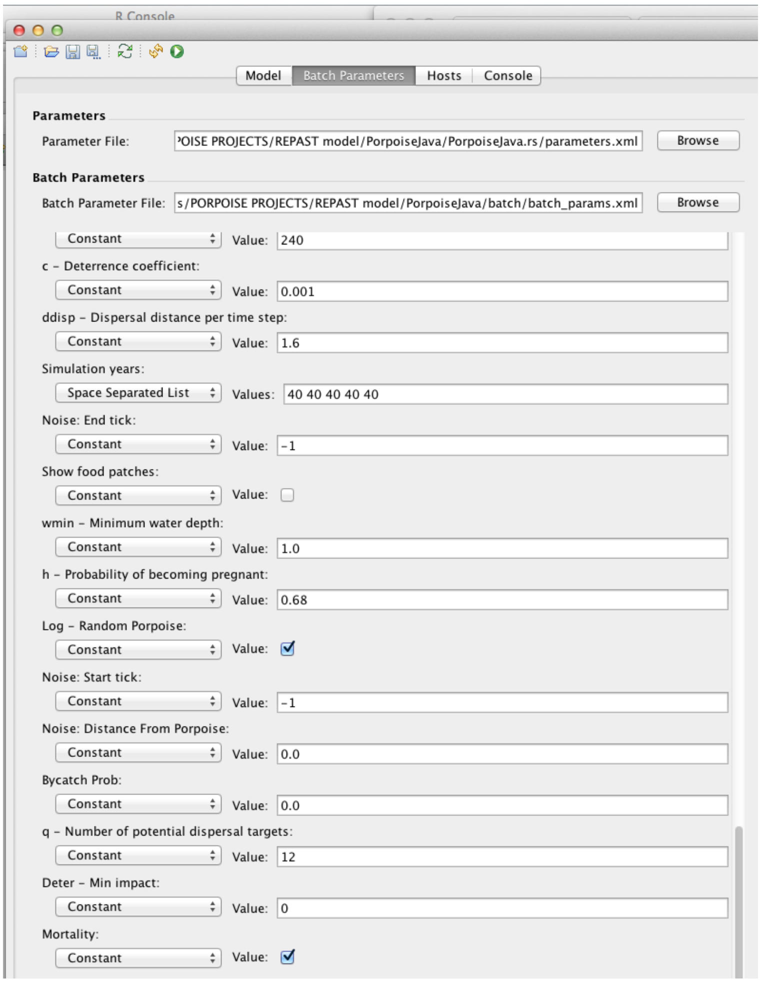


Figure 11. Visual example of different porpoise deterrence behaviours due to pile-driving noise in the DanTysk landscape of the DEPONS model. Porpoises that are deterred show up in purple. Panel A shows a scenario with a deterrence distance (d_{deter}) of 100 m with an impact of 238 dB (causing porpoises to be disturbed up to 23.8 km from pilings) and a deterrence coefficient (*c*) of 1. Panel B shows a scenario with a deterrence distance (d_{deter}) of 51 m with an impact of 238 dB (causing porpoises to be disturbed up to 12.1 km from pilings) and a deterrence coefficient (*c*) of 0.001.

Figure 12. The parameters tab of the Batch mode of the DEPONS model.



3 Results

3.1 Movement/dispersal and population size and dynamics

Population size and dynamics differed greatly between the 5 movement models considered (*Figs. 13* & *14*). Only considering the baseline (no pile-driving noise) scenario, the mean population size over the last 30 years of the simulation was smallest (mean = 105 ± 78.5 SD) in the CRW + low spatial memory model where simulated animals gradually diffused away from their starting point (*Fig. 13*). However, the population dynamics did not stabilize within 40 simulation years when using this movement model, as the population size continuously declined over time (*Fig. 14*). In contrast, the CRW + high spatial memory model produced a substantially greater population size (mean = 2404 ± 110 SD; *Fig. 13*). Nevertheless, in this model the population dynamics also did not stabilize as the population size continued to increase over time (*Fig. 14*).

Of the tested dispersal models, the dispersal away from low food availability sites yielded the lowest mean population size (mean = 255 ± 178 SD; *Fig. 13*). Similar to the CRW + low spatial memory model, this dispersal type did not produce stable population dynamics as the population size continuously declined over time (*Fig. 14*). Dispersal towards patches with high food availability yielded the greatest population sizes of all movement/dispersal models considered. When dispersal search was unrestricted, the mean population size over the last 30 years of the simulation was 9560 ± 50 SD (*Fig. 13*), and even higher when dispersal search was restricted to 200 km (mean = 11155 ± 56 SD; *Fig. 13*). Both dispersal towards food types produced stable population dynamics after the 10-year burn-in period (*Fig. 14*).

3.2 Pile-driving noise and population dynamics

A visual inspection of model output did not yield clear differences in population sizes and dynamics between the baseline scenario (without pile-driving noise) and pile-driving scenarios 1 and 2 for the years where pile driving took place (*Fig. 14*), and pile driving did not appear to influence the average population size (*Fig. 13*). However, the CRW movement models and the 'dispersal away' model did not produce stable population dynamics before pile-driving noise was introduced in the simulations (*Fig. 14*) and as such we cannot reliably quantify a statistical effect or any relation between pile-driving noise and porpoise population dynamics for these three models. In contrast, the dispersal towards food rich areas (both restricted and unrestricted search) did produce stable population dynamics after the 10-year burn-in period, and we tested for differences in the mean population size between pile-driving scenarios using generalised least squares regression. In both the restricted and unrestricted dispersal models we found a slightly higher population size in scenario 1 compared to the baseline (no noise) scenario (*Fig. 15*) but no difference between scenario 2 and the baseline scenario. This was because in scenario 2 the population size typically decreased compared to scenario 1, though this difference in population size between pile-driving scenarios 1 and 2 was not statistically significant (*Fig. 15*). These statistical tests should, however, be interpreted with caution, as the underlying movement models are unlikely to reflect real porpoise behaviour in the North Sea.

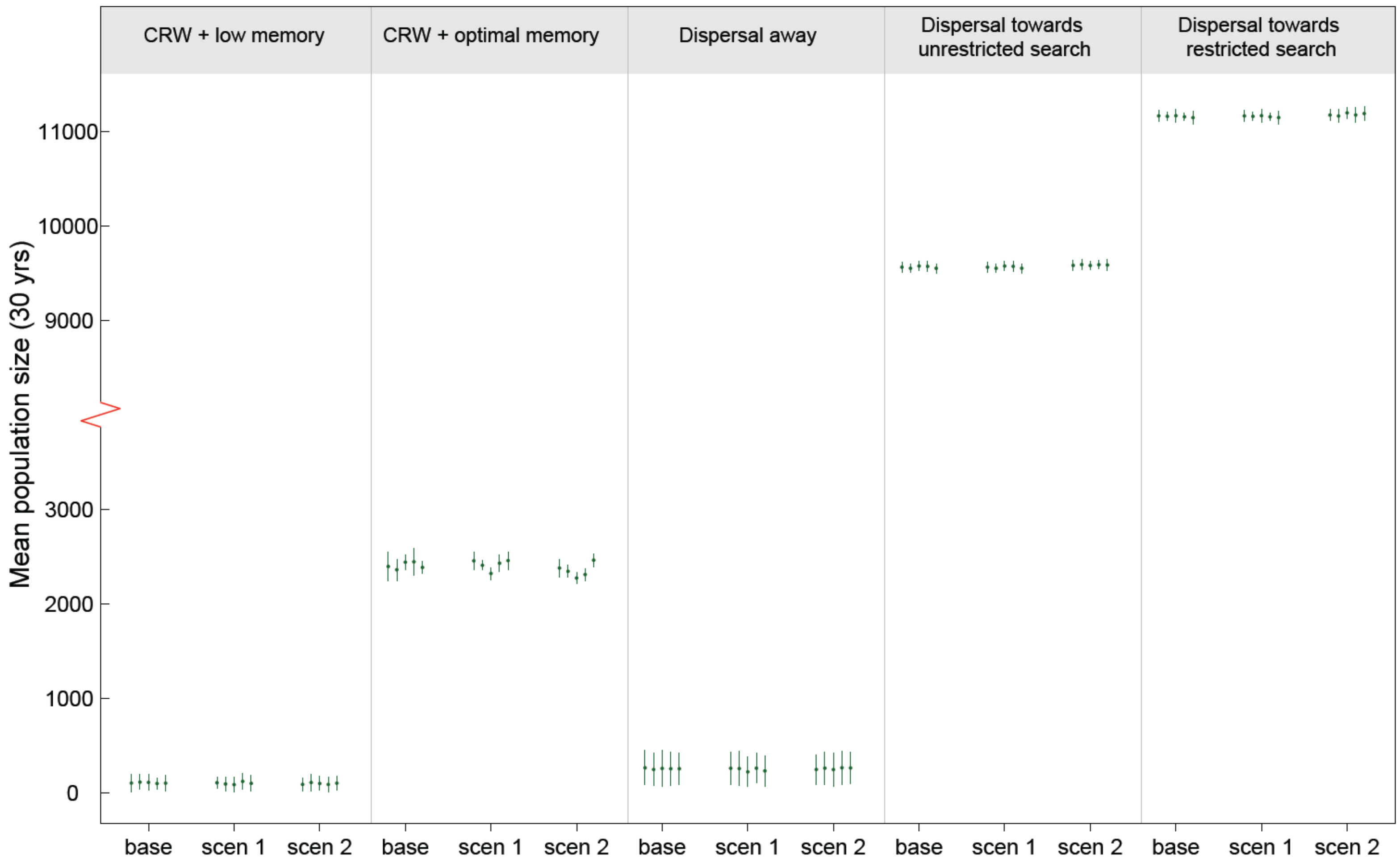


Figure 13. Overview of the mean population size over 30 years of simulated harbour porpoises in the North Sea across five different movement/dispersal models (*Table 1* & *Fig. 6*) and 3 pile-driving scenarios (*Table 2 & Fig. 7*). The mean population sizes (± 1 SD) were calculated for each of the 5 replicates separately using one yearly population count (on day 180) for the last 30 years of each simulation. Note the break on the y-axis. The model output should be interpreted with caution and be considered a preliminary result.

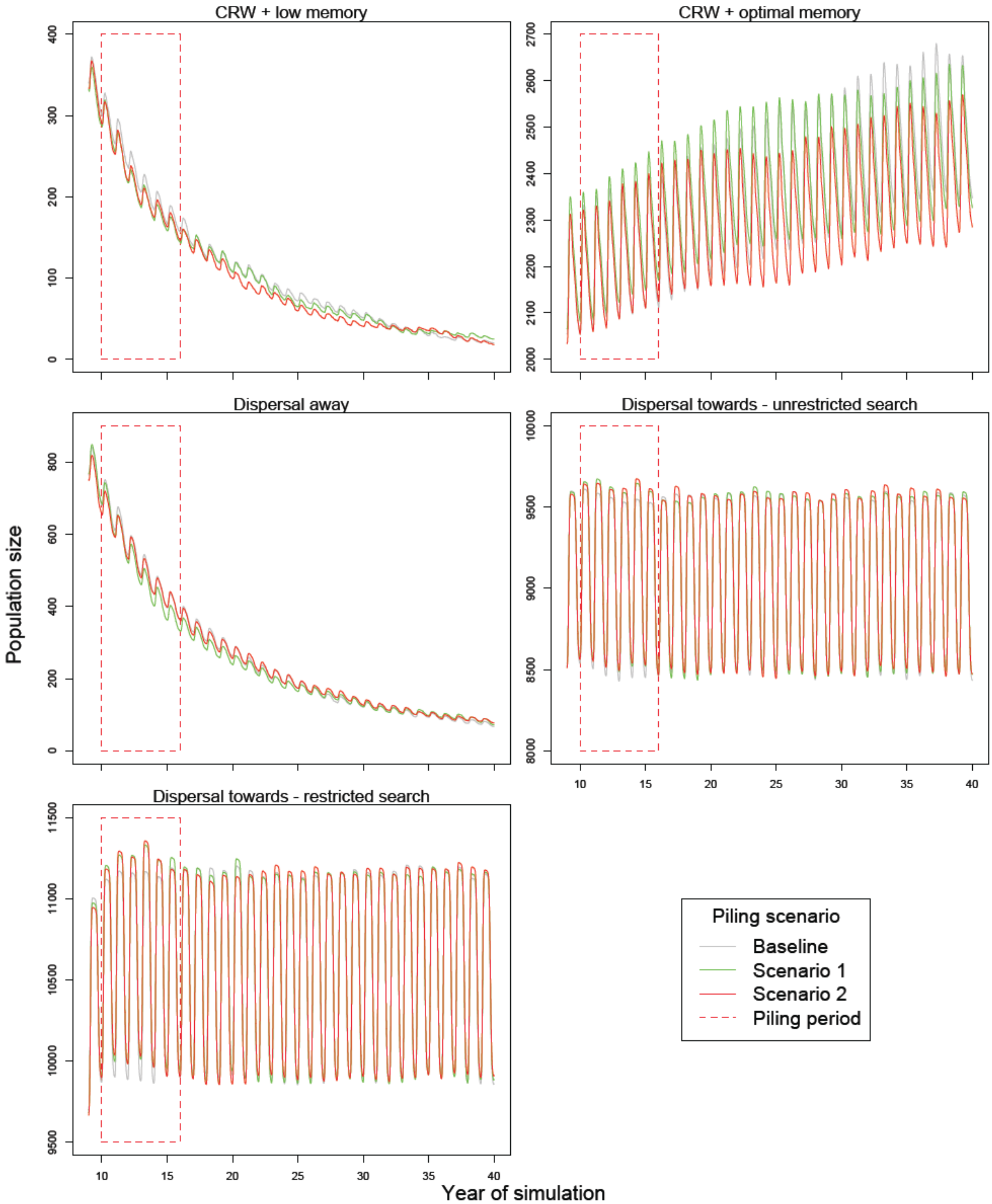


Figure 14. Variations in mean daily population size of simulated harbour porpoise in the North Sea across five different movement/dispersal models (*Table 1* & *Fig. 6*) and 3 pile-driving scenarios (*Table 2* & *Fig. 7*). Each curve shows the average of five replicate runs for a particular scenario. The dotted red box indicates the period in which pile-driving events occurred. The model output should be interpreted with caution and considered as a preliminary result.

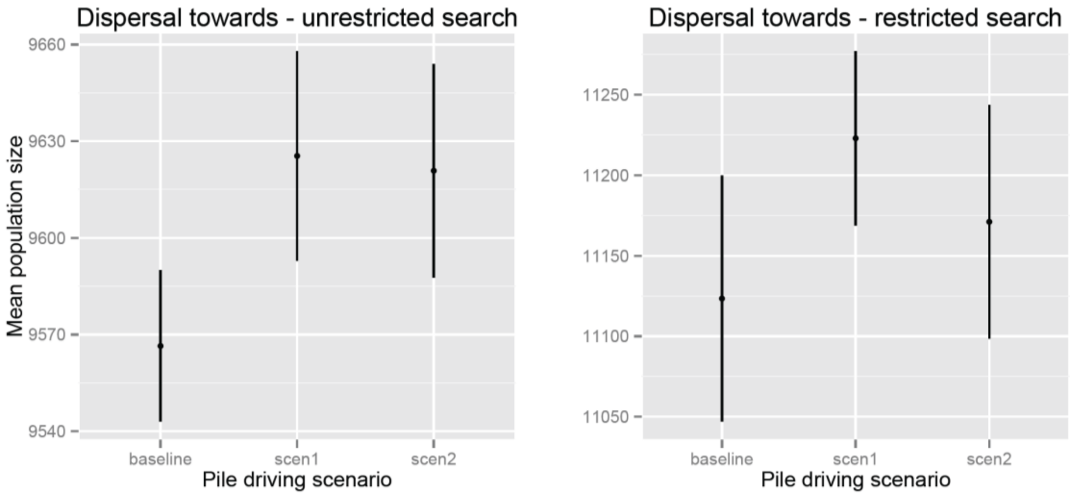


Figure 15. Effect plot of the generalised least squares regressions of the dispersal towards food rich sites (both unrestricted and restricted search; *Table 1* & *Fig. 6*) testing for differences in mean population size between the baseline (no pile-driving noise) and scenario 1 (realistic minimum) and 2 (realistic worst case) (*Table 2* & *Fig. 7*) The mean (and 95 % confidence interval) population sizes were calculated for each of the 5 replicate runs on day 180 between year 9 and year 15 in which pile-driving events occurred. The model output should be interpreted with caution and serves as a preliminary result.

4 Discussion

4.1 Effects of movement/dispersal strategies on population size and dynamics

We have explored the effect of five different movement/dispersal strategies on harbour porpoise population dynamics in the North Sea. The movement/dispersal strategies considered here were a combination of theoretical movement models (*Turchin 1998*) and dispersal behaviour observed by porpoises in the inner Danish waters (*Nabe-Nielsen et al. 2013b*; *Nabe-Nielsen et al. 2014*). Although these movement/dispersal models are unlikely to reflect real porpoise movement behaviour in the North Sea and as such inference from the current version of the DEPONS model is limited, our movement framework can provide valuable insight into how different movement behaviours influence population dynamics. Clearly the DEPONS model will improve greatly in quality once real movement behaviour of porpoises living in the North Sea becomes available (DEPONS SP 3 & 7).

Despite the limitations of empirical movement data from the North Sea, the five movement/dispersal strategies considered here had a strong influence on the population size and dynamics. Importantly, both the "CRW + low spatial memory" and the "dispersal away" strategies did not produce stable population sizes. In fact, with both strategies the population would likely go extinct if the simulation continued beyond 40 years. This is a clear indication that these two strategies are unlikely to reflect evolutionarily advantageous dispersal strategies for harbour porpoises in the North Sea. Similarly, the "CRW + high spatial memory" strategy also did not produce a stable population size but, instead, it steadily increased over time, even up to year 40 of the simulation. More detailed and longer simulations are required to determine if and when equilibrium can be reached using this movement strategy. Nevertheless, it remains unlikely that porpoises in the North Sea employ this strategy, as it lacks the long-distance dispersal or migratory movements that are common among marine and terrestrial mammals (*Fryxell & Sinclair 1988*; *Clapham et al. 1993*). However, the "CRW + high spatial memory" strategy does serve as a valuable theoretical model (*Turchin 1998*) and neatly demonstrates that cognitive processes are of great importance when studying animal movements and population dynamics (*Nathan et al. 2008*). The "Dispersal towards food rich areas" model produced stable population sizes after ten simulation years, with mean population sizes far greater than the other movement/dispersal models considered. Indeed, when energy levels start dropping in the area currently being used, dispersing towards areas where energy intake is likely greater should maintain or even increase energy levels and as such individual fitness and subsequently population growth. Our model showed that when the dispersal range is restricted to 200 km, the mean population size was higher than when using an unrestricted search model. This finding can be explained by an increased efficiency in foraging behaviour in the restricted model as it forces individuals to select and disperse towards a target block with sufficient food that can physically be reached before energy levels drop to levels associated with strongly increased mortality. This death-before-reaching-food process occurs more often in the unrestricted dispersal model and as such the equilibrium population size is lower compared to the restricted dispersal model.

4.2 Effects of pile-driving noise on population size and dynamics

To provide a first and preliminary evaluation of the effects of pile-driving noise from wind farm construction in the North Sea on porpoise population size and dynamics, we compared a baseline scenario (no pile-driving noise) with a most likely minimum development scenario (scenario 1) and a realistic worst case scenario for wind farm development (scenario 2). Deterrence behaviour of porpoises in the DEPONS model was calibrated in such a way that it produced the same reduction in porpoise densities up to 15 km from the noise source as observed before and during actual pile-driving events at the DanTysk wind farm site in the North Sea. As such, the current version of the DEPONS model does produce realistic changes in local population densities due to pile-driving noise.

Based on the current status of the DEPONS model, we did not observe a strong effect of pile-driving noise on harbour porpoise population size and dynamics. Strong conclusions cannot be made, as the dispersal behaviour in the current DEPONS model is unlikely to reflect true porpoise behaviour in the North Sea. Nevertheless, it is clear that the current pile-driving scenarios are unlikely to cause population crashes or trigger long-term population effects. In fact, and in contrast with the general notion that anthropogenic disturbances negatively affect individual fitness, we observed a slight but temporary increase in population size (*Fig. 15*) when pile driving was activated (baseline vs scenario 1). However, when the number of piling events increased further in space and time (scenario 1 vs scenario 2), we observed a minor decline in population size, though it remained higher than in the baseline period (baseline vs scenario 2).

More detailed and further simulations are required to determine whether these findings are robust and follow from tangible biological processes or whether it is based on incorrect assumptions of porpoise movements and deterrence behaviour. For example, the importance and sensitivity of the DEPONS model output to the parameter deterrence time (i.e. the number of steps [30 min.] the deterrence effect lasts) has not been explored in the current report. This parameter is likely to influence the time it takes before porpoises return to a construction site, which has been identified as potentially having a strong effect on the population size using the PCoD modelling framework (J. Harwood, pers. comm.). At present, the results are based on a deterrence time of 5 time steps (2.5 hrs.) after the noise has disappeared. This value functioned well when explaining the effects of noise from ships and operational wind turbines on the harbour porpoise population in the inner Danish waters (*sensu Nabe-Nielsen et al. 2014*). A preliminary analysis of the data collected by DanTysk (DEPONS SP 4) suggests that the time it takes for porpoise densities to recover in the piling area (i.e. return-times) is comparable to those observed in the current version of the DEPONS model (approximately 12 hours), suggesting that the employed deterrence time is a good first estimate. Longer deterrence times would have resulted in longer return-times and slower recovery of the population in the vicinity of the piling area. The results on deterrence behaviour are therefore preliminary. The importance of understanding porpoise return-times is indeed crucial as it may also provide some biological insight into the slight increase in porpoise population size during piling events. For example, it may be that, while porpoise abundance/density declines within a 15 km radius during pile-driving events, this time period allows nearly depleted food patches in the

DEPONS model to increase sufficiently to sustain larger porpoise population sizes than would be the case in the absence of noise.

4.3 IBM improvements and potential future developments

This report demonstrates how the individual-based population model that was developed by *Nabe-Nielsen et al. (2014)* can be used to evaluate the impact of pile-driving noise from wind farm construction on the porpoise population in the North Sea. Although we successfully reached this goal, the current status of the IBM and the output should be considered as under development and preliminary. Indeed, some processes in the current DEPONS model, especially those involved in the movement/dispersal models, are based on assumptions, as empirical data from the North Sea required to calibrate key parameters are currently lacking. Here we highlight some of the main points that require careful consideration and further development so as to improve the DEPONS model further. This list also includes improvements required to study the biological mechanisms governing porpoise population dynamics, which were not the main aim of this report, but will be a focus area in the future.

- Food availability is a major determinant of population dynamics of most species (*Gaillard et al. 2000*; *Sibly & Hone 2002*; *Oro et al. 2004*). The DEPONS model currently uses porpoise density as a proxy for food availability. Clearly, the output of the DEPONS model is sensitive to the quality of the underlying density maps. Nevertheless, we believe that the approach of using porpoise density as a proxy for food availability is suitable and robust when the aim is to estimate the effect of anthropogenic disturbances (e.g. pile driving) on porpoise population dynamics (*Nabe-Nielsen et al. 2014*). When using porpoise density as a proxy of food availability, food preferences and requirements for a balanced diet are implicitly taken into account. If a particular dispersal model enables the simulated porpoises to move realistically, it will also enable them to encounter simulated pile-driving areas and be scared away in a realistic fashion, which might not be the case if using prey data as model input. In contrast, when using the DEPONS model to gain understanding of the biological mechanisms governing porpoise population dynamics (as will be done in the future), a better approach would be to employ food availability maps directly. However, because data on the spatial and temporal distribution of porpoise prey items in the North Sea are limited, creating seasonal food availability maps is challenging. Further, data on the porpoise diet composition are scarce, making it difficult to assess the relative importance of different potential prey species. One possible approach to reach the goal of incorporating prey availability directly would be to employ data collected during scientific fish surveys. Such surveys provide detailed data of fish availability on a fine-spatial scale that could provide valuable estimates of variation in porpoise prey availability throughout the North Sea. Alternatively, forage maps can be modelled based on spatial and temporal variation in primary production (i.e. planktonic algae).

- Related to the previous point, the availability and spatial distribution of food for porpoises, as well as other species, change continuously and may be influenced by anthropogenic activities. One way to explore how pile driving influences the prey availability and at the same time get a direct estimate of the spatial distribution of prey would be to use sonars on commercial fishing vessels to monitor the distribution of fish. This could be combined with survey trawling and monitoring of porpoises before, during and after pile driving in order to establish the direct causal links between prey availability and porpoise behaviour. In the future, this kind of study might be a valuable alternative to traditional monitoring programmes.

- Another anthropogenic activity that influences the spatial and temporal distribution of porpoise prey is commercial fishing. A valuable future addition to the DEPONS model would be to introduce commercial fishing boats as agents so as to decrease the amount of food available for porpoises. This would allow for more realistic and detailed tests of how changes in forage availability influence porpoise behaviour as well as population dynamics. A related but easier aspect to incorporate in the DEPONS model is the effect of porpoise by-catch in gill nets on population dynamics (*Nabe-Nielsen et al. 2014*).

- We have already emphasized the importance of incorporating movement/dispersal models that are based on empirical movement data collected in the North Sea (as under DEPONS SP 3 & 7). This aspect is absolutely crucial as movement strategies influence how, where and when porpoises forage and as such subsequent population dynamics. The behavioural strategies considered in this report provide a good starting point and have inherent scientific value but to make the DEPONS model more realistic and provide guidance in wind farm construction planning, the inclusion of realistic movement and dispersal behaviours in the model are essential.

- Deterrence behaviour of individuals to pile-driving noise needs to be developed further. Data on deterrence time due to pile-driving noise are difficult to obtain but some insight may be gained from DEPONS SP 1, which can be used to further calibrate deterrence time. Performing a sensitivity analysis of the model will also reveal the strength of deterrence time on the DEPONS model output, which can then be used to compare its importance within the PCoD modelling framework (J. Harwood, pers. comm.).

- Porpoise return-times following pile-driving events (i.e. the time elapsed until densities around pile-driving sites return to pre-piling levels) are another aspect related to deterrence behaviour that needs to be inspected further. Insight into this process will be obtained using data collected under DEPONS SP 4, which are currently being analysed. In the current version of the DEPONS model, porpoise densities return to pre-piling levels in less than a day, which is consistent with preliminary findings from DEPONS SP 4. A better understanding of porpoise return-times is critical, as the preliminary results of this report suggest a positive feedback-loop may exist between return-times and food replenishment within the pile-driving areas. This should be studied in detail based on simulation output, but a more detailed investigation of the food levels in wind farm construction areas before, during and after turbine construction (using scientific fish surveys as discussed above) is necessary to shed light on the prevalence of such processes in nature (*Dåhne et al. 2013*).

- A complete sensitivity analysis of the parameters currently in the model is essential. This includes an analysis of the effects of altering the spatial and temporal distribution of food. This exercise will provide insight into the most important variables influencing the DEPONS model output (i.e.

population dynamics). Moreover, such an analysis may highlight parameters for which more data need to be collected if these turn out to have a major impact on the output but their values are based on assumptions or knowledge from other parts of the porpoise distribution. One example includes the parameter maximum dispersal distance. Here we subjectively choose a value of 200 km, as this is a distance that porpoises are known to disperse in the IDW. However, this value may be too conservative for porpoises living in the North Sea environment.

To conclude, the DEPONS model described in this report requires additional development and testing before robust conclusions concerning the effect of pile-driving noise on harbour porpoise population dynamics in the North Sea can be drawn. We have identified a number of crucial components that need to be incorporated into the DEPONS model to relax or corroborate current assumptions. Many of these outstanding issues will be addressed in the near future as part of the DEPONS project. Nonetheless, the current version of the DEPONS model can already be regarded as a valuable tool and solid framework to evaluate the effect of wind farm construction on porpoise population dynamics. Furthermore, the DEPONS model can, in the future, be extended to include other species, disturbances, and environmental processes not currently considered. Much exciting work remains to be done.

5 Literature

Avgar T, Mosser A, Brown GS & Fryxell JM (2013) Environmental and individual drivers of animal movement patterns across a wide geographical gradient. – Journal of Animal Ecology 82: 96-106. doi: 10.1111/j.1365-2656.2012.02035.x

Bailey H, Senior B, Simmons D, et al. (2010) Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. - Marine Pollution Bulletin 60: 888–897. doi: 10.1016/j.marpolbul.2010.01.003

Barton K a., Phillips BL, Morales JM & Travis JMJ (2009) The evolution of an "intelligent" dispersal strategy: biased, correlated random walks in patchy landscapes. - Oikos 118: 309-319. doi: 10.1111/j.1600-0706.2008.16936.x

Betke K & Schult-von Glahn M (2008) Prognose des Unterwassergeräusches beim Bau und beim Betrieb des Offshore-Windparks Borkum-West („alpha ventus") und Messung des Hintergrundgeräusches im Planungsgebiet. 41.

Börger L, Dalziel BD & Fryxell JM (2008) Are there general mechanisms of animal home range behaviour? A review and prospects for future research. - Ecology Letters 11: 637-650. doi: 10.1111/j.1461-0248.2008.01182.x

Bunnefeld N, Borger L, van Moorter B, et al. (2011) A model-driven approach to quantify migration patterns: individual, regional and yearly differences. - Journal of Animal Ecology 80: 466-476. doi: 10.1111/j.1365-2656.2010.01776.x

Clapham PJ, Baraff LS, Carlson CA, et al. (1993) Seasonal occurrence and annual return of humpback whales, *Megaptera novaeangliae*, in the southern Gulf of Maine. - Canadian Journal of Zoology 71: 440-443. doi: 10.1139/z93-063

Dåhne M, Gilles A, Lucke K, et al. (2013) Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. – Environmental Research Letters 8:025002. doi: 10.1088/1748-9326/8/2/025002

DeAngelis DL & Mooij WM (2005) Individual-based modeling of ecological and evolutionary processes. - Annual Review of Ecology, Evolution, and Systematics 36: 147-168. doi: 10.1146/annurev.ecolsys.36.102003.152644

Dobson FS & Jones WT (1985) Multiple Causes of Dispersal. - The American Naturalist 126: 855–858. doi: 10.2307/2461260

EU (1992) Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora.

Fryxell JM & Sinclair ARE (1988) Causes and consequences of migration by large herbivores. - Trends in Ecology & Evolution 3: 237-241.

Fryxell JM, Wilmshurst JF & Sinclair ARE (2004) Predictive models of movement by Serengeti grazers. - Ecology 85: 2429-2435.

Gaillard JM, Festa-Bianchet M, Yoccoz NG, et al. (2000) Temporal variation in fitness components and population dynamics of large herbivores. - Annual Review of Ecology and Systematics 31: 367-393. doi: 10.1146/annurev.ecolsys.31.1.367

Galanthay TE & Flaxman SM (2012) Generalized movement strategies for constrained consumers: ignoring fitness can be adaptive. - The American Naturalist 179: 475-489. doi: 10.1086/664625

Grimm V, Frank K, Jeltsch F, et al. (1996) Pattern-oriented modelling in population ecology. - Science of The Total Environment 183: 151-166. doi: 10.1016/0048-9697(95)04966-5

Grimm V & Railsback SF (2005) Individual-based modeling and ecology. Princeton University Press

Hawkes C (2009) Linking movement behaviour, dispersal and population processes: is individual variation a key? – Journal of Animal Ecology 78: 894-906. doi: 10.1111/j.1365-2656.2009.01534.x

Kramer-Schadt S, Revilla E, Wiegand T & Grimm V (2007) Patterns for parameters in simulation models. - Ecological Modelling 204: 553-556.

Kyhn LA, Tougaard J, Thomas L, et al. (2012) From echolocation clicks to animal density—Acoustic sampling of harbor porpoises with static dataloggers. - The Journal of the Acoustical Society of America 131: 550-560. doi: 10.1121/1.3662070

Morales JM, Haydon DT, Frair J, et al. (2004) Extracting more out of relocation data: Building movement models as mixtures of random walks. - Ecology 85: 2436-2445.

Nabe-Nielsen J, Tougaard J, Teilmann J & Sveegaard S (2011) Effects of wind farms on harbour porpoise behavior and population dynamics. - Scientific Report from Danish Centre for Environment and Energy No. 1. 48 pp.

Nabe-Nielsen J, Teilmann J & Tougaard J (2013a) Effects of wind farms on porpoise population dynamics. Danish Offshore Wind. Key Environmental Issues – a Follow-up. The Environmental Group: The Danish Energy Agency, The Danish Nature Agency, DONG Energy and Vattenfall, Copenhagen, Denmark, pp 61–68.

Nabe-Nielsen J, Tougaard J, Teilmann J, et al. (2013b) How a simple adaptive foraging strategy can lead to emergent home ranges and increased food intake. - Oikos 122: 1307-1316. doi: 10.1111/j.1600-0706.2013.00069.x

Nabe-Nielsen J, Sibly RM, Tougaard J, et al. (2014) Effects of noise and bycatch on a Danish harbour porpoise population. - Ecological Modelling 272: 242-251. doi: 10.1016/j.ecolmodel.2013.09.025

Nathan R, Getz WM, Revilla E, et al. (2008) A movement ecology paradigm for unifying organismal movement research. – Proceedings of the National Academy of Sciences of the United States of America 105: 19052-19059.

Olson KA, Fuller TK, Mueller T, et al. (2010) Annual movements of Mongolian gazelles: Nomads in the Eastern Steppe. - Journal of Arid Environments 74: 1435-1442. doi: 10.1016/j.jaridenv.2010.05.022

Oro D, Cam E, Pradel R & Martínez-Abraín A (2004) Influence of food availability on demography and local population dynamics in a long-lived seabird. - Proceedings of the Royal Society of London B: Biological Sciences 271: 387-396. doi: 10.1098/rspb.2003.2609

R Development Core Team (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Read AJ & Hohn AA (1995) Life in the fast lane: the life history of harbor porpoises from the Gulf of Maine. - Marine Mammal Science 11: 423-440. doi: 10.1111/j.1748-7692.1995.tb00667.x

Scheffer M, Baveco JM, DeAngelis DL, et al. (1995) Super-individuals a simple solution for modelling large populations on an individual basis. Ecological Modelling 80: 161-170. doi: 10.1016/0304-3800(94)00055-M

Schwarzkopf L & Alford RA (2002) Nomadic movement in tropical toads. - Oikos 96: 492-506. doi: 10.1034/j.1600-0706.2002.960311.x

Sibly RM & Hone J (2002) Population growth rate and its determinants: an overview. - Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 357: 1153-1170. doi: 10.1098/rstb.2002.1117

Sibly RM, Grimm V, Martin BT, et al. (2013) Representing the acquisition and use of energy by individuals in agent-based models of animal populations. - Methods in Ecology and Evolution 4: 151-161. doi: 10.1111/2041-210x.12002

Skellam JG (1951) Random Dispersal in Theoretical Populations. – Biometrika 38: 196-218. doi: 10.2307/2332328

Tougaard J, Kyhn L, Amundin M, et al. (2012) Behavioral Reactions of Harbor Porpoise to Pile-Driving Noise. In: Popper A & Hawkins A (eds) The Effects of Noise on Aquatic Life. Springer New York, pp 277–280.

Turchin P (1998) Quantitative analysis of movement: Measuring and modeling population redistribution in animals and plants. Sinauer Associates, Inc. Sunderland, Massachusetts, USA, Turchin, Peter; Univ. Connecticut, Storrs, Connecticut, USA.

Turner MG (2005) Landscape ecology: What is the state of the science? - Annual Review of Ecology, Evolution, and Systematics 36: 319-344.

Appendix 1 – Overview of simulation phases

All pile-driving scenarios investigated in this report (i.e. both the DanTysk and the North Sea simulations) consisted of 3 phases. The first phase is termed the pre-piling burn-in period, which was the time period required to let the porpoise population dynamics stabilise (i.e. reach equilibrium). In the North Sea simulations this period was defined as the first 10 years of the simulation (see *Fig. A1* below) while in the smaller DanTysk landscape the population stabilised within 1 simulation year. The simulation data acquired during the pre-piling burn-in period were discarded from all analyses and figures provided in this report, as a stable population is required to infer any effect of pile driving on population dynamics and population size. Once the burn-in period ended, the second phase of the simulation started in which pile driving was initiated. In the North Sea landscape this pile-driving period lasted approximately 6 years for the studied scenarios (see *Table 3* in the main text of this report), while in the DanTysk landscape piling lasted 1 year. The last phase of a simulation was the post-piling period, which in the North Sea landscape lasted for approximately 25 years (see *Fig. A1* below) to assess any long-term effects of pile-driving activities on porpoise population dynamics and population size. Simulations in the DanTysk landscape did not have a post-piling phase, as we were only interested in quantifying effects on porpoise densities before and during pile driving.

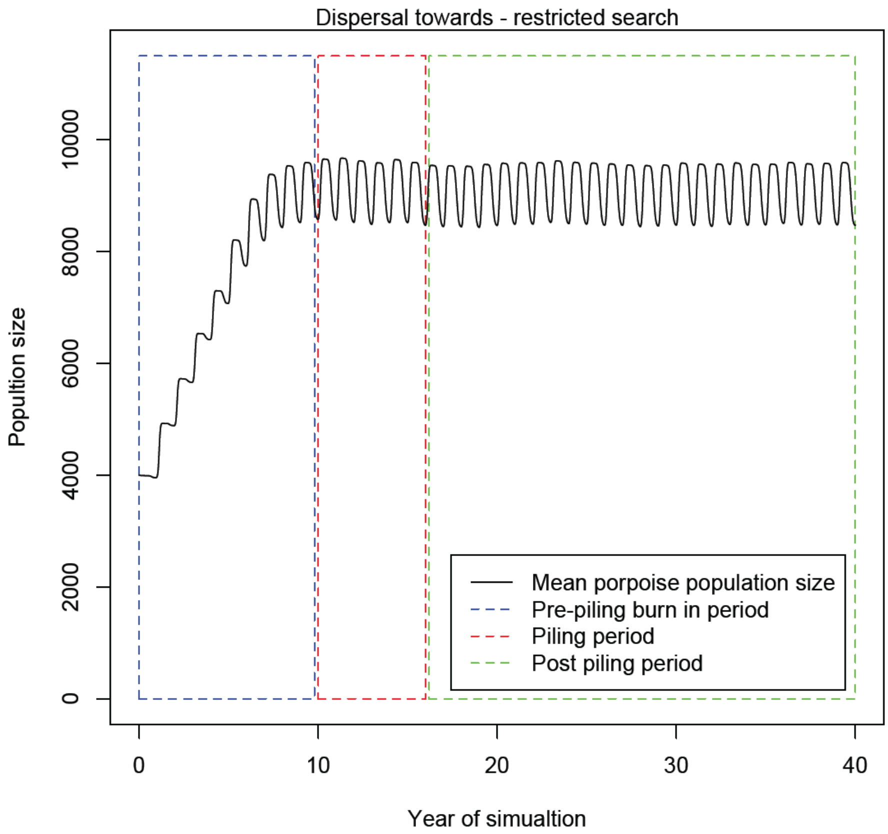


Figure A1. Overview of the 3 phases in each simulation in the North Sea landscape. The example in the figure uses the dispersal towards - restricted search porpoise movement strategy. The first phase is the pre-piling burn-in period (dotted blue rectangle) in which the population (solid black line) reaches a carrying capacity (i.e. stabilizes). The piling activities took place in the piling period (dotted red rectangle) after which the simulation ran for an additional 25 years (post-piling period; dotted green rectangle) to assess any long-term effects of pile driving on the porpoise population.

DISTURBANCE EFFECTS ON THE HARBOUR PORPOISE POPULATION IN THE NORTH SEA (DEPONS): STATUS REPORT ON MODEL DEVELOPMENT

The goal of this report is to provide a status update of an individual-based model (IBM) that is being developed to evaluate the impact of pile-driving noise from offshore wind farm construction on the harbour porpoise (*Phocoena phocoena*) population in the North Sea (DEPONS model). We considered five different porpoise movement and dispersal strategies in combination with three hypothetical pile-driving scenarios ranging from no noise to a realistic but worst case piling scenario. We compared the average simulated porpoise population sizes and dynamics across movement/dispersal models and pile-driving scenarios. Although the results should be considered preliminary, the patterns generated by the current version of the DEPONS model did not suggest any clear, long-lasting effects of pile-driving noise on the average porpoise population size and dynamics in the North Sea. We discuss several model components that need to be investigated in more detail so as to replace certain underlying assumptions in the model with a direct data driven parameterization approach.

ISBN: 978-87-7156-127-2
ISSN: 2245-0203