Southern North Sea Harbour Porpoise Population Modelling Validation – Population Impact Modelling Report

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Acronyms & Abbreviations

ADDs	Acoustic Deterrent Devices
CI	Confidence Interval
CL	Confidence Limit
C-POD	Continuous Porpoise Detector
DEFRA	Department for Environment, Food & Rural Affairs
EA1	East Anglia ONE
EC	European Commission / European Council
ERM	Environmental Resource Management
EU	European Union
GES	Good Environmental Status
GIS	Geographic Information System
HD	Habitats Directive
IAMMWG	Inter-Agency Marine Mammal Working Group
IBM	Individual-Based Model
ICES	International Council for the Exploration of the Sea
iPCoD	Interim Population Consequences of Disturbance
IMR	Norwegian Institute of Marine Research
ITT	Invitation to tender
JCP	Joint Cetacean Protocol
JNCC	Joint Nature Conservation Committee
MERP	Marine Ecosystem Research Project
MSFD	Marine Strategy Framework Directive
MU	Management Unit
NAMMCO	North Atlantic Marine Mammal Commission
NMFS	National Marine Fisheries Service
OSC	Ocean Science Consulting Ltd.
PAM	Passive Acoustic Monitoring
PPH	Porpoise Positive Hour
PPM^{-h}	Porpoise Positive Minutes per hour
PTS	Permanent Threshold Shift
SAC	Special Area of Conservation
SCANS	Small Cetaceans in European and Atlantic waters and the North Sea
SNS	Southern North Sea
SPR	ScottishPower Renewables
UXO	Unexploded Ordnance
WT	Waiting Time

1 INTRODUCTION

1.1 Project Background

The harbour porpoise (*Phocoena phocoena*) is the smallest and most commonly observed cetacean species found in UK waters. The species is protected under UK and international regulations but is susceptible to overlapping anthropogenic pressures across its range, such as bycatch in fisheries, chemical contamination and noise pollution. Current regulations require that the Favourable Conservation Status of the species be maintained or restored through appropriate conservation measures. As the harbour porpoise is listed under Annex II of the European Union (EU) Habitats Directive (incorporated into UK legislation), there is an additional need to establish a network of Special Areas of Conservation (SACs) for the species. The Southern North Sea (SNS) SAC is one such designated site (JNCC, 2019a), and the ScottishPower Renewables' (SPR) East Anglia ONE Offshore Wind Farm (henceforth referred to as EA1,and the focus of the current project), sits within this SAC's boundary. Harbour porpoises in this area are considered part of the North Sea Management Unit as originally reported by ICES (2014) and described in more detail by IAMMWG (2015).

Cetaceans such as harbour porpoises are known to be sensitive to anthropogenic noise pollution, such as that produced by offshore construction activities involving piling (e.g. Brandt et al., 2016; Carstensen et al., 2006; Teilmann and Carstensen, 2012). Considerable amounts of piling, associated with continued expansion of the offshore wind sector, are either ongoing or forecast to occur throughout the North Sea for the foreseeable future. There are concerns about this activity impacting porpoises through auditory injury, acoustic masking and disturbance, particularly when considering the cumulative acoustic impacts of multiple concurrent offshore wind construction projects and other industries such as shipping, and oil and gas exploration. This, in turn, has driven calls for more detailed assessment of how local disturbances might impact porpoise populations across larger spatial and temporal scales, as well as recognising the importance of considering and mitigating potential cumulative noise impacts

One way to address some of these requirements is through application of predictive models. The interim Population Consequences of Disturbance (iPCoD; Harwood et al., 2014; King et al., 2015) and DEPONS (Nabe-Nielsen et al., 2018 & 2021) models have been specifically developed to predict potential population-level effects of construction and operation of offshore renewable energy devices on harbour porpoises. These models offer an approach for assessing and quantifying the potential for long-term, aggregate/cumulative effects of marine industrial activities, to improve strategic planning, with a view to minimise impacts on harbour porpoise populations and not affect their Favourable Conservation Status, as required under the EU Habitats Directive and derived national legislation.

1.2 Project Objectives

The current project (Work Package B) seeks to clarify the consequences of the noise associated with construction of the EA1 wind farm on the wider North Sea harbour porpoise Management Unit. SAMS Enterprise (previously SAMS Research Services Ltd.; SRSL) will apply the two currently available population consequence modelling approaches developed for the North Sea (iPCoD and DEPONS) to

EA1, underpinned by observations of harbour porpoise acoustic presence using an array of autonomous porpoise click detectors (C-PODs) and full bandwidth acoustic recorders, collected during various stages of the construction process (Work Package A). SAMS Enterprise will assess applicability of both iPCoD and DEPONS models to EA1 data and evaluate these models' limitations and sensitivities to changes in crucial parameters, so that uncertainty in the results can be better understood.

The project aims to:

- Determine how harbour porpoises respond to pile-driving activities at a local scale in and around EA1, on the basis of data collected through Work Package-A (ITT-752262);
- Assess the use of collected acoustic data as a proxy for behavioural responses of porpoises towards offshore wind farm construction, which could improve input parameters for future model applications;
- Run available model frameworks using project-specific input data, including those obtained from analyses of the acoustic data, to assess potential larger-scale or cumulative impacts; and
- Evaluate and compare the suitability and sensitivity of iPCoD and DEPONS model approaches to assess population consequences to disturbance from pile-driving.

1.3 Document Purpose

The present Population Impact Modelling Report (Document Reference 02564_0010) is part of a series of documents produced for SPR as part of the delivery of the Southern North Sea harbour porpoise population modelling project. This document should be read in conjunction with the Data Quality Control Report (van Geel et al., 2023a), and the Acoustic Processing Report (van Geel et al., 2023b). The Data Quality Control Report describes the quality control process undertaken on the raw acoustic full bandwidth and C-POD data after having received these data from Ocean Science Consulting Ltd. (OSC) via SPR. The Acoustic Processing Report describes the acoustic processing undertaken in order to derive the parameters required to apply the iPCoD and DEPONS models in a project-specific context.

This Population Impact Modelling Report presents the applied modelling approach and subsequent results and explores which conclusions on population-level impacts on the wider North Sea harbour porpoise population from the construction of the EA1 offshore wind farm can be drawn based on currently available data using both iPCoD and DEPONS population impact modelling approaches.

2 ASSESSING POPULATION-LEVEL CONSEQUENCES OF IMPACTS

2.1 Predictive modelling approaches

One of the main approaches applied to assess long-term population-level impacts on marine mammals involves predictive modelling. In contrast to rule-based methods, where predicted number of deaths are compared against a set threshold for the number of deaths that a population can sustain (e.g. Wade, 1998), predictive modelling approaches are particularly suitable to assess future effects, in terms of the potential magnitude and significance, of sub-lethal impacts (Sparling et al., 2017). There are two main types of predictive modelling approaches to simulate population responses: *top-down* models require information on factors such as mortality and density dependence to simulate population responses (e.g. Matrix Models), whilst in *bottom-up* models these characteristics emerge from the actions of simulated individual animals (e.g. Individual-Based Models - IBMs; Table 1) (Sparling et al., 2017).

Table 1. *Summary of types of models used in the prediction of population dynamics. Adapted from Sparling et al., 2017.*

Model	***Description***
Matrix models	A matrix is a mathematical tool that can be used to predict population growth. Matrices can be used to predict the number of individuals in each population's age or stage classes at different time steps based on age/class-specific birth and death rates, and the number of individuals in the previous time step.
Leslie matrix models	A particular type of matrix model where the population is structured into discrete age or stage classes with specific birth and death estimates for each of these (e.g. iPCoD; see Section 2.2.1).
Individual-Based Models (also referred to as Agent-Based Models)	For a virtual population of animals, individual movements and energy balance are simulated over discrete time steps, whereby the movement and energy balance of each individual depends on encountered (environmental) conditions, their internal state, and past experiences. The population dynamics and spatial distributions of animals emerge as a result of the simulation of many individuals (e.g. DEPONS; see Section 2.2.2).

Predictive modelling approaches require information about the population under baseline (i.e. pre-impact) conditions, as well as knowledge about the likely effects of impacts on individual animals' behaviour and physiology that ultimately determine fitness. For Matrix Models, such as iPCoD, estimates of population size, and age- or stage-specific birth and death rates are required. For IBMs, such as DEPONS, the survival and reproductive rates of individuals are determined by their behaviour during simulation, as population vital rates and the number of individuals that can be supported by the environment (i.e. the carrying capacity) arise from simulated individuals ('agents') that are in competition for available food resources. The iPCoD and DEPONS population impact models used in the current project (Figure 1) were both developed to assess the impacts of offshore renewable energy-related development activity (notably noise associated with the piling of fixed offshore wind farms) on the harbour porpoise population in the North Sea (N.B. iPCoD can also be used for other species in UK waters).

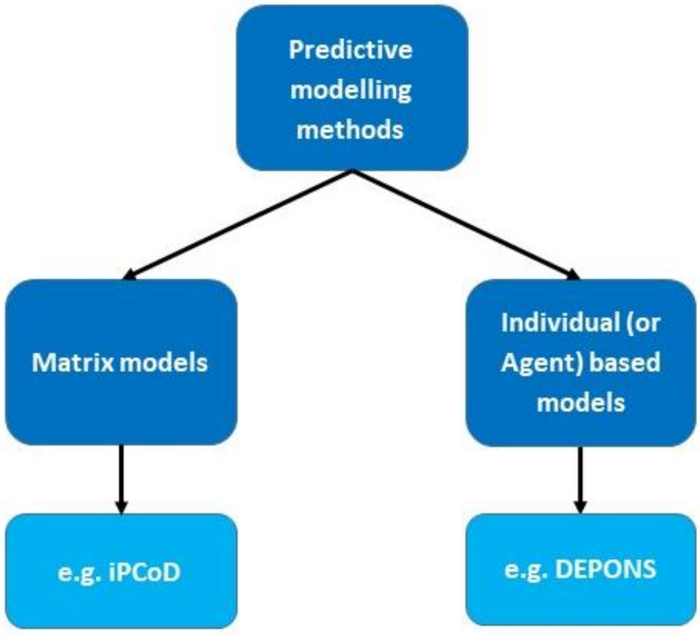

Figure 1. *Overview of predictive modelling approaches used to inform population-level consequences of impacts. Adapted from Sparling et al. (2017).*

2.2 Model descriptions

2.2.1 iPCoD

The iPCoD framework was developed to investigate the population consequences of the effects of exposure to noise, primarily from piling activity during offshore wind farm construction. The approach is based upon the basic Population Consequences of Acoustic Disturbance (PCAD) framework initially developed by the US Office of Naval Research Working Group on PCAD (NRC, 2005). PCAD/PCoD approaches require substantial amounts of high-quality data to develop the transfer functions to scale individual-level disturbance up to population-level consequences. Recognising the persistence of empirical data gaps of how changes in behaviour and hearing sensitivity affect the fitness (survival and reproduction) of individual marine mammals, the interim PCoD (iPCoD) framework provides a protocol for implementing an interim version of the PCoD approach. Specifically, the iPCoD approach incorporates a statistical distribution of the predicted effects of disturbance and a permanent threshold shift (PTS) in hearing sensitivity on individual survival and reproductive rates, with this distribution derived through expert elicitation (Booth & Heinis, 2018; Booth et al., 2019). Population impact simulations subsequently use randomly selected values from 1,000 iterations of the statistical distributions of predicted effects to capture the uncertainty and variability as expressed by the experts. This interim framework thus allows for the quantification of potential consequences of disturbance and/or injury that may result from offshore energy developments, despite a paucity of robust data regarding the relationships between impact levels and resulting behavioural and physiological changes affecting individual vital rates. The iPCoD model code is written as a series of successive R scripts, where user-defined parameters can be set to optimise site-specific population impact modelling.

In principle, the framework simulations involve a two-stage process. The first stage comprises a day-by-day simulation for a limited number of individuals (the number of which is determined by the size of the population; maximum is 1,000) throughout the predicted impact period. It identifies the number of individuals that experience disturbance and PTS, as well as the amount of impact experienced by each individual on an annual basis. This is based on user-defined estimates of 1) the number of individuals predicted to be impacted as a consequence of exposure to a single day of construction, 2) the piling schedule, and 3) an estimate of the proportion of the population that is considered vulnerable to the impacts. What constitutes the vulnerable section of the population is a judgement based on individual animals' movements in relation to the extent of the impact and the extent of the construction period. Whilst iPCoD allows for identification of, and comparison between, different vulnerable sub-populations, it is not otherwise spatially explicit.

The second stage extrapolates the results from the first stage to the total population to create a Leslie Matrix model that is subsequently used to assess the population dynamics of the impacted population. This is through modified survival and birth rates of individuals experiencing disturbance and PTS. At the same time, baseline survival and birth rates are applied to project the future trajectory of an un-impacted population in the absence of the anthropogenic pressure.

This process is repeated 1,000 times, with each simulation drawing parameter values from statistical distributions describing the uncertainty in the parameters. Differences between these 1,000 simulations are determined by:

- Environmental stochasticity[1]: variation in the survival and fertility rates resulting from changes in environmental conditions;
- Demographic stochasticity, i.e. individual variation in realised vital rates as a result of random processes;
- The statistical distributions on the effect of disturbance and PTS on vital rates, as obtained through the expert elicitation process.

This process results in outputs of trajectory distributions for both the un-impacted and impacted populations, which can then be compared to assess any predicted long-term population impact effects, as well as the uncertainty surrounding these predictions.

A schematic overview of the iPCoD framework is included in Figure 2. For detailed information on the iPCoD approach and how to implement the framework, see Harwood et al. (2014), King et al. (2015), and Sinclair et al. (2019) and references therein.

[1] Stochastic models incorporate uncertainty in prediction by drawing the values for each simulation from a range of possible values. Repeating the simulations multiple times results in the production of a statistical distribution of predictions, from which a mean with associated modelled variability can be derived (Sparling et al., 2017).

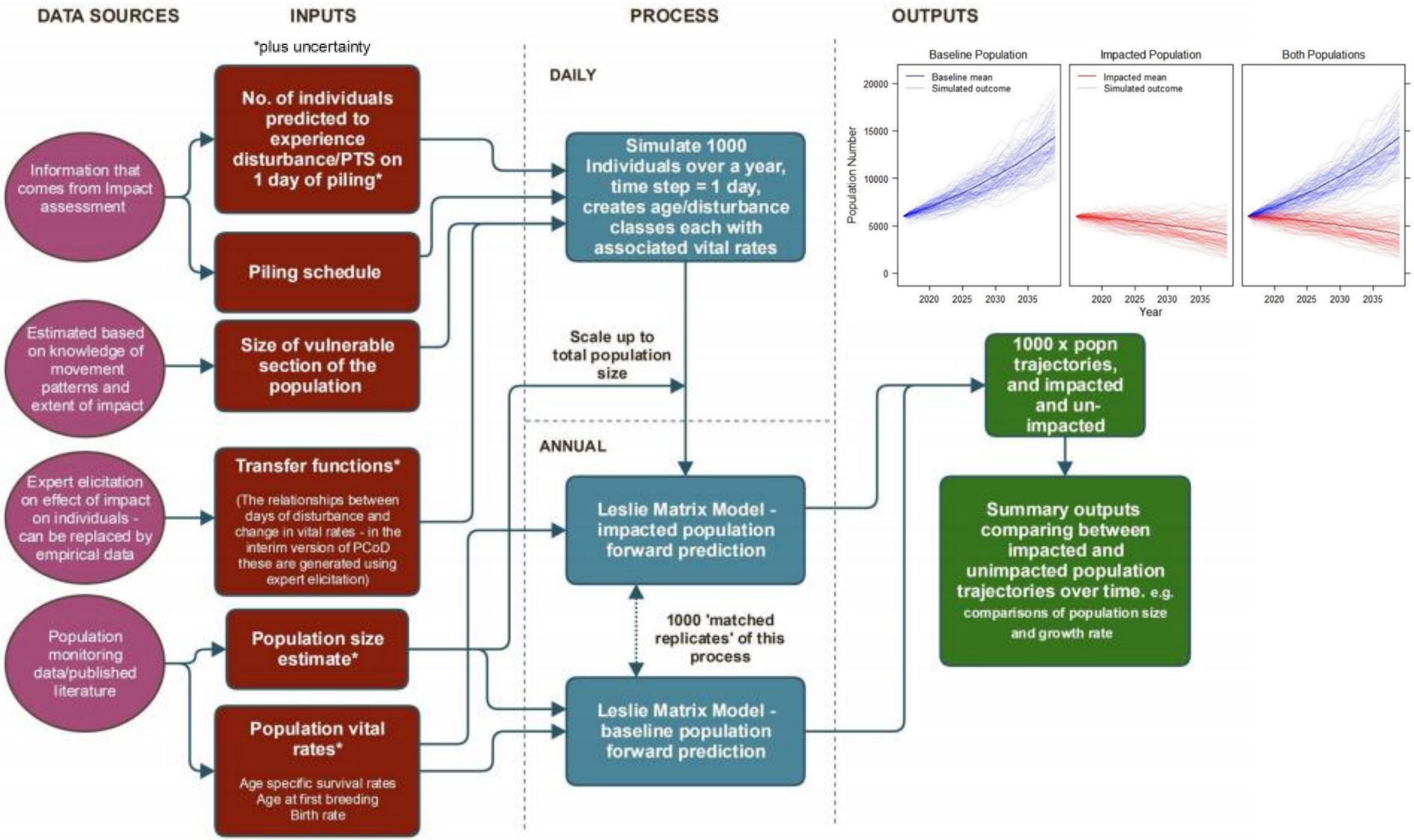

Figure 2. *Schematic representation of the Interim PCoD Framework. From Sinclair et al. (2019).*

2.2.2 DEPONS

The DEPONS modelling framework enables a cumulative assessment of population-level impacts of various impacts, including offshore construction activities, bycatch, and shipping, on harbour porpoises. DEPONS is an individual-based model that includes both temporal and spatial components to simulate porpoise movement and energetics. Population dynamics arise from the interplay between individual competition for food resources, and altered movements in response to present noise, through their potential consequences on foraging success and survival. In the model, survival is directly related to an individual's energy level, whilst foraging behaviour is affected by experienced noise levels.

In the North Sea region, which contains patchy, limited and seasonally fluctuating food resources, the fine-scale movements of simulated porpoises are dominated by correlated random walk behaviour as long as the energy intake is high. When local resources become depleted, individuals move towards known food patches, guided by a spatial memory of food patch locations and previous foraging success (Nabe-Nielsen et al., 2013). When food acquisition rate is persistently low and individuals cannot sustain their energy levels, fine-scale movements are abandoned and animals start to make large-scale movements to areas where foraging is potentially more profitable. The movements of simulated porpoises have been calibrated based on telemetry data collected from tagged animals in the North Sea (Nabe-Nielsen et al., 2018; van Beest et al., 2018a).

When a simulated porpoise encounters food, the animal's energy level increases (but levels off as the porpoise becomes saturated), whilst energy levels decrease when an animal moves. Additionally, time-dependent variability in energy expenditure is incorporated into the energy costs depending on season (with energy expenditure increasing in winter) and reproductive state (specifically lactation in females).

As the simulated porpoises move around, individuals may become exposed to piling and shipping noise, with received noise levels determining how strongly the animals will react to these events. This behavioural response, in turn, will affect an individual's energy balance by affecting foraging and travel behaviour, with potential consequences for survival.

Survival of adults and juveniles is directly determined by their energetic status: the lower an individual's energy levels are, the higher the risk of dying. The survival of dependent calves relates to the energy budget of their mothers, as lactating females experiencing food shortages will not immediately die but abandon their calves instead.

During a simulation, the model updates the status of various entities (e.g. porpoise movements, noise exposure, energetic status) in half-hourly time steps, and records the number of animals, their energy levels and the total amount of food once each day. At the end of each day, life history processes, such as death, mating, birth and weaning, have a certain probability of occurring, whilst food distribution maps change on a seasonal basis.

Each simulated porpoise present in the model is considered a 'super individual' and represents several real-world female porpoises. Independent (i.e. weaned) males are not modelled explicitly; instead, assuming an equal gender ratio, the population size is doubled at the end of a simulation to account for them.

A schematic overview of DEPONS is presented in Figure 3. Full supporting information on model development, calibration and implementation is provided in the DEPONS TRACE document (Nabe-Nielsen et al., 2021) and references therein.

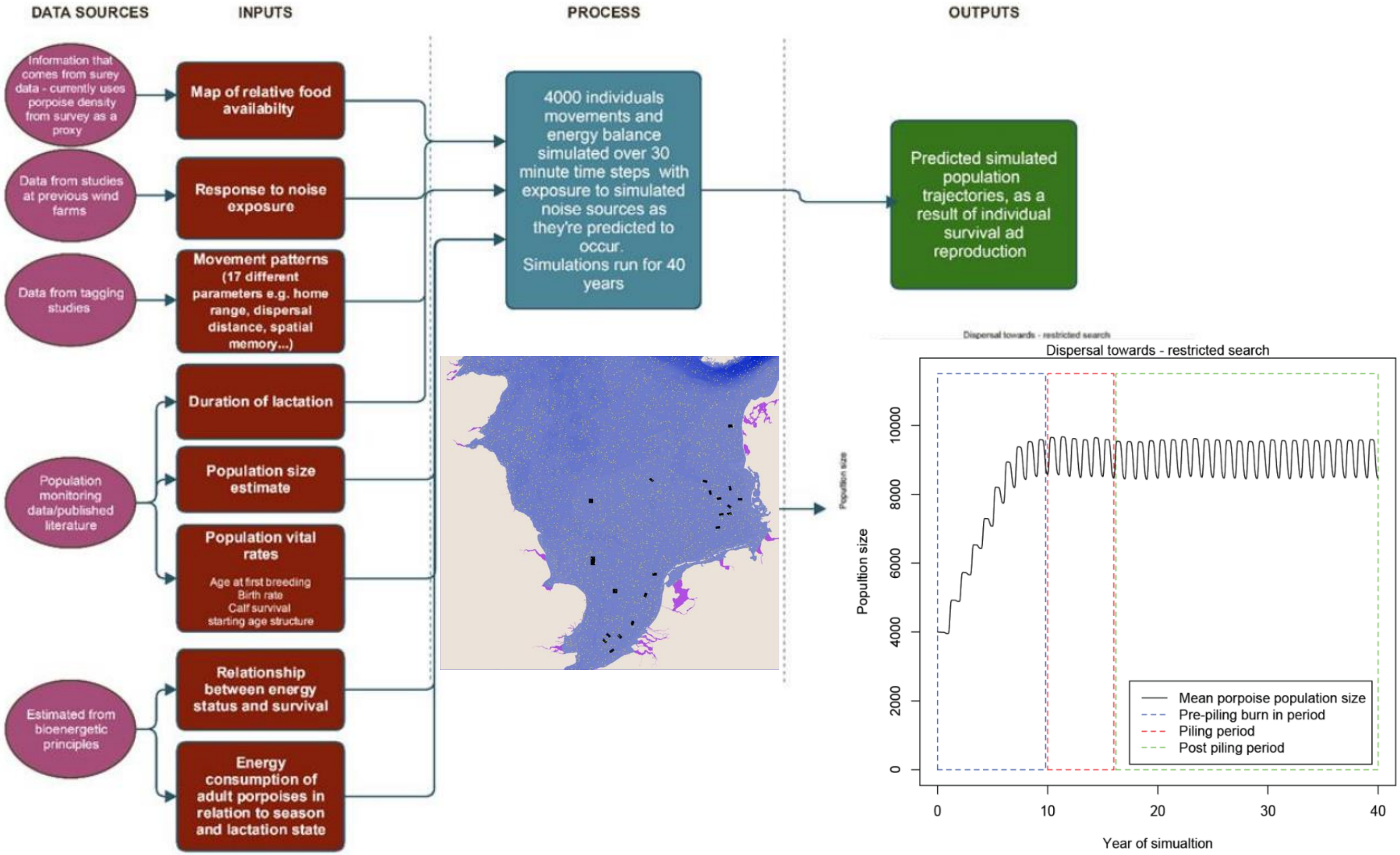

Figure 3. *Schematic representation of the DEPONS model. From Sparling et al. (2017).*

3 METHODOLOGY

3.1 iPCoD

iPCoD (developed by SMRU Consulting) requires specification of a variety of input parameters. Recommended values are provided for several of these when applied to modelling population-level impact on harbour porpoises in the North Sea (Sinclair et al., 2019 & 2020), whilst others can be optimised by the user to reflect site- or project-specific conditions.

In the current study, in addition to the applied piling schedule, project-specific inputs were sought for the following parameters:

- Management Unit / Population size;
- Vulnerable sub-population;
- Residual Disturbance; and,
- Site-specific density, which when multiplied with the piling Impact Zone provides an estimate of the number of individuals that could be disturbed. When multiplied with the PTS Zone, it provides an estimate of the number of individuals that may experience PTS.

Explanation of the selected input values for these model scenario parameters is presented below.

3.1.1 Parameter selection

3.1.1.1 Management Unit / Population size

The harbour porpoise population occupying the North Sea is considered a single Management Unit (MU), also referred to as an Assessment Unit (Figure 3; ICES, 2014; IAMMWG, 2015). The most recent abundance estimate for the size of this MU is 345,373 individuals, based on the SCANS-III survey undertaken in July 2016 (Hammond et al., 2021). There are presently insufficient data to identify smaller-scale population structuring within the North Sea MU (Murphy et al., 2019), and little is known about movement patterns of individual harbour porpoises in the North Sea region. Telemetry tracking studies in the northern part of the North Sea revealed that some individuals demonstrate wide-ranging movements (e.g. Stalder et al., 2020), but it is not known how representative these movements are across individuals of the wider MU. Given the current lack of knowledge of porpoise movements in the southern North Sea, the possibility of more regional movement exhibited by individuals in this area was explored while modelling impacts of EA1. Testing potential impacts on a hypothetical, smaller regional group allows for model exploration with explicitly conservative input parameters, and provides context for the results from models with more conventional parameters.

To explicitly assess the potential for impacts on a hypothetical regional group within the southern North Sea (referred to as the regional southern North Sea group), porpoise abundance estimates for SCANS-III Survey Blocks O, L, N, M and half of the estimated abundance for Block C[2] were aggregated (Figure 4).

[2] Only the eastern half of SCANS-III Block C is part of the range of the North Sea harbour porpoise MU as defined by IAMMWG (2015).

A summary of porpoise abundance estimates for both the entire North Sea MU and the hypothetical regional southern North Sea group, including associated lower and upper 95% confidence limits, is provided in Table 2, representing the six input values considered for the Population size (‘*pmean*’) model parameter.

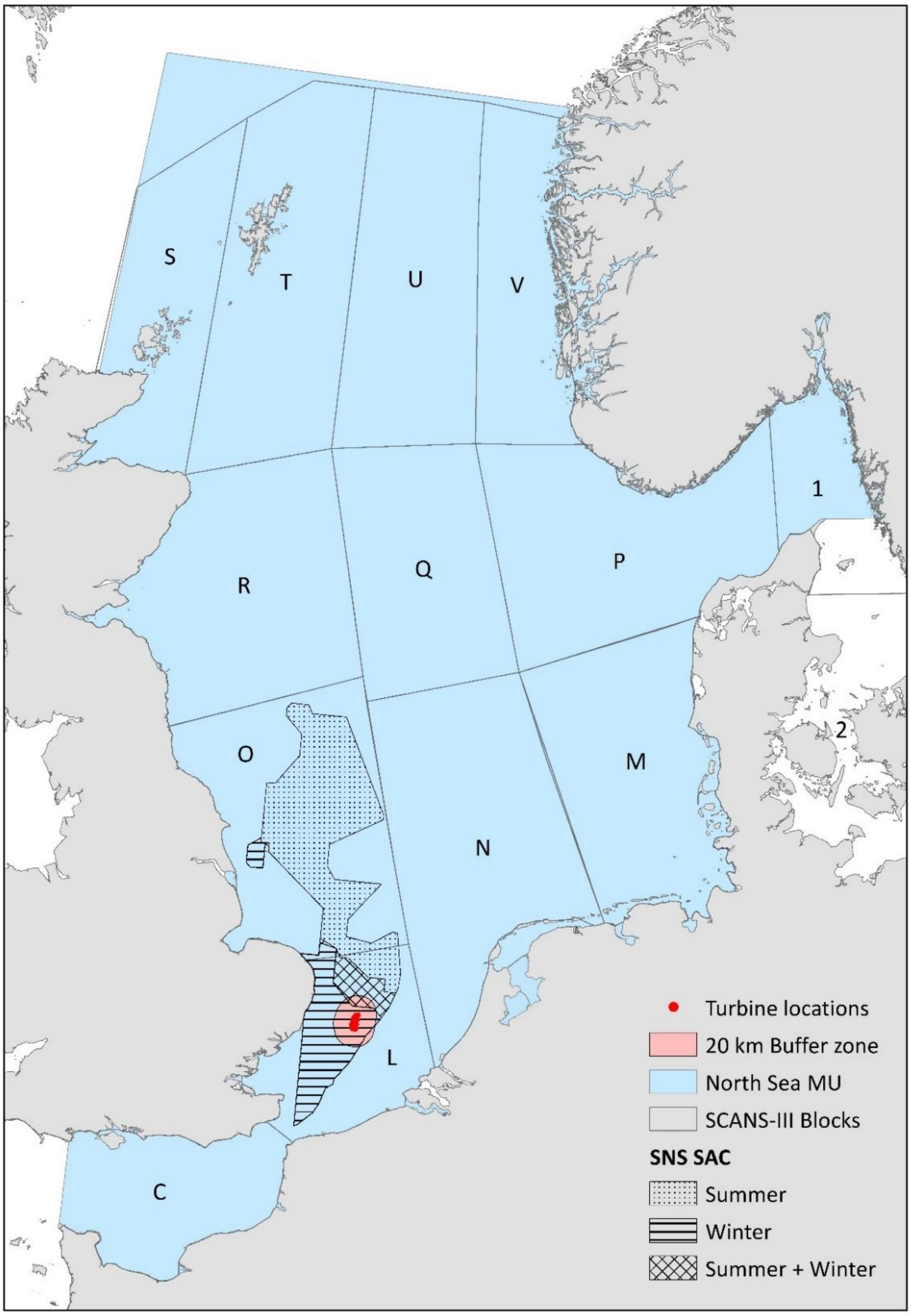

Figure 4. *Boundaries of the harbour porpoise North Sea Management Unit (from ICES 2014), the SCANS-III survey Blocks, the Southern North Sea Special Area of Conservation with specified seasonal areas, and the EA1 turbine locations surrounded by a 20 km buffer zone. Note, only the eastern section of Block C, which is part of the North Sea MU, is presented here.*

Table 2. *Most recent North Sea population abundance estimates from the SCANS-III survey in July 2016. 95% CL = 95% confidence limit; NS MU = North Sea Management Unit; SNS = southern North Sea region (i.e. SCANS-III Survey Blocks O + L + N + M + 1/2*C).*

MU / Population size	***Data Source***	***Reference***
345,373 (246,526 – 495,752)	Abundance (lower – upper 95% CL); SCANS-III NS MU	Hammond et al., 2021
154,932 (87,440 – 252,344)	Abundance (lower – upper 95% CL); SCANS-III SNS	

3.1.1.2 Vulnerable sub-population

Within the larger North Sesa MU, the iPCoD model requires the identification of a 'sub-population' that is vulnerable to noise disturbance. Given the current lack of information about movement patterns of individual harbour porpoises in the southern North Sea region, it is unknown whether a vulnerable sub-population needs to be identified and incorporated in the modelling (Hague et al., 2020).

In this project, three options were considered to define the vulnerable sub-population ('*vulnmean*'):

- The entire North Sea MU;
- Those individuals present in the southern North Sea region, as defined in Section 3.1.1.1 (SCANS-III Blocks M, N, O, L and the eastern part of Block C); and,
- Those individuals represented by the 'local' abundance estimates for SCANS-III Blocks L, O and the eastern part of Block C, immediately adjacent to the EA1 development.

The proportion of 'local porpoises' relative to the total SCANS-III North Sea MU estimate is 23.5%. The hypothetical regional southern North Sea porpoise abundance represents 44.9% of the total MU estimate. Likewise, the 'local' abundance estimate incorporates 52.4% of the hypothetical regional southern North Sea abundance estimate. As such, values of 0.25, 0.5 and 1.0 were identified as input values for the vulnerable sub-population in the modelling scenarios; the value of 0.25 only being relevant when considering one of the specified values for the entire North Sea MU as input for the population size. It is important to note that these identified vulnerable sub-populations persist in the simulations for the duration of the modelling period.

3.1.1.3 Residual Disturbance

The model requires the quantification of the number of days of Residual Disturbance ('*days*', in whole numbers) that is associated with each day of actual piling disturbance, whereby one day of disturbance results in a 6-hour period during which foraging and nursing ceases. Following the approach of Booth et al. (2017) and Graham et al. (2019), Waiting Time and Recovery Time were both assessed as a proxy for behavioural response duration. The analysis of the acoustic data, as outlined in the Acoustic

Processing Report (van Geel et al., 2023b), revealed an average Waiting Time (i.e. the period from cessation of piling up to the first porpoise detection; Thompson et al., 2010) of 6:50 hours over the entire construction period, with588 out of the 590 events included in the assessment showing a Waiting Time of < 48 hours. Data from seven wind turbines were also available to assess Recovery Time, defined as the time required for post-piling vocalisation activity to return to baseline values. The results indicated a return to within 10% of pre-piling porpoise levels within 21 hours after piling activities had stopped (van Geel et al., 2023b).

An effect duration of piling on nearby porpoise presence (i.e. within 2 km) of up to 46 hours has been reported by Brandt et al. (2016) for six of seven wind farms assessed. The results presented by Brandt et al. (2011) showed recovery to baseline PPM^{-h} levels to occur within 48 hours following cessation of piling activity, except for the monitoring location closest to the piling (average distance of 2.6 km to piling), where levels remained low for up to 72 hours.

While porpoise detections around EA1 might be temporarily reduced due to animals being displaced as a result of piling, this does not imply that these animals stop foraging during this period, as they are likely to resume foraging in their new surroundings. Noting results of trials on captive porpoises showing potential for fast recovery following disturbance in case of abundant food supply (Kastelein et al., 2019), uncertainty in Residual Disturbance was explicitly considered by specifying two input value options: 0 or 1 days.

3.1.1.4 Population density

Although population density (the number of individuals per km^2) is not a direct input parameter in the iPCoD model, it is required in combination with piling Impact Zone and the PTS Zone parameters, which for this project were identified as 615.75 km^2 and 0.95 km^2, respectively (van Geel et al., 2023b). Multiplication of population density values with these two parameters provides the following two essential input parameters to iPCoD: the number of disturbed individuals (‘*numDT*’) and the number of individuals that experiencing PTS (‘*numPt*’).

Harbour porpoise density information for the North Sea MU is available across a range of spatial and temporal scales. Available data are summarised in Table 3 and presented in Figures A1 - A7 in Appendix A, with localised densities obtained or estimated from referenced sources or associated supplementary material. More detailed information on site-specific density estimates (defined here as the area covered by a 20 km buffer zone around the EA1 wind turbines) extracted from GIS data is presented in Table 4. Older information is available (e.g. SCANS-I and SCANS-II estimates), and some of the studies included in Table 3 also provided information for earlier periods. For the purpose of this study, the assessment only included density information for the most recent year(s) reported. The majority of data considered here were collected during the summer period, and indicated a summer density estimate of <1 individual per km^2.

Table 3. *Overview of harbour porpoise density information. MERP = Marine Ecosystems Research Project; JCP = Joint Cetacean Protocol; CL = Confidence Limit; CI = Confidence Interval; Max = maximum. * See Table 4 for localised densities extracted from underlying data. ** These are unscaled density estimates and are not corrected for the size of the population.*

Density (individuals / km²)	***Data source***	***Reference***
< ~1.1 (estimated from figure)	Recorded winter (Oct - Mar) MERP 1980-2018	Waggitt et al., 2020; Figure A1
< ~0.45 (estimated from figure)	Recorded summer (Apr - Sep) MERP 1980-2018	Waggitt et al., 2020; Figure A1
< ~0.55 (estimated from figure) *	Predicted winter (Oct - Mar) MERP 1980-2018	Waggitt et al., 2020; Figure A1
< ~0.5 (estimated from figure) *	Predicted summer (Apr - Sep) MERP 1980-2018	Waggitt et al., 2020; Figure A1
0.607 (low 95% CL = 0.221 high 95% CL = 1.137)	Block L; SCANS-III July 2016	Hammond et al., 2021; Figure A2
0.52 (low 95% CL = 0.363; high 95% CL = 0.731)	North Sea MU; SCANS-III July 2016	Hammond et al., 2021; Figure A2
N/A ** (Whilst unscaled, these provide information on relative seasonal variability)	JCP winter (Jan - Mar), spring (Apr - Jun), summer (Jul - Sep) and autumn (Oct - Dec) 2010; Unscaled	Paxton et al., 2016; Figure A3
N/A **	JCP summer 2007 till 2010; Unscaled	Paxton et al., 2016; Figure A4
~0.051-0.2 (97.5% CI ~0.51-2.0) (estimated from figures) *	JCP summer 2007 till 2010; Scaled	Paxton et al., 2016; Figure A4
< 1.2 (lognormal 90% CI 0.81-2.0) (estimated from figures) *	SCANS-II, Dogger Bank & small-scale national surveys 2005-2013 spring (Mar - May)	Gilles et al., 2016; Figure A5
< 0.8 (lognormal 90% CI 0.81-1.5) (estimated from figures) *	SCANS-II, Dogger Bank & small-scale national surveys 2005-2013 summer (Jun - Aug)	Gilles et al., 2016; Figure A5
< 0.4 (lognormal 90% CI 0-0.8) (estimated from figures) *	SCANS-II, Dogger Bank & small-scale national surveys 2005-2013 autumn (Sep - Nov)	Gilles et al., 2016; Figure A5
0.3-2.1 (estimated from figures)	Observed JCP summer (Apr - Sep) 2006-2011	Heinänen & Skov, 2015; Figure A6
summer < 2.0; winter 2.01 - >3.0 (2006 & 2007), > 3.0 (2008 & 2009) (estimated from figures)	Predicted JCP summer & winter (Oct - Mar) 2006 till 2009	Heinänen & Skov, 2015; Figure A7
0.19 (lower CL = 0.008; upper CL = 0.32; max = 1.4)	Site-specific high-definition aerial survey Nov 2009 - Oct 2010	ERM, 2012

Limited information is available on seasonal variation in porpoise density in UK waters of the southern North Sea (Tables 3 & 4). Interpretation of this variation to infer relative scaling across seasons is impeded by different authors' choices regarding the clustering of months into seasons, the number of seasons assessed, as well as spatio-temporal differences in survey effort of underlying datasets and associated confidence/uncertainty (Figure 5). Nonetheless, it is important to consider that the EA1 wind farm is located within the 'winter' area of the SNS SAC, which was designated based on higher persistent densities for that season (JNCC, 2019b & 2020). Various studies report an overall increased porpoise presence in the southern North Sea in winter (e.g. see Table 3) and there is some suggestion in the acoustic data obtained in the present study too of increased porpoise detection rates in winter (van Geel et al., 2023b). For these reasons, application of an increased density in the winter months was considered appropriate.

As the SCANS-III data are the most up-to-date porpoise density data available, collected during a single summer using systematic, standardised surveys (Hammond et al. 2021), the average density estimate for SCANS-III Block L (0.607 individuals / km^2; Table 3) was selected as input value for the spring, summer and autumn seasons, with double this density for the winter period. This resulted in *numDT* input values of 374 and 748 individuals, respectively, for these seasonal periods, with associated *numPT* values of 1 and 2 individuals.

Additionally, the highest density values were defined as 6.096 individuals / km^2 during the winter months, and 4.046 individuals / km^2 for the rest of the year, representing more extreme values based on the local summer density extracted from the JCP results (Table 4). Application of these densities resulted in *numDT* input values of 3,754 and 2,502 individuals, and *numPT* values 6 and 4 individuals for winter and the rest of the year, respectively. Note that the *numPT* values are likely conservative as they do not take into account the deployment of ADDs to mitigate against PTS, and are based on PTS Zone modelling which assumes that animals remain within this zone for a 24-hour period (see van Geel et al., 2023b).

Table 4. *Average extracted harbour porpoise densities (individuals / km^2) and associated uncertainty over all grid cells fully or partially falling within the 20 km buffer zone. Note that lower and upper estimates present lognormal 90% Confidence Intervals (Gilles et al., 2016 & in prep), 5% and 95% quantiles (Waggitt, 2019), and 95% Confidence Intervals (Paxton et al., 2016). For season definitions applied by individual studies: see Table 3 & Figure 5.*

Month / Season	***Years***	***Lower estimate***	***Predicted density***	***Upper estimate***	***Reference***
Summer	2014-2019	0.605	0.729	0.909	Gilles et al., in prep[3]
January	1980-2018	0.500	0.518	0.536	Waggitt, 2019
February	1980-2018	0.508	0.527	0.546	Waggitt, 2019
March	1980-2018	0.510	0.529	0.549	Waggitt, 2019
April	1980-2018	0.504	0.523	0.542	Waggitt, 2019
May	1980-2018	0.489	0.507	0.523	Waggitt, 2019
June	1980-2018	0.467	0.483	0.499	Waggitt, 2019
July	1980-2018	0.445	0.461	0.477	Waggitt, 2019
August	1980-2018	0.430	0.448	0.464	Waggitt, 2019
September	1980-2018	0.432	0.450	0.466	Waggitt, 2019
October	1980-2018	0.447	0.464	0.480	Waggitt, 2019
November	1980-2018	0.468	0.485	0.500	Waggitt, 2019
December	1980-2018	0.487	0.504	0.520	Waggitt, 2019
Summer	2007-2010	1.393	2.554	**4.064**	Paxton et al., 2016[4]
Spring	2005-2013	0.933	1.146	1.412	Gilles et al., 2016
Summer	2005-2013	0.548	0.670	0.834	Gilles et al., 2016
Autumn	2005-2013	0.302	0.362	0.442	Gilles et al., 2016

Jan	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	
												iPCoD
+++	+++	+++	- - -	- - -	- - -	- - -	- - -	- - -	+++	+++	+++	Waggitt et al., 2020
+++	+++	+++	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	Paxton et al., 2016
ND	ND	+++	+++	+++	- + -	- + -	- + -	- - -	- - -	- - -	ND	Gilles et al., 2016
+++	+++	+++	- - -	- - -	- - -	- - -	- - -	- - -	+++	+++	+++	Heinänen & Skov, 2015

	Winter		Spring		Summer		Autumn
+++	Highest density	- + -	Intermed. density	- - -	Lowest density	ND	No Data

Figure 5. *Overview of relative seasonal variation in density at the EA1 wind farm (as derived from the density maps presented in Appendix A; relative comparison within studies only).*

[3] This work presents an update on the previously published seasonal density surface layers for harbour porpoise in the North Sea for the period 2005-2013 (Gilles et al., 2016). The updated summer density distribution is based on dedicated aerial survey data collected from 2014-2019 through national monitoring programmes, as well as from the SCANS-III survey.

[4] Scaled densities extracted using the JCP Phase-III extraction tool.

3.1.2 Modelling scenarios

To assess the population-level consequences of the piling activity during the construction of EA1 on the North Sea harbour porpoise population, a range of iPCoD scenarios were considered. These varied in the input values of the following input parameters: Population size, Vulnerable sub-population, Residual Disturbance, and the Site-specific density (affecting the number of disturbed individuals and the number of individuals experiencing PTS) (Table 5).

Table 5. *iPCoD harbour porpoise population impact modelling scenario parameters and their input values. CL = Confidence Limits. NS MU = North Sea Management Unit. SNS = southern North Sea. * Only relevant when applying one of the specified values for the entire porpoise MU as input for the population size.*

Parameter	***Input value***		
	Lower 95% CL	***Estimate***	***Upper 95% CL***
Population size - entire NS MU (number of individuals)	246,526	345,373	495,752
Population size - regional SNS group (number of individuals)	87,440	154,932	252,344
	Low	***Estimate***	***High***
Vulnerable sub-population (proportion)	0.25 *	0.5	1
		Estimate	***High***
Residual Disturbance (days)		0	1
NumDT (number of individuals)	Spring, summer & autumn	374	2,502
	Winter	748	3,754
NumPT (number of individuals)	Spring, summer & autumn	1	4
	Winter	2	6

Integration of the various input values identified in Table 5 resulted in 60 potential scenarios that could be modelled. To maximise efficiency, modelling started with a ‘conservative’ scenario, which combined the most conservative site-specific values among the input parameters considered here (Table 5):

- the smallest Population size (i.e. 87,440; Lower 95% CL of the regional southern North Sea group);
- the smallest proportion of Vulnerable sub-population (i.e. 0.5; representing the ‘local’ abundance estimate compared to the estimate for the ‘regional’ southern North Sea);
- a 1-day Residual Disturbance; and,
- the highest seasonal local density estimations to obtain the number of individuals experiencing disturbance and PTS in spring, summer and autumn (748 and 4 individuals for disturbance and PTS respectively), and 3,754 (disturbance) and 6 individuals (PTS) for the winter period.

Subsequent scenarios started from this ‘conservative’ scenario, with each parameter scaled down (stepwise, one step at a time), until no long-term difference could be identified between the modelled ‘un-impacted’ and ‘impacted’ populations. A significant difference was defined as an annual decline of 0.5% (DEFRA, 2019; see Section 3.3 for details), resulting in an impacted population size relative to the size of the un-impacted population of 88.67% at the end of the simulation. The likelihood of an annual decline of 1% (i.e. the population size of the impacted population being 78.57% of the un-impacted population at the end of the modelling period, in line with previously applied MSFD thresholds (Evans & Arvela, 2012; see section 3.3 for details) was also assessed.

The modelling was undertaken using iPCoD Version 5.2, which integrates the results from the most recent (2018) expert elicitations on the potential effects on porpoises of disturbance and PTS due to exposure to low frequency broadband pulsed noise (such as piling), thereby incorporating recent advances in knowledge and updated expert elicitation methods.

The framework Helpfile (Sinclair et al., 2019), and recently updated demographic information (Sinclair et al., 2020) provided recommendations for the other parameters that needed to be quantified. An overview of the scenario-specific parameters mentioned above, the fixed model parameters, and their input values are presented in Appendix B.

3.2 DEPONS

The DEPONS model (developed by Aarhus University) requires the specification of a large number of parameters to run successfully (52 in total). These can be broadly divided into three main categories: life history & energetics (13 parameters), animal movement & reaction to noise (28 parameters), and general model behaviour (11 parameters) (Nabe-Nielsen et al., 2021). These relate to porpoise movements in the absence of disturbance as derived from telemetry data, porpoise life history traits and energetics, sound propagation, and behavioural responses to noise (Nabe-Nielsen et al., 2013 & 2018; van Beest et al., 2018). Over the years, model parameterisation, validation and improvement have benefitted from increased availability of empirical data, notably from Danish harbour porpoise tagging studies and site-specific data obtained from studies around the first wind farms built in the North Sea. In the absence of comparable tagging data from the southern North Sea, opportunities for optimising DEPONS to project- and site-specific conditions are limited to a restricted number of parameters and settings, with default input values applied to most of the parameter selection options.

For the present study, project-specific inputs were considered for the following parameters:

- Piling schedule;
- Response Threshold;
- Deterrence Coefficient;
- Fertility values;
- various parameters related to general model behaviour:
    - landscape;
    - wind farm construction scenario; and,
    - the number of years over which each simulation was run.

These parameters are discussed in more detail below.

3.2.1 Parameter selection

3.2.1.1 Response Threshold & Deterrence Coefficient

The Response Threshold is defined as the received sound level (in dB re 1 µPa^{2}s SEL) beyond which porpoises start to be deterred. The Deterrence Coefficient is a unitless constant which assumes a linear relationship between received sound levels and the strength of an animal's subsequent reaction. Combined, these two parameters determine the length of the deterrence vector that describes the movement bias of the animal in response to a received noise level above the threshold value. The final movement vector (i.e. the actual movement of the animal per half-hour time step) is the combined result of the noise deterrence vector integrated with several other vectors related to correlated random walk and spatial memory movement (Nabe-Nielsen et al., 2021).

Analysis of the acoustic data revealed an overall frequency-weighted Response Threshold of 103.0 dB re 1 µPa^{2}s SEL, with porpoise presence negatively influenced at higher porpoise frequency-weighted received levels (van Geel et al., 2023b). However, it is worth noting that a movement response across a large number of individuals might be more accurately represented by a variation in responses, with some individuals being more sensitive to noise than others and/or as a result of behaviour/context-related sensitivity. Additionally, considering ongoing and proposed large-scale development of offshore wind farms across the North Sea, animals may habituate to piling noise, resulting in a change to the Response Threshold. Finally, the Response Threshold value derived here may represent a typical noise level associated with the onset of a response; the probability and severity of a response may, however, increase with increased received levels and is also dependent on background noise levels and the associated signal-to-noise ratio.

To approximate the variation and uncertainty in individual and/or behaviour/context-specific responses, and potential changes in Response Threshold through time, additional DEPONS scenarios with increased Response Thresholds were identified. Specification of these thresholds values was based on the unweighted dose-response curve presented by Graham et al. (2019). In their study, which defined a deterrence 'response' as a 50% reduction in the number of Porpoise Positive Hours (PPH) in the post-piling 24-hour period compared to those in the pre-piling 24-hour period, increases of 21.6, 29.3 and 37.0 dB re 1 µPa^{2}s SEL increased the probability of such a response from 0% to 25%, 50% and 75%, respectively. Applying these increases resulted in the following additional input values for the Response Threshold: 124.6, 132.3 and 140.0 dB re 1 µPa^{2}s SEL[5].

The Deterrence Coefficient (*c*) was calibrated by Nabe-Nielsen et al. (2018) in relation to an un-weighted Response Threshold obtained for the Gemini wind farm in the Netherlands. In order to investigate uncertainty in the transferability of this value (*c* = 0.07), sensitivity of model results to changes in the input value for this parameter was assessed by decreasing *c* by 50% (*c* = 0.035) and increasing it by 100% (*c* = 0.14), as recommended by the DEPONS model developer (J. Nabe-Nielsen, *pers. comm.*).

[5] Note: these unweighted values are subtly different to the harbour porpoise frequency-weighted levels. The frequency-weighted increases in noise levels related to increased probabilities of a response from 1% to 25%, 50%, and 75% were 23.0 dB, 32.3 dB, and 41.6 dB respectively (Graham et al., 2019). Due to the substantial time requirement to run DEPONS, it was decided not to re-run those scenarios that applied the actual frequency-weighted increases.

3.2.1.2 Fertility

The DEPONS default value for the probability that adult females become pregnant (*h*) is set as *h* = 0.68 based on information derived from porpoises in the Gulf of Maine, USA (Read & Hohn, 1995). This value falls between the previously recommended iPCoD setting for modelling the North Sea population under low adult survival (Fertility = 0.958) and under high adult survival (Fertility = 0.479). Recent data on porpoise fertility in UK porpoises (Murphy et al., 2015) have been used to develop a single adjusted recommended iPCoD value of *h* = 0.34 (Sinclair et al., 2020).

To align input parameters between iPCoD and DEPONS models whilst maintaining comparability with earlier published DEPONS results, all DEPONS scenarios in the present study were run using both *h* = 0.68 and *h* = 0.34.

3.2.1.3 Landscape

The landscape parameter provides a description of the environment in which the porpoise agents are modelled, and includes information on bathymetry, distance from coast, temporal variation in salinity and prey distribution, food patches, and model blocks representing the spatial modelling domain.

DEPONS comes with an example folder for the North Sea landscape, however, users are also able to specify a user-defined landscape. The user-defined landscape used in the current study was identical to the input files in the default North Sea landscape, but with changes made to the blocks file and, for some scenarios, the food distribution maps.

As DEPONS is a spatially explicit model, the blocks file was adjusted to allow temporal extraction of the modelled number of individuals present in the entire North Sea MU, within the SNS SAC, as well as within a 20 km buffer around the EA1 wind turbines (Figure 6). This allowed for investigation into post-piling recovery and localised long-term impacts within the SNS SAC and the buffer zone.

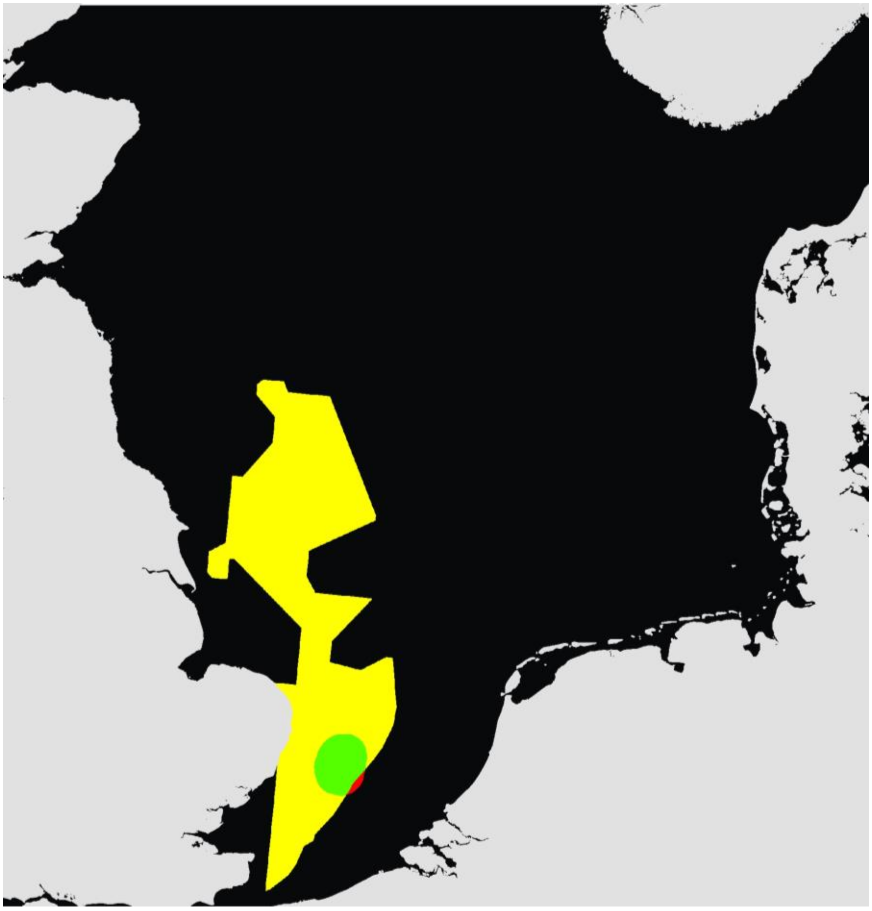

Figure 6. Adjusted DEPONS blocks file for the North Sea, reflecting the SNS SAC (yellow & green areas) and the 20 km buffer zone around the EA1 wind turbines (green & red areas). Note, the DEPONS North Sea spatial modelling domain does not cover the entire distributional range of the North Sea harbour porpoise Management Unit (see also Figure 4).

In DEPONS, default prey distribution maps are derived from seasonal porpoise distribution maps (Gilles et al., 2016), where porpoise densities are used as a proxy for food availability (Nabe-Nielsen et al., 2021). In the absence of porpoise density data for the winter season, the North Sea landscape (default) incorporates the autumn (September – November) maps for the winter months (December – February). As mentioned in Section 3.1.1.4, local harbour porpoise densities in the southern part of the SNS SAC, including around the EA1 wind farm, appear to be higher in winter. To reflect this, the seasonal porpoise densities in the spring and autumn food maps were compared, which revealed that the modelled porpoise density was higher in spring than in autumn. As such, additional DEPONS scenarios were run applying the spring food distribution map (rather than the autumn map) for the winter period in order to align with increased porpoise abundance observed in the winter.

3.2.1.4 Wind farm construction

In contrast to iPCoD, where each scenario simulates the impacted and un-impacted population simultaneously, DEPONS requires these to be modelled separately with the absence of piling activity modelled by not specifying a wind farm construction scenario (i.e. by switching the *Turbine* parameter to 'Off').

The construction scenario was based on the actual EA1 piling schedule and incorporated a 'burning-in' time of 15 or 25 years, depending on the particular scenario (see below). This burning-in period allowed the modelled population to reach a steady-state equilibrium before exposing it to piling activity and assess subsequent population dynamics.

Adjustments were made to align with the 30-day month applied in DEPONS, rather than using actual Date-Time stamps for each half-hour tick time step (referred to as '*tick*') used in the simulations.

3.2.1.5 Simulation years

DEPONS requires a 'burning-in' time in order to obtain a stabilised population, prior to subjecting the porpoise agents to the piling activity. Initial model runs used a burning-in period of 10 years, however the scenarios applying the Fertility value h = 0.34 resulted in populations that did not stabilise within that period; burning-in periods of 20 years were needed for the simulated populations to stabilise. Additionally, when applying the 10-year (h = 0.68) and 20-year (h = 0.34) burning-in periods, substantial increases in harbour porpoise numbers inside the SNS SAC were forecast for both Fertility scenarios, despite the overall population dynamics having reached steady-state equilibria. As such, the final model simulations were run for 40 (h = 0.68) and 50 years (h = 0.34), to cover the 25-year period used to investigate the long-term impacts of the various scenarios as well as a 15- or 25-year burning-in period; the burning-in periods were subsequently omitted from analysis.

3.2.2 Modelling scenarios

Combining the specified input value options mentioned above, where one parameter was changed at a time, resulted in the formulation of 16 defined modelling scenarios (Table 6).

Table 6. *DEPONS modelling scenarios. h = Fertility; T = Response Threshold; c = Deterrence Coefficient.*

Scenario	***h* = 0.68** (15-year burning-in period)	Scenario	***h* = 0.34** (25-year burning-in period)
1	Baseline (i.e. no piling)	9	Baseline (i.e. no piling)
2	*T* = 103.0; *c* = default (i.e. 0.07)	10	*T* = 103.0; *c* = default (i.e. 0.07)
3	*T* = 103.0; *c* = -50% (i.e. 0.035)	11	*T* = 103.0; *c* = -50% (i.e. 0.035)
4	*T* = 103.0; *c* = +100% (i.e. 0.14)	12	*T* = 103.0; *c* = +100% (i.e. 0.14)
5	*T* = 124.6; *c* = default (i.e. 0.07)	13	*T* = 124.6; *c* = default (i.e. 0.07)
6	*T* = 132.3; *c* = default (i.e. 0.07)	14	*T* = 132.3; *c* = default (i.e. 0.07)
7	*T* = 140.0; *c* = default (i.e. 0.07)	15	*T* = 140.0; *c* = default (i.e. 0.07)
8	As Scenario 2, but spring food maps (rather than autumn food maps)	16	As Scenario 10, but spring food maps (rather than autumn food maps)

Modelling was undertaken in DEPONS Version 2.2, with five replicate simulations completed for each scenario under consideration. Version 2.2 allowed for a more flexible specification of sound transmission loss, as well as simulation of how harbour porpoise populations are influenced by noise from ships, in addition to piling. Evaluating population-level impacts from shipping (whether associated with EA1 construction or unrelated commercial and recreational vessel movements), however, was deemed beyond the scope of this study, which focussed on effects from pin-piling.

The model's TRACE document (Nabe-Nielsen et al., 2021) provided input value recommendations for the majority of the model parameters. A Spreading Loss Factor of $\hat{\beta}$ = 17.75, and Absorption Coefficient of $\hat{\alpha}$ = 0.0005693 dB / m were applied (van Geel et al., 2023b). An overview of the above-mentioned scenario-specific parameters, the fixed model parameters, and their input values is outlined in Appendix B.

As each porpoise agent represents several real-life porpoises, the simulation outcomes represent unscaled numbers rather than the absolute population size, unless specified otherwise. With the exception of the results for the SAC and buffer zone during the 2017-2020 period (at resolution of individual days), the results are presented as relative population sizes compared to the 2017 pre-piling baselines. This facilitates the interpretation of results, as starting population sizes (i.e. after elimination of the burning-in periods) differed between scenarios, as well as among the five replicate simulations run for the same scenario.

3.3 Population-level impacts

Under the EU Habitats Directive (HD; EC, 1992), Member States are required to maintain or restore the Favourable Conservation Status of listed conservation priority species and habitats, including the harbour porpoise. In the UK, the HD has originally been transposed into UK law by the Conservation (Natural Habitats, &c.) Regulations 1994. As a HD Annex II listed priority species, porpoises are also specifically included under Descriptor 1 (Biological diversity) of the EU Marine Strategy Framework Directive (MSFD; EC, 2008 & 2017). Under this strategy, Member States are required to achieve Good Environmental Status (GES) for listed species and habitats. The criteria to assess conservation status are in essence equivalent between these Directives, with mammals (including cetaceans such as porpoises) being assessed based on a combination of population abundance, distributional range, population conditions (e.g. demographic characteristics and population genetic structure, where appropriate), extent and condition of their habitat and future prospects. A population decline of more than 1% per year is considered to signify Unfavourable HD conservation status (Evans & Arvela, 2012). Similarly, the MSFD has been transposed and implemented into UK legislation via the UK Marine Strategy Regulations 2010. Presently, a ~0.5% annual reduction in population size is considered to indicate a significant decrease in abundance (DEFRA, 2019).

In line with these assessment thresholds, the modelled iPCoD population size outcomes were assessed by obtaining the probability of an annual average population decline of more than 0.5% and 1% (i.e. the population size in 2040 being <88.67% and <78.57% of the pre-piling baseline, respectively). For DEPONS, the proportional population size outputs were similarly compared against those associated with an average annual population decline thresholds of 0.5% and 1%.

4 RESULTS

4.1 iPCoD

4.1.1 'Conservative' scenario

Selection of the 'conservative' option for each of the input parameters (Section 3.1.2; Table 6) revealed that noise outputs during construction of EA1 did not result in long-term population-level consequences. The results of this 'conservative' scenario indicated high levels of similarity between the impacted and un-impacted populations over the 25-year model run, with trajectories, 95% Confidence Intervals and population size distributions practically identical (Figures 7 & 8). The impacted population revealed a slightly increased probability for a >1% population decline compared to the un-impacted population (83 versus 80 out of the 1,000 modelled trajectories, respectively). For a >0.5% decline, these were 256 versus 249 of the 1,000 trajectories. The mean impacted population size at the end of the simulation stabilised at ~99.61% of the mean size of the un-impacted population (Figure 9).

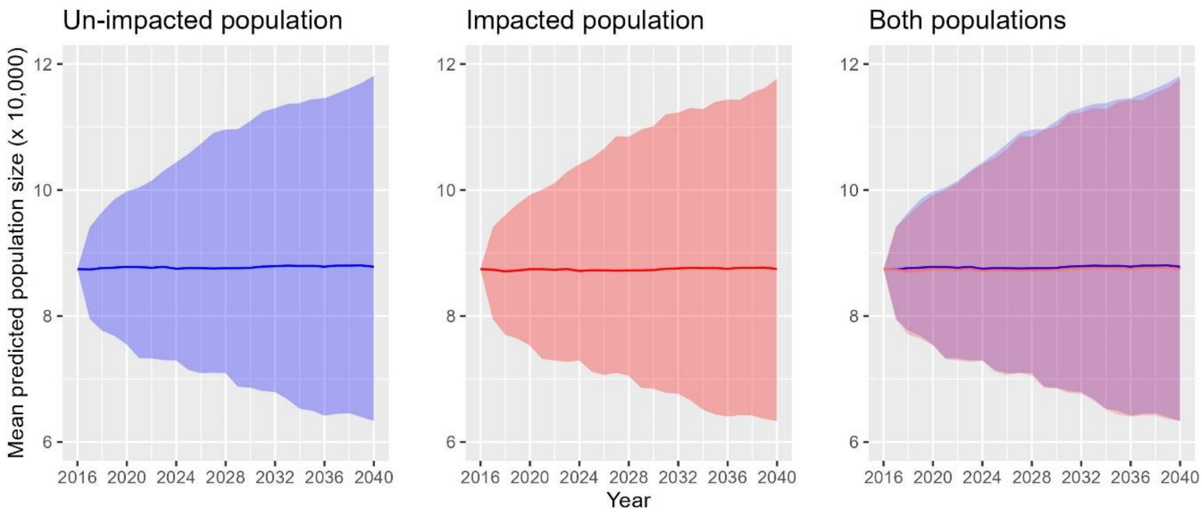

Figure 7. *Visualisation of the mean un-impacted and impacted population trajectories and associated 95% Confidence Intervals for the 'conservative' scenario. The right-hand panel indicates the considerable overlap between both scenarios.*

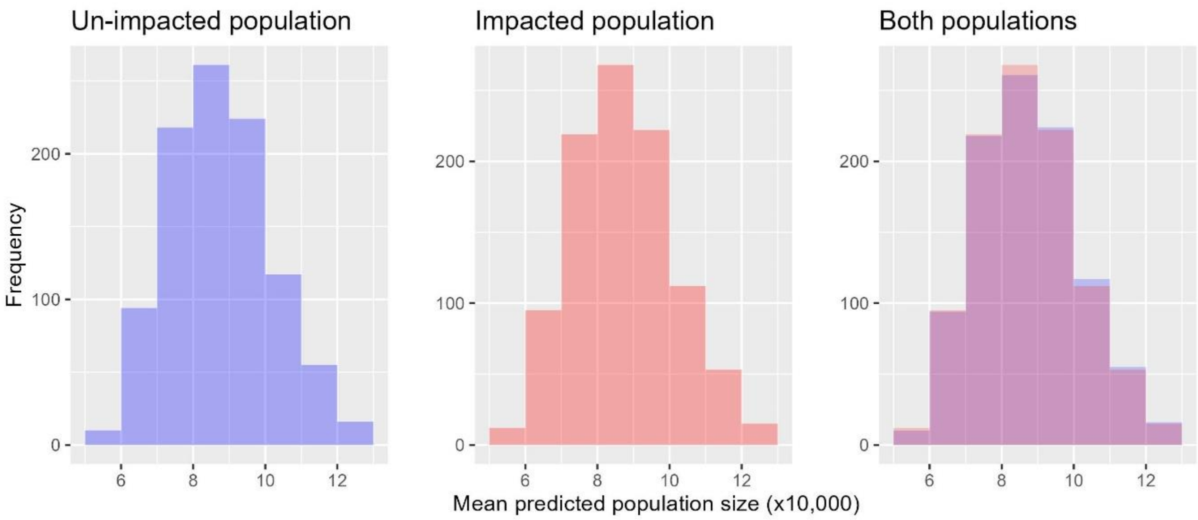

Figure 8. *Histogram of predicted population size at the end of the 25-year model simulation. The right-hand panel indicates the considerable overlap between both scenarios.*

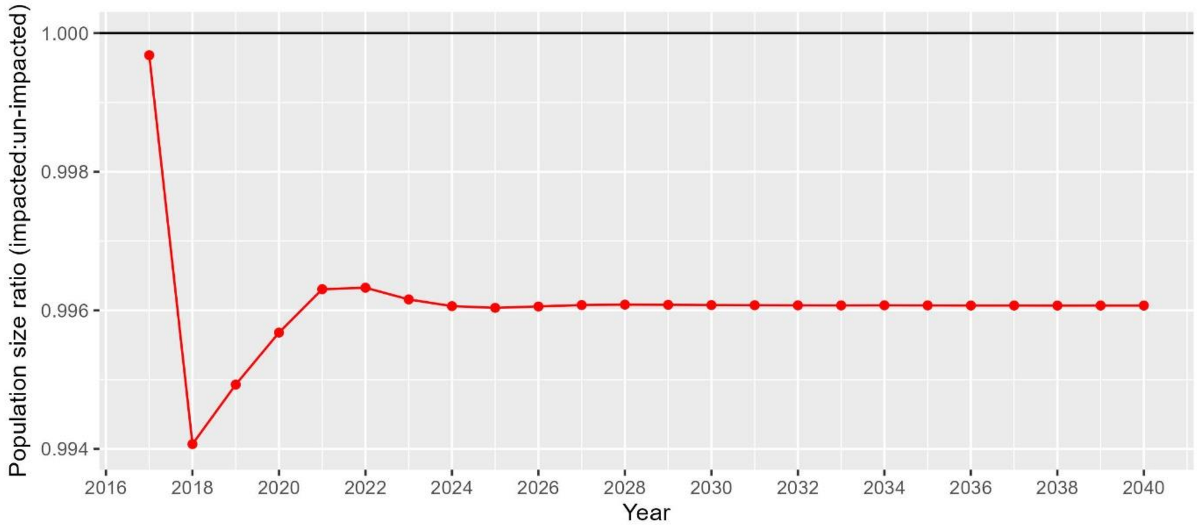

Figure 9. *Development of ratio between the predicted impacted and un-impacted population sizes during the 25-year model simulation. Note the scale on the y-axis.*

As the most 'conservative' scenario considered for this wind farm development did not result in a significant difference (i.e. an annual decline of 0.5%) between the mean impacted and un-impacted population sizes (the mean decline was ~0.39% over 25 years), scenarios with less conservative input values would not result in an impact either. Consequently, no additional scenarios were assessed.

4.2 DEPONS

4.2.1 Long-term population-level impacts

4.2.1.1 Fertility = 0.68 (Scenarios 1-8)

After the 15-year burning-in period, the population stabilised around 8,000 of the 10,000 original porpoise agents (Figure C1 in Appendix C). The DEPONS results of the five simulations per scenario (excluding the burning-in period) applying a Fertility value of 0.68 are presented in Figure D1 in Appendix D. Scenario averages are shown in Figure 10 below.

When considering the harbour porpoise North Sea MU, no annual rates of population declines >0.5% relative to the 2017 pre-piling levels were observed at the scale of scenario averages (Figure 10), with only one of the five individual non-piling baseline (S1) simulations illustrating such a decline (Figure D1). Despite the lack of substantial long-term impacts on the population size, after 25 years the average simulated porpoise population size was lower than the 2017 reference level for many modelling scenarios (Figure 10). The largest decline in average population size (5.37% overall reduction over 25 years) was observed in the non-piling baseline scenario. All scenarios illustrated considerable inter-annual and inter-simulation variation with population size fluctuating between approximately +4% and -7% of the 2017 pre-piling reference population size (up to approximately +8% and -12% for individual simulations; see Figure D1 in Appendix D for details).

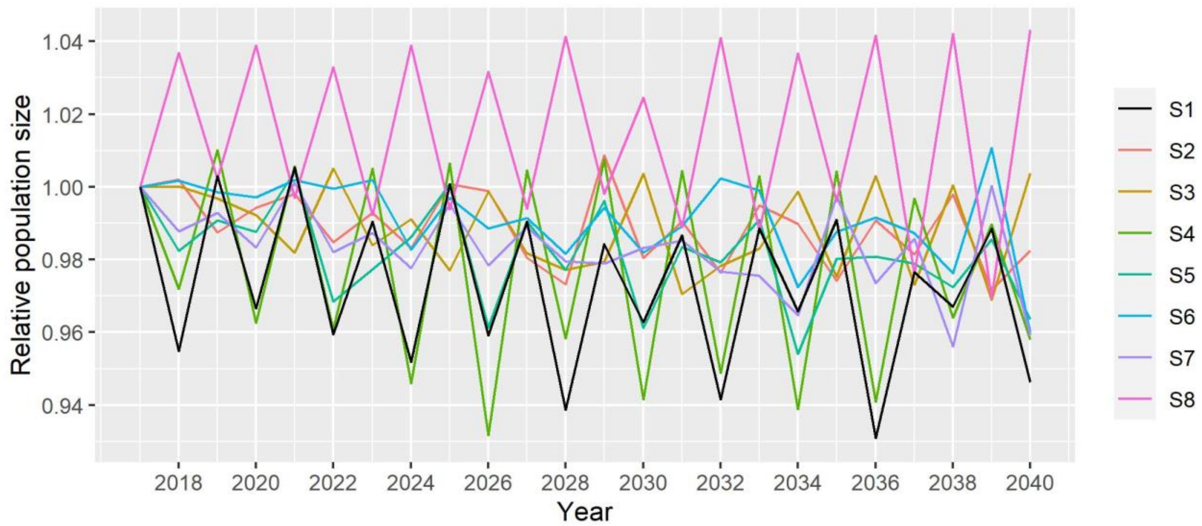

Figure 10. *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on the average of five simulations per scenario. The non-piling (baseline) scenario is presented in black. Scenario details are summarised in Table 6.*

4.2.1.2 Fertility = 0.34 (Scenarios 9-16)

Following the 25-year burning-in period, the population stabilised around 8,500 of the 10,000 porpoise agents (Figure C2 in Appendix C). The results for each of the five DEPONS simulations for the individual scenarios (S9-S16, see Table 6 for details) using the specified Fertility value of 0.34 are summarised in Figure D2 of Appendix D, with scenario means (scaled to pre-piling 2017 baseline values) presented in Figure 11 below.

Decreasing the Fertility value from 0.68 to 0.34 did not result in very different outcomes when compared to scenarios using a Fertility value of 0.68 (Section 4.2.1.1). Based on the modelled results, the construction of EA1 appeared to have no substantial long-term impacts on the North Sea population size in any of the individual piling scenarios or individual simulations. Population size averages at the end of the simulations were broadly comparable to the pre-piling population size. The largest decline was modelled for Scenario 10, and revealed an overall 2.12% decline over 25 years (Figure 11). Application of the smaller Fertility value also resulted in inter-annual and inter-simulation variability in population size; variability ranged between approximately +4% and -2.5% for the averaged scenarios (Figure 11), and between +8% and -7% for the individual simulations (see Figure D2 in Appendix D for details).

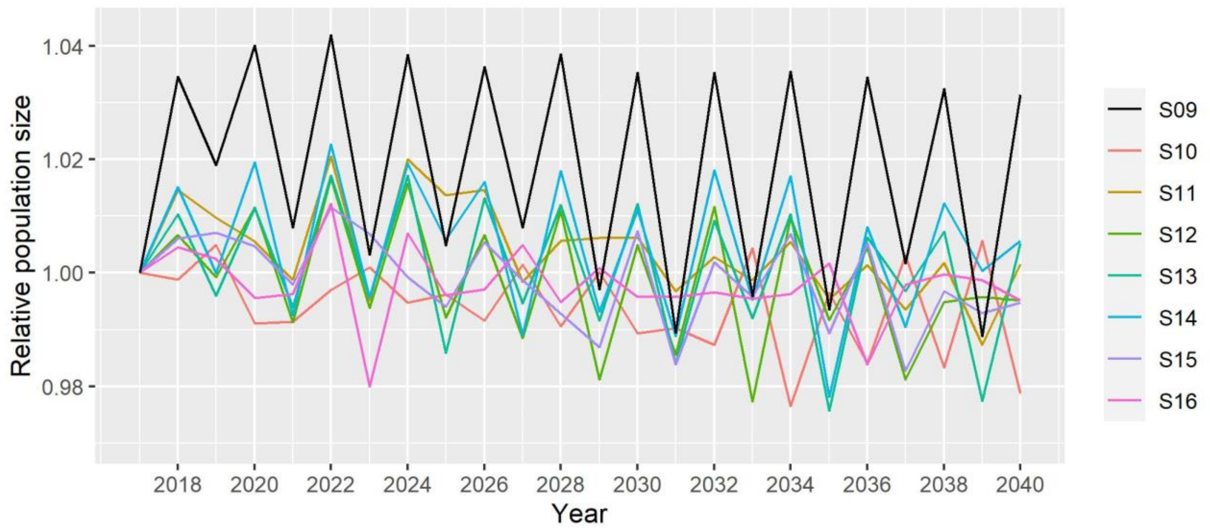

Figure 11. *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on the average of five simulations per scenario. The non-piling (baseline) scenario is presented in black. Scenario details are summarised in Table 6.*

4.2.2 Long-term and short-term Southern North Sea SAC impacts

4.2.2.1 Fertility = 0.68 (Scenarios 1-8)

Figure E1 in Appendix E illustrates changes in the number of porpoises (scaled relative to 2017 pre-piling conditions) predicted to occur within the Southern North Sea SAC boundary for each of the five simulations for Scenarios 1-8. The average trajectories of each of these eight scenarios have been summarised in Figure 12 below.

No substantial long-term negative impacts on the predicted numbers of porpoises present in SNS SAC were indicated by any of the modelling scenarios. Instead, most scenarios resulted in slightly increased average numbers of individuals expected within the boundary of the SNS SAC compared to 2017 levels (Figure 12), although individual simulations ranged from 10% above to 6% below the pre-piling reference value in any given year (Figure E1 in Appendix E).

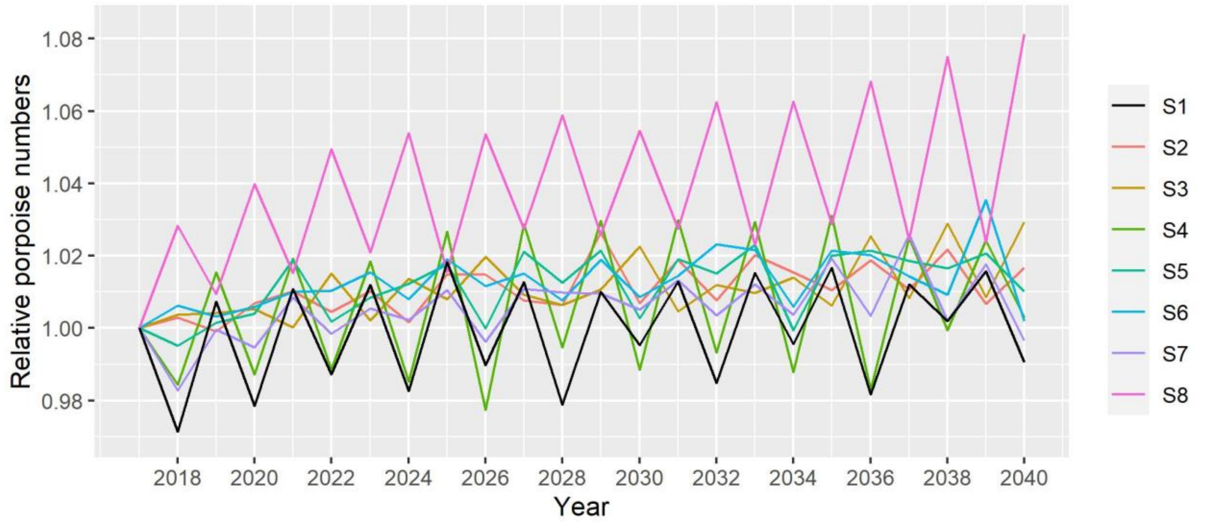

Figure 12. *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline level in 2017 for DEPONS simulations applying a Fertility value of 0.68 and based on the average of five simulations per scenario. The non-piling (baseline) scenario is presented in black. Scenario details are summarised in Table 6.*

When using a temporal resolution of days, rather than annual averages, predicted porpoise numbers fluctuated through the year, with increases reflecting calves being weaned and joining the juvenile population, and decreases indicating mortality due to competition for food (Nabe-Nielsen, 2021).

The predicted number of porpoises within the SNS SAC (NB.: unscaled to population size) decreased in all scenarios during the piling period (from 25/04/2018 until 30/01/2019), including the non-piling baseline, suggesting that this change might not be connected to ongoing piling activity (Figure 13). This suggestion was further supported by the fact that comparable decreases were also predicted during these months in both pre- and post-piling years (2017, 2019 and 2020) within each scenario.

In some scenarios (i.e. S1, S4, S5, S7 and S8), the predicted porpoise abundance fluctuated from one year to the next suggesting a biennial pattern. However, whilst predicted numbers were highest in 2017 & 2019 for most of these scenarios, an opposite pattern was present for Scenario 8 (i.e. highest modelled numbers for 2018 & 2020). As a result, on alternate years, Scenario 8 (incorporated increased local food supply at the EA1 site for December – February), revealed an overall decrease in the number of modelled porpoises in the wider SAC compared to the other scenarios. A full overview of the outcomes for the individual scenarios is provided in Figure F1 of Appendix F.

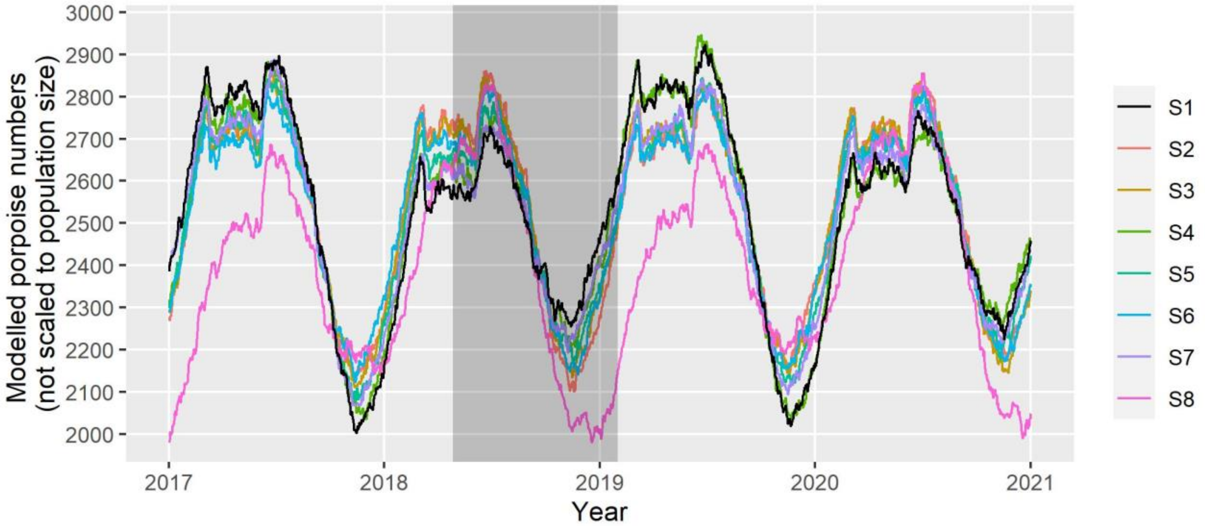

__Figure 13.__ Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020. Values were derived by applying a Fertility value of 0.68 and based on the five replicate simulations per scenario. Details of scenarios 1-8 are summarised in Table 6. The EA1 construction period is indicated by the dark grey rectangle.

4.2.2.2 Fertility = 0.34 (Scenarios 9-16)

An overview of the results for individual simulations for each scenario is provided in Figure E2 of Appendix E, and their averages are presented in Figure 14.

Similar to the results described in Section 4.2.2.1, no substantial long-term negative impacts on the predicted number of harbour porpoises within the SNS SAC were revealed when applying the lower Fertility value. In fact, the average estimates were higher at the end of the simulation duration for each of the scenarios (Figure 14). The reduced Fertility value resulted in slightly diminished inter-annual and inter-scenario differences within the SNS SAC (compare Figure E2 to Figure E1), with annual variability ranging from approximately -4% to +6% within individual simulations.

Modelled daily porpoise numbers (unscaled to population size) in the SAC based on scenarios using a Fertility value of 0.34 revealed very similar results to those modelled with a Fertility value of 0.68 (Section 4.2.2.1), with observed decreases from summer into winter reflected across the years for each of the scenarios simulated (Figure 15). Whereas the results of Scenarios 9-15 were very similar to each other, Scenario 16, which incorporated increased food availability at the EA1 wind farm during the winter, revealed a decrease in predicted number of porpoises within the SAC for the winter and following spring months in particular.

At a daily temporal resolution, some biennial fluctuation in the modelled porpoise abundance was noted in some scenario outputs. This biennial periodicity was not as pronounced as for those scenarios presented in Section 4.2.2.1, with the exception of Scenario 9 (non-piling baseline). The full results for individual scenarios are included in Figure F2 in Appendix F.

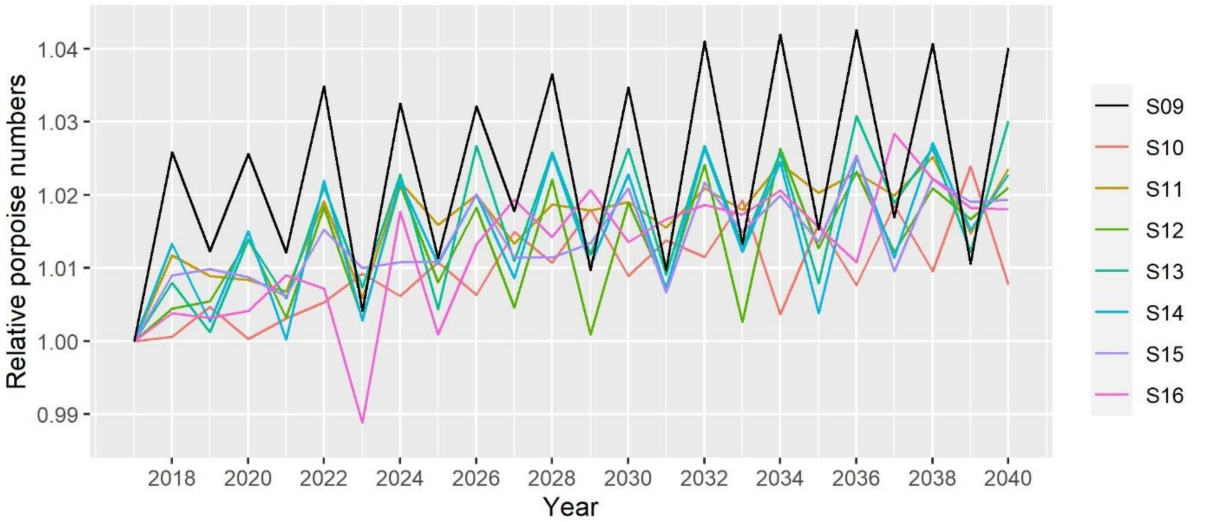

Figure 14. *Modelled number of porpoises within the SNS SAC boundary relative to numbers in 2017 (=pre-piling) for DEPONS simulations applying a Fertility value of 0.34 and based on the average of five simulations per scenario. The non-piling (baseline) scenario is presented in black. Scenarios details are summarised in Table 6.*

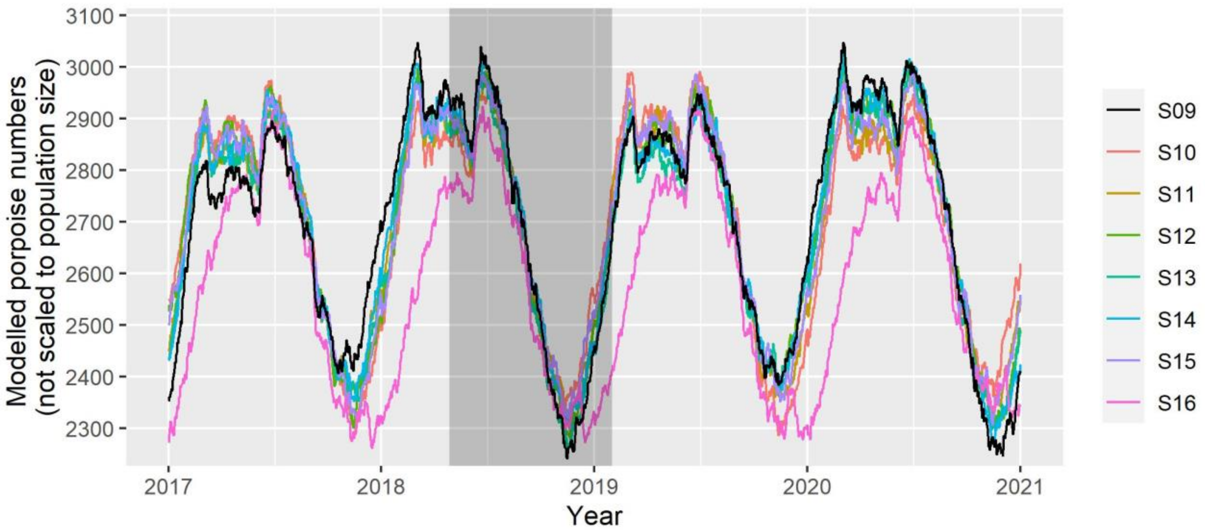

Figure 15. *Predicted daily average numbers of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020. Values were derived by applying a Fertility value of 0.34 and based on the five simulations per scenario. Details of scenarios 9-16 are summarised in Table 6. The EA1 construction period is indicated by the dark grey rectangle.*

4.2.3 Short-term localised impacts

4.2.3.1 Fertility = 0.68 (Scenarios 1-8)

Whilst predicted porpoise numbers were much lower in the 20 km buffer zone around the EA1 turbine locations compared to the much larger SNS SAC, the overall pattern of porpoise presence was broadly similar (Figure 16). There was a negative trend in predicted numbers throughout the piling period, which was mirrored in all scenarios including the non-piling baseline, as well as for the same months in non-piling years. Figure G1 of Appendix G presents the results for all individual scenarios.

In contrast to the SNS SAC results (Section 4.2.2), the localised increased winter food availability modelled in Scenario 8 was reflected in higher predicted porpoise numbers in the buffer zone during these months. Additionally, outcomes from Scenario 8 also predicted an overall higher number of porpoises present year-round within the 20 km buffer zone, when compared to Scenarios 1-7 (Figure 16).

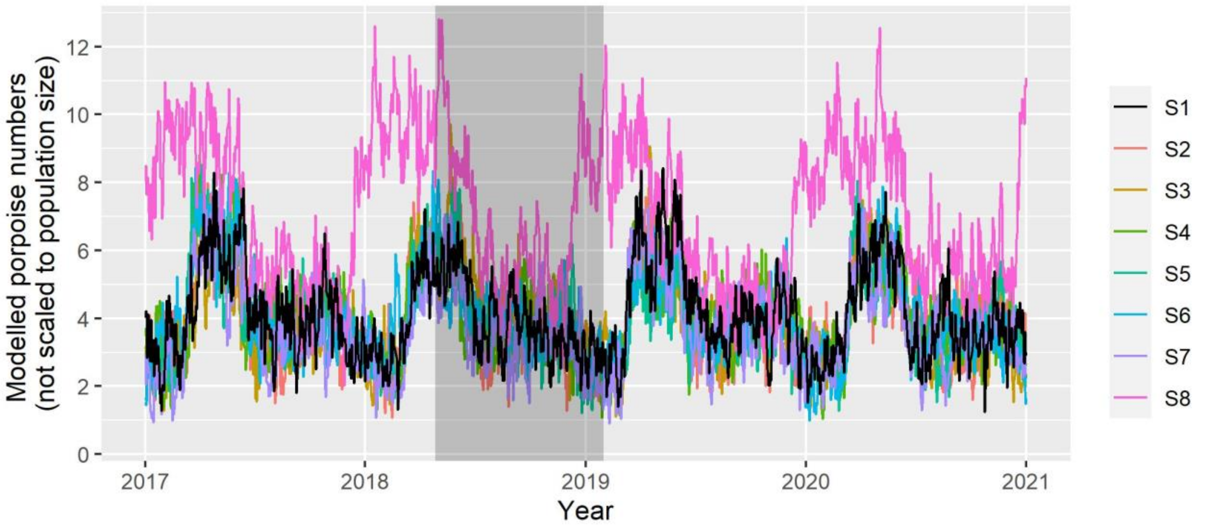

Figure 16. *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. Details of scenarios 1-8 are summarised in Table 6. The EA1 construction period is indicated by the dark grey rectangle.*

4.2.3.2 Fertility = 0.34 (Scenarios 9-16)

Decreasing the Fertility value revealed very similar patterns of predicted porpoise abundance for the 20 km buffer zone as described for those above (Section 4.2.3.1), with numbers declining from spring into summer across years, irrespective of ongoing piling activity (Figure 17). Likewise, there was little difference between Scenarios 9-15 which were based on identical food availability, whilst the increased local winter food availability in Scenario 16 resulted in higher numbers of predicted porpoises over the winter period, as well as an increased year-round presence generally. The results for individual scenarios are presented in Figure G2 of Appendix G.

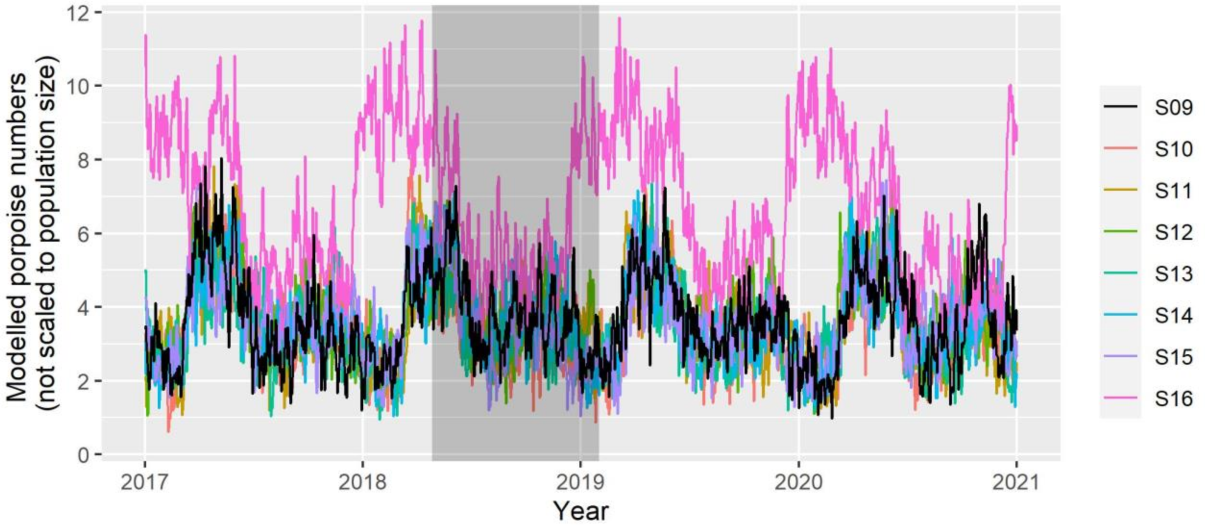

Figure 17. *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.34. Details of scenarios 9-16 are summarised in Table 6. The EA1 construction period is indicated by the dark grey rectangle.*

5 DISCUSSION

This study investigated the impacts of piling activity associated with the construction of the ScottishPower Renewables East Anglia ONE offshore wind farm on the harbour porpoise population inhabiting the North Sea. The potential for population-level impacts, as well as the suitability of the models to detect these, were assessed through integration of project-specific results from passive acoustic monitoring of porpoises (C-PODs) and sound propagation modelling (calibrated by means of full bandwidth acoustic data) into the application of two population impact modelling frameworks (iPCoD and DEPONS).

5.1 Local responses by porpoises to EA1 construction

Analysis of C-POD data collected prior to, during and post-construction of the EA1 wind farm revealed that harbour porpoises were present at the site throughout the monitoring period (March 2018 – June 2019; Figures 7 & 8 and Tables 5 & 6 in van Geel et al., 2023b). Their presence (indicated by detections of echolocation) varied throughout the year and across the acoustic array. Detection rates of porpoise presence were generally lower at sites located within the wind farm compared to those sites that were further away. For monitoring locations within and close to the wind farm, porpoise detection rates were higher during non-piling periods compared to times when piling activities took place (April 2018 – January 2019), and post-piling detection rates remained low compared to pre-construction. Statistical modelling of passive acoustic detection data revealed clear negative effects of piling, with an overall decrease in porpoise detections out to 14.0 km from the piling locations. At this distance, the overall predicted frequency-weighted received level was 103.0 dB re 1 $\mu Pa^2 s$ SEL (Figures 14 & 15 in van Geel et al., 2023b).

Localised, short-term responses of harbour porpoises in relation to EA1 piling were observed, with temporal absences or reductions in porpoise detections due to displacement and/or altered vocalisation behaviour. Waiting Time and Recovery Time were both assessed to obtain project-specific information, although efforts to assess Recovery Time were severely hampered by the lack of suitable data (see Sections 3.1.3.3 and 3.1.4 in van Geel et al., 2023b). Analysis of the acoustic data revealed a decrease in Waiting Time with increasing distance from piling, and an average Waiting Time (i.e. the time interval between the end of piling and the first porpoise echolocation detection recorded thereafter) of 6:50 hours for the 384 piling events within the 14.0 km distance from piling activity across the entire construction period. Analysis of the EA1 data additionally revealed that porpoises were not detected before piling had restarted on 236 occasions. In 588 out of the 590 events included in the assessment, a Waiting Time of less than 48 hours was found (the other two lasting 59 and 78 hours). However, no efforts were made to correct the post-piling Waiting Time for typical non-detection periods that would also have been present if piling had not taken place. Limited data were also available to assess Recovery Time, broadly defined as the time required for post-piling vocalisation activity to return to baseline values. The results, based on the construction of seven wind turbines, indicated a return to within 10% of pre-piling porpoise levels (assessed as Porpoise Positive Hours (PPH) and average Porpoise Positive Minutes per hour (PPM-h) during a 24-hour period) within 21 hours after piling activities had stopped (van Geel et al., 2023b).

Despite some data gaps during winter, porpoise detection rates appeared to be higher in winter compared to summer (Figures 7 & 8 in van Geel et al., 2023b), potentially reflecting seasonal variability in habitat use. This observation supports previous results showing higher local porpoise densities in the southern North Sea during the winter period (e.g. Gilles et al., 2016; Heinänen & Skov, 2015; Paxton et al., 2016; Waggitt et al., 2020). In fact, the EA1 wind farm is located within an area of the Southern North Sea SAC defined as the 'winter area' (October – March), based on seasonally persistent above-average porpoise densities (Heinänen and Skov, 2015; JNCC, 2019b). A general decrease in porpoise detections during the construction period (most of which occurred during the summer months) could thus be anticipated based on natural seasonal variation at the site. This assumption is supported by the results of the DEPONS simulations where modelled porpoise numbers were extracted for the area contained within the SAC boundary (Figures 13 & 15), as well as for the 20 km buffer zone around the wind turbines (Figures 16 & 17). For both spatial scales, predicted numbers of local porpoises decreased during the construction phase; this decrease was, however, comparable to the declines predicted for the baseline year 2017, as well as to those declines predicted during the post-construction years 2019 and 2020, independent of the scenario assessed. Observed declines in local densities were therefore most likely driven by seasonal changes in porpoise distribution.

5.2 Evaluation of iPCoD and DEPONS population impact models

5.2.1 Population-level and smaller-scale impacts

To our knowledge, this study is the first to apply both the iPCoD and DEPONS modelling frameworks simultaneously to data from the same offshore wind farm. Additionally, this is the first time that such modelling was undertaken for a UK wind farm using project-specific parameter input values obtained from data collected during its construction, rather than requiring input from other projects and making multiple assumptions about crucial details such as piling schedules at the pre-consenting stage.

Overall, the application of both frameworks indicated an absence of long-term population-level impacts on harbour porpoises in response to piling activity associated with the construction of the EA1 wind farm. In particular, the results of both frameworks showed that modelled population sizes of populations exposed to piling activity could not be differentiated from those under baseline conditions following a 25-year simulation period. Both iPCoD and DEPONS modelling results showed high average population sizes (relative to baseline) predicted at the end of the simulations, with none of the averaged scenarios indicating a strong probability of a long-term annual decline in abundance of 0.5% or 1% (i.e. population levels reduced to 88.67% or 78.57% of the starting population).

Specifically, under the 'conservative' iPCoD scenario (applying a population size of 87,440 individuals), a >1% decline occurred in 80 & 83 out of 1,000 modelled trajectories for un-impacted and impacted populations, respectively. Cases where predicted declines of >1% of the undisturbed model populations were observed resulted from environmental stochasticity. Under 'conservative' simulation conditions, the increased probability of piling-associated risk of a >1% population decline (i.e. accounting for this occurring in the absence of piling disturbance as simulated for the un-impacted population) was 0.3% (3 in 1,000). For an annual >0.5% decline, this was 0.6% (6 in 1,000).

Whilst an annual >0.5% or >1% reduction in harbour porpoise population size, as a result of construction activity at EA1, can therefore not be completely ruled out based on these iPCoD results, the probability of this appears very low. Similarly, none of the DEPONS averaged scenarios predicted a long-term annual decline of >0.5% or >1%, irrespective of the spatial scale at which the data were assessed.

Although no long-term population-level effects were revealed, the fact that DEPONS is a spatially explicit model meant that potential impacts on porpoise numbers at smaller spatial scales could also be explored, specifically within the Southern North Sea SAC and a 20 km buffer zone around the EA1 development. Due to underlying model differences and inconsistent parameterisation, the iPCoD and DEPONS models and their results are not directly comparable (for reviews see Mortensen & Thomsen, 2019; Nabe-Nielsen & Harwood, 2016). These differences resulted in that both models were not always run at the same spatial resolution. Unlike DEPONS, iPCoD is not spatially explicit, and although assessments on smaller spatial scales could be addressed, predicted porpoise numbers could not be readily extracted for the SNS SAC and the buffer zone from the results obtained here. Likewise, DEPONS simulated across the entire North Sea domain, which meant that effects on a hypothetical southern North Sea grouping (as was applied for iPCoD) could not be explored. Alterations could be made to use DEPONS to explore the dynamics of a small, isolated porpoise population in a subsection of the North Sea, if conclusive evidence were to become available that supported the existence of such a population.

Modelling results at the scale of the SNS SAC revealed neither short- nor long-term negative impacts of piling on predicted porpoise numbers within the SAC boundary, with final annual predicted numbers in the SAC slightly higher than, or comparable to, numbers at the start of simulations across all scenarios. Daily modelled porpoise numbers fluctuated throughout the year, but predicted numbers during construction periods were similar to those predicted for the same periods in non-piling years. Likewise, the model outcomes for the 20 km buffer zone were very similar between most scenarios. For both these smaller spatial scales, observed patterns of porpoise abundance were not significantly influenced by application of the different Fertility values. The differences between scenarios in predicted porpoise numbers were mainly driven by changes to the food distribution maps used for the winter months (Scenarios 8 & 16), with reduced numbers within the SAC and increased numbers in the buffer zone.

5.2.2 Interpretation of 'No-impact' results

The results of both modelling frameworks revealed a lack of long-term population impacts at the North Sea scale. This, however, does not mean that there was no local impact on the population, but confirms previous suggestion that the large porpoise population as a whole appears inherently resilient to discrete spatio-temporal impacts such as the EA1 pile-driving activity, partly because individuals are able to temporarily move away.

The fact that no long-term population-level impacts were demonstrated when these frameworks were applied to a single development is not inherently surprising. Smith et al. (2019) were also unable to demonstrate long-term cumulative impacts of piling and blasting on porpoises when applying iPCoD to assess the impacts of seven offshore wind construction developments and a harbour expansion project off eastern Scotland over a ~7-year construction period. Booth et al. (2017) applied two different dose-response functions to estimate the number of disturbed individuals, and a more nuanced approach to incorporate disturbance to investigate the impacts of 13 offshore wind farm developments constructed in English North Sea waters over a 12-year period. Using a range of quite conservative scenarios, their results still only indicated a 0.3-5.2% piling-associated increase in the risk of a >1% decline in average annual harbour porpoise population size 12 years after construction ended (i.e. at year 24 of the simulation). The probability of increased risk depended strongly on assumptions on the specification of the vulnerable sub-population, applied density estimates and noise impact range (through the dose-response function), as well as modelled (residual) disturbance days and associated impact ranges; all of which are poorly understood, as described above.

When applying DEPONS to assess the impacts of different piling regimes to the construction of numerous offshore wind developments throughout the southern North Sea (i.e. 65 wind farms representing 3,900 individual turbines), resulting population dynamics were indistinguishable from a non-piling baseline when an 8.9 km impact range was incorporated in the simulations (Nabe-Nielsen et al., 2018). Finally, the construction of 1,650 wind turbines in German waters over a 20-year period, when applying 11.35 km and 25 km as maximum response distances, also did not reveal any localised short- or long-term impacts (Nabe-Nielsen, 2021). The lack of longer-term piling impacts, even at smaller spatial scales like those demonstrated in the current study, might result from simulated animals simply returning and continuing to forage after having been temporarily displaced by piling noise (Nabe-Nielsen et al., 2018), or the movement of different, naïve animals into the area.

5.2.3 Model parameterisation and sensitivity: Uncertainty and caveats

To reflect site- and project-specific conditions as realistically as possible, several model input values were derived from analyses of acoustic data collected at EA1 and associated noise propagation modelling, whereas others were obtained from updated literature directly relevant to the North Sea harbour porpoise population. In particular, project-specific inputs were identified for the following model parameters values or input data:

- piling schedule,
- source level,
- Absorption Coefficient,
- Spreading Loss Factor,
- Response Threshold,
- Deterrence Coefficient,
- Impact Zone,
- PTS Zone,
- Residual Disturbance,
- Population size,
- Vulnerable sub-population,
- calf survival,
- adult survival,
- Fertility,
- Site-specific porpoise density and associated seasonal variation in this,

- food availability, and
- the number of simulation years.

For all other model parameters, recommended or default settings, as advised by iPCoD and DEPONS supporting material, were used. Uncertainty in input values for several of these project-specific parameters was considered and incorporated into the stepwise approach for iPCoD and into the 16 fixed DEPONS scenarios.

5.2.3.1 Modelling framework sensitivity

Incorporation of different input values may aid in the assessment of model sensitivity. In this study, a comprehensive assessment of the sensitivity of the models to the applied input values was impeded by the fact that neither of the population impact modelling frameworks showed long-term population-level impacts for any of the scenarios assessed.

Overall, application of conservative iPCoD parameter input values did not result in a long-term population-level impact and thus less conservative scenario options were not explored further. The results of the different DEPONS scenarios were generally very similar, apart from those where the food availability was changed from default, and then only when assessed at smaller spatial resolution (SNS SAC; buffer zone) and temporal scale (daily average).

Whilst it is possible that the models were not sensitive to the specific input values for the different model parameters applied here, it is more plausible that the observed lack of a population response in the two modelling frameworks indicates that the population as a whole is not affected by the studied disturbances. This is especially likely when considering the relatively small spatial and temporal scale of the impact of a single development in relation to the abundance of the harbour porpoise North Sea Management Unit, and the geographical scale across which it occurs.

5.2.3.2 Information derived from the acoustic data

This study is underpinned by modelling porpoise presence derived from acoustic monitoring, and is therefore subject to the same caveats associated with all passive acoustic monitoring programmes, in that it relies on animals vocalising to detect their presence (Verfuss et al., 2018). Additionally, detectability is influenced by a range of factors including ambient noise levels (Clausen et al., 2019), as well as the source level and orientation of porpoise's directional echolocation (Nuuttila et al., 2018; Macaulay et al., 2020). Moreover, reduced detection rates may reflect a decrease in animal presence, altered vocalisation behaviour, or both. There is limited information on the vocal behaviour of porpoises in relation to piling noise, and with respect to movements of individual animals in response to noise impact (Koschinski et al., 2003; van Beest et al., 2018b). Despite these uncertainties, previous studies have shown that acoustic detections can be used as relative indices for porpoise presence (e.g. Brandt et al., 2016; Kyhn et al., 2012; Mikkelsen et al., 2016; Williamson et al., 2016), and can thus serve as suitable proxies for the general usage of an area.

For this project, acoustic porpoise presence data were collected before, during, and after EA1 construction activity by means of a passive acoustic monitoring (PAM) array. Assessing the effects of piling on harbour porpoises requires some understanding of the naturally occurring patterns of porpoise detections in the study area in the absence of piling. Year-round baseline data were unfortunately unavailable, and only very limited amounts of data existed for the pre-construction period, as well as for the autumn and winter of 2018/2019 which coincided with piling. Overall, monitoring efforts were unequal in time and space. This, in turn, prevented a full investigation of the natural inter-annual and inter-seasonal variability of porpoise presence, and their variability during piling across the array (van Geel et al., 2023b). In addition, the PAM array's ability to detect porpoises was compromised at times of higher flow speeds. To increase confidence that observed occurrence patterns reflected porpoise behaviour, rather than changes in detectability, data compromised by tidal flow or persistent vessel noise were excluded (up to 38.7%) for individual C-POD monitoring locations. As a result, the data included in the current study represented only those periods coinciding with reduced tidal flow and vessel noise, which affected moorings across the array to varying degrees.

The current work focussed on the impacts of pin-piling, and as such did not explicitly incorporate other noise related to wind farm construction, such as vessel activity, UXO clearance, and geophysical/geotechnical surveys related to EA1, as well as noise originating from general shipping in the area. Although the use of Acoustic Deterrent Devices (ADDs) has been reported to impact harbour porpoise response levels to piling activity (Graham et al., 2019), disturbance from ADDs versus pin-piling was not disentangled here. Pre-piling activation of ADDs were, however, incorporated in the computation of the PTS Zone (which is based on a 24-hour noise exposure). Additionally, the piling Impact Zone, representing the area around piling activity where the presence of porpoise detections was negatively influenced, not only reflects porpoises' vocalisation and/or distributional responses in relation to piling noise, but also balances these responses against presence of other anthropogenic pressures, as well as ecological characteristics of the habitat (e.g. abundance of prey).

In this project, the number of individual porpoises potentially experiencing PTS over a 24-hour period was estimated based on the NMFS (2018) and Southall et al. (2019) criteria without simulating an aversive movement response by porpoises. Non-piling construction activities and noise from other industries adjacent to the EA1 site, however, were not considered. As demonstrated in the current study, as well as described in the scientific literature (e.g. Brandt et al., 2018; Dähne et al., 2013 & 2017; Graham et al., 2019 & 2023; Teilmann & Carstensen, 2012), porpoise detection rates are reduced (i.e. move away from and/or alter vocal behaviour) around piling locations, with impacts continuing for some time after construction activities have ceased. Impact Zones and probability of PTS calculated based on the assumption that animals flee from the source at the onset of disturbance can differ substantially from those that assume stationary animals (Faulkner et al., 2018; Heinis et al., 2022). Bearing in mind that ADDs were deployed to mitigate against PTS occurring (Graham et al., 2019 & 2023; Thompson et al., 2020), this suggests that the estimated number of porpoises experiencing PTS, as applied here, is likely conservative. The current version of iPCoD is less sensitive to this parameter, however, since the updated expert elicitation results were incorporated (Booth & Heinis, 2018), resulting in a much-reduced predicted effect of PTS on survival and fertility. Moreover, despite conservative input values, no long-term population impact was predicted by iPCoD. DEPONS directly incorporates the animals' ability to move away from the piling zone prior to piling when actively deterred, so DEPONS assumes that animals do not experience PTS. Although not done in the current study, ADD transmission details could be added to the construction schedule if further focus were required.

Calculations of the Received Level and PTS Zone used here were based on modelled piling source levels transmitted into the environment. Any model describing the propagation of these noise emissions represents a simplification that approximates reality, like the iPCoD and DEPONS models themselves. For instance, a single source level may be derived for the construction of an individual pin-pile based on the maximum hammer energy. In reality, however, noise levels vary throughout a piling event, as a result of variation in applied hammer energy (ramping up protocols; penetration-depth related energy requirements) and changes in the amount of energy being transmitted into the sediment when piles are driven further into the seafloor (Banda & Cook, 2018; Martin & Barclay, 2019; Thompson et al., 2020). Additionally, the results presented by Thompson et al. (2020) indicate a stronger relationship between at-distance pin-piling noise level and pile penetration depth than with hammer energy. Model assumptions not only affect the incorporation of the piling activity, but also apply to inclusion of natural parameters affecting sound propagation, such as seasonally fluctuating water temperature, stratification of the water column, and differences in weather conditions (Malme et al., 1995). Considering the need for such generalisations, the transmission loss model developed for this study, which combined two propagation modelling techniques and incorporated project-specific information on piling and environmental conditions, was calibrated using locally-obtained acoustic measurements to optimise the model and minimise uncertainty where possible.

5.2.3.3 Population-specific data

Based on currently available data, the most appropriate scale for assessing population-level impact on porpoises in the North Sea is the entire North Sea Management Unit (ICES, 2014; IAMMWG, 2015; Murphy et al., 2019). The MU's abundance estimate and associated confidence levels from the SCANS-III survey were used in this study, together with the estimates for a hypothetical regional southern North Sea group. The inclusion of a hypothetical group occupying the southern North Sea area was directed by the general lack of knowledge about movement patterns of individual porpoises, particularly in the southern North Sea where the focus of this study was.

Based on data obtained from satellite-tagged porpoises in Danish waters, some of these tagged individuals have been reported to undertake long-distance movements, crossing the North Sea into Scottish coastal waters, as well as northwards to coastal waters off Norway (Nielsen et al., 2018; Stalder et al., 2020). However, even these observations are based on data of <100 individuals and it is unclear how representative they are for the entire population within the North Sea MU. Analysis of these tagging data showed high-intensity usage of Danish, Swedish and Norwegian coastal waters, a degree of summer site-fidelity for some individuals, and a general lack of movement into the southern North Sea (Nielsen et al., 2018), indicating the potential for spatial stratification across the wider North Sea MU area.

For the purposes of this study, efforts were therefore made to explicitly explore the impacts of EA1 construction activities on a hypothetical regional, southern North Sea grouping, despite the current lack of scientific support for population sub-division within the North Sea MU (Murphy et al., 2019). This approach, combined with the abundance estimates and associated confidence intervals from the recent SCANS-III survey (Hammond et al., 2021), resulted in six levels of potential iPCoD input values to account for uncertainty in the Population size. Likewise, uncertainty in the proportion of the population affected by the piling (due to lack of porpoise mobility in the North Sea) was accounted for in the iPCoD scenarios by testing three different values of the Vulnerable population size parameter.

Various studies have reported on porpoise densities in the (southern) North Sea (ERM, 2012; Gilles et al., 2016 & in prep.; Hammond et al., 2021; Heinänen & Skov, 2015; Paxton et al., 2016; Waggitt et al., 2020), with spatio-temporal data coverage and resolution of analyses differing between studies. All of these studies have their own underlying assumptions, caveats, and limitations, but a common theme among these studies was the limited data availability for the winter period. In addition, it is difficult to estimate local absolute densities based on acoustic detections from static recorders, and this requires substation additional efforts (Kyhn et al., 2012; Marques et al., 2012; Thomas & Burt, 2016; Jacobson et al., 2017). Moreover, porpoise densities in any one location within large management units may strongly deviate from average values as animals respond to localised environmental conditions to an as-yet unknown extent. These aspects highlight the need for continued visual (aerial or otherwise) and/or acoustic monitoring surveys, particularly including increased efforts during winter. While this could be on an individual project-basis, a more coordinated year-round regional programme, as well as continuation and seasonal broadening of larger-scale monitoring programmes (e.g. SCANS-IV) would be highly beneficial. Despite the difficulties comparing the various studies cited above, a comprehensive exploration of these data, including extraction of localised densities within the 20 km buffer zone around the EA1 wind turbines, allowed for an assessment of inter-study and seasonal variability in density, resulting in a reduction of the uncertainty in the density parameter. Uncertainty was also considered through the specification of different densities as applied in the iPCoD modelling framework.

Ideally, population-level impact assessments should include all natural (e.g. grey seal predation, bottlenose dolphin attacks, and infectious diseases) and anthropogenic pressures experienced by the population of interest (e.g. Dutch Ministry of Agriculture, Nature and Food Quality, 2020). Threats to harbour porpoises in the UK and the wider North Atlantic, with potential for long-term impacts on population health, include bycatch in fisheries, acoustic disturbance, chemical pollution, collisions, habitat degradation, prey depletion and climate change (IAMMWG et al., 2015; Murphy et al, 2019). As stated by the IAMMWG et al. (2015) "*It should be noted that the cumulative effect of any combination of these pressures may result in more deleterious consequences than any single pressure in isolation*". At present, no population models exist that enable assessment of the cumulative impacts of all these stressors on the harbour porpoise population in the North Sea.

The current study focussed on assessing the impacts of piling activity on North Sea harbour porpoises; other anthropogenic pressures were not explicitly considered when computing PTS and TTS Zones, with the exception of ADD activity associated with piling. Apart from other noise sources, including shipping and seismic surveys, one of the main anthropogenic pressures on porpoises within the wider North Sea is the substantial bycatch of porpoises in commercial fisheries, with an estimated 95% CI of 1,235 – 1,990 porpoises being bycaught annually in the North Sea ecoregion in 2013 (ICES, 2015), and between 1,175 – 2,126 individuals per annum in 2017 (ICES, 2019). Much higher upper 95% confidence limit estimates are presented in Murphy et al. (2019) for the North Sea between 2009-2017, with up to 3,405 and 6,369 individuals bycaught per annum, depending on the assessment methodology applied. To bring these bycatch levels into perspective, the 'conservative' iPCoD scenario assumed that 2,502 and 3,754 individuals would be disturbed, and 4 and 6 individuals might potentially experience PTS, on a given piling day for the spring, summer and autumn period and the winter period, respectively.

Despite currently being limited in their capability to incorporate multiple anthropogenic pressures, both iPCoD and DEPONS modelling frameworks allow the user to specify the number, or proportion of the population, of annual deaths due to bycatch, collisions with renewable energy devices or from any other cause leading to mortality. As such, both iPCoD and DEPONS allow bycatch to be included in population-level impact assessments. Although incorporating bycatch provides a more realistic prognosis of projected long-term population dynamics, it complicates assessment of the impacts resulting specifically from piling activities. For this project, it was, therefore, decided to run the main scenarios without the incorporation of additional bycatch (J. Nabe-Nielsen & C. Booth, pers. comm.; Nabe-Nielsen et al., 2014). As such, any cumulative effects of EA1 wind farm construction on long-term harbour porpoise population trajectories simulated by both these models remains unexplored. However, bycatch is indirectly captured as part of the demographic parameters in iPCoD; in DEPONS this pressure is used indirectly through incorporation into the area's carrying capacity.

5.2.3.4 Food availability

The ecological importance of the EA1 site to harbour porpoises is not well understood. However, local persistent above-average observed densities in winter underpinned the original designation of the area as part of the SNS SAC, indicating that the wider EA1 area may serve an important role for porpoises, at least for part of the year. By default, DEPONS incorporates the re-scaled porpoise density maps (Gilles et al., 2016) using them as a proxy for prey availability. Whilst not applied in the current study, a more flexible approach is possible, and other porpoise distribution maps (e.g. Waggitt et al., 2020) or calorific/biomass prey maps (e.g. Ransijn et al., 2019) could be incorporated; mean food availability values across the modelling domain (i.e. the North Sea) should, however, preferably be kept the same if alternative data were to be used (J. Nabe-Nielsen, pers. comm.) as these values relate to various other, calibrated model parameters.

In this study, uncertainty about food availability during the winter period (resulting from a lack of porpoise winter distribution data in the study by Gilles et al. (2016)), was addressed by comparing scenarios that used the original autumn food maps for the winter months (i.e. Scenarios 1-7 & 9-15), versus alternative scenarios that applied the spring food maps instead (Scenarios 8 & 16). Although resulting model outcomes were broadly similar among these scenarios, the differences demonstrated at finer spatio-temporal scales indicate the importance of carefully considering modelling requirements, especially in the light of recent developments incorporating energetic models (see Section 5.3.1).

5.2.3.5 Effect of parameter selection

In this study, the 'conservative' scenario stress-tested the iPCoD model using somewhat extreme, but plausible values. As the results of this scenario did not reveal a long-term impact, no further iPCoD scenarios were tested. The current section therefore focusses on the effects of the model parameters in relation to the spatial component of the DEPONS outcomes only.

To align with the updated Fertility input value recommended for the iPCoD model when assessing impacts on porpoises in the North Sea, DEPONS simulations were conducted using a Fertility value of 0.34 in addition to the default value of 0.68. The application of these Fertility values did result in the DEPINS model stabilising at different population levels; when DEPONS results are being presented, such information should be included. Additionally, rather than being reflected in the long-term DEPONS model outcomes, the Fertility value substantially affected the amount of time required for the populations to stabilise, and thus the burning-in time that needed to be applied before formal simulation of the effects of piling could start. Further, the burning-in period had to be extended beyond the required number of simulation years to obtain a stable starting population, as predicted numbers within the SNS SAC area continued to increase sharply for several years after the total population size had already stabilised. Despite extending the burning-in periods even further (to 15 and 25 years), porpoise numbers in the SAC continued to increase slowly throughout the simulations, irrespective of which Fertility value was applied.

Although it would take a detailed analysis of the temporal changes in the modelled large-scale porpoise movement behaviour in order to confirm (J. Nabe-Nielsen, pers. comm.), the observed requirement for longer stabilising periods for the SNS SAC scenarios might be related to the position of the SAC relative to the Dogger Bank, a well-known foraging hotspot for porpoises in the central North Sea. Given the Dogger Bank's central location and strong attraction to porpoises, animals might take longer to redistribute to, and obtain a memory of, the more distant southern part of the SAC where EA1 is located.

Presentation of daily predicted porpoise numbers for the SNS SAC and 20 km buffer zone (rather than as proportional predicted numbers of animals present) demonstrated that changing the winter food distribution maps led to differences in simulated local porpoise numbers, with decreased numbers in the SAC, and increased presence in the buffer zone. Considering that the alternative food distribution maps specifically reflected increased food availability at the EA1 site, the latter result is not surprising. Applying the spring food distribution maps instead of autumn maps during the winter months did also not result in the occurrence of long-term population-level effects.

5.3 Management implications

5.3.1 Application of population impact modelling frameworks

The continued development of offshore renewable energy, including wind farms, supports the goal of achieving the UK's Net Zero and climate targets. Developers, regulators and decision makers are unanimous in agreement that the sustainable progression of marine renewable energy industries must be achieved without causing irreversible long-term environmental impacts.

The strength of the iPCoD and DEPONS modelling frameworks to evaluate potential impacts of renewable energy projects lies in their utility in assessing large-scale, aggregate impacts (i.e. underwater noise) across multiple offshore developments (e.g. Booth et al., 2017; Brandt et al., 2016; de Jong et al., 2019; Heinis et al., 2019; Nabe-Nielsen et al., 2018; Rumes & Bebosschere, 2018). With respect to offshore wind farm construction, for example, these models can be particularly relevant in a marine spatial planning context by allowing explorations of the impacts of different piling scenarios

(Nabe-Nielsen et al., 2018). Likewise, they have aided in identifying noise thresholds for offshore wind developments to be built in Dutch waters after 2023 (Heinis et al., 2019), investigating the effects of mitigation measures such as bubble curtains and noise mitigation screens in reducing piling impacts (Pettex et al., 2018; Rumes & Bebosschere, 2018; Verfuss et al., 2016), as well as in assessing scenarios for mitigating harbour porpoise bycatch (Lusseau et al., 2023; van Beest et al., 2017). These models can thus serve as tools to assess applicability of mitigation strategies and help focus ongoing research towards addressing important data gaps for future assessments of cumulative and potential population-level effects of anthropogenic disturbance.

With offshore wind farm construction expected to continue in the southern North Sea over the next several decades, it is important to assess cumulative impacts of these developments, in concert with other pressures, such as bycatch and noise from other sources like seismic surveys and shipping. Although currently still limited in their capacity to undertake such cumulative impact assessments, these modelling frameworks are increasingly able to address this requirement. Currently, developments are ongoing to explore the use of energetic models within the iPCoD model (Harwood et al., 2020), and to integrate an additional movement element to allow incorporation of repeat exposures. In addition, ongoing iPCoD development efforts seek to improve the potential negative and positive impacts of operational wind farms (e.g. as artificial reefs) and also to understand the cumulative impact of multiple stressors (e.g. noise, pollution, climate change). Progression of these developments will further improve marine mammal assessments for offshore renewable developments, and may allow assessment of how sensitivity to different disturbances varies with resource availability and life history stage. Similarly, an energetic model has recently been developed (Gallagher et al., 2021a & b); although not yet publicly available, this component is intended to be implemented into future versions of DEPONS, as is an explicit evaluation of bycatch (for Inner Danish waters; van Beest et al., 2017). Additionally, as part of the Horizon 2020 SATURN project[6], detailed effects of ship noise on porpoise behaviour and a transmission loss model have recently been incorporated into DEPONS Version 3.0[7]. Implementation of these components allows the impacts on adults and calves to be modelled more accurately, and further increase suitability of the DEPONS model for cumulative impact assessments.

The cumulative impact element is of particular importance, as results of the current study suggest that application of either iPCoD or DEPONS frameworks to single wind farm developments is unlikely to be informative when applied to the large and wide-ranging harbour porpoise North Sea MU, given the low probability of detection of significant impacts. This conclusion is supported by various other studies demonstrating zero or very low probability of impact even when applying these frameworks to construction of multiple developments spanning a much larger spatial scale and temporal window than the piling activity for EA1 (Booth et al., 2017; Nabe-Nielsen, 2021; Nabe-Nielsen et al., 2018; Smith et al., 2019).

It is currently unclear whether the lack of population-level impact from a single wind farm construction would also be found if this activity were to be evaluated in combination with other existing pressures through application of more realistic scenarios that take cumulative impacts from multiple stressors into account. However, the frameworks would potentially be able to detect more localised impacts

[6] https://www.marei.ie/project/saturn-solutions-at-underwater-radiated-noise/.
[7] https://github.com/jacobnabe/DEPONS.

(i.e. confined in time and space) associated with construction of a single wind farm, if the impacts of piling noise were to be assessed in combination with other existing pressures. For example, bycatch, causes substantial direct mortality and is a major concern for the North Sea porpoise population, but remains challenging to accurately quantify (Dolman et al., 2016; IJsseldijk et al., 2018 & 2021) and largely unmanaged across Europe, including in the North Sea (Carlén et al., 2021; Rogan et al., 2021). Bycatch-related mortality is therefore expected to have a more notable impact on long-term population trajectories (Nabe-Nielsen et al., 2014). As offshore construction activities add to the overall impact on the porpoise population, the current results need to be considered in the context of all existing pressures on the population to ensure effective conservation management of protected species and the wider marine environment. When applied to small-scale and short-term offshore renewables construction projects, model results such as presented in this report should be considered with these other (cumulative) pressures in mind. While population impact modelling of individual pressures such as the construction of a single wind farm might provide information about the scale of expected impact to the population, the severity of these impacts to long-term population health can only be understood when the most important pressures to the population are modelled cumulatively. Population consequences of disturbance models are thus best placed to assess the relative scale of impacts on populations. For iPCoD, it is, however, important to realise that once a population is declining, there is no feedback loop within the framework that would allow the population to recover, other than through stochastic processes. In any case, further work to quantify the relative significance of different pressures on harbour porpoise populations is urgently required.

Given the above discussion, it is clearly important to consider the context when using population consequences of disturbance models to assess potential impacts of planned wind farm construction activities. Crucially, it is important to consider whether these models are able to prove relevant information at the spatio-temporal scales typically required for assessment of short-term individual projects, and whether their results would aid in current regulatory processes (e.g. environmental impact assessments).

In addition, ongoing and future climate change will result in redistribution of porpoise prey and predators (Sadykova et al., 2020) in the North Sea with the potential for as-yet unknown population-level impacts on harbour porpoises in this MU (but see Gallagher et al., 2021b). Additional factors such as other noise sources (e.g. shipping and seismic surveys) and chemical pollution also impact this population (Sarnocińska et al., 2020; Williams et al., 2020). An apparent lack of population-level consequences of individual projects such as EA1, especially when assessed in isolation from other stressors, does thus not negate the need for appropriate mitigation of noise impacts from piling, e.g. via alternative installation methods (Potlock et al., 2023), or noise abatement (Dähne et al., 2017; Merchant, 2019; Verfuss et al., 2019), especially given these measures' benefits to the wider ecosystem (Risch et al., 2021). Various technological and operational measures of reducing noise output associated with offshore wind farm construction have been suggested (Merchant 2019; Merchant and Robinson, 2020 and references in these), and these should be considered carefully by developers and regulators, especially for developments within or adjacent to a SAC.

5.3.2 Piling impacts within UK SACs

The results of the current study contribute to the limited amount of available information on harbour porpoise disturbance by pin-piling (Brandt et al., 2016; Graham et al., 2019). At present, the recommended impact range that should be applied when assessing the impacts of pin-piling on porpoises within English, Welsh and Northern Irish SAC boundaries, as stated in the Guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs (England, Wales & Northern Ireland)' (JNCC, 2020), is based on a single study by Graham et al. (2019). The result of the current study therefore provides relevant information from another project area, which can be incorporated into future iterations of this Guidance.

Analysis of C-POD data collected at 12 monitoring sites during construction of the EA1 wind farm (involving 310 pin-piles in total) indicated that construction activity had a negative impact on harbour porpoise detections out to 14.0 km from the piling locations (Figure 14 in van Geel et al., 2023b). Despite marked methodological differences to the approach undertaken by Graham et al. (2019), the impact radius identified here does not deviate widely from the recommended Effective Deterrence Range (EDR) of 15 km. However, the 1 km difference between the two deterrence ranges does translate into somewhat different overall impact areas (615.75 km^2 versus 706 km^2), which could have potential relevance for the management of piling schedules of future developments.

It is important to reiterate that the Impact Zones established in this study (based on actual field data) capture porpoises' responses to all EA1 construction-related activities (e.g. increased vessel traffic, ADD use, UXO detonations), as well as construction activities in neighbouring wind farm development sites and other ongoing unrelated activities (e.g. traverse of cargo vessels) in the surrounding area, rather than solely measuring the impacts from EA1 piling activity. It is reasonable to assume that porpoise distribution and/or vocalisation behaviour are affected by this wide range of activities occurring alongside piling at any particular wind farm development site. For example, responses to non-piling activities have been demonstrated for wind farm construction in Scotland, where porpoise occurrence and detection rates of 'buzzes' (suggesting foraging activity) were negatively influenced by jacket and turbine installation works and presence of support vessels (Benhemma-Le Gall et al., 2021). Similarly, observed pre-construction declines in porpoise presence in German waters could have occurred in response to construction-related activities like vessel movements and preparations for impact mitigation (i.e. bubble curtain deployment) (Brandt et al., 2016).

As such, modelling received levels based solely on the propagation of piling noise, while ignoring these other sound sources, may result in predicted sound levels that differ substantially from actual levels experienced by porpoises, with potential negative consequences if these are then converted into insufficiently conservative Impact Zones. This study therefore supports the decision set out in the JNCC Guidance to base recommendations on field data rather than on acoustic modelling, as it more comprehensively integrates cumulative effects of different (construction-related) activities.

Finally, the JNCC Guidance specifies that seasonality needs to be considered when assessing the impacts of noise and planning construction activities within or adjacent to SACs with seasonal components (JNCC, 2020). Seasonality is important not just in terms of porpoise distribution but also when assessing the vulnerability of animals to disturbance. For example, the recently developed energy budget model developed for Inner Danish waters (Gallagher et al., 2021a; to be implemented into DEPONS) showed that animals were most sensitive to seismic surveys in late summer and autumn

(August – November) when they needed to forage intensively to obtain sufficient fat reserves to survive the subsequent winter. Conversely, inexperienced, recently weaned juveniles may be at particular risk of disturbance during early summer, especially when in the process of switching from smaller, abundant yet energy-poor prey (e.g. gobies) towards larger, more energy-rich prey that is more difficult to catch (e.g. sandeels, clupeids; Leopold & Meesters, 2015). Exploration using future model iterations, equipped energy budget elements, may be able to identify similar periods of highest sensitivity to further construction activities in the East Anglia region and elsewhere within the SNS SAC, that can be taken into consideration when developing piling schedules.

5.4 Recommendations

Based on experiences and outcomes of the current project, which focussed on impacts of wind farm construction on harbour porpoises in the North Sea within a UK management context, the project team has developed a series of recommendations. These recommendations are based on results of this specific project but are, in our opinion, more widely applicable across projects, and should be of interest to a wide audience of stakeholders, including developers and regulatory bodies in the UK and beyond.

5.4.1 Data collection before, during and after wind farm construction

- There is a need for strategic and regulator-led monitoring at high temporal and spatial resolution. This should include regional (e.g. SAC-wide) and large-scale SCANS-like surveys, results of which should be shared among all stakeholders. Regional monitoring data should be collected year-round to address existing data gaps, especially during winter months during which data collection has historically been very limited. Large-scale surveys should ideally be carried out every six years to ensure data collection at spatio-temporal scales relevant to populations, ensuring consistent, integrated data collection to underpin impact assessments. Developer-supported inputs via data collected for impact assessment baseline or post-consent monitoring would be valuable in supporting the regional and large-scale data collection, especially in the southern North Sea, where several developments fall within, or are in close proximity to, the SNS SAC. Dual-purpose monitoring (i.e. monitoring for offshore renewable energy developments and regulator-led SNS SAC monitoring) and data sharing between projects should be encouraged.
- The use of complementary approaches, for example periodic visual surveys to estimate absolute abundance and long-term passive acoustic monitoring to identify fine-scale temporal trends, is encouraged. A combination of boat-based visual and towed acoustic surveys, aerial surveys and static acoustic monitoring would be appropriate to obtain datasets that are of suitably high resolution, both in the temporal and spatial domain. New technologies such as autonomous survey vehicles might enhance current monitoring strategies; their use should be further developed during on-going and future projects.
- Sufficient site-specific pre-, during, and post-construction data should be collected, during all seasons. Ideally, up to one full year of pre- and post-construction monitoring should be undertaken

to assess potential impacts and allow quantification of field-based effective deterrent ranges (EDR) (JNCC, 2020).

- All equipment used for monitoring needs to be calibrated and this calibration information should be publicly available. Calibration is of particular importance for noise measurements during construction, especially if these data are to be used for sound source propagation modelling that underpins estimation of impact ranges for potential auditory injury and behavioural change.

5.4.2 Population impact assessments

- At present, marine mammal population impact assessments typically incorporate aggregate impacts, including from multiple renewable energy projects and from other industries (e.g. shipping, seismic surveys, fisheries bycatch etc.), in a qualitative manner. Ideally, population impacts assessments should consider cumulative impacts quantitatively. While both iPCoD and DEPONS modelling frameworks remain under continuous development, neither can currently be used for quantitative cumulative impact assessments that integrate multiple sectors. Incorporating the full range of pressures to which harbour porpoises are known to be subjected would allow for a more realistic simulation of long-term population trajectories.
- While the iPCoD and DEPONS modelling frameworks are particularly useful in exploring relative benefits of construction alternatives, it is important to recognise the advantages and limitations of these models and be clear about the context in which they are being used, and which questions they can and cannot answer (see Section 5.3.1 for more detail on strengths and limitations of these approaches).

5.4.3 Impact mitigation

- The best way to avoid impact from offshore wind-related construction noise to harbour porpoises (and other species) at individual and population levels is to reduce noise levels at source. Rather than focussing on undertaking modelling assessments to quantify expected long-term population-level impacts of noise associated with offshore wind farm construction on a limited number of species, efforts and funding should be directed towards effective noise mitigation such as bubble curtains and alternative piling solutions to benefit the wider ecosystem; the development of new mitigation approaches suitable for application in deeper waters should also be further encouraged.
- If noise source mitigation is applied during construction, its relative effectiveness with respect to impact reduction should be carefully monitored and outcomes shared between projects as appropriate.

  In the absence of noise source mitigation, baseline monitoring information should be used to identify how to minimise impact to vulnerable species of regulatory interest, such as harbour porpoises, for example through improved spatio-temporal coordination and planning of ongoing construction activities within and across multiple sites.

5.4.2 Engagement

- Regular, transparent engagement between regulators and all stakeholders (including multiple developers where appropriate) will allow improved regional-scale planning within and across offshore wind farm development projects, to avoid or reduce aggregate impacts of developments, including those already under construction, those that are currently consented and those that are still in the planning stages. In addition, an ongoing, open dialogue among stakeholders and regulators is recommended to ensure agreement on the overarching monitoring strategy and to ensure that relevant data are efficiently shared across projects. Finally, such engagement is recommended to clarify the context and the appropriateness of using iPCoD and DEPONS modelling approaches, and to be clear about whether/how the outcomes of any modelled scenarios might be used by the regulator in the consenting process.

6 CONCLUSIONS

This report presents the application of the iPCoD and DEPONS modelling frameworks to assess the long-term consequences of the EA1 wind farm construction on the harbour porpoise population in the North Sea. Analysis of acoustic monitoring data collected around the EA1 site through Work Package-A (ITT-752262), demonstrated short-term negative effects of piling activity on harbour porpoise acoustic detection rates, as expected (van Geel et al., 2023b). Although porpoises were present at the site throughout the monitoring period (March 2018 – June 2019), detection rates were higher during non-piling periods compared to times when piling activities took place (April 2018 – January 2019), particularly within or close to the EA1 site; post-piling detection rates remained low compared to the pre-construction baseline. Despite large 95% confidence intervals, results of the posterior simulation indicated that the median probability across 500 simulations of detecting harbour porpoises during piling was lower than during the non-piling period out to a distance of 14.0 km from the piling activity. Finally, the acoustic data indicated higher numbers of porpoise detections during winter months, supporting previous observations that underpinned establishment of a Special Area of Conservation in this area (van Geel et al., 2023b).

The iPCoD and DEPONS modelling frameworks were applied using project-specific parameter input values to evaluate the likelihood that EA1-related piling had a significant negative population-level impact. Based on the simulations undertaken here, neither iPCoD nor DEPONS model revealed long-term population-level (North Sea scale) impacts in response to the EA1 piling activity. There was no indication that population size would be expected to decline within the 25 years modelled in this study; no differences were apparent between simulated un-impacted/baseline populations and impacted populations when subjected to several scenarios that represented both uncertainty in parameter input values and uncertainty in model sensitivity to these input values.

Based on these outcomes, and ignoring all other pressures experienced by this Management Unit that may affect population dynamics (e.g. bycatch and vessel noise), it appears likely that a population-level impact of a single wind farm development cannot be demonstrated with either of these modelling frameworks. This is largely due to the discrepancy in scale between the localised and relatively short-term impact of an individual development and the large-scale harbour porpoise North Sea Management Unit. This raises the issue of whether the use of these modelling frameworks is appropriate to address questions about population-level impact in the context of single-project environmental impacts assessments for harbour porpoise in the North Sea, and the various caveats highlighted above should be carefully considered. Instead, multi-development population-level assessments should be undertaken, potentially coordinated by the regulator, in combination with more localised impact assessments of individual wind farms. The latter may be particularly relevant in cases where animals do not move freely among different parts of the population range. Additionally, impacts on populations need to be assessed across stressors. There is a risk that ignoring other co-occurring pressures may result in an incomplete picture of long-term population trajectories that should be carefully considered if these models are to be used more widely. Instead, these modelling frameworks are perhaps better suited to large-scale assessments and the exploration of multiple different or mitigation impact scenarios for marine spatial planning applications.

Crucially, the absence of population-level impacts when applying these models to individual projects and in isolation of other important pressures (such as bycatch) should not lead to the conclusion that impacts are negligible and mitigation is therefore not necessary. Given the substantial amount of uncertainty included in these models and the lack of data especially at smaller spatial scales, populations models such as iPCoD and DEPONS can act to provide guidance as to the potential scale of impacts, but they do not negate the necessity of mitigation to reduce potential impacts. The collection of project-specific monitoring data to gain a thorough understanding of how protected species in different regions of the North Sea may react towards offshore renewable construction is further vitally important to improve future assessments.

In conclusion, this study has provided new insights in the potential impacts of piling on harbour porpoises during offshore wind farm construction and explored the strengths and weaknesses of currently available frameworks for assessing population-level consequences of disturbance in the context of offshore wind farm construction. Our study shows that models are flexible and ready to be used with project-specific data. However, while both iPCoD and DEPONS are considered particularly suitable for application in a marine spatial planning framework, their applicability in assessments of individual projects, especially when considered in isolation from other major stressors affecting the population of interest, is less clear and is not recommended unless all possible caveats are carefully considered.

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8 REFERENCES

Banda, N., and Cook, S. (2018). East Anglia ONE Offshore Windfarm - Foundation T&I Package: As-Built Noise Monitoring Report (Analysis and modelling of underwater noise generated during the construction of EA ONE Offshore Wind Farm). Report EA1-INL-M-VOO-570004 prepared by Seiche Environmental on behalf of van Oord for East Anglia ONE limited: 30 pp.

Benhemma-Le Gall, A., Graham, I.M., Merchant, N.D., and Thompson, P.M. (2021). Broad-scale responses of harbour porpoises to pile-driving and vessel activities during offshore windfarm construction. *Frontiers in Marine Science* 8, 664724 (18 pp). doi: 41.3389/fmars.2021.664724.

Booth, C.G. and Heinis, F. (2018). Updating the Interim PCoD Model: Workshop Report - New transfer functions for the effects of permanent threshold shifts on vital rates in marine mammal species. Unpublished Report SMRUC-UOA-2018-006, submitted to the University of Aberdeen and Department for Business, Energy and Industrial Strategy (BEIS): 34 pp.

Booth, C., Harwood, J., Plunkett, R., Mendes, S. and Walker, R. (2017). Using the 'Interim PcoD' framework to assess the potential effects of planned offshore wind developments in eastern English waters on harbour porpoises in the North Sea. Natural England Joint Report Number 024: 39 pp. Available at: http://publications.naturalengland.org.uk/publication/4813967957950464 [Accessed July 28, 2023].

Booth, C.G., Heinis, F., and Harwood, J. (2019). Updating the Interim PCoD Model: Workshop Report - New transfer functions for the effects of disturbance on vital rates in marine mammal species. Unpublished Report SMRUC-BEI-2018-011, submitted to the Department for Business, Energy and Industrial Strategy (BEIS): 28 pp.

Brandt, M.J., Diederichs, A., Betke, K., and Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series* 421: 205–216. doi: 10.3354/meps08888.

Brandt, M.J., Dragon, A.-C., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G., Wahl, V., Michalik, A., Braasch, A., Hinz, C., Ketzer, C., Todeskino, D., Gauger, M., Laczny, M., and Piper, W. (2016). Effects of offshore pile driving on harbour porpoise abundance in the German Bight. Assessment of noise effects. Final report prepared for Offshore Forum Windenergy: 246 pp. Available at: https://tethys.pnnl.gov/sites/default/files/publications/Brandt-et-al-2016.pdf [Accessed July 28, 2023].

Brandt, M.J., Dragon, A.-C., Diederichs, A., Bellmann, M.A., Wahl, V., Pipier, W., Nabe-Nielsen, J., and Nehls, G. (2018). Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. *Marine Ecology Progress Series* 596: 213–232. doi: 10.3354/meps12560.

Carlén, I., Nunny, L., and Simmonds, M.P. (2021). Out of sights, out of mind: How conservation is failing European porpoises. *Frontiers in Marine Science* 8, 617478 (15 pp). doi: 10.3389/fmars.2021.617478.

Carstensen, J., Henriksen, O., and Teilmann, J. (2006). Impacts of offshore wind farm construction on harbour porpoises: Acoustic monitoring of echolocation activity using porpoise detectors (T-

PODs). *Marine Ecology Progress Series* 321: 295–308. doi: 10.3354/meps321295.

Claussen, K.T., Tougaard, J., Carstensen, J., Delefosse, M., and Teilmann, J. (2019). Noise affects porpoise click detections – The magnitude of the effect depends on logger type and detection filter settings. *Bioacoustics* 28(5): 443–458. doi: 10.1080/09524622.2018.1477071.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., Sundermeyer, J., and Siebert, U. (2013). Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. *Environmental Research Letters* 8(2), 025002 (16 pp). doi: 10.1088/1748-9326/8/2/025002.

Dähne, M., Tougaard, J., Carstensen, J., Rose, A., and Nabe-Nielsen, J. (2017). Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbourr porpoises. *Marine Ecology Progress Series* 580: 221–237. doi: 10.3354/meps12257.

De Jong, C.A.F., Heinis, F., von Benda-Beckmann, A.M., and Binnerts, B. (2019). Testing CEAF in SEANSE case studies - Impact of piling for wind farms on North Sea harbour porpoise population. TNO Report 2019 R11563: 48 pp. Available at: https://northseaportal.eu/downloads/ [Accessed July 28, 2023].

DEFRA (Department for Environment Food & Rural Affairs) (2019). Marine Strategy Part One: UK updated assessment and Good Environmental Status: 107 pp. Available at: https://www.gov.uk/government/publications/marine-strategy-part-one-uk-updated-assessment-and-good-environmental-status [Accessed July 28, 2023].

Dolman, S., Baulch, S., Evans, P.G.H., Read, F., and Ritter, F. (2016). Towards an EU Action Plan on cetacean bycatch. *Marine Policy* 72: 67–75. doi: 10.1016/j.marpol.2016.06.020.

Dutch Ministry of Agriculture, Nature and Food Quality (2020) Updated Conservation Plan for the harbour porpoise *Phocoena phocoena* in the Netherlands: Maintaining a Favourable Conservation Status: 131 pp. Available at: https://open.overheid.nl/documenten/ronl-dfa0b577-d562-4115-9fd5-110e8bd6eb02/pdf [Accessed July 28, 2023].

EC (European Council) (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043 [Accessed July 28, 2023].

EC (European Commission) (2008). Directive 2008/56/EC of the European Parliament of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1567028582748&uri=CELEX:32008L0056 [Accessed July 28, 2023].

EC (European Commission) (2017). Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017D0848 [Accessed July 28, 2023].

ERM (Environmental Resource Management) (2012). East Anglia ONE Offshore Windfarm –

Environmental Statement. Volume 2 Offshore. Document Reference 7.3.6 Chapter 11 – Marine Mammals. ERM, East Anglia Offshore Wind Limited: 83 pp.

Evans, D., and Arvela, M. (2012). Assessment and reporting under Article 17 of the Habitats Directive. Explanatory Notes & Guidelines for the period 2007-2012: 123 pp. Available at: https://circabc.europa.eu/sd/a/2c12cea2-f827-4bdb-bb56-3731c9fd8b40/Art17-Guidelines-final.pdf [Accessed July 28, 2023].

Faulkner, R.C., Farcas, A., and Merchant, N. (2018). Guiding principles for assessing the impact of underwater noise. *Journal of Applied Ecology* 55(6): 2531–2536. doi: 10.1111/1365-2664.13161.

Gallagher, C.A., Grimm, V., Kyhn, L.A., Kinze, C.C., and Nabe-Nielsen, J. (2021a). Movement and seasonal energetics mediate vulnerability to disturbance in marine mammal populations. *The American Naturalist* 197(3): 296–311. doi: 10.1086/712798.

Gallagher, C.A., Chimienti, M., Grimm, V., and Nabe-Nielsen, J. (2021b) Energy-mediated responses to changing prey size and distribution in marine top predator movements and population dynamics. *Journal of Animal Ecology* 91(1): 241–254. doi: 10.1111/1365-2656.13627.

Gilles, A., Viquerat, S., Becker, E.A., Forney, K.A., Geelhoed, S.C.V., Haelters, J., Nabe-Nielsen, J., Scheidat, M., Siebert, U., Sveegaard, S., van Beest, F.M., van Bemmelen, R., and Aarts, G. (2016). Seasonal habitat-based density models for a marine top predator, the harbor porpoise, in a dynamic environment. *Ecosphere* 7(6), e01367 (22 pp). doi: 10.1002/ecs2.1367.

Graham, I.M., Merchant, N.D., Farcas, A., Barton, T.R., Cheney, B., Bono, S., and Thompson, P.M. (2019). Harbour porpoise responses to pile-driving diminish over time. *Royal Society Open Science* 6, 190335 (13 pp). doi: 10.1098/rsos.190335.

Graham, I.M., Gillespie, D., Gkikopoulou, K.C., Hastie, G.D., and Thompson, P.M. (2023). Directional hydrophone clusters reveal evasive responses of small cetaceans to disturbance during construction at offshore windfarms. *Biology Letters* 19, 20220101 (6 pp). doi: 10.1098/rsbl.2022.0101.

Hague, E.L., Sinclair, R.R., and Sparling, C.E. (2020). Regional baselines for marine mammal knowledge acros the North Sea and Atlantic areas of Scottish waters. *Scottish Marine and Freshwater Science* 11(2): 305 pp. Available at: https://data.marine.gov.scot/dataset/regional-baselines-marine-mammal-knowledge-across-north-sea-and-atlantic-areas-scottish [Accessed July 28, 2023].

Hammond, P.S., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., Macleod, K., Ridoux, V., Santos, M.B., Scheidat, M., Teilmann, J., Vingada, J., and Øien, N. (2021). Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. SCANS-III: 41 pp. Available at: https://scans3.wp.st-andrews.ac.uk/files/2021/06/SCANS-III_design-based_estimates_final_report_revised_June_2021.pdf [Accessed July 28, 2023].

Harwood, J., King, S.L., Schick, R., Donovan, C., and Booth, C. (2014). A protocol for implementing the Interim Population Consequences of Disturbance (PCoD) approach: Quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations.

Report SMRUL-TCE-2013-014. *Scottish Marine and Freshwater Science* 5(2): 90 pp. Available at: http://www.gov.scot/Resource/0044/00443360.pdf [Accessed July 28, 2023].

Harwood, J., Booth, C., Sinclair, R., annd Hague, E. (2020) Developing marine mammal dynamic energy budget models and their potential for integration into the iPCoD framework. *Scottish Marine and Freshwater Science* 11(11): 79 pp. Available at: https://data.marine.gov.scot/dataset/developing-marine-mammal-dynamic-energy-budget-models-and-their-potential-integration-0 [Accessed July 28, 2023].

Heinänen, S. and Skov, H. (2015). The identification of discrete and persistent areas of relatively high harbour porpoise density in the wider UK marine area. Joint Nature Conservation Committee, JNCC Report No. 544: 108 pp. Available at: https://hub.jncc.gov.uk/assets/f7450390-9a89-4986-8389-9bff5ea1978a [Accessed July 28, 2023].

Heinis, F., de Jong, C.A.F., von Benda-Beckmann, S., and Binnerts, B. (2019). Kader Ecologie en Cumulatie – 2018 Cumulatieve effecten van aanleg van windparken op zee op bruinvissen. HWE and TNO, Report 18.153RWS_KEC2018: 59 pp. (In Dutch). Available at: https://www.noordzeeloket.nl/publish/pages/157579/kec_update_2018_effecten_impulsief_geluid_op_bruinvissen_20190124def.pdf [Accessed July 28, 2023].

Heinis, F., de Jong, C.A.F., and von Benda-Beckmann, A.M. (2022). Framework for assessing Ecological and Cumulative Effects 2021 (KEC 4.0) – Marine mammals. TNO Report TNO 2021 R12503-UK: 86 pp. Available at: https://repository.tno.nl/islandora/object/uuid%3A11e3bc5d-baec-4178-bada-56df2fdce9d8 [Accessed July 28, 2023].

IAMMWG (Inter-Agency Marine Mammal Working Group) (2015). Management Units for cetaceans in UK waters (January 2015). JNCC Report No. 547, JNCC, Peterborough: 37 pp. Available at: https://hub.jncc.gov.uk/assets/f07fe770-e9a3-418d-af2c-44002a3f2872 [Accessed July 28, 2023].

IAMMWG (Inter-Agency Marine Mammal Working Group), Camphuysen, C.J., and Siemensma, M.L. (2015). A conservation literature review for the harbour porpoise (*Phocoena phocoena*). JNCC Report No. 566. JNCC, Peterborough: 95 pp. Available at: https://hub.jncc.gov.uk/assets/e3c85307-1294-4e2c-9864-f4dd0f195e1e [Accessed July 28, 2023].

ICES (International Council for the Exploration of the Sea) (2014). OSPAR request on implementation on MSFD for marine mammals. Special Request. Available at: https://ices-library.figshare.com/articles/report/OSPAR_request_on_implementation_of_MSFD_for_marine_mammals/18687344 [Accessed July 28, 2023].

ICES (International Council for the Exploration of the Sea) (2015). Report of the Working Group on Bycatch of Protected Species (WGBYC). 2-6 February 2015, Copenhagen, Denmark. ICES CM 2015\ACOM:26: 80 pp. Available at: https://www.ascobans.org/en/document/ices-2015-report-working-group-bycatch-protected-species-wgbyc [Accessed July 28, 2023].

ICES (International Council for the Exploration of the Sea) (2019). Working Group on Bycatch of Protected Species (WGBYC). ICES Scientific Reports. 1:51: 163 pp. doi: 10.1789/ices.pub.5563.

IJsseldijk, L.L., ten Doeschate, M.T.I., Davison, N.J., Gröne, A., and Brownlow, A.C. (2018). Crossing boundaries for cetacean conservation: Setting research priorities to guide management of harbour porpoises. *Marine Policy* 95: 77–84. doi: 10.1016/j.marpol.2018.07.006.

IJsseldijk, L.L., Scheidat, M., Siemensma, M.L., Couperus, B., Leopold, M.F., Morell, M., Gröne, A., and Kik, M.J.L. (2021). Challenges in the assessment of bycatch: Postmortem findings in harbor porpoises (*Phocoena phocoena*) retrieved from gillnets. *Veterinary Pathology* 58(2): 405–415. doi: 10.1177/0300985820972454.

Jacobson, E.K., Forney, K.A., and Barlow, J. (2017). Using paired visual and passive acoustic surveys to estimate passive acoustic detection parameters for harbour porpoise abundance estimates. *Journal of the Acoustical Society of America* 141(1): 219–230. doi: 10.1121/1.4973415.

JNCC (Joint Nature Conservation Committee) (2019a). 1351 Harbour porpoise *Phocoena phocoena*. Available at: https://sac.jncc.gov.uk/species/S1351/ [Accessed July 28, 2023].

JNCC (Joint Nature Conservation Committee) (2019b). Harbour porpoise (*Phocoena phocoena*) Special Area of Conservation: Southern North Sea. Conservation objectives and advice on operations: 25 pp. JNCC, Aberdeen. Available at: https://data.jncc.gov.uk/data/206f2222-5c2b-4312-99ba-d59dfd1dec1d/SouthernNorthSea-conservation-advice.pdf [Accessed July 28, 2023].

JNCC (Joint Nature Conservation Committee) (2020). Guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs (England, Wales & Northern Ireland). JNCC Report No. 654: 14 pp. JNCC, Peterborough. Available at: https://hub.jncc.gov.uk/assets/2e60a9a0-4366-4971-9327-2bc409e09784 [Accessed July 28, 2023].

Kastelein, R.A., Helder-Hoek, L., Booth, C., Jennings, N., and Leopold, M. (2019). High levels of food intake in harbour porpoises (*Phocoena phocoena*): Insights into recovery from disturbance. *Aquatic Mammals* 45(4): 380–388. doi: 10.1578/AM.45.4.2019.380.

Koschinski, S., Culik, B., Damsgaard Henriksen, O., Tregenza, N., Ellis, G., Jansen, C., and Kathe, G. (2003). Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series* 265: 263–273. doi: 10.3354/meps265263.

King, S.L., Schick, R.S., Donovan, C., Booth, C.G., Burgman, M., Thomas, L., and Harwood, J. (2015). An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution* 6(10): 1150–1158. doi: 10.1111/2041-210X.12411.

Kyhn, L.A., Tougaard, J., Thomas, L., Duve, L.R., Stenback, J., Amundin, M., Desportes, G., and Teilmann, J. (2012). From echolocation clicks to animal density – Acoustic sampling of harbor porpoises with static dataloggers. *Journal of the Acoustical Society of America* 131(1): 550–560. doi: 10.1121/1.3662070.

Leopold, M.F., and Meesters, E.H.W.G. (2015). Not all harbour porpoises are equal: Which factors determine what individual animals should, and can eat? Pp 29-55 in: Leopold, M.F. Eat and be eaten: Porpoise diet studies. PhD Thesis, Wageningen University, the Netherlands: 240 pp. Available at: https://www.vliz.be/imisdocs/publications/309933.pdf [Accessed July 28, 2023].

Lusseau, D., Kindt-Larsen, L., and van Beest, F.M. (2023) Emergent interactions in the management of multiple threats to the conservation of harbour porpoises. *Science of the Total Environment* 855, 158936 (10 pp). doi: 10.1016/j.scitotenv.2022.158936.

Macaulay, J.D., Malinka, C.E., Gillespie, D., and Madsen, P.T. (2020). High resolution three-dimensional beam radiation pattern of harbour porpoise clicks with implications for passive acoustic monitoring. *Journal of the Acoustical Society of America* 147(6): 4175–4188. doi: 10.1121/10.0001376.

Malme, C.I., Beranek, B., and Newman Inc. (1995). Chapter 4 – Sound propagation: pp 59–86. In: Richardson, W.J., Greene Jr., C.R., Malme, C.I., and Thomson, D.H. (eds). Marine mammals and noise. Academic Press, San Diego.

Marques, T.A, Thomas, L., Martin, S.W., Mellinger, D.K., Ward, J.A., Moretti, D.J., Harris, D., and Tyack, P.L. (2012) Estimating animal population density using passive acoustics. *Biological Reviews* 88(2): 287–309. doi: 10.1111/brv.12001.

Martin, S.B., and Barclay, D.R. (2019). Determining the dependence of marine pile driving sound levels on strike energy, pile penetration, and propagation effects using a linear mixed model based on damped cylindrical spreading. *Journal of the Acoustical Society of America* 146(1): 109–121. doi: 10.1121/1.5114797.

Merchant, N.D. (2019). Underwater noise abatement: Economic factors and policy options. *Environmental Science and Policy* 92: 116–123. doi: 10.1016/j.envsci.2018.11.014.

Merchant, N.D., and Robinson, S.P. (2020). Abatement of underwater noise pollution from pile-driving and explosions in UK waters. Report of the UKAN workshop held on Tuesday 12 November 2019 at The Royal Society, London: 31pp. doi: 10.6084/m9.figshare.11815449.

Mikkelsen, L., Rigét, F.F., Kyhn, L.A., Sveegaard, S., Dietz, R., Tougaard, J., Carlström, J.A.K., Carlén, I., Koblitz, J.C., and Teilmann, J. (2016). Comparing distribution of harbour porpoise (*Phocoena phocoena*) derived from satellite telemetry and passive acoustic monitoring. *PLoS ONE* 11(7), e0158788 (16 pp). doi: 10.1371/journal.pone.0158788.

Moore, J.E. and Read, A.J. (2008). A Bayesian uncertainty analysis of cetacean demography and bycatch mortality using age-at-death data. *Ecological Applications* 18(8): 1914–1931. doi: 10.1890/07-0862.1.

Mortensen, L.O., and Thomsen, F. (2019). BSH Cumulative Impact Study 2019 – Comparative study of DEPONS and iPCoD. Report prepared by DHI for Bundesamt für Seeschiffaht und Hydrographie: 11 pp. Available at: https://northseaportal.eu/publish/pages/144481/comparison_of_depons_and_ipcod_dhi.pdf [Accessed July 28, 2023].

Murphy, S., Barber, J.L., Learmonth, J.A., Read, F.L., Deaville, R., Perkins, M.W., Brownlow, A., Davison, N., Penrose, R., Pierce, G.J., Law, R.J., and Jepson, P.D. (2015). Reproductive failure in UK harbour porpoises *Phocoena phocoena*: Legacy of pollutant exposure? *PLoS ONE* 10(7), e0131085 (32 pp). doi: 10.1371/journal.pone.0131085.

Murphy, S., Tougaard, J., Evans, P.G.H., Caurant, F., and Hammond, P.S. (2019). Area Status Report North Sea: pp 150–192. In: Report of joint IMR/NAMMCO international workshop on the status of harbour porpoises in the North Atlantic. NAMMCO (North Atlantic Marine Mammal Commission) and the IMR (Norwegian Institute of Marine Research), Tromsø, Norway. Available at: https://nammco.no/wp-content/uploads/2020/03/final-report_hpws_2018_rev2020.pdf [Accessed July 28, 2023].

Nabe-Nielsen, J. (2021). Impacts of wind farm construction and the importance of piling order for harbour porpoises in the German Exclusive Economic Zone of the North Sea – Assessment based on DEPONS 2.2. Aarhus University, DCE - Danish Centre for Environment and Energy: 10 pp. Scientific note No. 2021|68. Available at: https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2021/N2021_68.pdf [Accessed July 28, 2023].

Nabe-Nielsen, J., and Harwood, J. (2016) Comparison of the iPCoD and DEPONS models for modelling population consequences of noise on harbour porpoises. Aarhus University, DCE – Danish Centre for Environment and Energy: 22 pp. Scientific Report from DCE No. 186. Available at: http://dce2.au.dk/pub/SR186.pdf [Accessed July 28, 2023].

Nabe-Nielsen, J., Sibly, R.M., Tougaard, J., Teilmann, J., and Sveegaard, S. (2014). Effects of noise and by-catch on a Danish harbour porpoise population. *Ecological Modelling* 272: 242–251. doi: 10.1016/j.ecolmodel.2013.09.025.

Nabe-Nielsen, J., Tougaard, J., Teilmann, J., Lucke, K., and Forchhammer, M.C. (2013). 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., van Beest, F.M., Grimm, V., Sibly, R.M., Teilmann, J., and Thompson, P.M. (2018). Predicting the impacts of anthropogenic disturbances on marine populations. *Conservation Letters* 11, e12563 (8 pp). doi: 10.1111/conl.12563.

Nabe-Nielsen, J., van Beest, F.M., Grimm, V., Sibly, R.M., Teilmann, J., and Thompson, P.M. (2021). TRACE document DEPONS 2.2: Individual-based model for simulating impact of wind farm construction noise on the North Sea harbour porpoise population: 62 pp. Available at: https://github.com/jacobnabe/DEPONS/blob/master/DEPONS%202.2%20%E2%80%93%20TRACE%202021-08-31.pdf [Accessed July 28, 2023].

Nielsen, N.H., Teilmann, J., Sveegaard, S., Hansen, R.G., Sinding, M.-H.S., Dietz, R., and Heide-Jørgensen, M.P. (2018). Oceanic movements, site fidelity and deep diving in harbour porpoises from Greenland show limited similarities to animals from the North Sea. *Marine Ecology Progress Series* 597: 259–272. doi: 10.3354/meps12588.

NMFS (National Marine Fisheries Service) (2018). Revisions to: Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (Version 2.0): Underwater thresholds for onset of permanent and temporary threshold shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59: 167 pp. Available at: https://www.fisheries.noaa.gov/resource/document/technical-guidance-assessing-effects-anthropogenic-sound-marine-mammal-hearing [Accessed July 28, 2023].

NRC (National Research Council) (2005). Marine mammal populations and ocean noise: Determining when noise causes biologically significant effects. National Research Council; Division on Earth and Life Studies; Ocean Studies Board; Committee on Characterizing Biological Significant Marine Mammal Behavior: 126 pp. Available at: https://www.nrc.gov/docs/ML1434/ML14345A574.pdf [Accessed July 28, 2023].

Nuuttila, H.K., Brundiers, K., Dähne, M., Koblitz, J.C., Thomas, L., Courtene-Jones, W., Evans, P.G.H., Turner, J.R., Bennell, J.D., and Hiddink, J.G. (2018). Estimating effective detection area of static passive acoustic data loggers from playback experiments with cetacean vocalisations. *Methods in Ecology and Evolution* 9(12): 2362–2371. doi: 10.1111/2041-210X.13097.

Paxton, C.G.M., Scott-Hayward, L., Mackenzie, M., Rexstad, E., and Thomas, L. (2016). Revised Phase III data analysis of Joint Cetacean protool data resources. JNCC Report No 517. JNCC, Peterborough. Available at: https://hub.jncc.gov.uk/assets/01adfabd-e75f-48ba-9643-2d594983201e [Accessed July 28, 2023].

Pettex, E., Folegot, T., Clorennec, D., and Martinez, L. (2018). Quantifier les conséquences du dérangement acoustique sur les populations de mammifères marins: Un outil d'aide à la décision pour le développement des parcs éoliens en mer. Actes du Séminaire Eolien et Biodiversité, Artigues-près-Bordeaux, France, 21-22 Novembre 2017: 128–131. (In French). Available at: https://crerco.fr/IMG/pdf/seminaire_eolien_et_biodiversite_2017_actes.pdf [Accessed July 28, 2023].

Potlock, K.M., Temple, A.J., and Berggren, P. (2023). Offshore construction using gravity-base foundations indicates no long-term impacts on dolphins and porpoises. *Marine Biology* 170, 92 (14 pp). doi: 10.1007/s00227-023-04240-1.

Ransijn, J.M., Booth, C., and Smouth, S.C. (2019). A calorific map of harbour porpoise prey in the North Sea. JNCC Report No. 633: 29 pp. JNCC, Peterborough. Available at: https://hub.jncc.gov.uk/assets/c12c1b45-73ba-4402-a8f5-ec0275a72cf1 [Accessed July 28, 2023].

Read, A.J., and Hohn, A.A. (1995). Life in the fast lane: The life history of harbor porpoises from the Gulf of Maine. *Marine Mammal Science* 11(4): 423–440. doi: 10.1111/j.1748-7692.1995.tb00667.x.

Risch, D., Calderan, S., Leaper, R., Weilgart, L., and Werner, S. (2021). Current knowledge already justifies underwater noise reduction. *Trends in Ecology and Evolution* 36(5): 381–382. doi: 10.1016/j.tree/2020/12/010.

Rogan, E., Read, A.J., and Berggren, P. (2021). Empty promises: The European Union is failing to protect dolphins and porpoises from fisheries by-catch. *Fish and Fisheries* 22(4): 865–869. doi: 10.1111/faf/12556.

Rumes, B., and Bebosschere J. (2018). Chapter 8 – Modelling the impact of pile driving on porpoise population in the Belgian part of the North Sea: pp 117–128. In: Degrear, S., Brabant, R., Rumes, B., and Vigin, L. (eds.) Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Assessing and managing effect spheres of influence. Brussels, Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management Available at:

https://odnature.naturalsciences.be/downloads/mumm/windfarms/winmon_report_2018_final.pdf [Accessed July 28, 2023].

OSPAR (2021). Intermediate Assessment 2017 – Harbour porpoise bycatch. Available at: https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/biodiversity-status/marine-mammals/harbour-porpoise-bycatch/ [Accessed July 28, 2023].

Sadykova, D., Scott, B.E., De Dominics, M., Wakelin, S.L., Wolf, J., and Sadykov, A. (2020). Ecological cost of climate change on marine predator-prey population distributions by 2050. *Ecology and Evolution* 10(2): 1069–1086. doi: 10.1002/ece3.5973.

Sarnocińska, J., Teilmann, J., Dalgaard Balle, J., van Beest, F.M., Delefosse, M., and Tougaard, J. (2020). Harbor porpoise (*Phocoena phocoena*) reaction to a 3D seismic airgun survey in the North Sea. *Frontiers in Marine Science* 6, 824 (10 pp). doi: 10.3389/fmars.2019.00824.

Sinclair, R., Booth, C., Harwood, J. and Sparling, C. (2019). Helpfile for the interim PCoD v5 model: 63 pp. Available at: https://www.smruconsulting.com/population-consequences-of-disturbance-pcod [Accessed July 28, 2023].

Sinclair, R.R., Sparling, C.E., and Harwood, J. (2020). Review of demographic parameters and sensitivity analysis to inform inputs and outputs of Population Consequences of Disturbance assessments for marine mammals. *Scottish Marine and Freshwater Science* 11(14): 74 pp. Available at: https://data.marine.gov.scot/dataset/review-demographic-parameters-and-sensitivity-analysis-inform-inputs-and-outputs-0 [Accessed July 28, 2023].

Smith, H., Carter, C., and Manson, F. (2019). Cumulative impact assessment of Scottish east coast offshore windfarm construction on key species of marine mammals using iPCoD. Scottish Natural Heritage Research Report No. 1081: 37 pp. Available at: https://www.nature.scot/naturescot-research-report-1081-cumulative-impact-assessment-scottish-east-coast-offshore-windfarm [Accessed July 28, 2023].

Sparling, C.E., Thompson, D., and Booth, C.G. (2017). Guide to Population Models used in Marine Mammal Impact Assessments. JNCC Report No. 607. JNCC, Peterborough. Available at: https://hub.jncc.gov.uk/assets/e47f17ec-30b0-4606-a774-cdcd90097e28 [Accessed July 28, 2023].

Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P., and Tyack, P.L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals* 45(2): 125–232. doi: 10.1578/AM.45.2.2019.125.

Stalder, D., van Beest, F.M., Sveegaard, S., Dietz, R., Teilmann, J., and Nabe-Nielsen, J. (2020). Influence of environmental variability on harbour porpoise movement. *Marine Ecology Progress Series* 648: 207–219. doi: 10.3354/meps13412.

Teilmann, J., and Carstensen, J. (2012). Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic - Evidence of slow recovery. *Environmental Research Letters* 7, 045101 (10 pp). doi: 10.1088/1748-9326/7/4/045101.

Thomas, L., and Burt, M.L. (2016). Statistical analysis of SAMBAH survey and associated data. CREEM Technical Report 2016-1, University of St Andrews: 130 pp. Available at: https://research-repository.st-andrews.ac.uk/handle/10023/17328 [Accessed July 28, 2023].

Thompson, P.M., Graham, I.M., Cheney, B., Barton, T.R., Farcas, A., and Merchant, N.D. (2020). Balancing risks of injury and disturbance to marine mammals when pile driving at offshore windfarms. *Ecological Solutions and Evidence* 1(2), e12034 (12 pp). doi: 10.1002/2688-8319.12034.

Thompson, P.M., Lusseau, D., Barton, T., Simmonds, D., Rusin, J., and Bailey, H. (2010). Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Marine Pollution Bulletin* 60: 1200–1208. doi: 10.1016/j.marpolbul.2010.03.030.

van Beest, F.M., Nabe-Nielsen, J., Carstensen, J., Teilmann, J., and 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. Scientific Report from DCE No. 140: 43 pp. Available at: http://dce2.au.dk/pub/SR140.pdf [Accessed July 28, 2023].

van Beest, F.M., Kindt-Larsen, L., Bastardie, F., Bartolino, V., and Nabe-Nielsen, J. (2017). Predicting the population-level impact of mitigating harbor porpoise bycatch with pingers and time-area fishing closures. *Ecosphere* 8(4), e01785 (17 pp). doi: 10.1002/ecs2.1785.

van Beest, F.M., Teilmann, J., Dietz, R., Galatius, A., Mikkelsen, L., Stalder, D., Sveegaard, S., and Nabe-Nielsen, J. (2018a). Environmental drivers of harbour porpoise fine-scale movements. *Marine Biology* 165, 95 (13 pp). doi: 10.1007/s00227-018-3346-7.

van Beest, F.M., Teilmann, J., Hermannsen, L., Galatius, A., Mikkelsen, L., Sveegaard, S., Dalgaard Balle, J., Dietz, R., and Nabe-Nielsen, J. (2018b). Fine-scale movement responses of free-ranging harbour porpoises to capture, tagging and short-term noise pulses from a single gun. *Royal Society Open Science* 5(1), 170110 (14 pp). doi: 10.1098/rsos.170110.

van Geel, N.C.F., Wittich, A., and Benjamins, S. (2023a). Southern North Sea harbour porpoise population modelling validation – Data Quality Control Report. A report by SRSL for ScottishPower Renewables: 28 pp.

van Geel, N.C.F., Benjamins, S., Risch, D., Allen, C., and Wittich, A. (2023b). Southern North Sea harbour porpoise population modelling validation – Acoustic Processing Report. A report by SRSL for ScottishPower Renewables: 82 pp.

Verfuss, U.K., Gillespie, D., Gordon, J., Marques, T.A., Miller, B., Plunkett, R., Theriault, J.A., Tollit, D.J., Zitterbart, D.P., Hubert, P., and Thomas, L. (2018). Comparing methods suitable for monitoring marine mammals in low visibility conditions during seismic surveys. *Marine Pollution Bulletin* 126: 1–18. doi: 10.1016/j.marpolbul.2017.10.034.

Verfuss, U.K., Plunkett, R., Booth, C.G., and Harwood, J. (2016). Assessing the benefit of noise reduction measures during offshore wind farm construction on harbour porpoises. Report Number SMRUC-WWF-2016-008 provided to WWF UK: 41 pp. Available at: https://www.wwf.org.uk/sites/default/files/2016-

10/15_11_24_wwf___finalreport%5B1%5D.pdf [Accessed July 28, 2023].

Verfuss, U.K., Sinclair, R.R., and Sparling, C.E. (2019). A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters. NatureScot Research Report 1070: 77 pp. Available at: https://www.nature.scot/doc/naturescot-research-report-1070-review-noise-abatement-systems-offshore-wind-farm-construction-noise [Accessed July 28, 2023].

Wade, P.R., (1998) Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science* 14(1): 1-37. doi: 10.1111/j.1748-7692.1998.tb00688.x.

Waggitt, J. (2019). Data from: Distribution maps of cetacean and seabird populations in the North-East Atlantic. *Dryad*, dataset. doi: 10.5061/dryad.mw6m905sz.

Waggitt, J.J., Evans, P.G.H., Andrade, J., Banks, A.N., Boisseau, O., Bolton, M., Bradbury, G., Brereton, T., Camphuysen, C.J., Durinck, J., Felce, T., Fijn, R.C., Garcia-Baron, I., Garthe, S., Geelhoed, S.C.V., Gilles, A., Goodall, M., Haelters, J., Hamilton, S., Hartny-Mills, L., Hodgins, N., James, K., Jessop, M., Kavanagh, A.S., Leopold, M., Lohrengel, K., Louzao, M., Markones, N., Martínez-Cedeira, J., Ó Cadhla, O., Perry, S.L., Pierce, G.J., Ridoux, V., Robinson, K.P., Santos, M.B., Saavedra, C., Skov, H., Stienen, E.W.M., Sveegaard, S., Thompson, P., Vanermen, N., Wall, D., Webb, A., Wilson, J., Wanless, S., and Hiddink, G.J. (2020). Distribution maps of cetacean and seabird populations in the North-East Atlantic. *Journal of Applied Ecology* 57: 253–269. doi: 10.1111/1365-2664.13525.

Williams, R., ten Doeschate, M., Curnick, D.J., Brownlow, A., Barber, J.L., Davison, N.J., Deaville, R., Perkins, M., Jepson, P.D., and Jobling, S. (2020). Levels of polychlorinated biphenyls are still associated with toxic effects in harbor porpoises (*Phocoena phocoena*) despite having fallen below proposed toxicity thresholds. *Environmental Science and Technology* 54(4): 2277–2286. doi: 10.1021/acs.est.9b05453.

Williamson, L.D., Brookes, K.L., Scott, B.E., Graham, I.M., Bradbury, G., Hammond, P.S., and Thompson, P.M. (2016). Echolocation detections and digital video surveys provide reliable estimates of the relative density of harbour porpoises. *Methods in Ecology and Evolution* 7(2): 762–769. doi: 10.1111/2041-210X.12538.

9 APPENDIX A – HARBOUR PORPOISE POPULATION DENSITY DATA

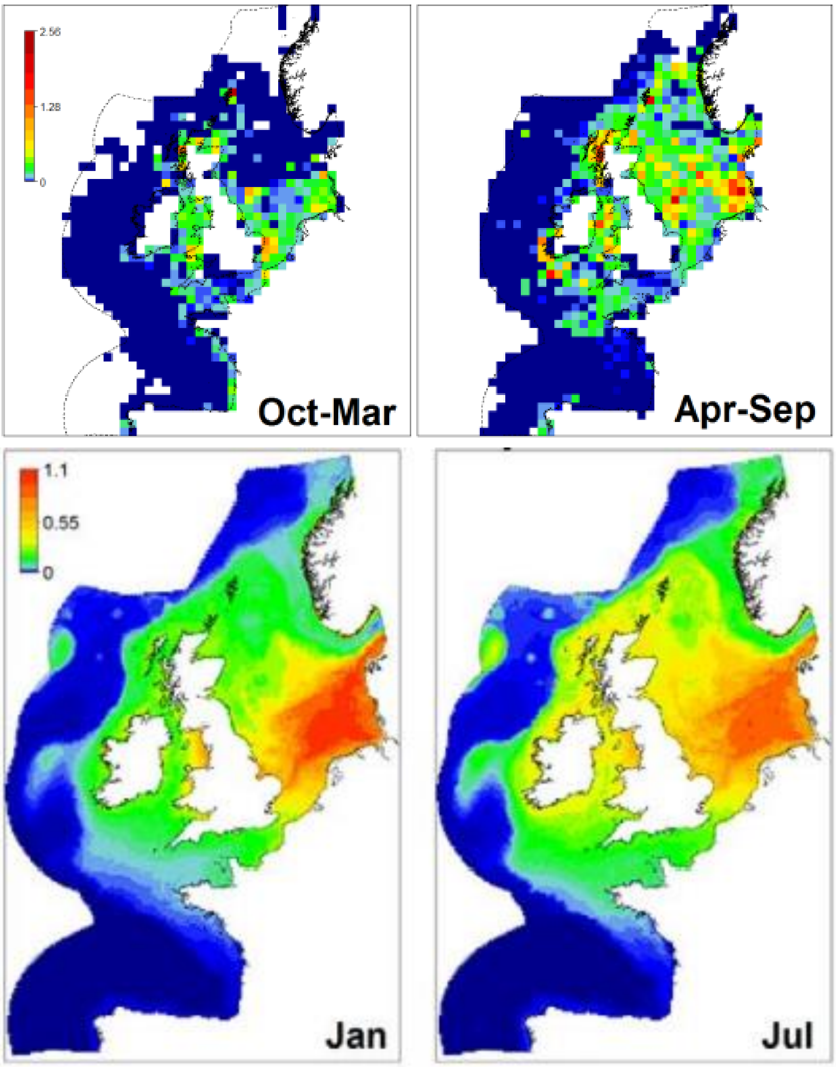


Figure A1: *Harbour porpoise densities (animals per km^2) as recorded seasonally (top); and as predicted for January and July (bottom) based on data 1980-2018. From Waggitt et al. (2020).*

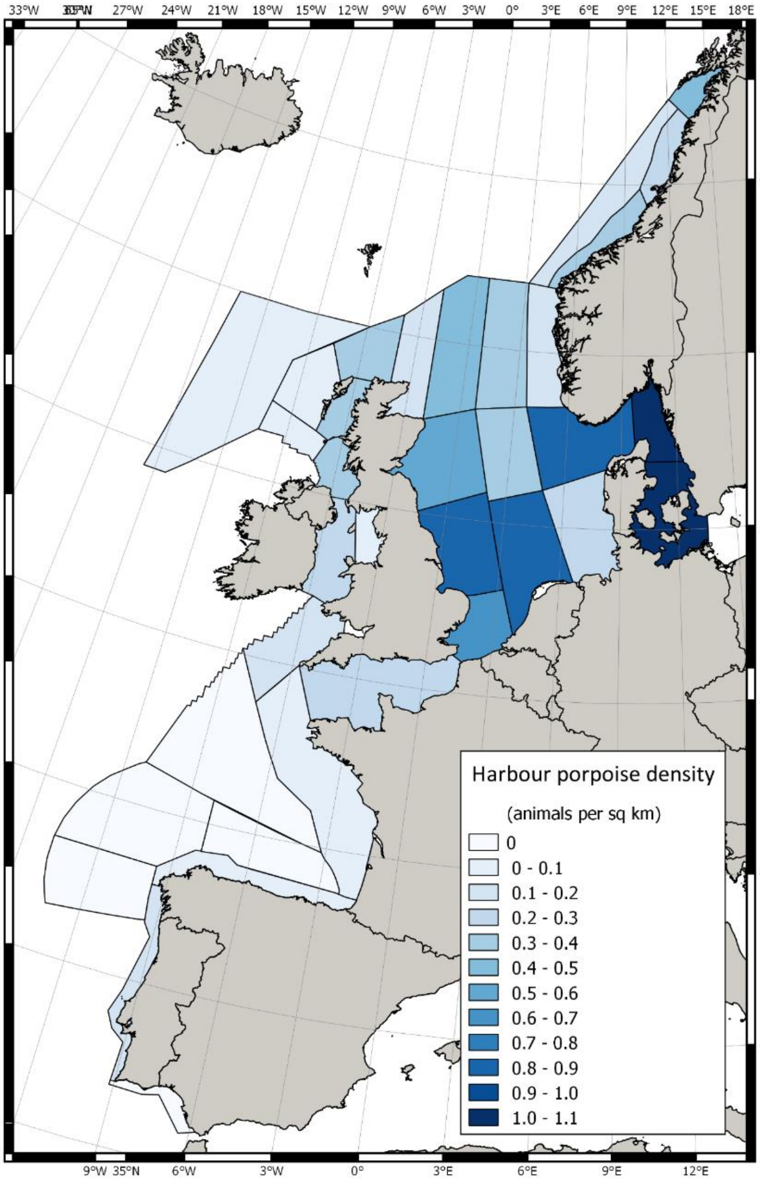


Figure A2. *Harbour porpoise density results for SCANS-III in July 2016. From Hammond et al. (2021).*

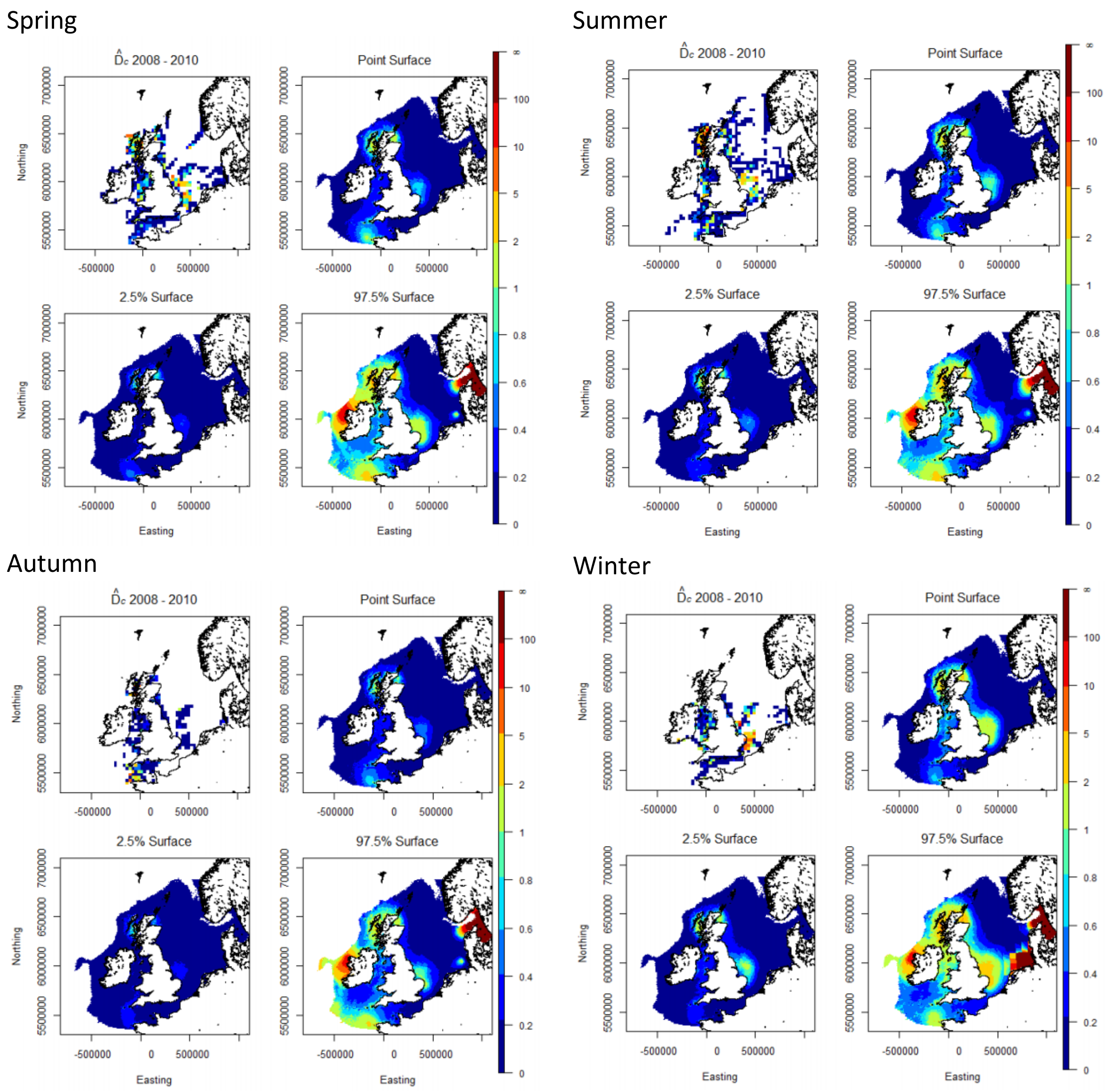


Figure A3. *Unscaled seasonal harbour porpoise JCP Phase III densities for 2010, representing for each season the mean input densities and realised effort 2008-2010 (top left), predicted densities (top right), lower bound (2.5%) confidence interval (bottom left), and upper bound (97.5%) confidence interval (bottom right). Adapted from Paxton et al. (2016).*

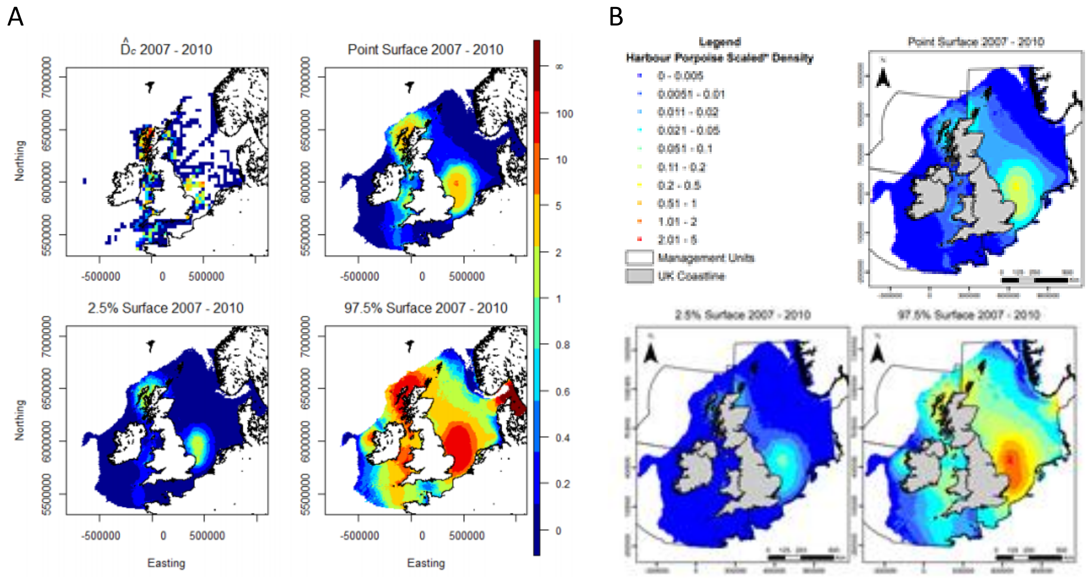


Figure A4. *Unscaled summer harbour porpoise JCP Phase III densities for 2007-2010 (A), and scaled porpoise densities (B), for each case representing predicted densities (top right); lower bound (2.5%) confidence interval (bottom left), and upper bound (97.5%) confidence interval (bottom right). Input densities and realised effort are also provided (A top left). From Paxton et al. (2016), with scaled density map created by JNCC.*

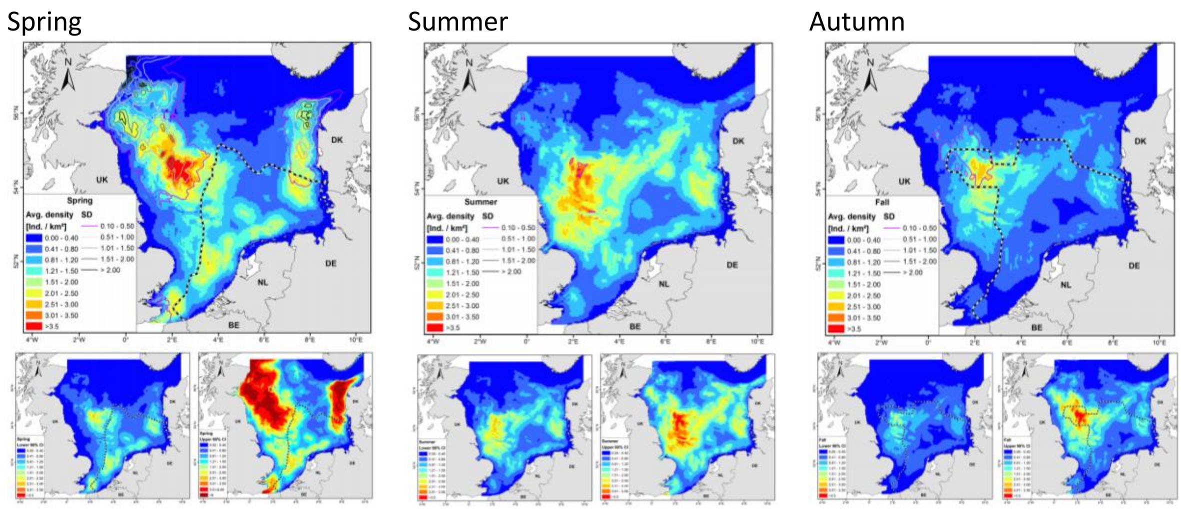


Figure A5. *Seasonal harbour porpoise densities for Spring, Summer and Autumn 2005-2013, in each case representing predicted densities (top), the lower lognormal 90% confidence interval (bottom left) and the upper lognormal 90% confidence interval (bottom right). From Gilles et al. (2016).*

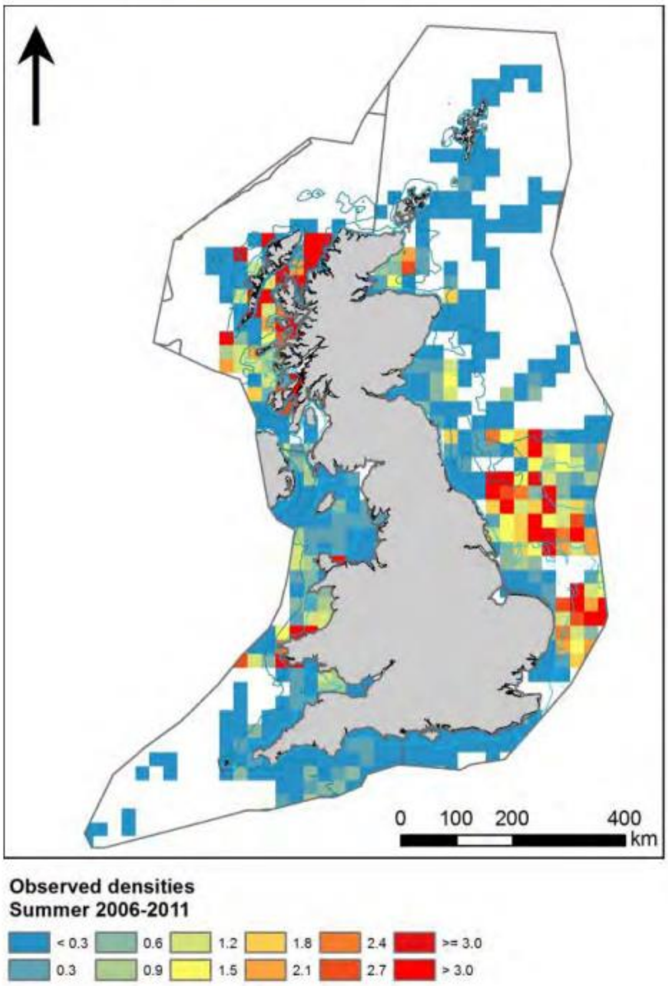


Figure A6. *Mean observed JCP harbour porpoise densities for summer (April – September) 2006-2011. White squares indicate absence of survey effort. From Heinänen & Skov (2015).*

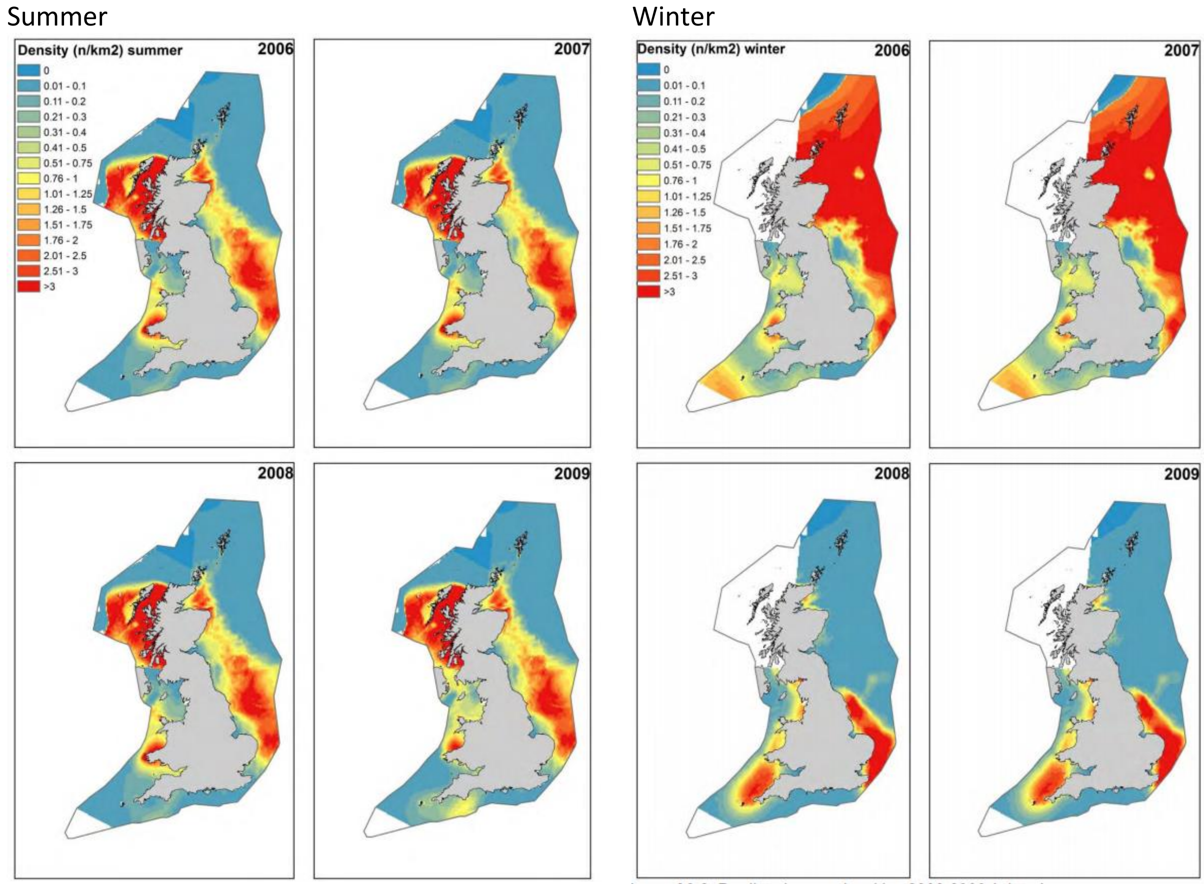


Figure A7. *Mean predicted JCP harbour porpoise densities for summer (April – September; left 4 panels) and winter (October – March; right 4 panels) for each year from 2006 to 2009. From Heinänen & Skov (2015).*

10 APPENDIX B – MODEL SCENARIO PARAMETERS, FIXED MODEL PARAMETERS, AND THEIR INPUT VALUES

The following section provides a summary overview of the iPCoD and DEPONS input values for the model scenario parameters (i.e. those parameters for which the input values will be varied for the different model runs), and for the fixed model parameters (i.e. those model parameters with a fixed input value for all simulations.

10.1 iPCoD

10.1.1 Scenario-specific parameters

Table B1. *Summary of iPCoD scenario-specific parameters and their input values. CL = confidence limits.*

Scenario Parameter	***Description***	***Value***	***Source***
pmean	Population size	246,526 345,373 495,752 87,440 154,932 252,344	North Sea MU abundance estimates from SCANS-III & 95% CL (Hammond et al., 2021) SNS abundance estimates from SCANS-III & 95% CL (Hammond et al., 2021)
vulnmean	vulnerable sub-population; i.e. the proportion of animals in the population that is actually likely to be vulnerable to the effects of piling	0.25 0.5 1	SCANS-III abundance estimates for various geographic areas relative to the relevant population size
days	Number of days of 'residual' disturbance associated with each day of actual disturbance for the proportion of the population described by 'prop_days_dist'	0 1	Overall Waiting Time = 6:50:29 hours (van Geel et al., 2023b)
numDt	Number of animals modelled to experience disturbance during each day of construction activity	374 & 748 2,502 & 3,754	Mean Impact Zone = 615.75 km^2 (van Geel et al., 2023b) multiplied by seasonal density; densities of 0.607 & 1.214 (latter winter only) applied to obtain the 'estimate', and 4.064 & 6.096 (latter winter only) for 'conservative' values
numPt	Number of animals modelled to experience PTS during each day of construction activity	1 & 2 4 & 6	Mean PTS Zone = 0.95 km^2 (van Geel et al., 2023b) multiplied by seasonal density; densities of 0.607 & 1.214 (latter winter only) applied to obtain the 'estimate', and 4.064 & 6.096 (latter winter only) for 'conservative' values

10.1.2 Fixed model parameters

Table B2. *Summary of iPCoD fixed model parameters and their input values.*

Fixed Parameter	***Description***	***Value***	***Source***
spec	Species; harbour porpoise	HP	
nboot	Number of times the simulation is run	1,000	Sinclair et al., 2019
propfemale	Proportion of females in the population	0.5	Sinclair et al., 2019
threshold	Threshold size for demographic stochasticity; will be implemented if pmean*propfemale < threshold	1,000	Sinclair et al., 2019
Surv[1]	Annual calf survival rate	0.8455	Sinclair et al., 2020
Surv[7]	Annual juvenile survival rate	0.85	Sinclair et al., 2019 & 2020
Surv[13]	Annual adult survival rate	0.925	Sinclair et al., 2020
Fertility	Fecundity rate (average probability of giving birth) for mature females	0.34	Sinclair et al., 2020
age1	Age at which a calf becomes independent from its mother	1	Sinclair et al., 2019 & 2020
age2	Average age a female gives birth to the first calf	5	Sinclair et al., 2019 & 2020
pile_years	Number of years piling occurred	2	Piling schedule
prop_days_dist	Proportion of disturbed individuals that experience the number of days of 'residual' disturbance specified by 'days'	1	
other_days	'Residual' disturbance experienced by the remaining proportion of the population (to be specified if 1-'prop_days_dist' > 0)	0	
Pilesx1	Number of piling operations	1	
seasons	Number of seasons[8]; allows for incorporation of seasonal differences in densities	4	
Avoid	Disturbed animals will avoid piling operations when experiencing residual disturbance	False	Sinclair et al., 2019
Day1	PTS can occur on any day that an individual is disturbed (FALSE), or animals are only vulnerable to PTS on the first day that they are experiencing disturbance (TRUE)	FALSE	
years	Number of years for the simulation	25	Sinclair et al., 2019
NCollisions	Number of individuals predicted to be killed each year as a result of collisions with renewable energy devices or other activities that results in multiple deaths each year	0	

[8] Seasons defined as winter (December, January and February); spring (March, April and May); summer (June, July and August); and autumn (September, October and November) (Sinclair et al., 2019).

10.2 DEPONS

10.2.1 Scenario-specific parameters

Table B3. *Summary of DEPONS scenario-specific parameters and their input values. The 'code names' are the names used in the Repast Java code in the current version of the model.*

Code name (Parameter)	***Description***	***Values***	***Source***
h (*h*)	Probability that adult females become pregnant	0.34 0.68	Current report (see Section 3.2.1.2)
RT (*T*)	Response threshold; received sound level above which porpoises start to getting deterred	103.0 124.6 132.3 140.0	Current report (see Section 3.2.1.1)
c (*c*)	Deterrence coefficient	0.035 0.07 0.14	Current report (see Section 3.2.1.1)
Landscape	The landscape that is used for the simulation	UserDefined with spring or autumn food maps applied for the winter months	Current report (see Section 3.2.1.3)
turbines (Turbines)	The wind farm construction scenario that is used in a simulation. It reads in the selected text file that defines the turbine locations, period of activity etc.	Off User-def	Current report (see Section 3.2.1.4)
simYears	Number of simulation years	40 50	Current report (see Section 3.2.1.5)

10.2.2 Fixed model parameters

Table B4. *Summary of DEPONS fixed model parameters and their input values. PSM = Persistent spatial memory. CRW = Correlated random walk. The 'code names' are the names used in the Repast Java code in the current version of the model. Standard values of parameters written as N(x,y) indicate random values drawn from a Gaussian distribution with mean x and standard deviation y.*

Code name (Parameter)	***Description***	***Values***	***Source***
Einit (E_{init})	Initial energy level for porpoises	N(10; 1)	Nabe-Nielsen et al., 2020
Elact (E_{lact})	Energy use multiplier for lactating mammals	1.4	Nabe-Nielsen et al., 2020
Euse (E_{use})	Energy use per half-hour step in May – September	4.5	Nabe-Nielsen et al., 2020
Ewarm (E_{warm})	Energy use multiplier in warm water	1.3	Nabe-Nielsen et al., 2020
PSM-Type (psmType)	Controls the type of large-scale movements used by porpoises	PSM-Type2	Nabe-Nielsen et al., 2020
PSM_angle (*PSM_angle*)	Maximum absolute turning angle after each PSM large-scale move	20	Nabe-Nielsen et al., 2020
PSM_dist (*PSM_dist*)	Distance to target when initiating PSM moves	N(300; 100)	Nabe-Nielsen et al., 2020
PSM_log (*PSM_log*)	Parameter controlling logistic increase in turning angle during large-scale movement	0.6	Nabe-Nielsen et al., 2020
PSM_tol (*PSM_tol*)	Tolerance band within which the target cell group is selected (PSM_dist ± PSM_tol) when initiating PSM behaviour	5	Nabe-Nielsen et al., 2020
Psi_deter (Ψ_{deter})	Deterrence decay constant; decrease in deterrence per time step after noise has stopped	50	Nabe-Nielsen et al., 2020
R1 (R_1)	Mean and standard deviation in $\log_{10}(d/100)$, where d is the distance moved per time step	N(1.25; 0.15)	Nabe-Nielsen et al., 2020
R2 (R_2)	Variation in turning angle between steps	N(0; 4)	Nabe-Nielsen et al., 2020
Ships enabled (shipsEnabled)	Whether ships are simulated	False	N/A
Umin (U_{min})	Minimum food level in a patch; the starting value for logistic replenishment of the food	0.001	Nabe-Nielsen et al., 2020
a (a_0)	Autoregressive coefficient for $\log_{10}(d/100)$, where d is distance per CRW move	0.35	Nabe-Nielsen et al., 2020
- (a_1)	Coefficient indicating effect of water depth on $\log_{10}(d/100)$	0.0005	Nabe-Nielsen et al., 2020

- (a_2)	Coefficient indicating effect of salinity on $\log_{10}(d/100)$	-0.02	Nabe-Nielsen et al., 2020
alphaHat ($\hat{\alpha}$)	Absorption coefficient for sound	0.0005693	van Geel et al., 2023b
b (b_0)	Autoregressive coefficient for turning angles in CRW	-0.024	Nabe-Nielsen et al., 2020
- (b_1)	Coefficient indicating effect of water depth on turning angles in CRW	-0.008	Nabe-Nielsen et al., 2020
- (b_2)	Coefficient indicating effect of salinity on turning angles in CRW	0.93	Nabe-Nielsen et al., 2020
- (b_3)	Intercept from regression of turning angle on salinity and bathymetry	-14	Nabe-Nielsen et al., 2020
beta (β)	Survival probability constant	0.4	Nabe-Nielsen et al., 2020
betaHat ($\hat{\beta}$)	Spreading loss factor for sound; the parameters $\hat{\beta}$ and $\hat{\alpha}$ determine the sound transmission loss	17.75	van Geel et al., 2023b
bycatchProb (bycatchProb)	Randomly selected proportion of the population to remove each year; can take any value in range 0–1	0	Nabe-Nielsen et al., 2020
ddisp (d_{disp})	Distance moved per time step while using large-scale movements	1.05	Nabe-Nielsen et al., 2020
debug (debug)	Built-in code testing parameter (values 0–5); when set to 0 no code testing / debugging occurs	0	N/A
dmax_deter (d_{max_deter})	Maximum deterrence distance; Enables user to introduce distance limit for response to noise	1,000	Nabe-Nielsen et al., 2020
dmax_move ($d_{maxmove}$)	Maximum value of $\log_{10}(d/100)$ while using fine-scale moves; here d is distance moved per time step	1.73	Nabe-Nielsen et al., 2020
k (k)	Inertia constant; the animal's tendency to keep moving using CRW irrespective of foraging success	0.001	Nabe-Nielsen et al., 2020
porpoiseCount (porpoiseCount)	Number of porpoise agents in the simulation when initiated	10,000	Nabe-Nielsen et al., 2020
q1	PSM Type 3 travel distance weight	0.02	Nabe-Nielsen et al., 2020
rR (r_R)	Reference memory decay rate	0.04	Nabe-Nielsen et al., 2020
rS (r_S)	Satiation memory decay rate	0.04	Nabe-Nielsen et al., 2020
rU (r_U)	Food replenishment rate; the rate that food recovers after being eaten	0.1	Nabe-Nielsen et al., 2020
randomSeed (randomSeed)	Allows the user to reproduce simulation output of earlier model runs by using the same random seed as previously used; can take any integer value	Random	Nabe-Nielsen et al., 2020

tdisp (t_{todisp})	Time before onset of large-scale movement; standard value based on the observations that captive porpoises appear to starve after not eating for three days	3	Nabe-Nielsen et al., 2020
tdeter (t_{deter})	Residual deterrence time; number of time steps the deterrence effect lasts when the animal is no longer exposed to noise	0	Nabe-Nielsen et al., 2020
tgest (t_{gest})	Gestation time	300	Nabe-Nielsen et al., 2020
tmating (t_{mating})	Mating day	N(225; 20)	Nabe-Nielsen et al., 2020
tmature (t_{mature})	Age of maturity	3.44	Nabe-Nielsen et al., 2020
tmaxage (t_{maxage})	Maximum age of porpoises	30	Nabe-Nielsen et al., 2020
tnurs (t_{nurs})	Nursing time	240	Nabe-Nielsen et al., 2020
trackedPorpoiseCount (trackedPorpoiseCount)	Number of porpoise agents for which to track the xy coordinates (to monitor their movements)	1	N/A
wdisp (w_{disp})	Minimum water depth while using large-scale movement	4	Nabe-Nielsen et al., 2020
wmin (w_{min})	Minimum water depth required by porpoises	1	Nabe-Nielsen et al., 2020
wrapBorderHomo (wrapBorderHomo)	Whether the border of the landscape should wrap. Can take the values "false" or "true". The landscape is without borders when “wrapBorderHomo”= “true” and “landscape”= ”Homogeneous”.	False	N/A

11 APPENDIX C – DEPONS POPULATION STABILISATION

Appendix C presents the mean annual-averaged estimated population of porpoise agents across the five simulations per scenario (summarised in Table 6) throughout the modelling period, revealing the levels at which the populations stabilise. Note the different time scales on the x-axes.

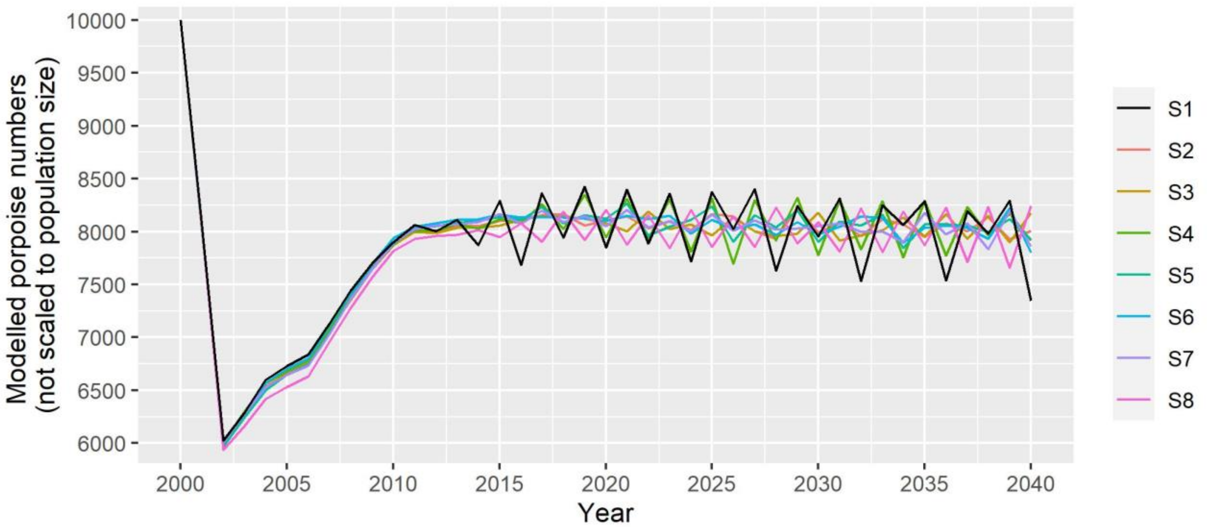


Figure C1. *Population stabilisation under DEPONS scenarios applying a Fertility value of h = 0.68 (S1-S8).*

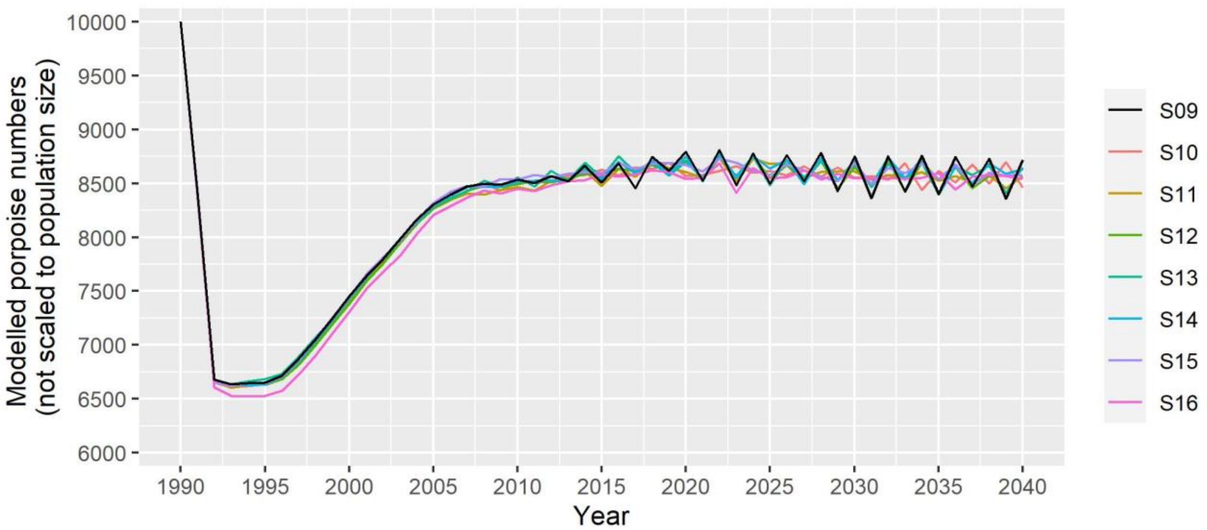
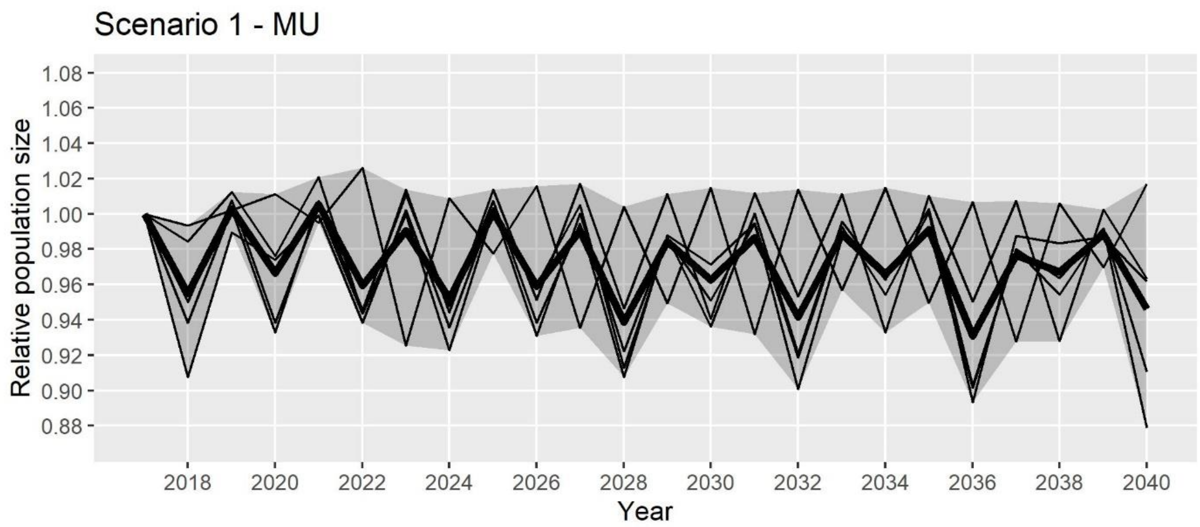


Figure C2. *Population stabilisation under DEPONS scenarios applying a Fertility value of h = 0.34 (S9-S16).*

12 APPENDIX D – DEPONS ANNUAL MANAGEMENT UNIT RESULTS FOR INDIVIDUAL SCENARIOS

12.1 Fertility = 0.68 (Scenarios 1-8)

Figure D1 presents the population-level results for the individual simulations for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.68. For each scenario, the five runs are presented with their mean trajectory in bold. These averaged results are also included in Figure 10.



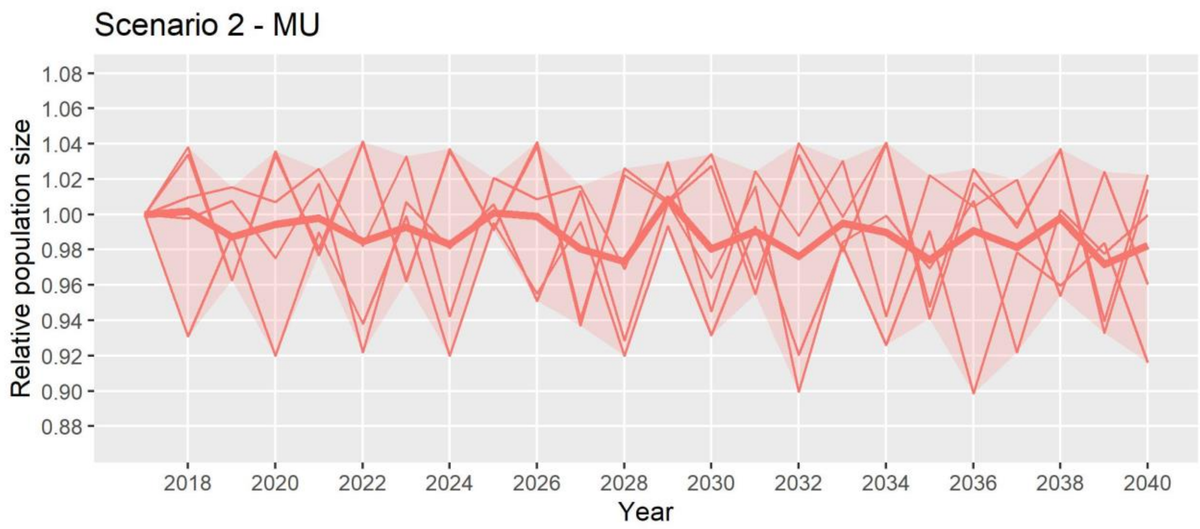


Figure D1. *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

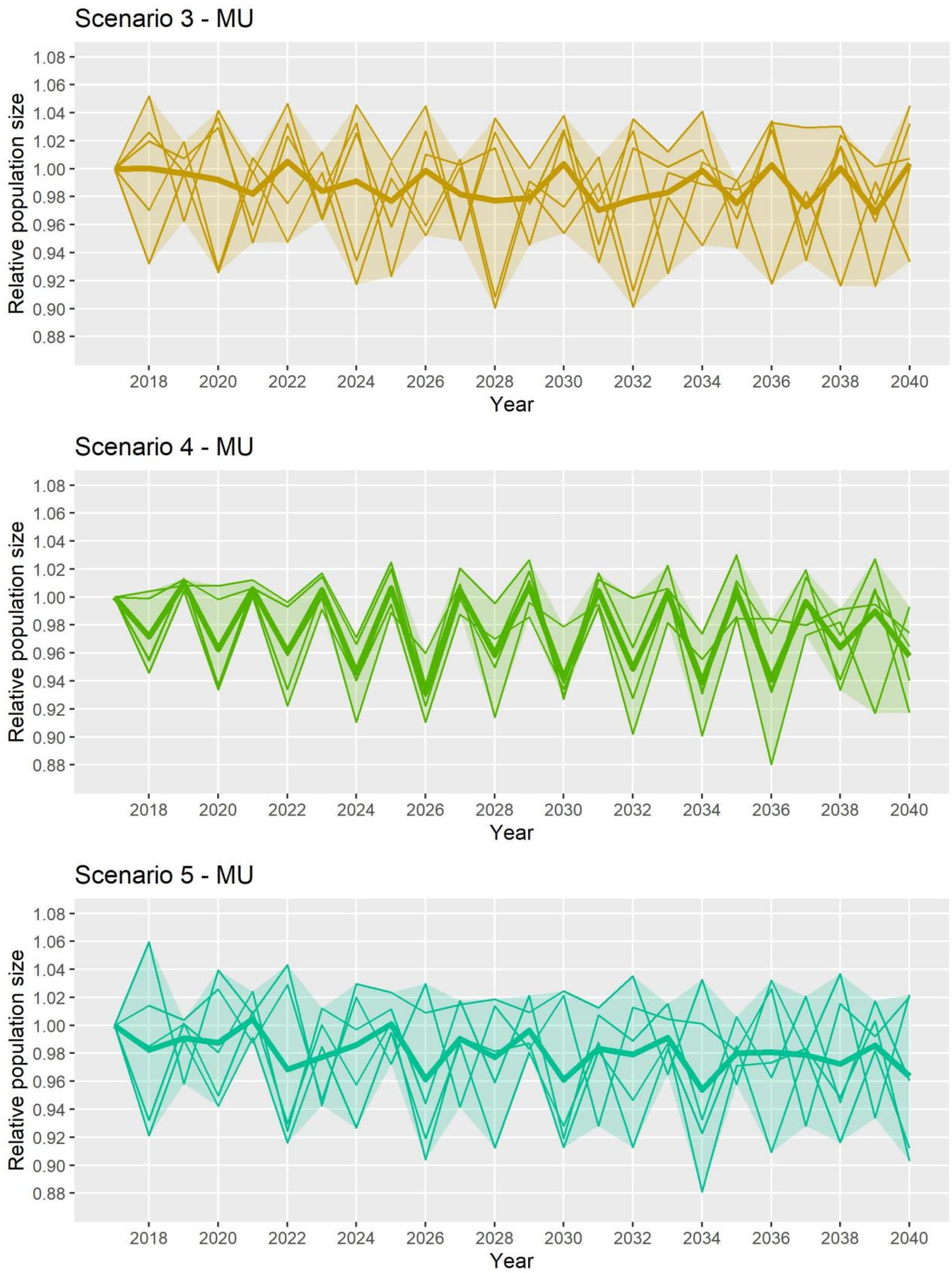


Figure D1 (Continued). *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

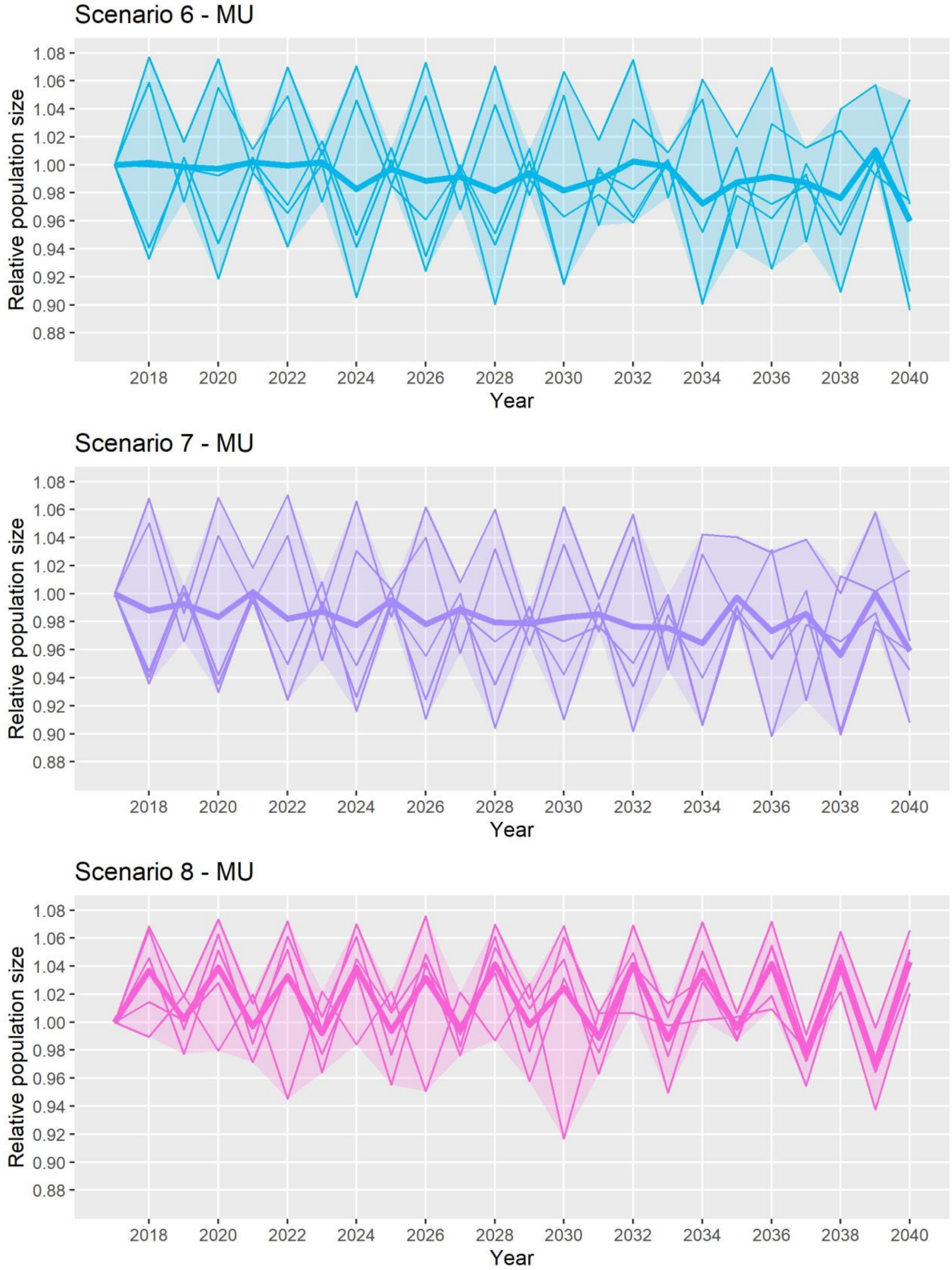


Figure D1 (Continued). *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

12.2 Fertility = 0.34 (Scenarios 9-16)

Figure D2 presents the population-level results for the individual simulations for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.34. For each scenario, the five runs are presented with their mean trajectory in bold. These averaged results are also included in Figure 11.

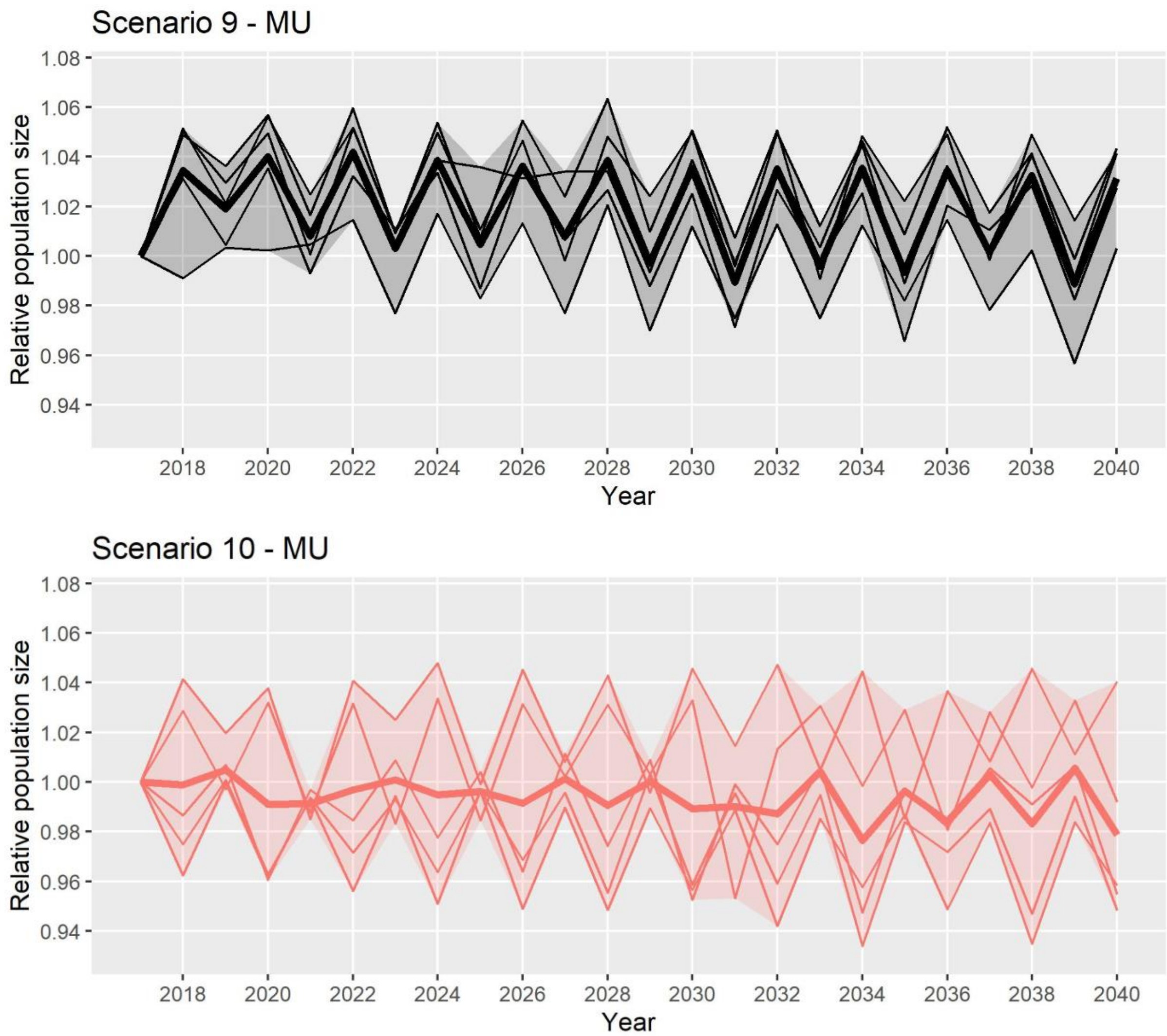
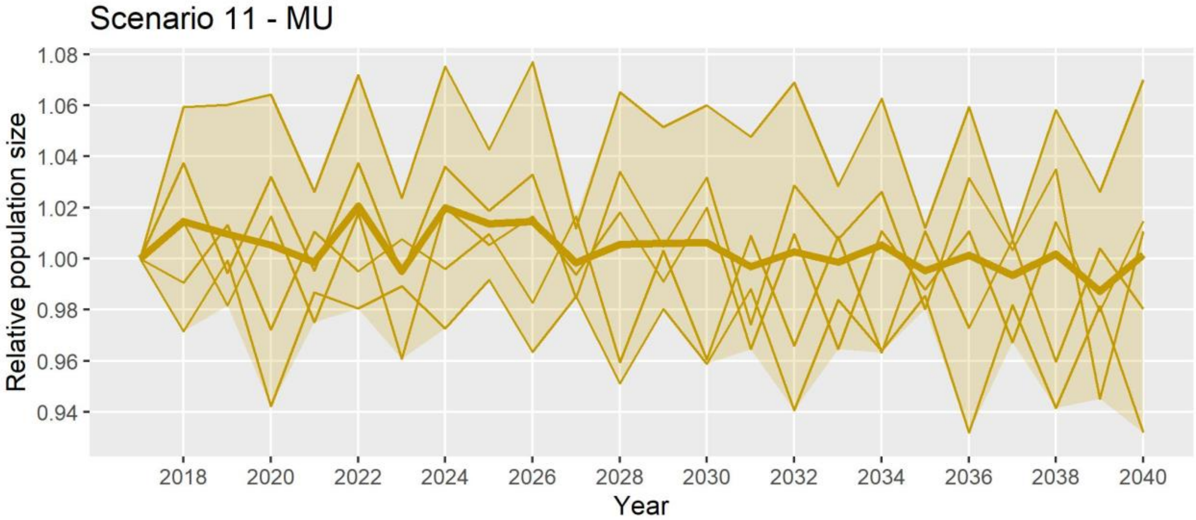
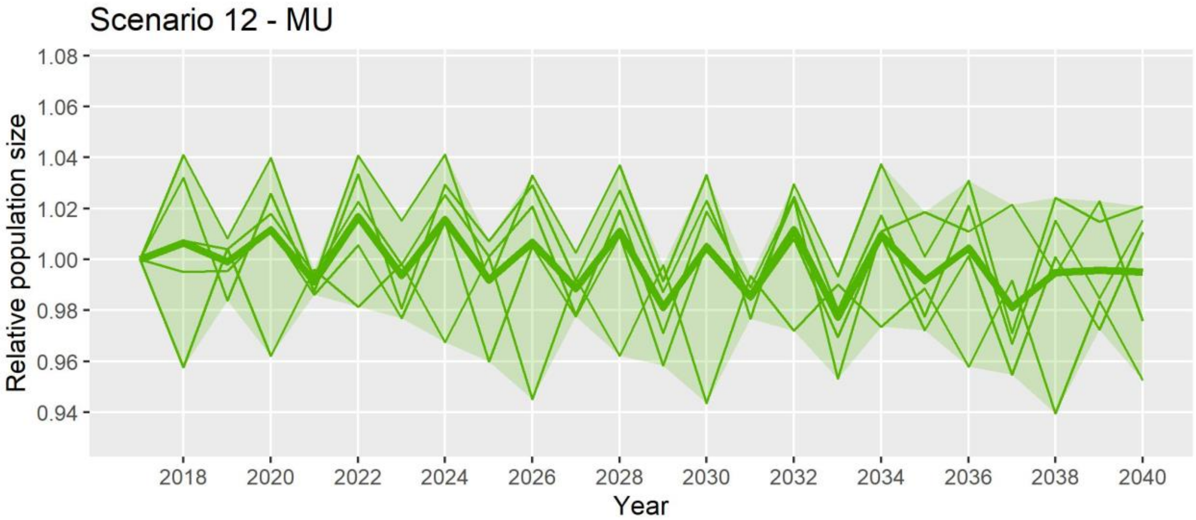


Figure D2. *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*





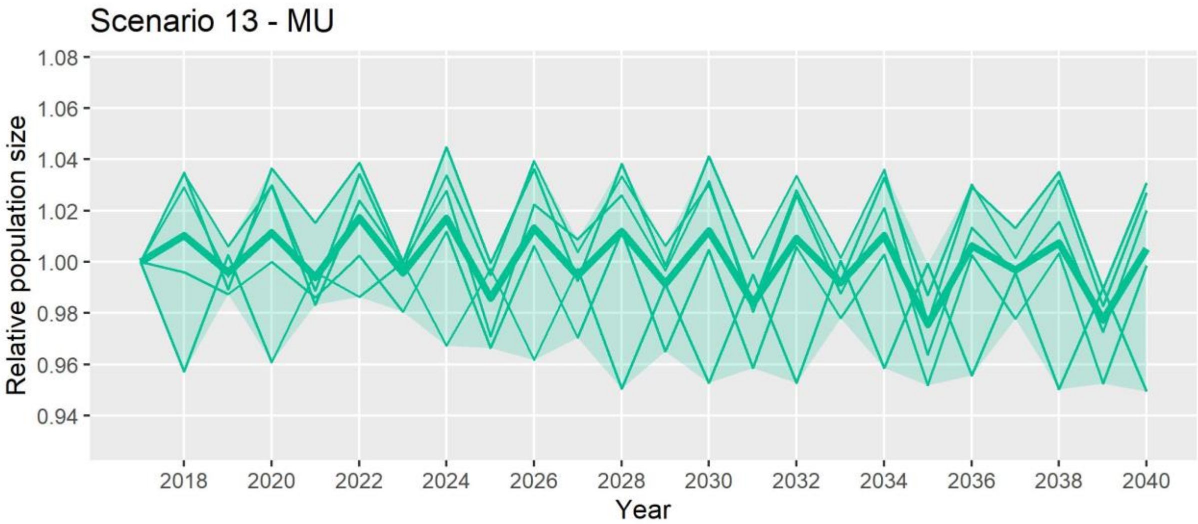


Figure D2 (Continued). *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

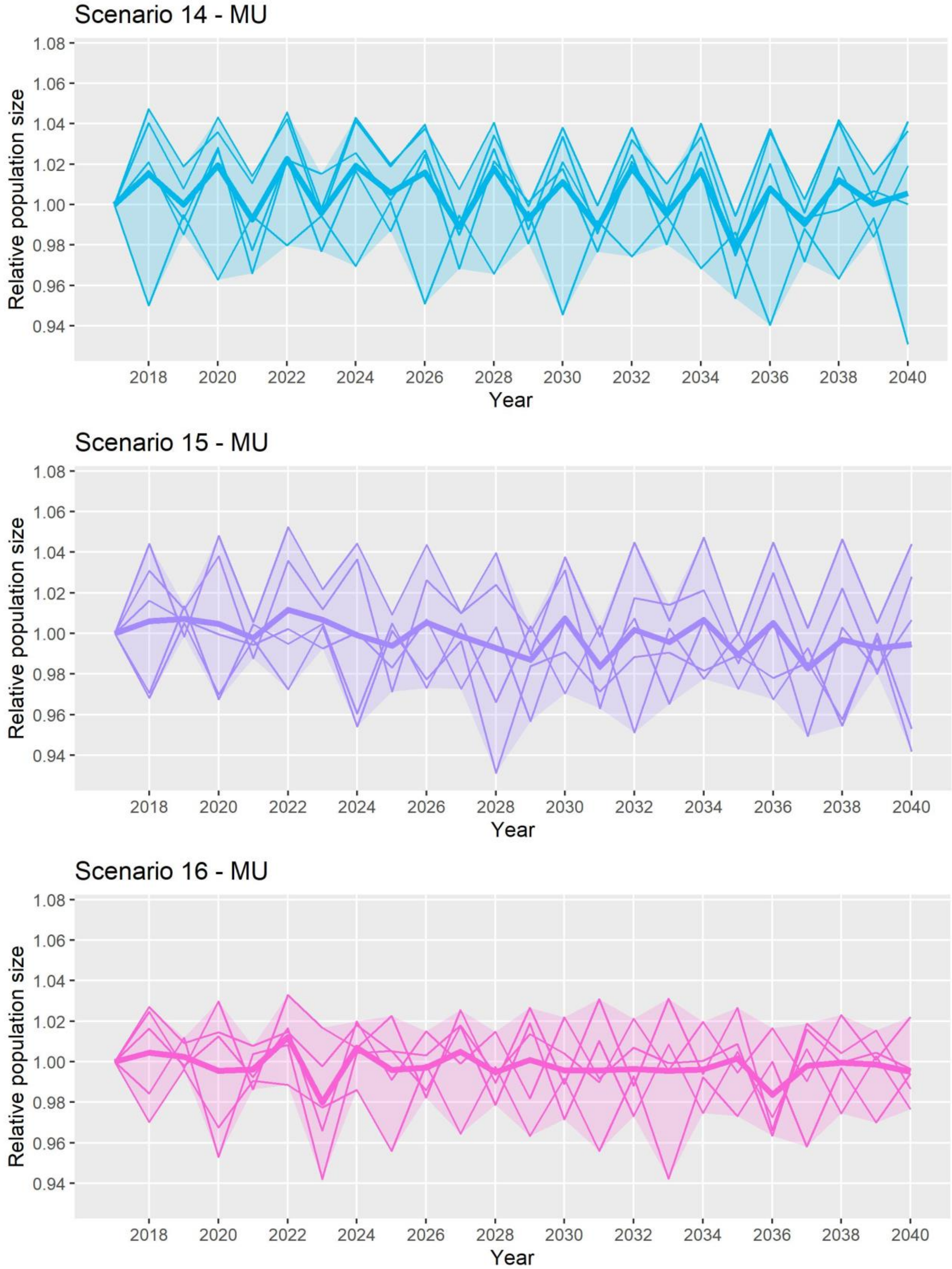
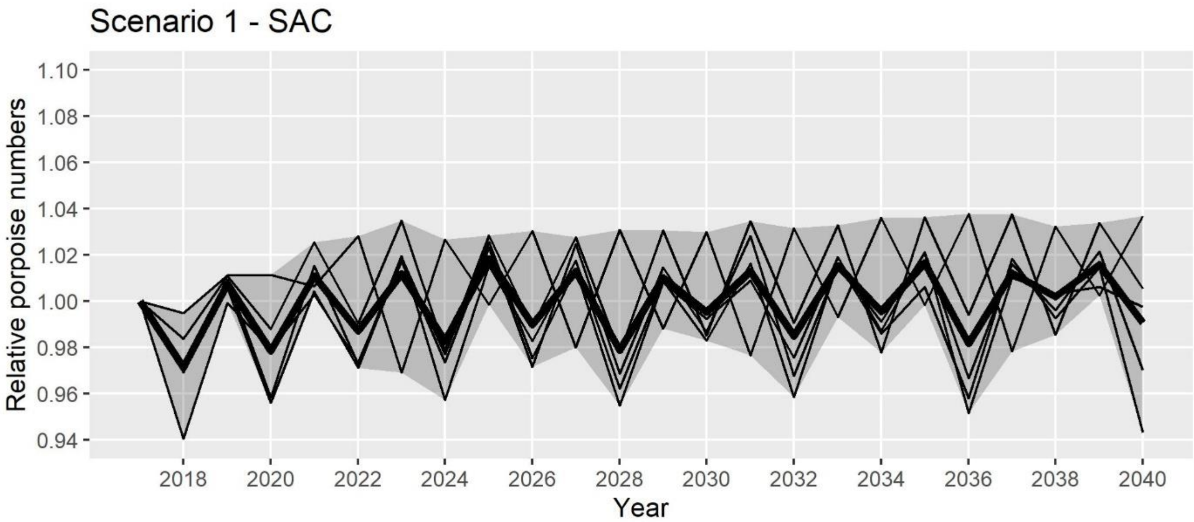


Figure D2 (Continued). *Porpoise population size relative to the pre-piling baseline level in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

13 APPENDIX E – DEPONS ANNUAL SOUTHERN NORTH SEA SAC RESULTS FOR INDIVIDUAL SCENARIOS

13.1 Fertility = 0.68 (Scenarios 1-8)

Figure E1 presents the SNS SAC results for the individual simulations for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.68. For each scenario, the five runs are presented with their mean trajectory in bold. These averaged results are also included in Figure 12.



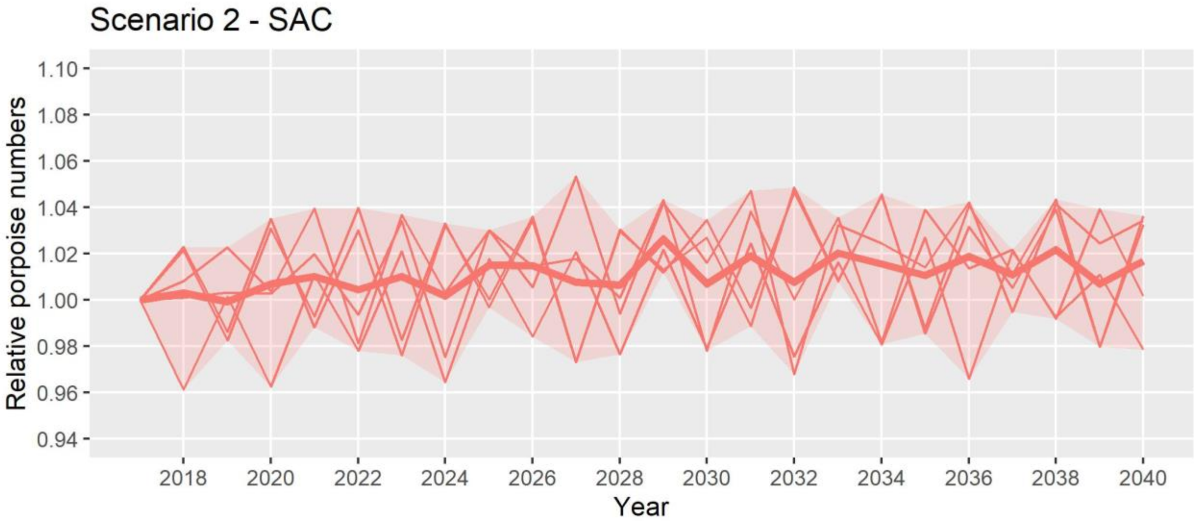
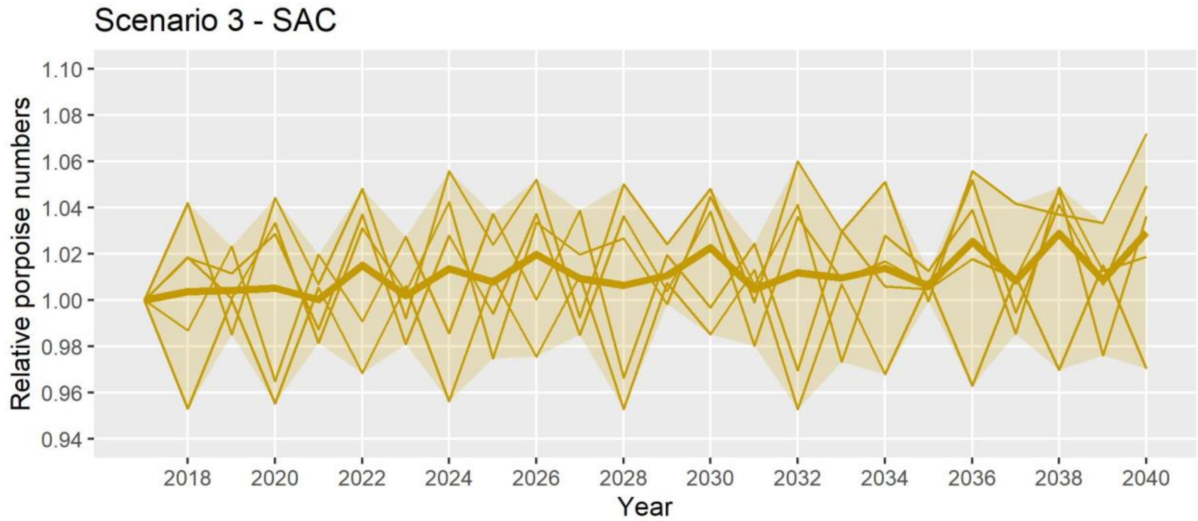
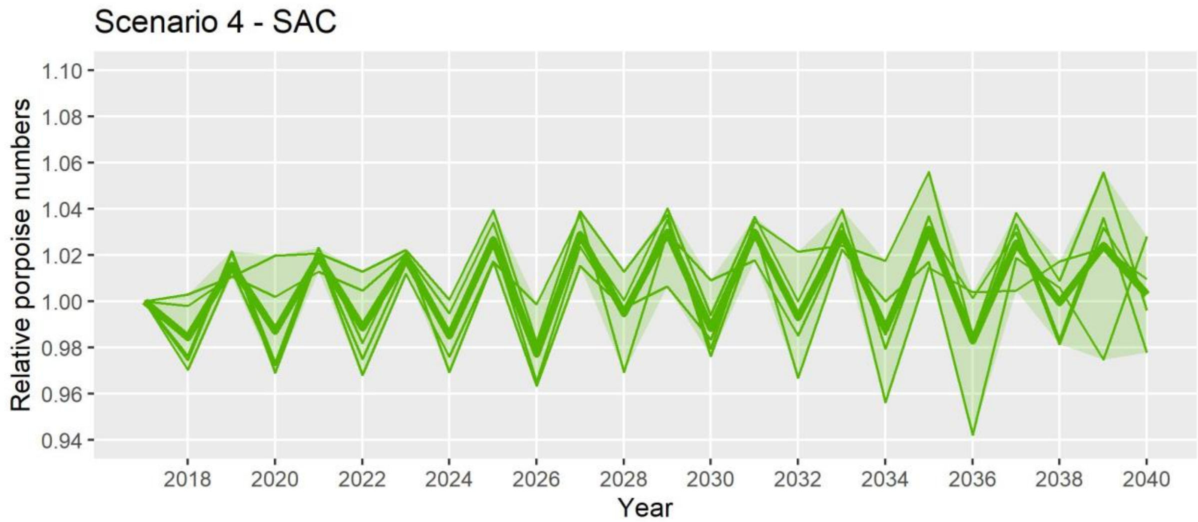


Figure E1. *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*





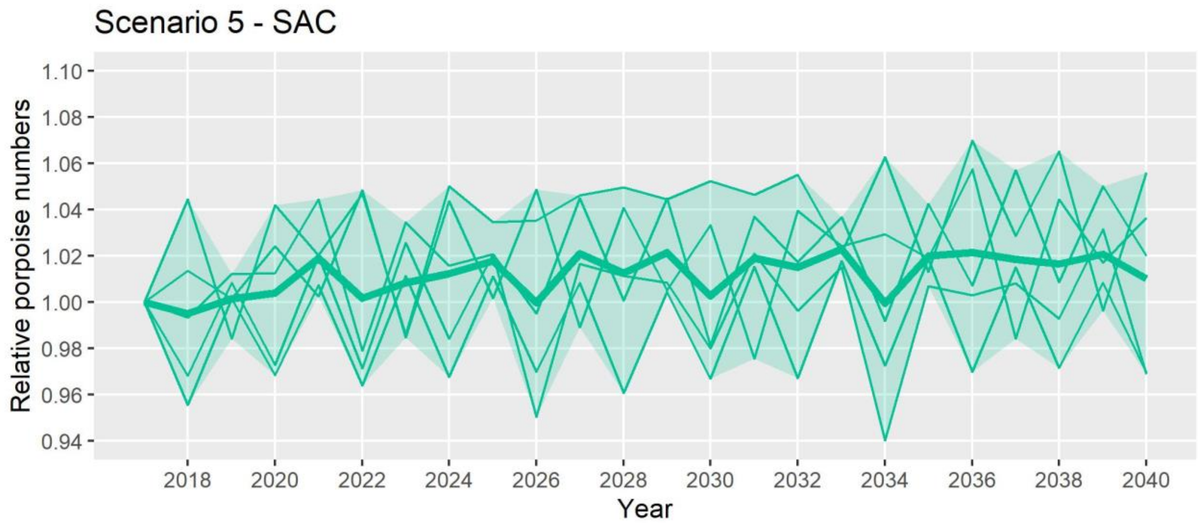


Figure E1 (Continued). *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

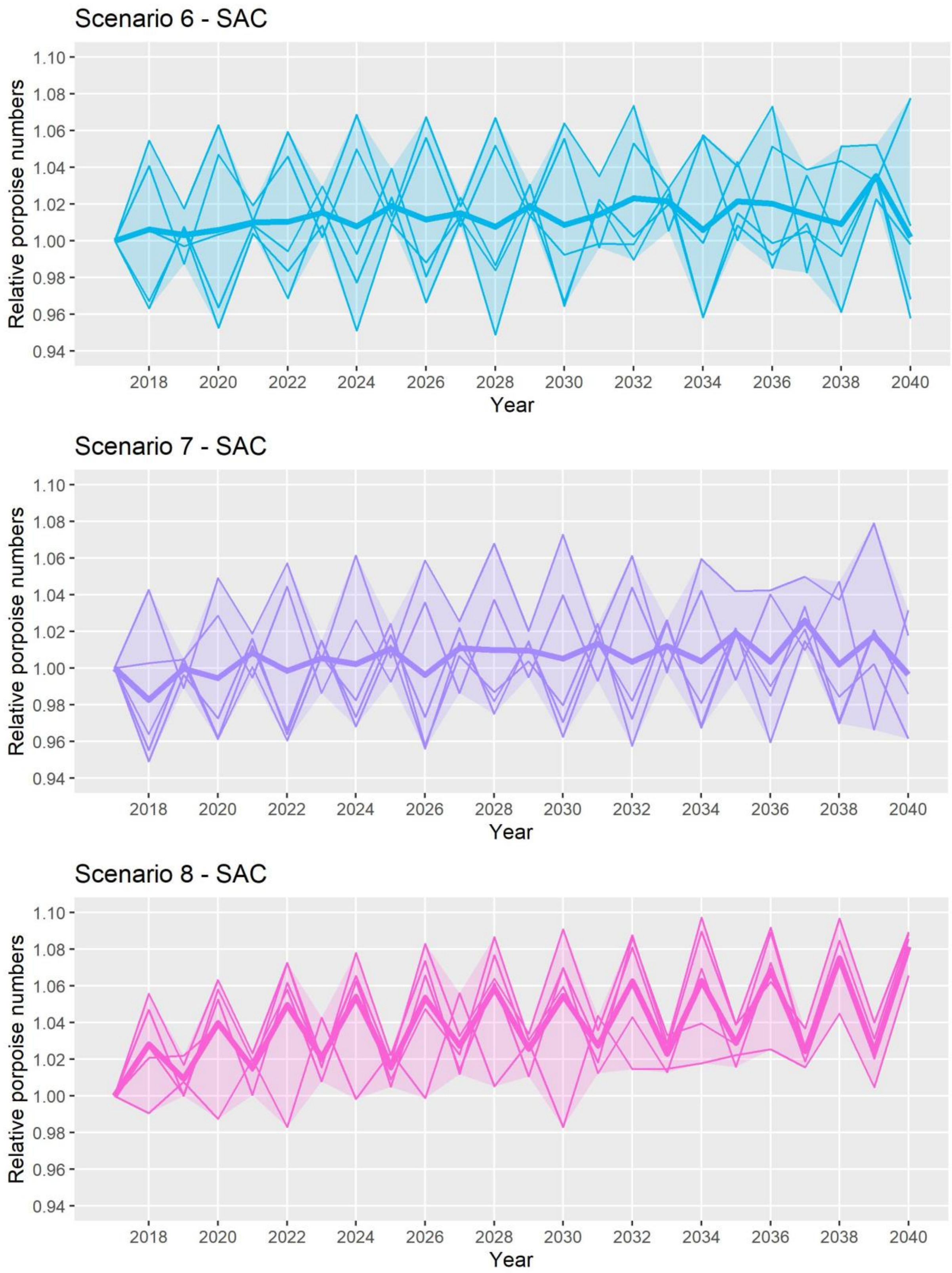


Figure E1 (Continued). *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S1-S8, applying a Fertility value of 0.68 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

13.2 Fertility = 0.34 (Scenarios 9-16)

Figure E2 presents the SNS SAC results for the individual simulations for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.34. For each scenario, the five runs are presented with their mean trajectory in bold. These averaged results are also included in Figure 14.

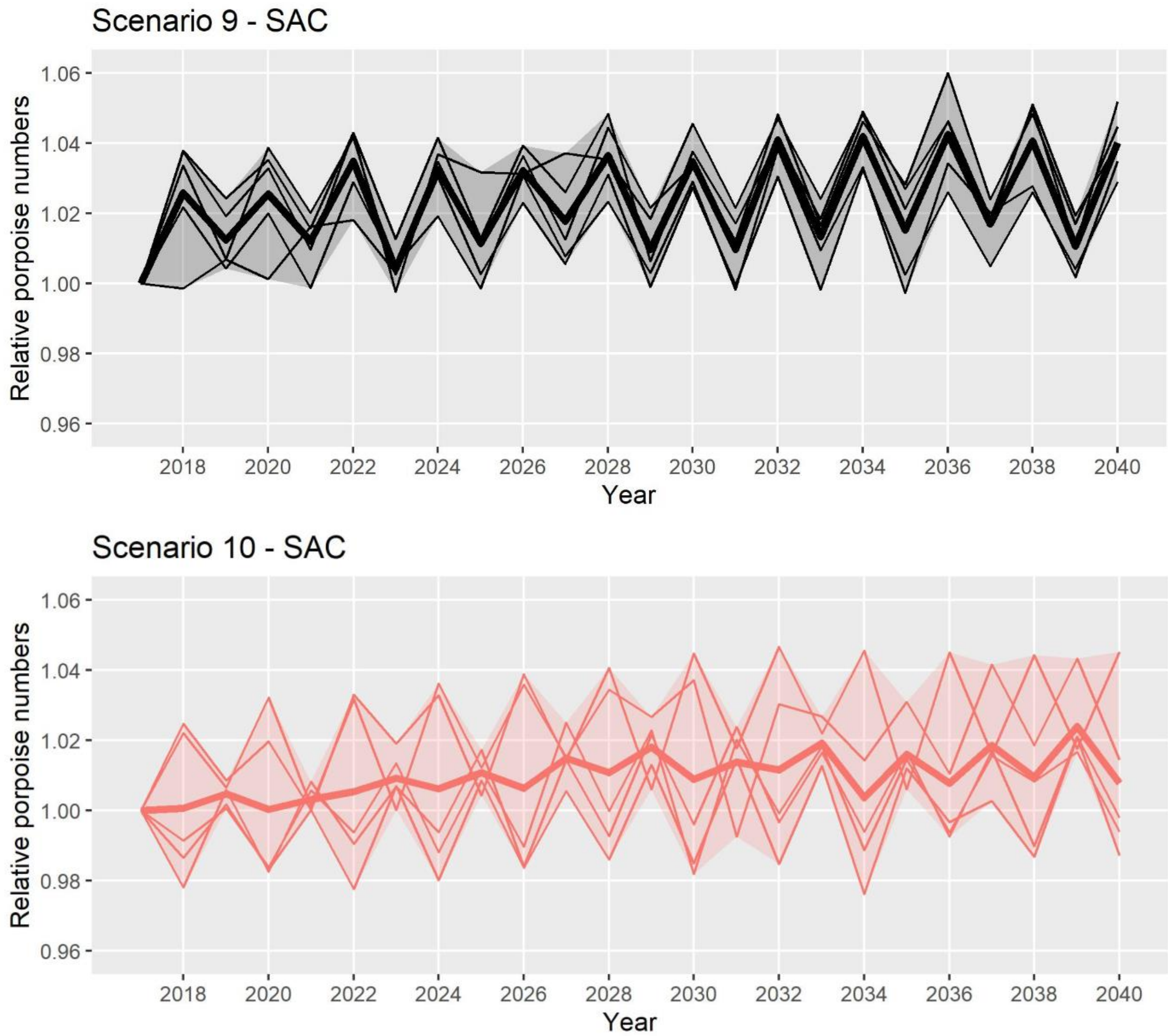


Figure E2. *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

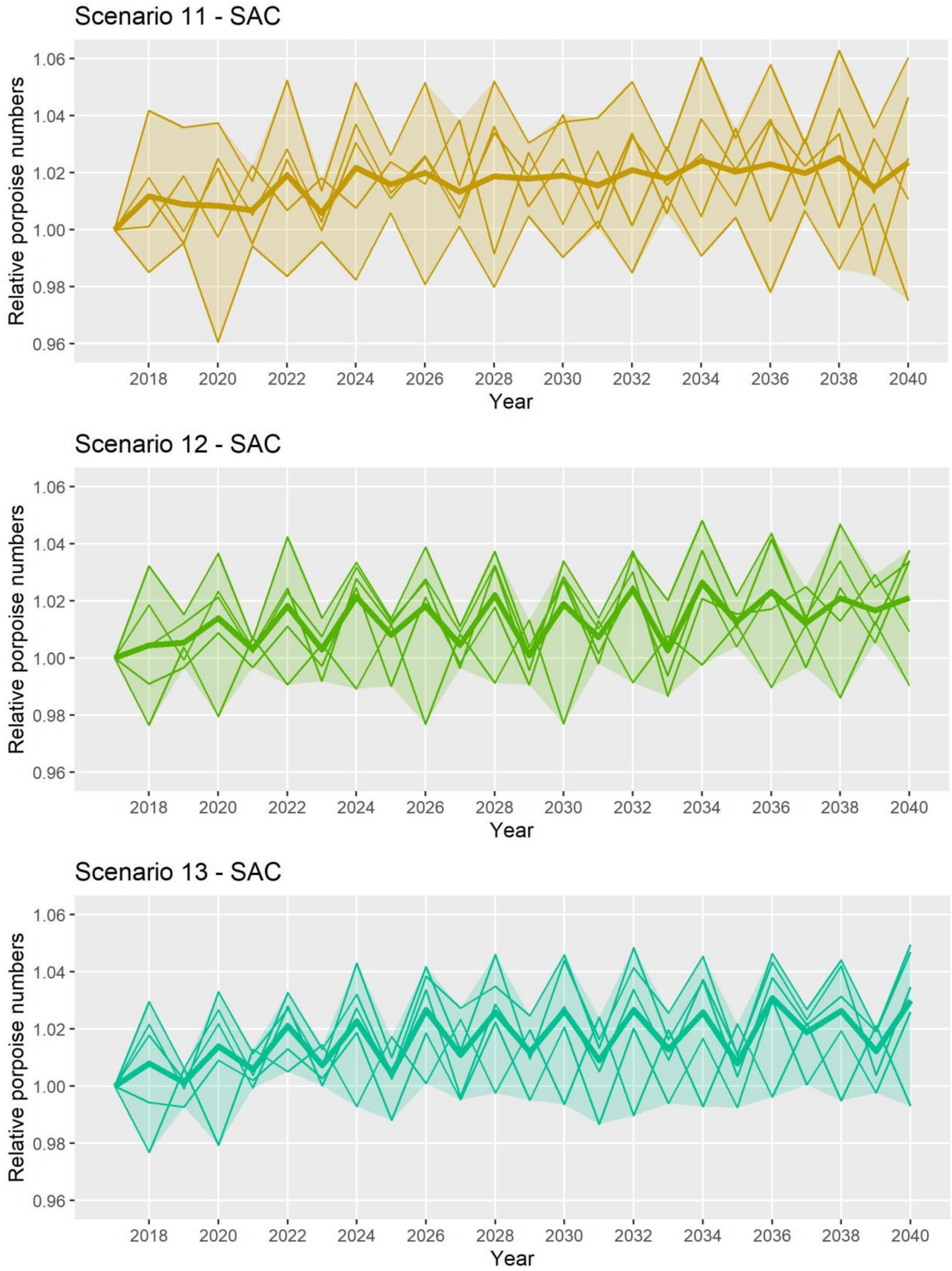


Figure E2 (Continued). *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

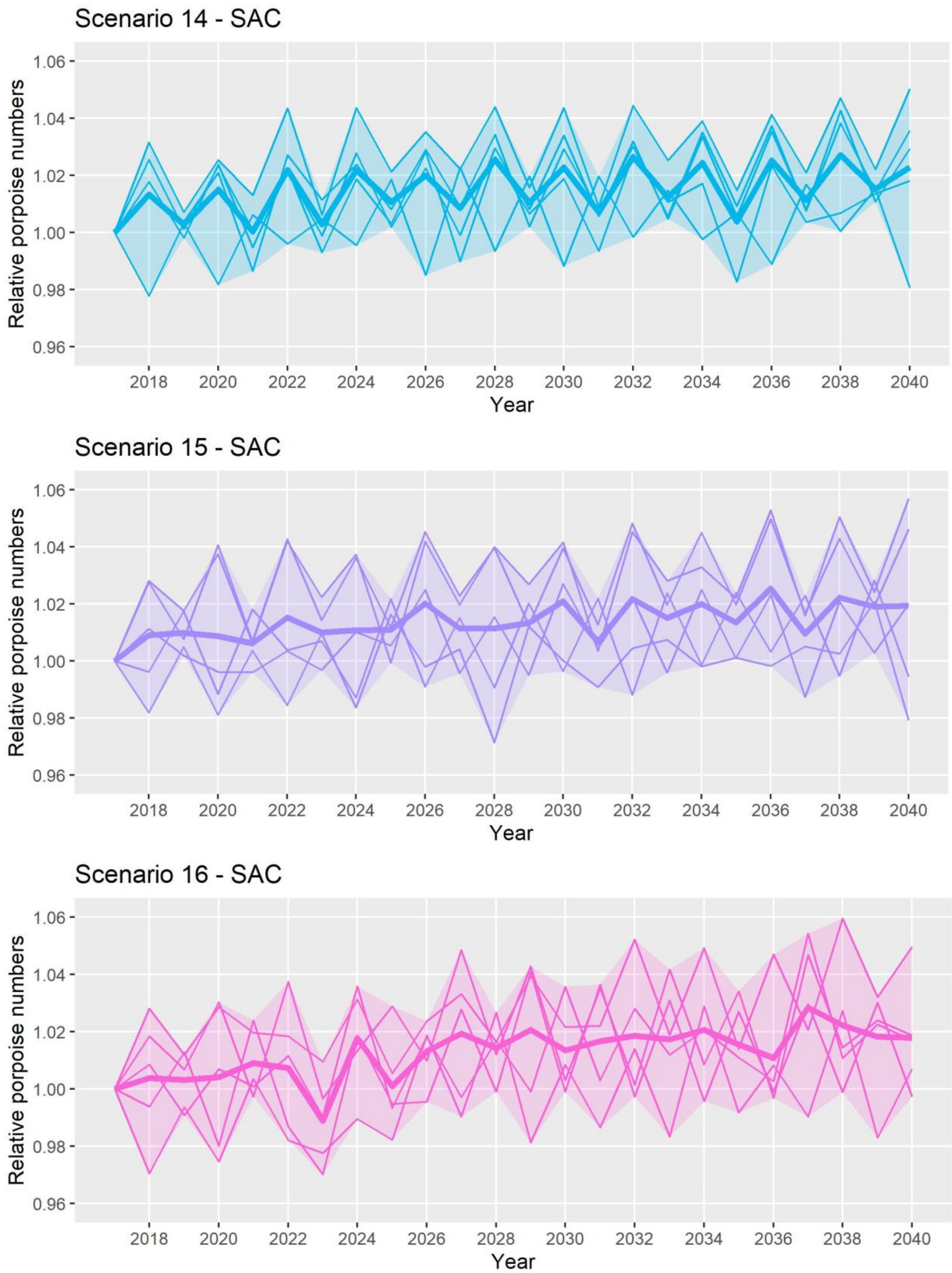
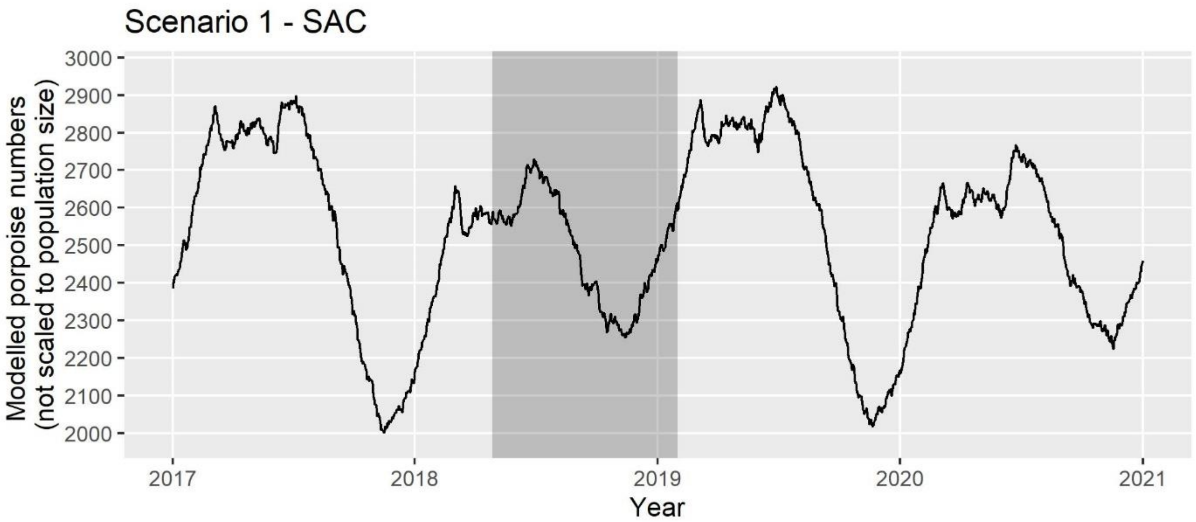


Figure E2 (Continued). *Modelled number of porpoises within the SNS SAC boundary relative to the pre-piling baseline number in 2017 for DEPONS simulations S9-S16, applying a Fertility value of 0.34 and based on five simulations per scenario. The shaded area represents the annual minima and maxima.*

14 APPENDIX F – DEPONS DAILY SNS SAC RESULTS 2017-2020 FOR INDIVIDUAL SCENARIOS

14.1 Fertility = 0.68 (Scenarios 1-8)

Figure F1 presents the results for the daily averaged predicted harbour porpoise numbers within the SNS SAC boundary for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.68.



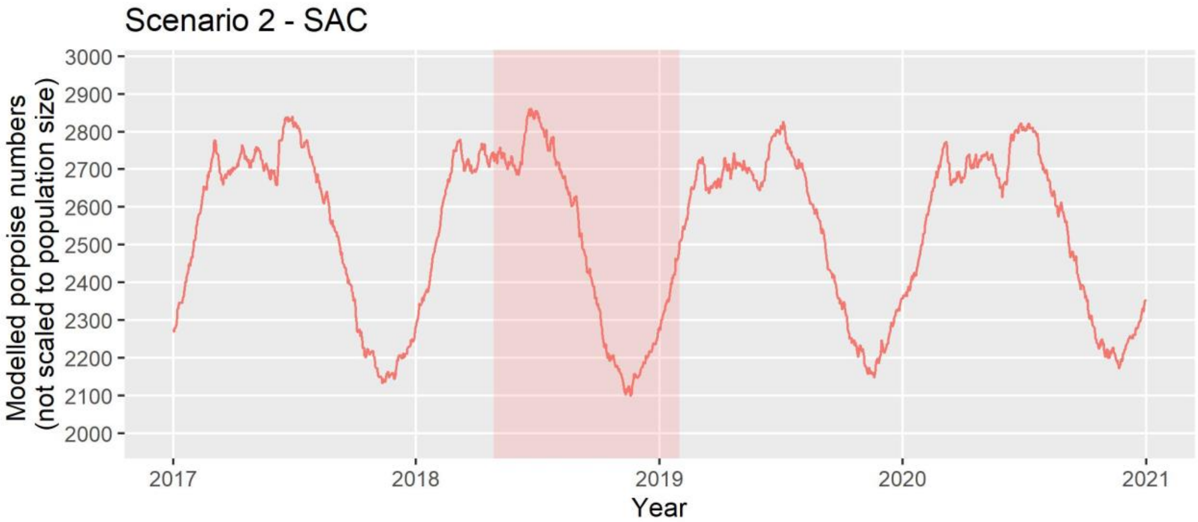


Figure F1. *Predicted daily average number harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

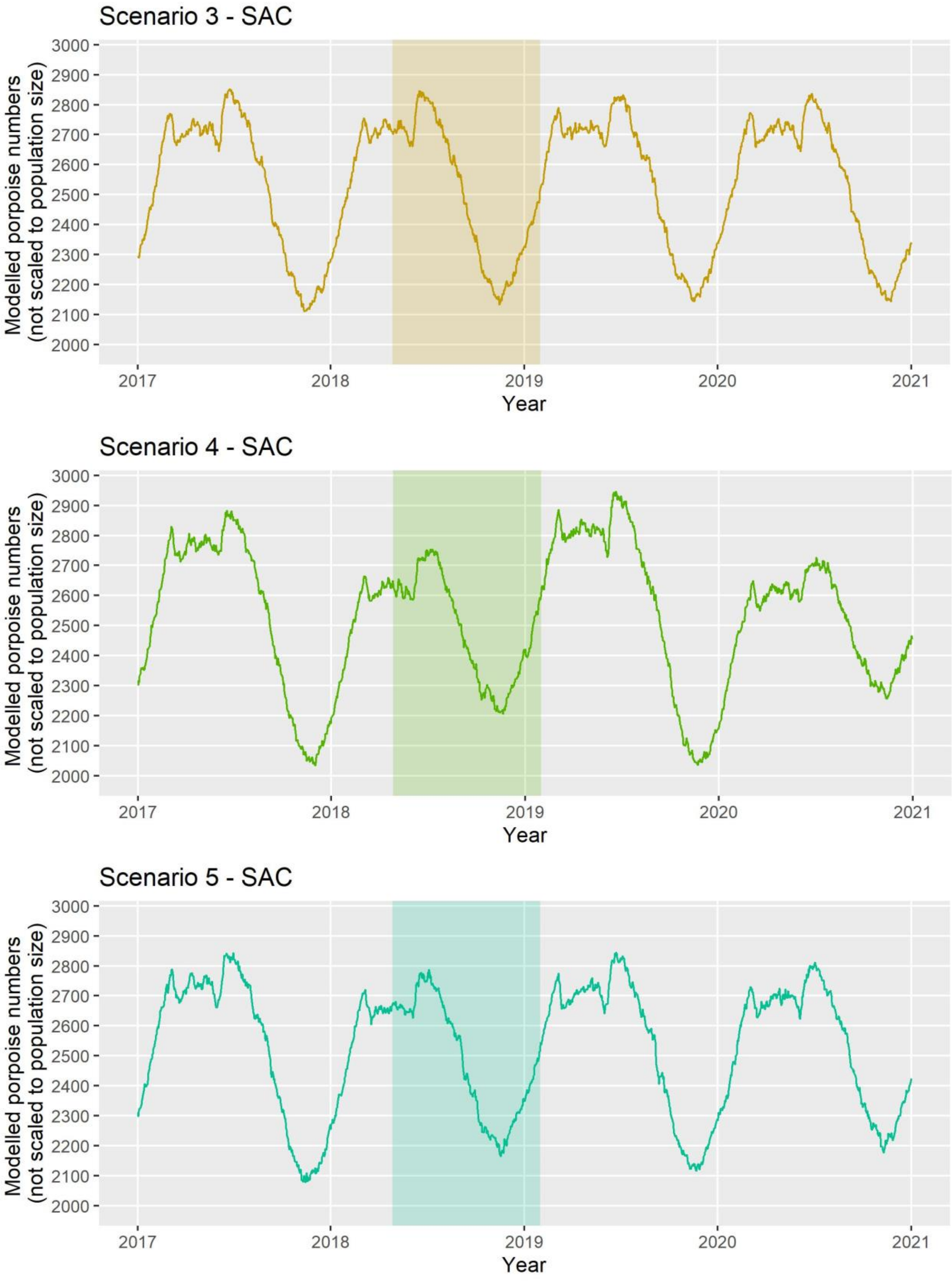


Figure F1 (continued). *Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

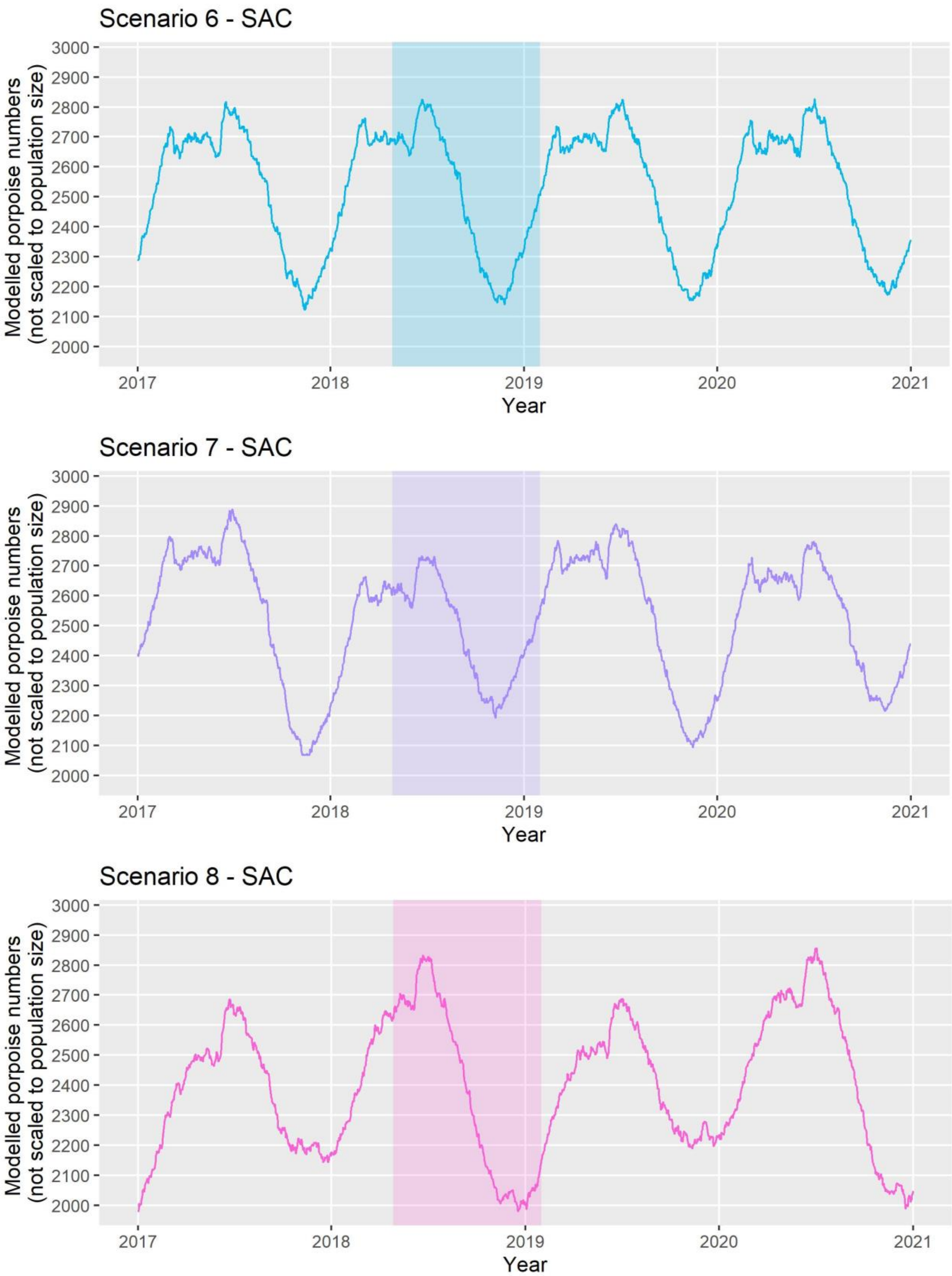
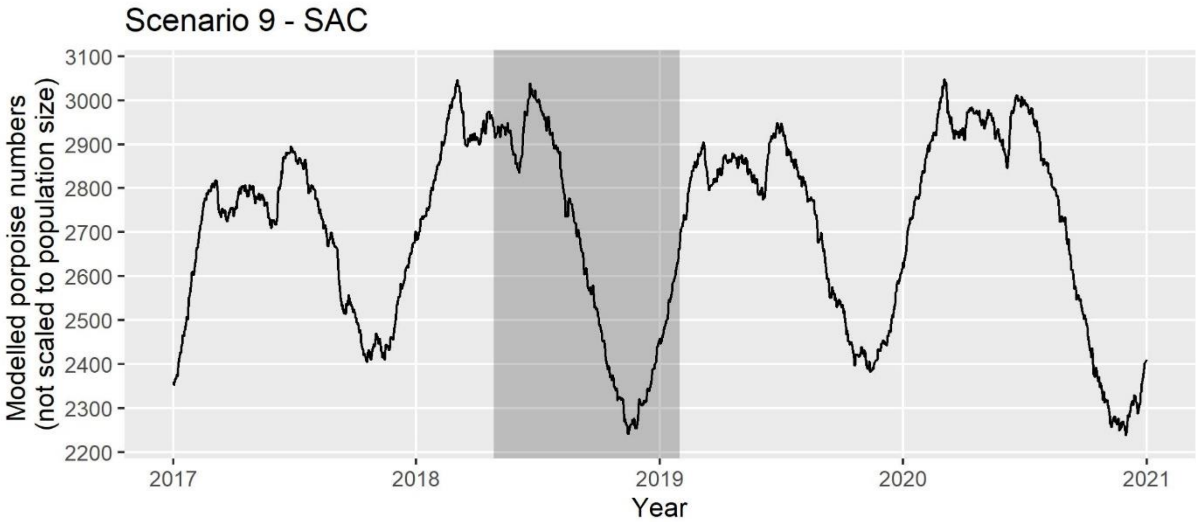


Figure F1 (continued). *Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

14.2 Fertility = 0.34 (Scenarios 9-16)

Figure F2 presents the results for the daily averaged predicted harbour porpoise numbers within the SNS SAC boundary for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.34.



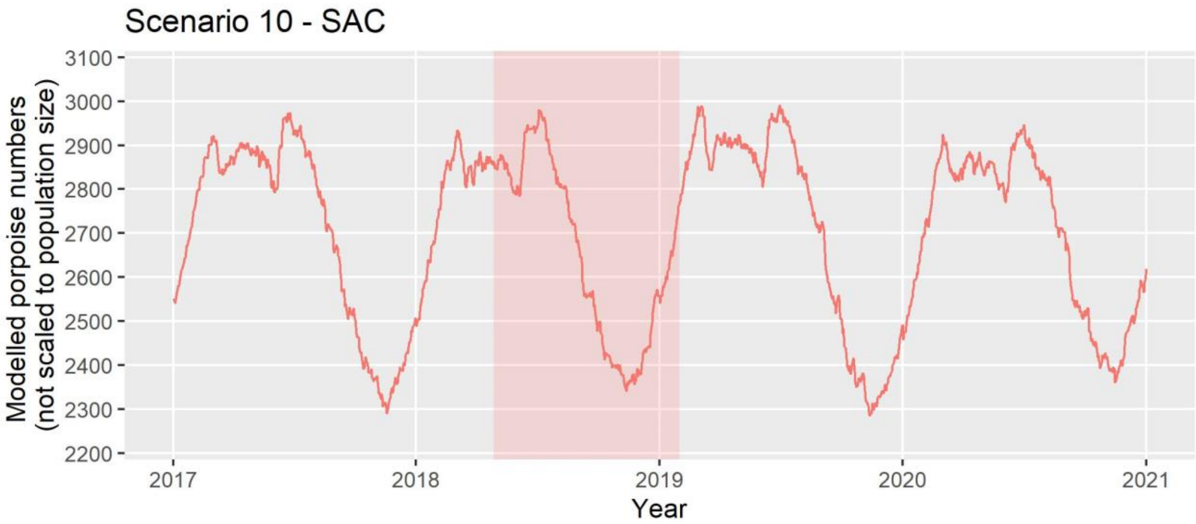
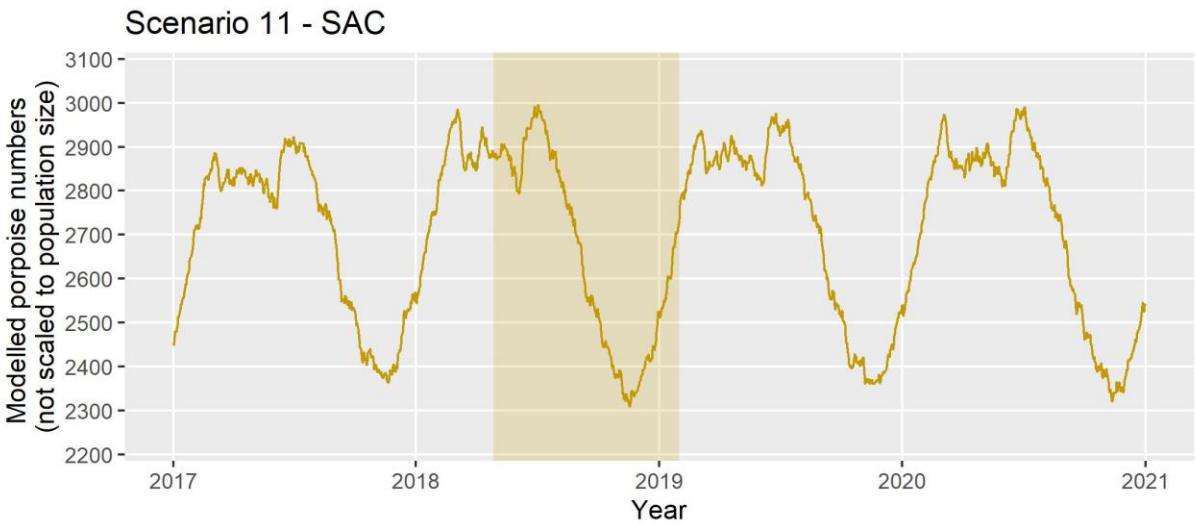
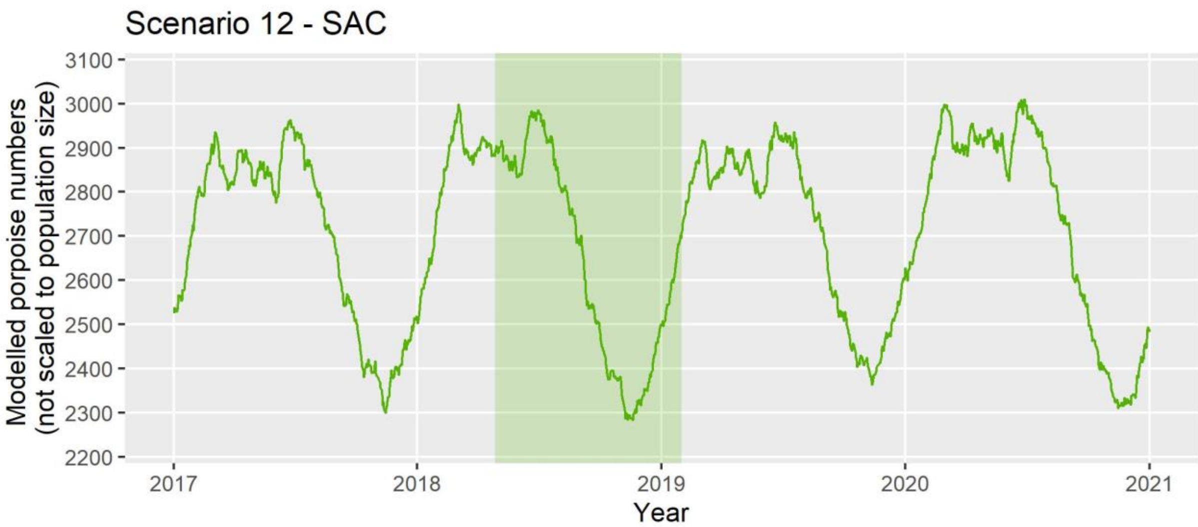


Figure F2. *Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.34 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*





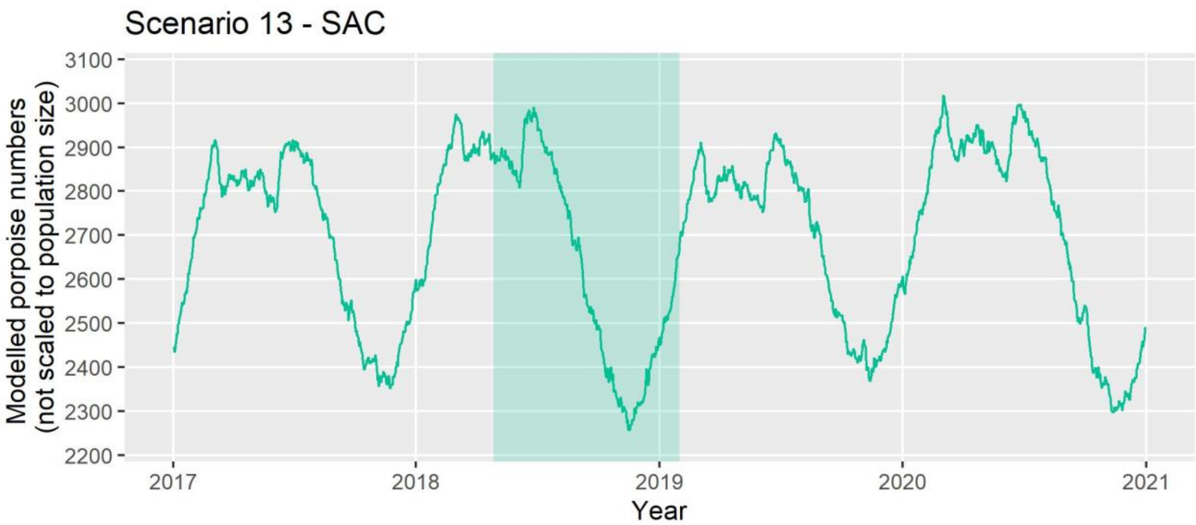


Figure F2 (continued). *Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.34 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

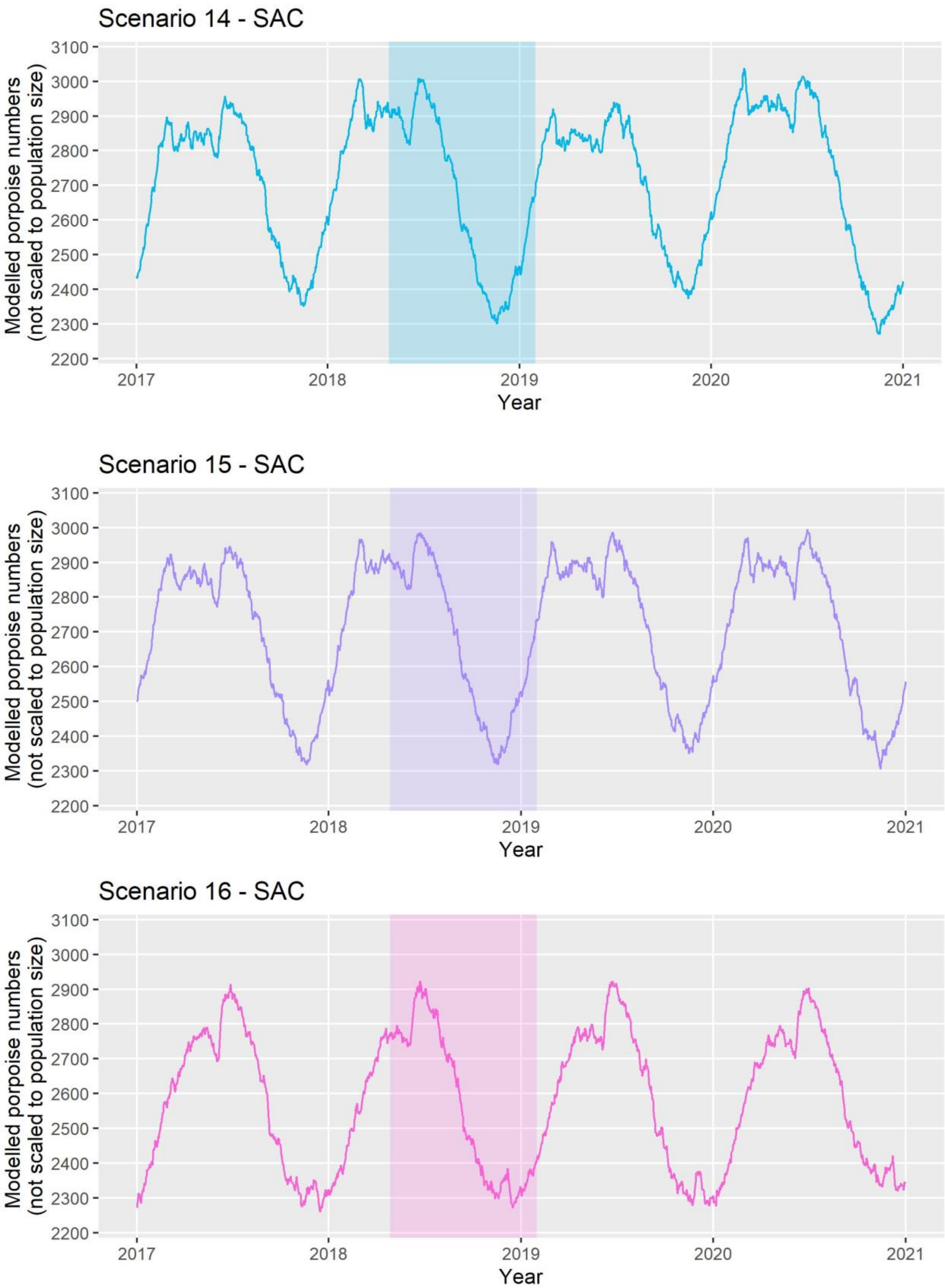


Figure F2 (continued). *Predicted daily average number of harbour porpoises (not scaled to population size) within the Southern North Sea SAC for 2017-2020 derived by applying a Fertility value of 0.34 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

15 APPENDIX G – DEPONS DAILY 20 KM BUFFER ZONE RESULTS 2017-2020 FOR INDIVIDUAL SCENARIOS

15.1 Fertility = 0.68 (Scenarios 1-8)

Figure G1 presents the results for the daily averaged predicted harbour porpoise numbers within the 20 km buffer zone for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.68.

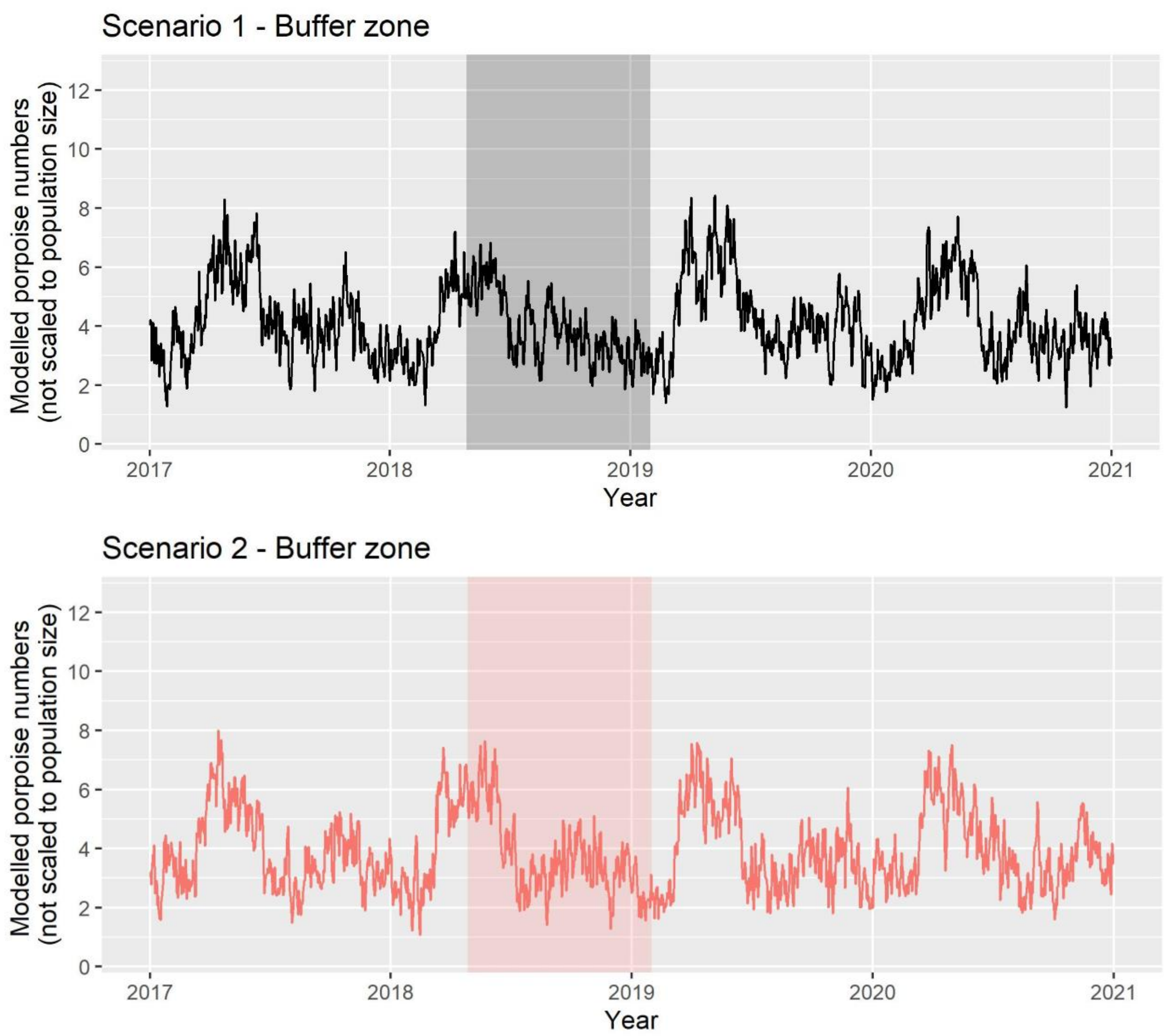


Figure G1. *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

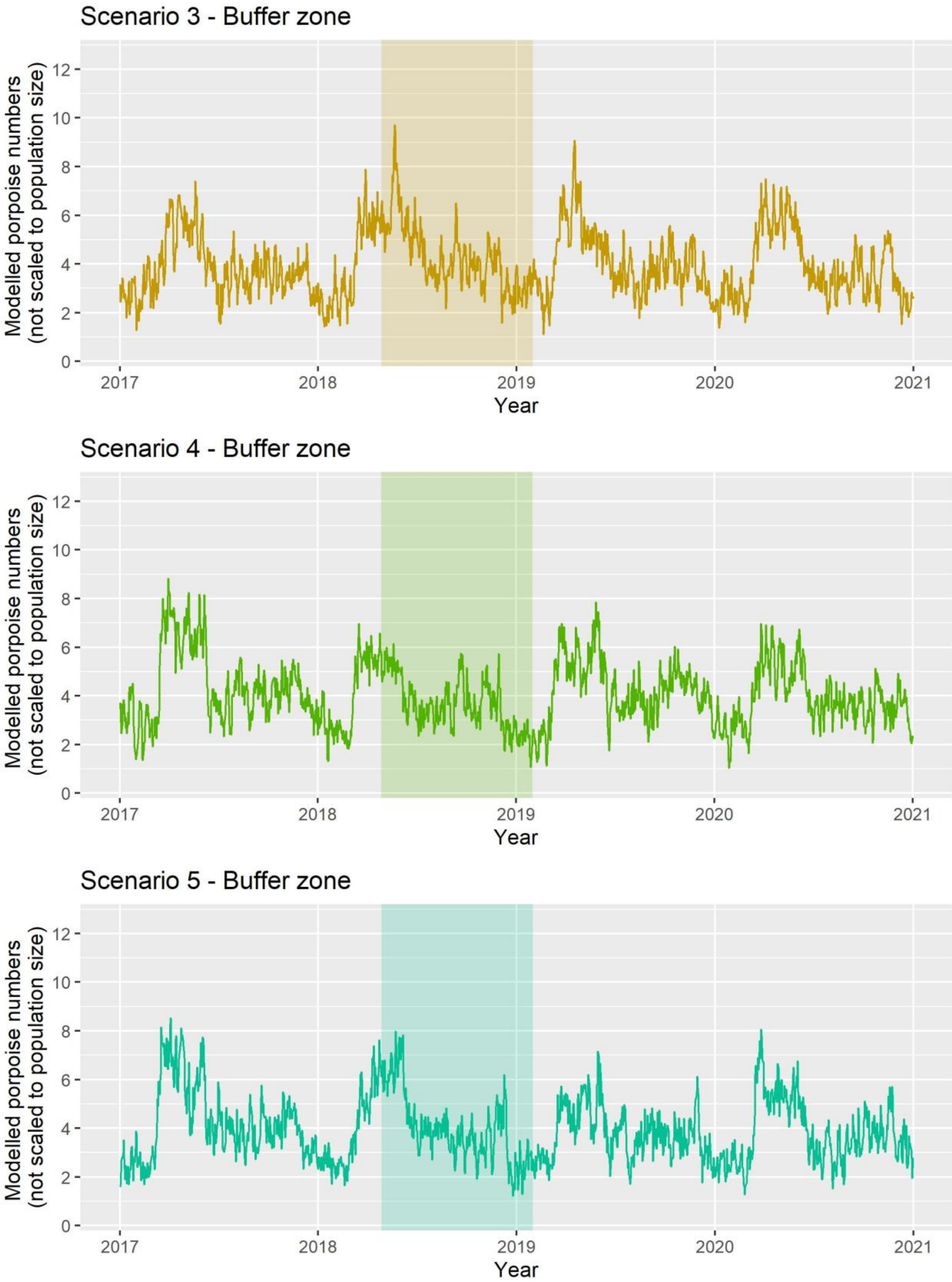
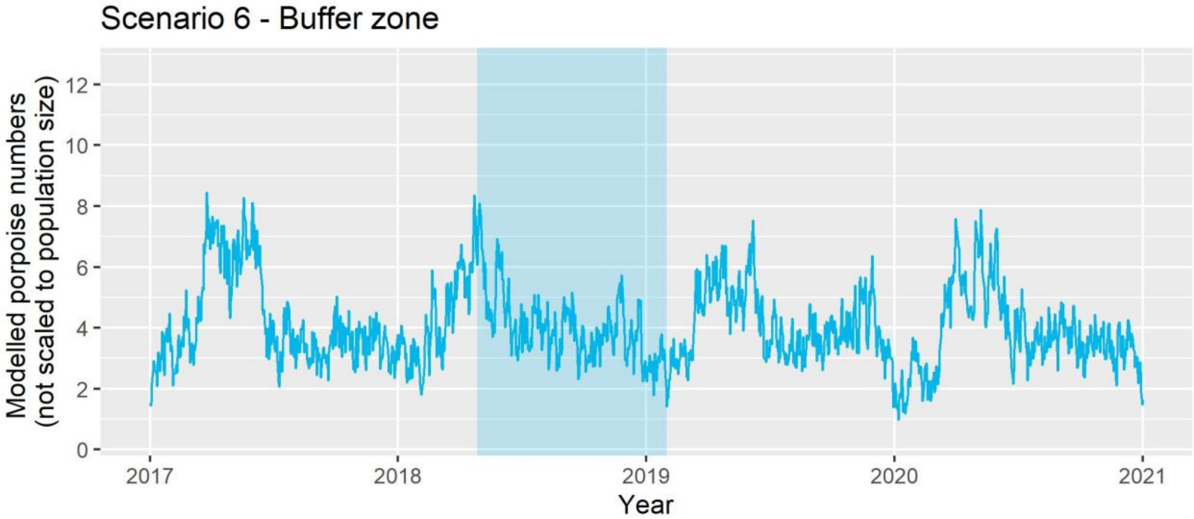
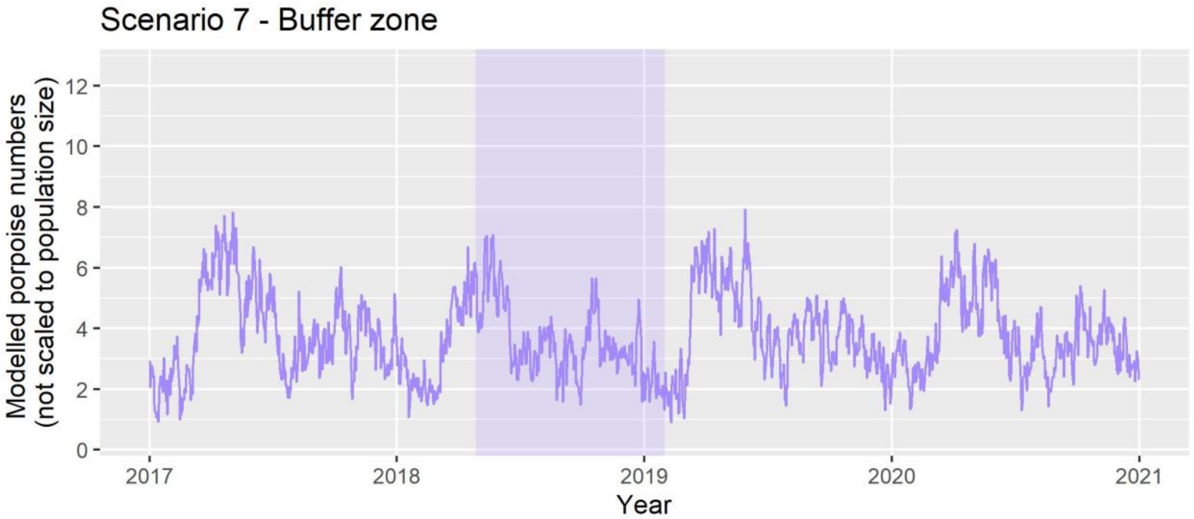


Figure G1 (Continued). *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*





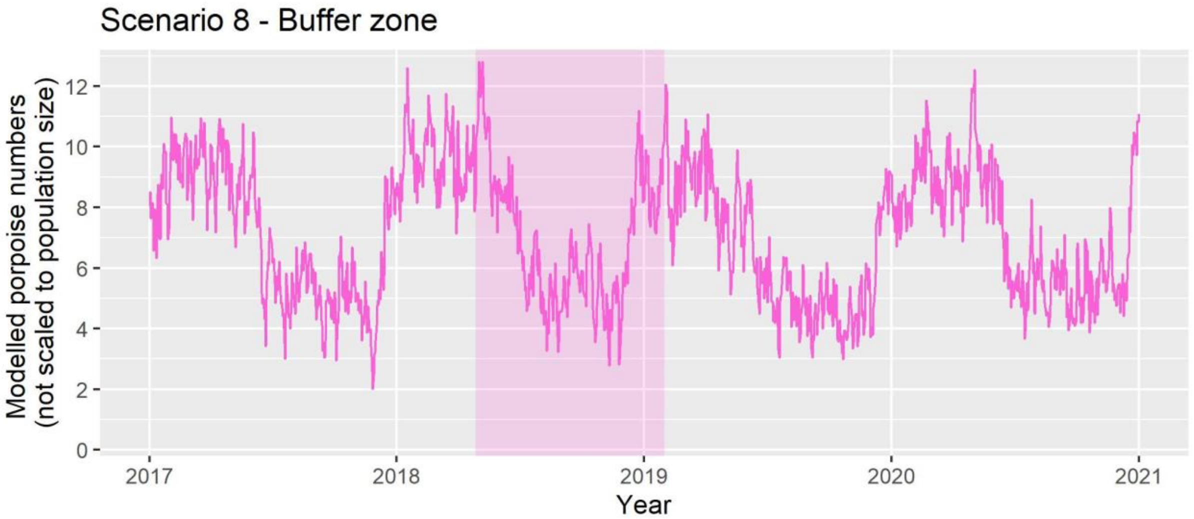


Figure G1 (Continued). *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.68 and based on the five simulations per scenario. The EA1 construction period is indicated by the coloured rectangle.*

15.2 Fertility = 0.34 (Scenarios 9-16)

Figure G2 presents the results for the daily averaged predicted harbour porpoise numbers within the 20 km buffer zone for each of the eight scenarios (summarised in Table 6) modelled using a Fertility value of 0.34.

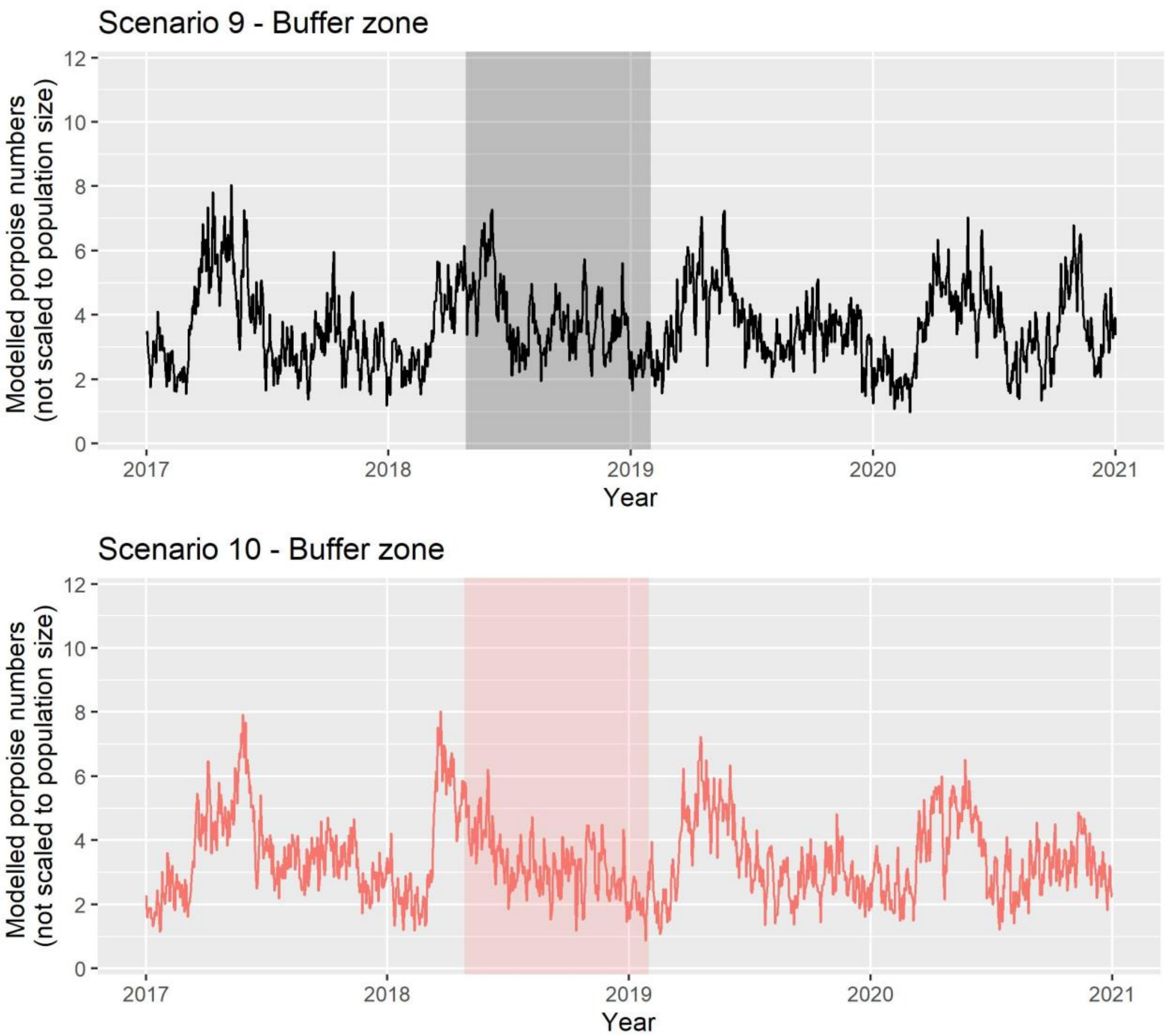


Figure G2. *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.34. The EA1 construction period is indicated by the coloured rectangle.*

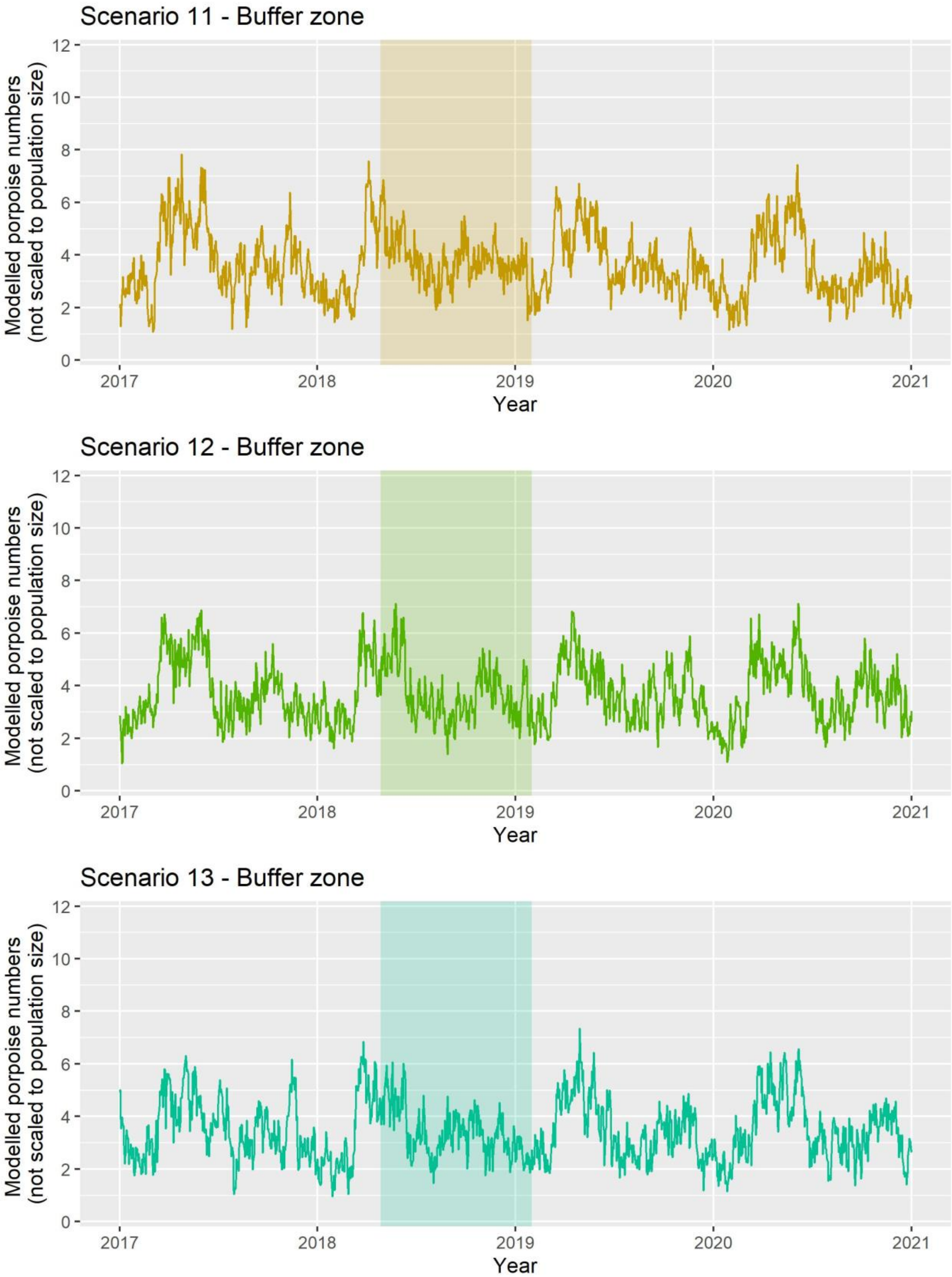


Figure G2 (Continued). *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.34. The EA1 construction period is indicated by the coloured rectangle.*

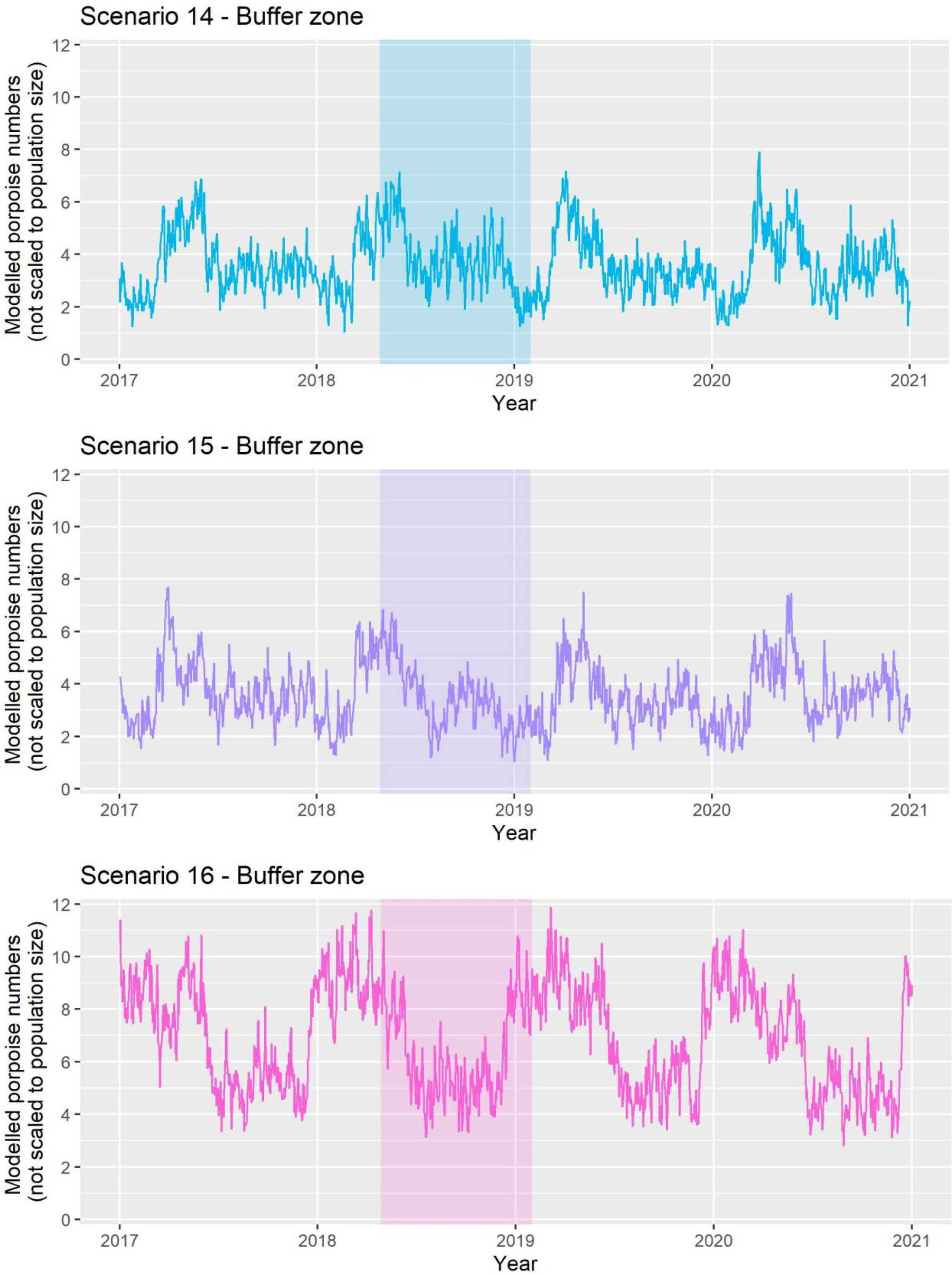


Figure G2 (Continued). *Daily average number of predicted harbour porpoises (not scaled to population size) within the 20 km buffer zone around the EA1 wind farm for 2017-2020 derived by applying a Fertility value of 0.34. The EA1 construction period is indicated by the coloured rectangle.*