BERWICK BANK WIND FARM **OFFSHORE ENVIRONMENTAL IMPACT ASSESSMENT**

APPENDIX 11.4, ANNEX H: SENSITIVITY ANALYSIS OF PARAMETERS AND ASSUMPTIONS IN THE SEABORD MODEL

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Sensitivity Analysis of Parameters and Assumptions in the SeabORD Model

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Contents

1. Executive summary

- There are currently two methods used to try to understand the consequences of displacement and barrier effects of offshore wind farms on seabirds in the UK. The “matrix” approach uses maximum abundances of birds within the footprint of a proposed wind farm derived from at-sea surveys, alongside species-specific displacement rates and displacement mortality rates to predict total mortality. The seabORD tool (Searle *et al*. 2018) uses complex individual-based modelling to simulate the energetic consequences of birds foraging elsewhere due to displacement from an offshore wind farm site and/or having to travel further to their foraging locations to avoid windfarms due to barrier effects.
- It is widely acknowledged that the matrix approach is simplistic and that since the displacement mortality rates used are based solely on expert judgement, there is currently low confidence in this parameter. However, seabORD is extremely complicated and inaccessible, and there are concerns that the drivers underlying survival and reproductive rates predicted by the model are not fully understood. Furthermore, seabORD often predicts much higher rates of mortality (by an order of magnitude) than is expected from expert judgement. However, the outputs from seabORD are now being used as a basis to inform SNCB advice on displacement mortality rates for use with the matrix approach. This has clear implications for assessments of the ecological impact of consented and proposed projects.
- The aim of this work is to assess the key sources of uncertainty and sensitivities associated with the seabORD model and in that light, understand the extent to which the model is appropriate for informing displacement mortality rates for use with the matrix approach. This was achieved by (1) reviewing the model to identify underlying parameters and assumptions, (2) determining a level of confidence in each parameter/assumption based on the supporting evidence provided by the tool authors and additional evidence identified during a literature review and (3) testing the sensitivity of key parameters and assumptions under a single scenario to understand the potential consequences of varying individual input parameters within a realistic range of values.
- The study identified 81 different parameters and assumptions underlying the model, ranging from parameters that are well supported by published primary literature based on robust data, to parameters determined by expert opinion or calibration within the model, and assumptions that represent conservative simplifications for the model. Twenty-one of the parameters and assumptions were assigned within the lowest confidence category (“C”) based on either a lack of relevant empirical data or an unfounded assumption. The authors of the tool are working on refinement and incorporation of some of the key input parameters such as those relating to adult over-winter survival and prey distribution (Searle *et al*. 2022). The model is therefore a work in progress.
- The study identified that several of the assumptions underlying the model are precautionary such that combined with precaution in advised displacement rates, impacts may be substantially over-estimated.
- One of the key inputs for the model are the underlying bird and prey density maps, to which the model is highly sensitive. The bird maps provided with the publicly available Searle *et al*. 2018 model are based on relatively small sample sizes that are only available for certain colonies and the prey maps derived from these are generated such that large prey patches are likely to be predicted away from the colonies, potentially leading to strong displacement impacts as simulated birds are displaced to locations beyond the offshore wind farm footprint. Use of direct modelling for prey density as proposed in Searle *et al* 2022 provides a possible solution to this issue. Where mapped data are not available, the alternative assumptions of a distance decay relationship between bird density and distance to colony, and a uniform prey distribution do not resemble the map-based data and give rise to very different predictions. If the mapped data are assumed to be representative, then the distance decay/uniform prey assumptions seem unsuitable as a substitute.
- A key component of the seabORD model is the need to calibrate the prey level inputs used for each species and colony combination being modelled. This currently involves re-running the model with different input prey levels to find the range of values under which the model returns baseline adult mass and chick mortality rates consistent with pre-defined values representing “moderate” conditions. For each species and colony modelled, the range of prey values is sampled during runs to capture uncertainty associated with this highly

sensitive parameter. That different prey levels must be set for each colony draws into question the level of realism underlying the model.

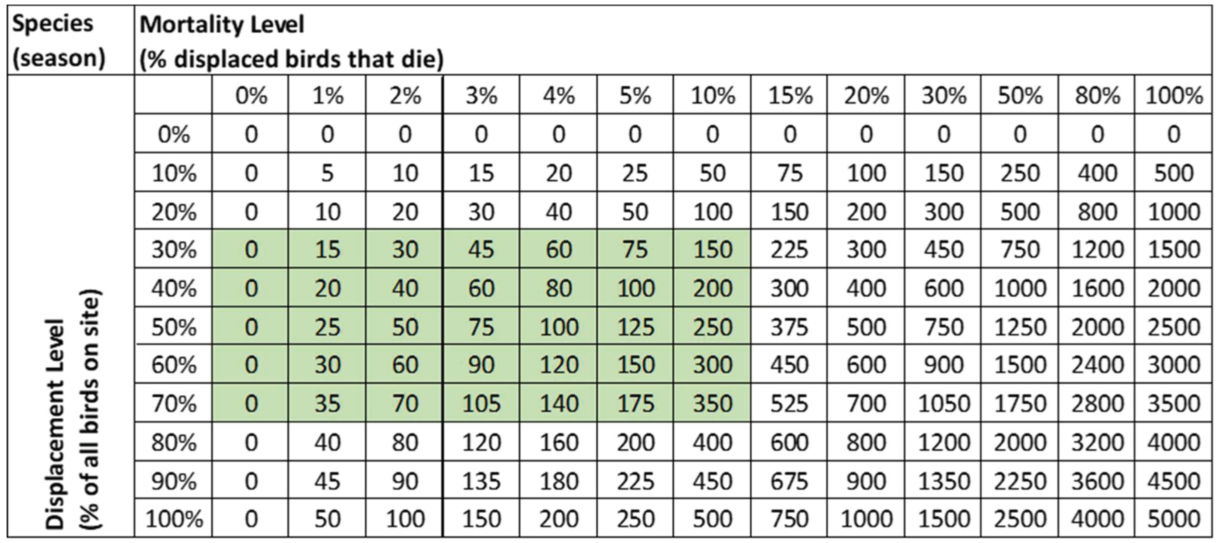
- A measure of uncertainty is provided with seabORD output metrics. However, this reflects just a small portion of the total uncertainty inherent within the modelling process. As observed by the authors (Searle *et al*, 2018; 2022) additional and very substantial sources of uncertainty, such as uncertainty associated with parameter estimation, the structural uncertainty associated with the model, and the uncertainty associated with the spatial distributions of birds and prey are not incorporated, thus providing outputs that inaccurately represent the true uncertainty associated with the modelling process. The authors recommend further work to incorporate additional sources of uncertainty into model outputs but it is acknowledged that the full uncertainty cannot be defensibly captured for parameters and assumptions for which no direct information is available (Searle *et al*., 2022).
- Methods for deriving mortality rates comparable to those used in the matrix model are unclear since it is currently practically impossible to generate comparable outputs among the two methodologies. Direct comparison of predicted numbers of mortalities is problematic because seabORD cannot generally be run to include all colonies that might contribute to the birds on site (nor does it incorporate transient birds). Additionally, seabORD mortality rates reflect mortality across an entire year, whilst the matrix model is run for each season separately. The "snapshot" functionality included within the seabORD tool does allow simulated at-sea surveys to be carried out during model runs, but there are a number of factors which will affect the comparability of the numbers of birds simulated as in snapshot and those that would be used in reality. For example, the seabORD snapshot method assumes that birds are equally likely to be within the wind farm footprint at any point within the time step (including during the night), seabORD generates its snapshot metric based on the average number of birds across the simulated snapshots, rather than the peak as is used for the displacement matrix and, as noted, the seabORD predicted mortality rate includes over-winter survival, but for the matrix approach, over-winter survival is assessed in a separate model. If mortality rates for use with the matrix approach were to be derived from simulated snapshots, they would therefore be inflated.
- Sensitivity testing identified that the model is highly sensitive to several of the input parameters assigned with the highest uncertainty scores. Prey calibration suppressed sensitivity to all parameters tested to a greater or lesser extent, but there is still significant sensitivity, particularly to the way in which the distribution of birds and prey is defined. It was also noted that due to the complex nature of the model, sensitivity of individual parameters is tightly linked to the values of other parameters, suggesting that separate sensitivity analyses would need to be carried out for any given combination of input parameters being used in order to understand how parameters interact in each specific case. However, this is clearly not feasible in practise.
- Over-winter survival rates predicted by the seabORD model for the baseline appear to be significantly lower than those that would be expected in reality. This appears to be a structural issue with the model expected to result in over-estimation of adult mortality rates.
- The seabORD model is a complex and intricate model for which it is difficult to assess correct levels uncertainty, to derive generally applicable sensitivities or to understand the specifics of the interplay of the different components giving rise to the outputs for any given scenario. However, it is clear that the model is associated with a large amount of uncertainty and that the model can be highly sensitive to certain key input parameters. Given this, it does not seem to be the correct tool to derive the concise, transparent and comparable predictions required for general use for impact assessment in its current form.

2. Introduction

The evidence base for understanding the environmental effects of offshore wind farms is expanding, however there are still many elements where there is uncertainty. Three types of impact are generally considered for offshore birds: direct mortality through collision with rotating turbine blades, loss of foraging habitat as a result of displacement from the vicinity of the development, and increased travel times to foraging locations due to a barrier effect of the development. Collision mortality is a direct impact which can be predicted using industry-standard modelling approaches. However, the impacts of displacement on an individual's survival and reproductive success are much more difficult to understand and predict.

There are currently two methods used to try to understand the magnitude of displacement and barrier effects for offshore wind farms in the UK. The first is known as the "matrix" approach (SNCBs, 2022). In this approach, bird observations collected during at-sea surveys carried out at the site of a proposed wind farm development are used to calculate the number of birds with the potential to be displaced. This value becomes the bottom right-hand value in a matrix representing increasing proportions of birds susceptible to displacement down the rows and the proportion of displaced birds that will result in a mortality across the columns. Expert judgement is then used to indicate the region on the matrix reflecting the most appropriate rates and therefore the predicted impact (Figure 2.1). Separate matrices are generated for each of the biologically defined seasons for each species giving rise to seasonal mortality estimates.

Source: Natural Power



Species (season)		**Mortality Level (% displaced birds that die)**												
Displacement Level (% of all birds on site)		0%	1%	2%	3%	4%	5%	10%	15%	20%	30%	50%	80%	100%
	0%	0	0	0	0	0	0	0	0	0	0	0	0	0
	10%	0	5	10	15	20	25	50	75	100	150	250	400	500
	20%	0	10	20	30	40	50	100	150	200	300	500	800	1000
	30%	0	15	30	45	60	75	150	225	300	450	750	1200	1500
	40%	0	20	40	60	80	100	200	300	400	600	1000	1600	2000
	50%	0	25	50	75	100	125	250	375	500	750	1250	2000	2500
	60%	0	30	60	90	120	150	300	450	600	900	1500	2400	3000
	70%	0	35	70	105	140	175	350	525	700	1050	1750	2800	3500
	80%	0	40	80	120	160	200	400	600	800	1200	2000	3200	4000
	90%	0	45	90	135	180	225	450	675	900	1350	2250	3600	4500
	100%	0	50	100	150	200	250	500	750	1000	1500	2500	4000	5000

Figure 2.1: An example displacement matrix for a hypothetical species and season at a hypothetical wind farm. The number in the bottom right-hand corner represents the seasonal mean peak abundance of birds predicted to occur within a proposed wind farm footprint based on site-specific survey data. The values represent the number of adult birds predicted to be displaced under different probabilities that a given bird encountering the wind farm will be displaced (the "Displacement Level") and of mortality resulting from the displacement of displaced birds (the "Mortality Level"). The shaded cells represent the most realistic scenario in the light of empirical evidence and expert judgement for that species. (Adapted from SNCBs, 2022)

More recently, developers proposing sites in Scottish waters have also been asked by the Statutory Nature Conservation Bodies (SNCBs) to undertake more complex modelling to predict these effects, to be presented alongside the displacement matrix (e.g. Inch Cape, 2018). The outputs from these more complex models are also now being used as a basis to inform SNCB advice on displacement mortality rates for use with the matrix approach (SSE, 2022; Searle *et al*. 2020). The models themselves are based on Searle *et al.* (2014), a complex individual-based model which aims to simulate the energetic consequences of birds foraging elsewhere due to displacement from an offshore wind farm site and/or having to travel further to their foraging locations to avoid windfarms due to barrier effects. The potential impacts of these additional costs on survival of both adults and their chicks are also simulated within the model. This model has since been adapted and developed into a tool (seabORD) with the intention of allowing stakeholders in the offshore wind energy industry to run a version of the model in order to assess potential impacts of specific wind farm sites, both alone and in combination with other local developments (Searle *et al*. 2018). The authors have also identified a range of improvements and updates which could be made to incorporate important new evidence into the tool and generate a more reliable representation of uncertainty in its outputs for future versions (Searle *et al*. 2022).

It is widely acknowledged that the matrix approach is simplistic (SNCBs, 2022; King, 2021) and that since the mortality axis is based solely on expert judgement, there is currently low confidence in this parameter. However, it is simple to use and interpret and is also easy to update in light of new evidence (King, 2021). The seabORD tool is more "biologically relevant" in that it seeks to replicate biological processes and is able to generate a number of different metrics to illustrate the potential effects of an offshore wind farm development on the survival and reproductive rates of key seabird populations. However, the model is extremely complicated and inaccessible, and there are concerns that the drivers underlying survival and reproductive rates predicted by the model are not fully understood and the results are therefore difficult to interpret (King, 2021). This concern is increased by the fact that seabORD often predicts much higher rates of mortality (by an order of magnitude) than is expected from expert judgement (ICOL, 2018; Searle *et al*. 2020) with clear implications for assessments of the ecological impact of consented and proposed projects (King, 2021). It has been noted that different versions of the model (2014 and 2018) generate very different predictions, despite being based, with a few exceptions, on a very similar set of parameters and assumptions, and the same principles (ICOL, 2018). Inch Cape have also identified unintuitive patterns in the outputs, for example, very different effects of displacement mortality upon colonies at similar distances from the development being investigated, and stronger cumulative effects on populations that are on average farther away from the developments being considered than closer populations (ICOL, 2018). The model is extremely sensitive to the maps used to simulate the distribution of foraging seabirds within the model, in some cases creating predictions in which the broad confidence intervals around the predicted impacts do not overlap (Searle *et al.*, 2020). This is a particular concern given that detailed underlying bird and prey distribution data are currently only provided for four SPA populations within the Forth and Tay region (Buchan Ness to Collieston Coast; Fowlsheugh; Forth Islands; and St. Abb's Head to Fast Castle) meaning that broad-brush assumptions must be made if other colonies are to be included in analyses. Furthermore, the model has currently been parameterised and calibrated using data predominantly collected within the Forth and Tay region which may not be applicable to other regions in which assessments will take place (King, 2021).

The authors of the model state that a comprehensive sensitivity analysis of SeabORD is needed in order to determine the relative influence of the different parameters upon the key SeabORD outputs and inform future refinement of the model (Searle *et al*. 2022). To date, we are not aware of a full sensitivity analysis having been published for the seabORD model but here we provide some first steps towards understanding what these relative sensitivities may be. In this report we seek to gain an understanding of the key uncertainties and sensitivities associated with the seabORD model and in that light, understand the extent to which the model is fit for purpose to be used in assessment of mortality through displacement and barrier effects at proposed wind farm developments at this time, both within the Forth and Tay region for which the model was first applied and also beyond that region. The aim is not to accurately quantify model uncertainty rather to investigate and qualify the sensitivity of as many parameters and structural elements as possible. This process was carried out in four stages:

1. Review the model and identify underlying parameters and assumptions
2. Determine a level of confidence in each parameter/assumption based on the supporting evidence provided by the tool developers and additional evidence identified during a literature review
3. Test the sensitivity of key parameters and assumptions to understand the potential consequences of adjusting individual parameters within the range of realistic values using an illustrative example scenario
4. Synthesise the results of stages 2 and 3 to draw conclusions regarding the validity and applicability of the seabORD model to inform determination of the effects of displacement for proposed offshore wind farm developments within and outwith the Forth and Tay region in its current form

3. MATLAB code

The current seabORD model was written in the programming and numeric computing platform MATLAB and the seabORD tool has been designed to run via a downloadable user-friendly application within which a limited number of input parameters can be entered or updated. However, the seabORD model requires a large number of parameters and assumptions, many of which are not editable using the user-interface. Natural Power were therefore provided with the underlying MATLAB code for seabORD version 1.2 and used this for sensitivity testing of parameters that are not editable within the user-interface.

Many of the assumptions underlying the seabORD model are deeply embedded within the mechanics of the code so that it is not possible to adjust them without re-writing the code in a significant way to ensure that all other assumptions remain valid and operating as they should. Therefore, Natural Power did not investigate the sensitivity of assumptions that would require such re-writing of code (although code was edited to update parameters that were hard-coded).

A review of the overall structure of the code was performed in order to understand the underlying logic and identify relevant parameters. No structural issues were identified although it is noted that the code is heavily dependent on "for loops" (used to repeat a block of code several times) as it steps through each simulated day. MATLAB is typically most efficient when code is carried out in array operations. As a result, repeated running of the code and sensitivity analysis are time consuming. This finding supports the observation by Searle *et al*. 2022 that greater computational efficiency of seabORD is required and would be possible to implement.

The MATLAB code was provided as a zip file ("SeabORD-Matlab-1.2.zip") downloaded from a private GitHub repository. This contained a file named seabORDsim.m, which is the main function that runs the seabORD model, and a folder labelled "Private", containing 65 "modules" (files containing MATLAB code for specific functions that are called by the main function in the seabORDsim.m file). In addition, there were two files associated with the MATLAB user-interface ('parameters.m' and 'seabORDmodel.m') and a README file specifying the version of the model.

MATLAB code can only be run interactively within the MATLAB computing environment in order to interrogate temporary variables. When running the code for the first time, it became apparent that it was not compatible with the older version of MATLAB being used and also that a number of additional MATLAB toolboxes (collections of pre-written mathematical or computational functions) were also required. We identified that MATLAB 2017a or higher and three toolboxes: the Mapping Toolbox, Optimisation Toolbox and Statistics and Machine Learning Toolbox, were required to run the code.

The "Private" folder name is treated in a particular way by MATLAB and is used for ensuring that the functions within that folder take precedence over any identically named functions in other directories but are only used when MATLAB is run one folder level above i.e. a private folder in a separate directory will not be used locally. The private folder is used by MATLAB when executing the compiled model (e.g. via the GUI) but cannot be used when running the code via the command line. It was therefore necessary to rename this folder prior to running the MATLAB script. All code appeared to be bespoke to the tool other than the A* pathfinding algorithm which was written by Einar Ueland. The copyright and metadata associated with this algorithm is provided in a sub-folder within the "Private" folder. A* is used in the tool to find the minimal distance between two points, accounting for barriers.

4. Model description

4.1. Aims

The aim of this section of the report is to provide a summary overview of the seabORD model structure and to identify the parameters and assumptions underpinning it. Due to the complexity of the model, a general model overview is presented first to allow the reader to familiarise themselves with the way in which the model runs. The process by which the model is implemented is then described in Section 4.3. Where additional information regarding specific steps was considered useful, these are provided in subsequent sections.

Each step of the model is associated with a variety of parameters and assumptions, presented in Table 5.1 in Section 5. These parameters and assumptions are numbered for ease of cross-referencing.

4.2. Model overview

SeabORD is an individual-based model, meaning that the model seeks to replicate processes that occur at an individual level in order to infer population level consequences.

It is currently parameterised for four species: kittiwake, guillemot, razorbill and puffin.

The model seeks to simulate the fate of individuals over the chick-rearing period (the part of the breeding season between chick hatching and fledging), as well as extrapolating the outcome of this to predict over-winter mortality rates, providing estimates of annual mortality and reproductive success.

The model simulates movement of foraging birds in space within a user-defined area (the 'extent') (**1**). The extent is divided up into a grid (**2**) in which each cell that is at-sea represents a possible foraging location for seabirds (Figure 4.1).

The model is structured in time steps representing 24-hour periods for guillemot, razorbill and puffin, and 36-hour periods for kittiwake (3). For each species, the total number of time steps (4) for a simulation is determined by the number of hours in a chick-rearing period divided by the length of a single time step. Duration of chick-rearing period is also species-specific.

All pairs of birds within the simulation are assumed to begin as breeders and a single chick is simulated for each.

Simulated adults will split their time among four behaviours:

- resting on the sea (each adult must spend at least an hour per 24-hour period resting on the sea - 5)
- attendance at the colony (each adult provisioning a chick and in good condition, i.e. a body weight of > 90% its initial body mass, will spend 50% of its time at the colony to ensure 100% attendance across the two parents)
- flying to forage locations
- actively foraging

For each time step, each simulated adult will complete foraging trips with the aim of meeting its own daily energetic requirement (DER) as well as half that of its chick (6). Adults will not collect more than the required amount of food to meet this goal (7). Within a time step, once adults have met their own DER as well as half of that of their chick, spent an hour per 24 hours resting on the sea and spent 50% of their time at the colony (if they have a living chick and a body weight of >90% of their initial body mass) (8), any remaining time will be split equally between resting on the sea and attendance at the colony (9;10).

Each simulated adult bird has a "behavioural mode" determining how they partition their time, which is updated as the simulation progresses. These can be:

1. prioritises attending the colony for at least 50% of their time over spending sufficient time foraging to achieve the total combined DER (body mass > 90% initial body mass and is provisioning a chick)
2. prioritises spending sufficient time foraging to achieve DER over attending the colony for at least 50% of their time (body mass between 80% and 90% of initial body mass and is provisioning a chick) (11)
3. nest abandonment (body mass <80% initial body mass / chick has died / partner has switched to nest abandonment), prioritises achieving DER over attendance at the colony and required DER no longer includes that of its chick (12)
4. dead (body mass <60% of initial body mass) (13;14)

For adults with chicks, if an adult cannot meet the combined DER in a time step the deficit will be shared equally between itself and its chick (e.g. if it achieved 50% of its target DER, it would be assigned 50% of its own DER and the chick would be assigned 25% (half of 50%) of its DER). (15)

Displacement and barrier impacts of offshore wind farms (OWFs, referred to in the literature accompanying the model as Offshore Renewable Energy Developments or ORDs) are simulated as changes in forage site selection and route to and from foraging sites respectively.

To compare scenarios with and without OWFs, matched pair simulations are run in which prey conditions and the initial mass, daily energy expenditure (DEE), initial forage site locations and other stochastic processes within the model (which may be altered due to displacement in the presence of OWFs) for each time step for each individual are identical.

Prior to running a seabORD analysis for which a new set of input parameters are to be used, a calibration process must be carried out by the user to determine appropriate values for the upper and lower prey level input parameters which determine the amount of prey resource available to the birds (16;17). Trial runs must be conducted in which a range of individual prey values are used until the maximum and minimum values that give rise to "moderate" conditions in the baseline (i.e. without OWFs) are identified. Moderate conditions are defined as the prey values within which the baseline model returns an adult body mass loss within specified lower and upper thresholds and a chick survival rate above a specified lower threshold (18). Species-specific values derived from literature for these are provided with the tool. This process must be repeated for each species-colony combination resulting in different upper and lower prey level input parameters for each.

4.3. Model process

Model simulations progress as follows.

For each run:

1. A number of adult birds are simulated for each colony based on the specified colony size (breeding pairs) (19) and fraction of the population to run (20).
2. Each simulated bird is assigned an initial mass sampled from a normal distribution described by a mean and standard deviation (21). Since birds begin at 100% of their initial mass, all begin prioritising attendance at the nest over achieving their daily energy requirements (behavioural mode 1).
3. Each simulated bird is assigned an initial daily energy expenditure (DEE) sampled from a normal distribution described by a mean and standard deviation (22). Daily energy requirement (DER) is then calculated by dividing DEE by an assimilation efficiency (23).
4. Initial chick mass is sampled from a normal distribution described by a mean and standard deviation (24). Chick DER is assumed to remain constant throughout the chick-rearing period (25;26).
5. Each simulated adult bird is given an impact susceptibility status which remains constant throughout the simulation. The user defines the percentage of the population that will be displaced (27), and the percentage of displaced birds that will also be barriered (28), and each bird is assigned to a category with a probability based on these percentages. Susceptibility status for each bird can be one of:
    - Not susceptible to barrier or displacement effects
    - Only displacement susceptible (will pass through, but not forage within an OWF)
    - Displacement and barrier susceptible (will not pass through or forage within an OWF) (29;30)
6. Overall prey quantity for a run is determined by stratified random sampling based on user-defined upper and lower boundaries (16;17) that should represent "moderate" conditions (as defined below). The strata comprise bands of equal width within the range of prey values provided, determined such that the number of strata is equal to the number of runs. For each run, a prey value is randomly selected from within the corresponding band. The aim is that the full range of possible prey values constituting "moderate" conditions (see Section 4.2 for details) will be reflected across the runs (18).
7. For each foraging location (grid cell), the available prey is calculated by dividing the total available prey for the run across the grid according to (31):
    a. A prey distribution map (GAM models of at-sea bird distributions derived from tracking data but excluding the effects of distance to colony are provided with the tool – see section 4.5) (Figure 4.1) (32;33).
    b. A uniform distribution in which prey are assumed to be evenly distributed across the box bounding the spatial extent over which the model is run. (34)

For each time step within a run:

8. Each simulated bird is assigned a foraging location within the grid based on either (35):
    a. a map of bird distributions (maps derived from GAM modelling of GPS tracking data from colonies of interest are provided with the tool (Section 4.5; Figure 4.1)) (36;37)
    b. a distance decay function (Figure 4.1) (38). The distance decay function assumes that foraging location usage by birds declines exponentially with distance from the colony (39). Relative abundance in each grid cell is calculated as:

$$RA_i = \frac{(1-p)^{d_i/r}}{d_i}$$

    Where *RA* is relative abundance in the *i*th grid cell, *r* is the user-defined maximum foraging range (40) and *p* is the user-defined proportion of foraging that occurs within the foraging range (41).

    Feeding locations for an individual remain the same within a time step but vary among time steps (42;43)

9. For impact scenarios, displacement susceptible birds assigned to a location within the OWF footprint (44) or user-defined footprint border (45) are assigned to a new grid cell within the user-defined footprint buffer (46) with a probability based on the distribution of prey within the buffer zone (47).
10. For each bird, the flight path used to travel between the colony (48) and the foraging site is constructed. This is determined in the following ways

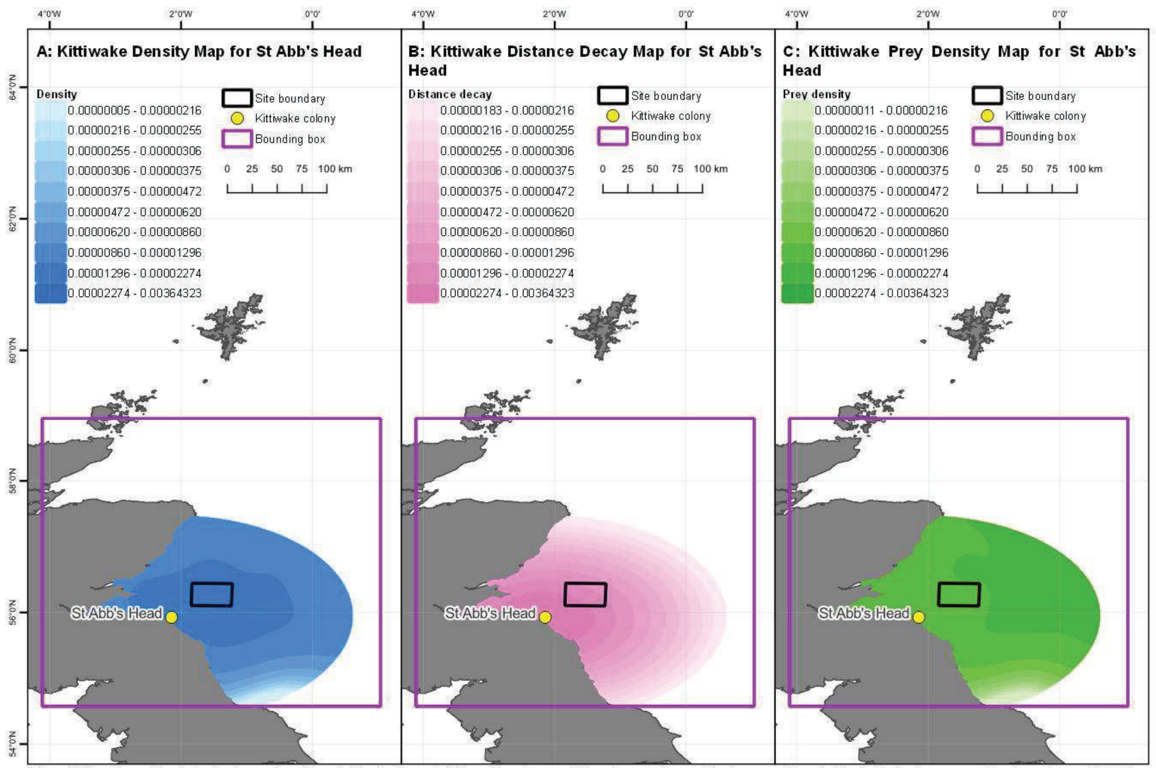
   a. Where no barriers are present, flight paths will consist of straight lines running between the colony and the foraging location (49).
   b. Birds are assumed not to fly over land, so A* pathfinding is used to find the most efficient path around land (50).
   c. For impact scenarios, birds barriered by an OWF will skirt around the perimeter of the OWF if barrier navigation is set to “perimeter” (51;52).
   d. For impact scenarios, birds barriered by an OWF will use A* pathfinding to find the most efficient path to their foraging location avoiding the OWF if barrier navigation method is set to “A* pathfinding” (53)

11. Time taken to travel to a foraging location is calculated as the distance travelled multiplied by the average flight speed of the bird (54).
12. Time taken to forage is based on an intake rate modelled as a type II functional response (i.e. intake rate increases linearly with prey density until a maximum is reached, representing the handling time for each prey item) (55;56;57). This relationship is used to simulate decline in intake rate over time due to prey depletion and to calculate total prey consumed up to time *t*. Competition is incorporated by dividing the intake rate in the absence of competition by an intra-specific competition effect calculated by raising the total number of birds foraging within the grid cell to the power of an interference coefficient, *m* (59), reducing the intake rate multiplicatively. For each new foraging trip, the prey is assumed to have returned to its previous level (58; 60)
13. For each time step, each bird completes between 1 and 6 foraging trips to their chosen foraging location (61). Every possible scenario (from 1 to 6 trips) is simulated, and the final number of trips selected for a given individual in a given time step is the number of trips which minimises total time requirement to reach the target DER. (For each trip the bird will aim to collect 1/n_trips of its target DER). (62) If the DER cannot be met under any number of trips, then the number that results in the maximum prey intake (minimising DER deficit) is selected. The amount of time allowed for these trips varies depending on state of the bird. If its body mass is above 90% of its initial body mass (8;11) and it has a chick, then only half of the time (minus an hour per 24 hours for resting on sea (5)) will be available for foraging as it will spend 50% of its time at the colony (6). If its body mass is below 90% of its initial mass (8;11) or has abandoned its breeding attempt, all of its time (minus an hour for resting on sea (5)) will be available for foraging as it will prioritise achieving its DER over spending time at the colony.
14. At the end of the time step, chick body mass and status (alive or dead) and adult body mass and behavioural mode are updated and the adult DER for the subsequent time step is calculated.
    a. Chick body mass: chick mass change within a time step is estimated as a function of the maximum possible mass gain (G) (63), intake during the time step, DER and the proportion of the daily energy intake that would correspond to 0 mass change (P) (64).
    b. Chick status: chicks are either alive or dead. Death may occur by exposure, predation or starvation, as well as by an additional stochastic process included to reflect baseline chick mortality rates (65). A chick left unattended for 18 hours or more is assumed to die of exposure (66). Predation of chicks occurs with a probability defined by a linear relationship with unattendance time (up until the chick was assumed to have died of exposure) (67;68). Starvation occurs when a chick’s body mass drops below 60% of that for a hypothetical chick receiving its DER on each time step up to that point (69). For puffin, chicks have no risk of predation or exposure up until they reach 70% of their ideal weight for that step, at which point they are assumed to leave the burrow and this relationship is also applied to them (70).
    c. Adult body mass: adult mass at the end of the time step is calculated as a function of the mass at the beginning of the time step, the amount of energy gained during the time step, the DER for the time step and the energy density of the bird’s tissue (71;72).
    d. Adult behavioural mode: this is adjusted based on current body mass as a proportion of initial body mass as described above. Adults will also switch to nest abandonment mode if their chick has died or if their partner has switched to nest abandonment mode.
    e. Adult DER: time spent carrying out the four different activities are multiplied by species- and activity-specific energy costs (73;74;75;76) and an energy cost of warming food is also added (77). Energy is converted into grams per day according to an assumed energy density of 6.1kJ/g (78).

At the end of a run:

15. The difference in adult mass at the end of the chick-rearing season compared to a bird of average mass at the end of the chick-rearing season in the absence of an OWF is assumed to be related to the probability of over-winter survival according to a logistic relationship (79) constructed using a parameter *b*, representing the strength of the relationship between mass and survival (80), and *s0* representing the baseline survival rate (associated with a bird of average mass in the absence of an OWF). Different values of *s0* are used to calculate adult over-winter survival separately for “good”, “moderate” and “poor” years (81).

Source: Natural Power



Notes: a) Information on this plan is directly reproduced from digital and other material from different sources. Minor discrepancies may therefore occur. Where further clarification is considered necessary, this is noted through the use of text boxes on the plan itself. b) For the avoidance of doubt and unless otherwise stated: 1. this plan should be used for identification purposes only, unless otherwise stated in accompanying documentation. 2. The Natural Power Consultants Limited accepts no responsibility for the accuracy of data supplied by third parties.

Coordinate System: WGS 84
Prepared by: DM 15-11-2022
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Figure 4.1: Example bird and prey density maps: (A) density map for kittiwake from St Abbs Head provided with the publicly available seabORD displacement tool (B) density map for kittiwake from St Abbs Head based on the distance decay function and (C) density map for kittiwake prey for kittiwake from St Abbs Head provided with the publicly available seabORD displacement tool.

4.4. Linking seabORD to the displacement matrix

The model generates a range of output metrics relating to body mass, distance flown by adults, chick survival, and adult survival in good, moderate and poor years. These estimates are provided for each colony selected for inclusion, under both the baseline and impact scenarios. Estimates of additional mortality are also presented, calculated as the difference between mortality in the impact and baseline scenarios, divided by the total number of birds in that group (e.g. adults at St. Abb’s Head if calculating additional mortality for adults at this colony). It is important to note that these are not directly comparable to the mortality rates used in the displacement matrix as they relate to the entire population rather than the subset of birds that are predicted to be directly impacted by the proposed wind farm. The tool also provides metrics that relate to only those birds within a simulation that experienced displacement and/or barrier effects in the impact scenario. However, these are still not comparable since not all birds that encounter the wind farm during the simulations would be captured within the at-sea snapshot surveys used to derive abundances for the displacement matrix.

The tool does include an option to simulate "snapshot" surveys during baseline runs in order to provide abundances equivalent to those used in the matrix model (i.e. derived from at-sea snapshot densities corrected for detectability). For a site where at-sea data has been collected, this functionality could provide a useful mechanism for validating the spatial predictions of the seabORD model, as a density for the OWF footprint could be derived and compared with that observed in the real world. It can also be used to generate a mortality rate that is similar to that used in the matrix model, by dividing the output metric P2 (additional mortality per bird observed in snapshot) by the displacement rate (but see discussion in section 7.6).

In the current release of the tool it is possible to simulate snapshot surveys during three time steps of the model. For each time step within which a snapshot will be generated, the amount of time spent within the wind farm for each bird is used along with the length of the time step to calculate how many birds would be within the wind farm footprint for any given instantaneous snapshot.

4.5. The GAM distribution model

Theoretically, the bird distributions underlying the "map" method of selecting bird foraging locations within seabORD can be derived from any source as long as it is colony-specific, and can be assumed to represent the distribution of birds foraging and resting on the sea (i.e. it excludes birds flying to and from forage locations or attending their colony). If a prey distribution map is also to be derived from these data, then there must also be some way of partitioning the effects of accessibility of a location and competition within that location from the effects of suitability of the location (assumed to be driven by prey availability). Searle *et al*. 2014 set out a methodology to model bird distribution that would meet these criteria, described in brief below.

For each species, at sea distribution maps (assumed to represent birds either foraging or resting on sea) were generated from GPS logger data collected from individuals breeding at each of the relevant SPAs for which data are included with the seabORD model (Buchan Ness to Collieston Coast; Fowlsheugh; Forth Islands; St. Abb's Head to Fast Castle). The loggers recorded the location of each tagged bird every 100 seconds (assuming an accurate fix can be obtained at that point in time). Data points were removed if they were:

- Spurious duplicate records due to loss of signal to the satellite
- Obvious spurious locations (implausibly large distances to the colony)
- Within 1 km of the colony – to ensure birds attending the colony were not included
- Travelling at speed (14 km/hour or above – determined by reviewing the bimodal distribution of flight speeds present in the data) – as these birds were assumed to be travelling to/from foraging locations

Binomial general additive models were then used based on a 0.5 km^2 grid of control points (0s) and bird locations from the tracking data (1s). For each colony, the grid extended to either the maximum reported foraging range or the maximum (plausible) distance present in dataset for each species away from that colony (apart from for kittiwake in which the threshold included more than 99.96% of observed locations).

Models were structured to include two components:

- Accessibility: a distance effect from the SPA itself as well as the distance to the other nearest SPA (to account for the potential effect of intraspecific competition), both of which were assumed to have linear effects on log(density)
- Suitability: a smooth term modelling underlying variation not explained by distance to SPAs, assumed to represent the effect of underlying environmental covariates

Searle *et al*. (2014), initially attempted model fitting using environmental covariates such as depth, sea surface temperature etc. However, this was unsuccessful as covariates trialled did not explain the patterns in the data, and so was abandoned. Subsequent analyses of tracking data for seabORD have therefore modelled data using a spatial smoother as described above (e.g. Searle *et al*., 2020).

As described previously, prey distribution is assumed to be represented by the suitability part of the model, so this map is simply the smooth component of the model (excluding the effects of distance to the colony).

5. Confidence index

5.1. Aims

The aim of this part of the project was to develop a confidence index to rank the parameters and assumptions identified within the seabORD model according to the evidence base for each.

5.2. Methods

Parameters and assumptions identified during the model summary section are presented in Table 5.1 along with their associated confidence scores. Each parameter or assumption was given two scores. The "Data source" score represents the type of data underlying the parameter or assumption. This score ranges from 1 to 6, where 1 is the best supported and 6 the least well-supported. This score was assigned as followed:

- 1 = based on direct empirical data
- 2 = modelled/inferred from indirect data (this was also applied if the source could not be accessed or identified)
- 3 = was described as based on empirical data but no specific reference(s) was cited and Natural Power could not identify the reference
- 4 = expert judgement
- 5 = calibrated from the model, parameter was set such that the model yields results consistent with observed data when run under baseline conditions
- 6 = simplification for the model, no support for the assumption/parameter cited

For parameters and assumptions supported by published literature, the publication(s) was reviewed and a "data quality/applicability" score was assigned based on the sample size, the applicability of the species studied and the relevance of the geographic area, dates and circumstances under which the data were collected. This score was assigned as:

- A = high relevance and sample size
- B = intermediate relevance and/or sample size
- C = low relevance or poor sample size

For parameters and assumptions not supported by published literature, an "ornithologists" score was assigned based on in-house expert opinion on the appropriateness of the parameter. This score was assigned as:

- A = parameter or assumption believed to be sound and well supported by our understanding of seabird biology
- B = parameter or assumption is plausible but others are equally likely
- C = parameter or assumption believed to be improbable

The combined score with the highest confidence is therefore A1 and that with the lowest, C6. The letters take precedence over the numbers such that we have more confidence in a parameter or assumption with a score of A6 than one with a score of B1 and similarly we have a higher confidence in a parameter or assumption with a score of B6 than on with a score of C1.

The literature review was then extended to identify any other published data or information that could inform each parameter, and any alternative parameter values or assumptions were compiled. These were used to inform a sensitivity analysis described in Section 6.

5.3. Results

The confidence indices assigned to each parameter and assumption within the model are presented within Table 5.1.

Table 5.1: **Parameters and assumptions of the seabORD model and associated confidence scores. Parameters are listed in order of confidence, with those with most uncertainty at the top. Numbers preceeding parameter names relate to the order that they are described in the model description. A final score of A1 represents parameters with the most confidence and C6, those with the least confidence. Letters should be considered before numbers such that a parameter or assumption scored A6 will have more confidence than a parameter or assumption scored B1. White cells represent parameters in the model whilst shaded cells represent assumptions of the model. For the scores, DS represents the "Data Source" score, DQ represents the "Data Quality" score and OS represents the "Ornithologists Score" (see scoring system described in Section 5.2).**

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score DS	DQ	OS	Final	Comments
7. An adult will not accrue more energy when foraging than is required to meet its own DER (the energy required to replace the energy expended during the previous timestep) and half that of its chick (a constant - see parameter 25) if the chick is still alive (All species) See section 4.2	Determines adult energetic requirement from foraging and thus amount of time spent foraging versus other activities	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This seems unlikely. It seems likely that adult birds would take in more than just the amount required to cover their daily energy requirements if they could, particularly if they have abandoned their nest and their main priority is now making up lost mass and maximising their chances of survival over the winter. However, there must be a saturation point at which adult and chick cannot process anymore. This was not tested for sensitivity as changing this in the script would require an extensive review and changes to the code.
8. Adults that are 90% or more of their initial body weight will attempt to spend 50% of their time at the colony to ensure that the chick is attended 100% of the time throughout the chick-rearing season. See section 4.2 and model step 13.	Determines how a simulated bird spends its time	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This seems particularly unlikely for puffin, whose chicks are safe within burrows. But even for other species, we know that adults spend less and less time at the colony as the season progresses, when chicks are less likely to succumb to exposure and predation. This decline in attendance may be in some way implicitly included within the model as adults are more likely to drop below the 90% threshold at later time steps. However, it doesn't allow for reasonably well provisioned adults to maximise their over-winter survival probability (mass) by increasing time spent foraging at later time steps. This was not tested for sensitivity due to changes to time budgets requiring an extensive code review to ensure no knock-on impacts occurred from changes.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
15. Any deficit in DER within a time step is shared equally between a parent and its chick, regardless of the status of each (All species) See section 4.2	Determines how energy deficit is divided among individuals	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This seems like an oversimplification. If the parent has a good body mass, it seems unlikely that it would not provide its chick with sufficient food to meet its requirements. It is normal in many species for parents to lose condition over the course of their breeding efforts as they prioritise the provisioning of offspring until the point where they cannot. So it would seem logical that if the parent is in good condition daily DER deficit are more likely to be upon the parent. A 50:50 split seems reasonable when the parent is not in good condition, and there are already mechanisms in place within the model to allow abandonment when the condition of adults becomes too low. This was not changed for sensitivity testing as it would require extensive information on how adults provision chicks under different scenarios. However, this has been identified by the tool authors as an assumption which is over-simplistic and will likely have important implications for the model outputs (Searle et al. 2022).
26. Chick DER remains constant regardless of the age or mass of the chick (All species) See model step 4.	Used to determine energetic requirement of a chick at each time step	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This is very unlikely. Baird 1994 state (in the abstract) that feeding rate went up in chicks as they aged, suggesting that DER also increased. It makes sense that DER would be related to body mass. This was not changed for sensitivity testing as it would require extensive changes to the model structure to update chick DER based on the current timestep.
38. Bird foraging patterns are accurately represented by a distance decay relationship (no effect of environmental heterogeneity/prey availability) (All species) See model step 8.	Used to calculate bird distribution within the bounded region	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	It is known that distributions of foraging birds at sea are not represented well by such simple relationships since prey distribution is a key driver of distribution. The authors of the tool state that "some defence for the use of this approach where a species-specific estimate of rate of distance decay is available lies in the fact that predictions from models containing only “distance to colony” effects fit observed GPS data well (Wakefield *et al*., 2017)." The model used by Wakefield *et al*. was not the same distance decay model as is used within the seabORD tool and the comparability of the two methods is questionable. The suitability of a distance decay relationship will also very much depend on the specific site for which the distribution is being modelled and in most instances the decay function as it currently stands is likely to be unsuitable due to the patchy distribution of prey resource which will underly at-sea seabird distributions. Results for sensitivity testing for this parameter are presented here.
39. Specification of distance decay relationship (All species) See model step 8.	Used to calculate bird distribution within the bounded region	Inbuilt, same across all species	Chosen because widely used and only has one unknown parameter	NA	6		C	C6	This model was selected based on the fact that it can be easily parameterised using values that there are estimates of.
42. All foraging trips within a time step are to	Used to select foraging locations for	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This seems unlikely - considering that a bird that has selected a poor foraging location in its initial foraging trip within a time step would be likely to try

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
the same location (All species) See model step 8.	adult birds at each time step								somewhere else next time. This assumption is contrary to universally observed foraging patterns. This was not tested for sensitivity as this would have required extensive changes to the underlying model.
43. Forage site selection in subsequent time steps is independent of that in previous time steps. (All species) See model step 8.	Used to select foraging locations for adult birds at each time step	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	This also seems unlikely. Unless prey distribution is very variable among days, it can be expected that a bird that has found a good foraging location in one time step would likely return there in subsequent time steps. This was not tested for sensitivity as this would have required comprehensive code review and changes to the underlying model.
52. Birds travel around the edge of the area they're barriered from until reaching their original direct flight path route on the other side (All species) See model step 10.	Used to determine the flight path of barriered birds	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	It is plausible that a bird would skirt around the edge of a perceived obstacle, especially on first encounter with it. However, it seems probable that once it gets to the end of the length of the wind farm, it would then cut across to reach its destination rather than continuing to skirt around until it reaches its original flight trajectory. In the worst case - a long thin windfarm with its longest axis oriented perpendicular to the bird's direction of travel - this could almost double barrier effects compared to the more logical assumption that when able to travel unimpeded in a straight line to a foraging location, birds would do so. It also seems plausible that barrier sensitive birds encountering a wind farm may also decide to change their foraging location completely. Perimeter pathfinding was compared to A* pathfinding techniques in sensitivity testing. Results for sensitivity testing for this parameter are presented here.
58. Assumes that prey depletion occurs within a foraging trip but that at the following trip, the prey has returned to original levels (All species) See model step 12.	Determines intake rate	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	The assumption that prey densities replenish within the course of a day is expected to be violated in reality. Prey levels and distribution are more likely to be dynamic, both changing throughout time and being impacted by removal from predators. This was not tested for sensitivity as would have required extensive changes to the model workings.
60. No inter-specific competition (All species) See model step 12.	Determines intake rate	Inbuilt, same across all species	Simplification for model	NA	6		C	C6	While it is clear why this decision was taken for simplicity and to minimize time spent running parallel simulations of multiple species, the assumption that there is no inter-specific competition is likely violated. Other species may be feeding on the same prey stock - not only limited to seabirds but also other fish and marine mammals. Additionally, prey that are captured by the study species may be stolen by other species. This is not explicitly parameterised in the model, rather it is an omission and was therefore not altered for sensitivity testing as introducing this element would require extensive alterations.
68. The relationship between time spent unattended and	Determines probability of chick survival	Inbuilt, same across all species	Simplification for model		6		C	C6	We know that time spent attending the colony declines as the breeding season progresses and the chick becomes less vulnerable.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
vulnerability to predation and exposure does not change as chick-rearing progresses See model step 14.									This rule was not altered for sensitivity testing as would require a re-work of the model; however, the critical time threshold after which the chick dies from predation or exposure was altered.
16. Upper prey quantity (All species) See section 4.2 and model step 6.	Determines prey availability across the bounded region	User-defined, species- and may need to be colony-specific	Recommended to be based on trial runs to achieve adult mass loss and chick survival rates representative of "moderate" prey availability	174g derived in worked example as suitable for kittiwake at Forth Islands	5		C	C5	This is a calibration factor that ensures that the adult mass loss during the chick-rearing season and the chick mortality rates over the same period are consistent with what is observed in reality (see assumption 18). The model output is highly sensitive to the prey quantity input so the authors of the tool developed a stratified random approach to sampling across the range of "moderate" prey values to capture the uncertainty associated with this parameter. Results for sensitivity testing for this parameter are presented here.
17. Lower prey quantity (All species) See section 4.2 and model step 6.	Determines prey availability across the bounded region	User-defined, species- and may need to be colony-specific	Recommended to be based on trial runs to achieve adult mass loss and chick survival rates representative of "moderate" prey availability	158g derived in worked example as suitable for kittiwake at Forth Islands	5		C	C5	See above.
59. Interference coefficient (m) (All species) See model step 12.	Determines intake rate	Inbuilt, same across all species	Expert judgement	0.02	4		C	C4	This value was cited as being arrived at through expert judgement in Searle *et al*. 2018 and through calibration in Searle *et al*. 2022. In Searle *et al*. 2014, it is stated that the value is informed by Ens and Goss-Custard 1984, Goss-Custard *et al*. 1995 and Dolman *et al*. 1995. The former references relate to oystercatchers and the latter to snow buntings. These species exhibit fundamentally different foraging behaviour to seabirds, not least because their prey source is sedentary, compared to the highly mobile prey resource being exploited by seabirds. Additionally, it is noted that the intake rate was parameterised in the absence of any competition effects to match observed numbers and lengths of foraging trips within the time step periods, prior to the application of competition effects into the algorithm. This implies that the data the parameterisation were based on are collected from birds that experience no competition effects. Since this seems unlikely, it is possible that the interference coefficient is reducing simulated foraging efficiency to below that that would be expected in reality. Results for sensitivity analysis for this parameter are presented here.
24. Initial chick body mass mean and standard deviation (Guillemot, razorbill and puffin) See model step 4.	Used to assign chick initial mass	Inbuilt, species-specific	Baird 1994	Guillemot: mean = 75.8 g, SD = 1 g; Razorbill: mean = 64.9 g, SD = 6.3 g; Puffin: mean = 42.2 g, SD = 3.7 g	2	C		C2	Specific references are not provided for this and we have been unable to identify one specific source so it is difficult to assess data quality. This was not tested for sensitivity as sensitivity testing was undertaken for kittiwake.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score DS	DQ	OS	Final	Comments
5. Minimum time spent resting on sea (All species) See section 4.2 and model step 13.	Determines how simulated birds spend their time	Inbuilt, same across all species	Daunt *et al*. 2002	1 hour per 24 hours	1	C		C1	This parameter is a single value applied across all species but is based on a study of kittiwake. The study uses tracking data to investigate the proportion of time spent by kittiwake undertaking different activities by Daunt *et al*. (2002). It is based on a single year's worth of data (1999) collected from 9 individuals from the Isle of May in June. The results are geographically relevant, but the sample size is small and the temporal coverage is low, and the data only cover one of the four species. In addition, the rate of 1 hour per 24 is not specifically identified or referred to in the paper. Results for sensitivity testing for this parameter are presented here.
13. Proportion of initial mass below which adult is assumed dead (Kittiwake, razorbill and puffin) See section 4.2	Determines the state of a bird	Inbuilt, same across all species	Golovkin, 1963	0.6 of own initial starting mass	1		C	C1	This parameter is the same for all four species in the model. It is based on Golovkin 1963, who found that unfed guillemots in the southwest Barents Sea had lost approximately 60% of their body mass at death. We have been unable to access this article so are unable to comment on the data underlying this finding. The study also addresses kittiwake but no information is provided regarding the findings relating to kittiwake. We consider it unlikely that the same thresholds will apply across all species. Results for sensitivity testing for this parameter are presented here.
54. Bird flight speed (Kittiwake) See model step 11.	Used to calculate time spent travelling	Inbuilt, species-specific	Pennycuick, 1997	Kittiwake: 13.1 m/s	1	C		C1	The report cites Pennycuick 1997 but this actually refers uses data presented in Pennycuick 1987. Flight speed was estimated using ornithodolites. N = 18 for kittiwake. Other significantly different values exist in the literature (e.g. 8.71 m/s reported in Skov *et al*. 2018, N = 287) and appropriate flight speeds for assessments have been a subject of some discussion (e.g. RoyalHaskoning DHV, 2020). Given the much larger sample sizes, the more recent Skov estimate is better supported. Results for sensitivity testing for this parameter are presented here.
77. Energy cost of food warming (All species) See model step 14.	Determines DER	Inbuilt, species-specific	Gremillet *et al.* 2003	Kittiwake: 34.15 kJ/day; Guillemot: 65.07 kJ/day; Razorbill: 47.317 kJ/day; Puffin: 35.84 kJ/day	1	C		C1	This cost is an additional fixed amount per day that is added at the end of the energy expenditure calculation. It is based on Grémillet *et al.* 2003, a study to model food requirements of wintering cormorants in an inland freshwater body. When originally applied, the value was included in energy expenditure calculations which did not include specific foraging energy costs. It is not clear whether this additional energy cost should be included in the calculations at all as they are likely covered by foraging costs (74), and the data the assumption is based on is not applicable to the species being modelled within seabORD. Results for sensitivity analysis for this parameter are presented here.
80. Strength of association between mass and survival (slope parameter) (Kittiwake) See model step 15.	Determines probability of winter survival	Inbuilt, species-specific	Derived from the literature (Oro and Furness, 2002)	0.038	1	C		C1	Oro and Furness 2002 studied a kittiwake a population in Shetland experiencing variable, and in some years, low food abundance. A more recent study of data collected in the Forth and Tay region based on good sample sizes of birds and data collected over a number of years found no statistical support for a relationship of mass with over-winter survival but provides a point estimate and confidence intervals which can be used as alternative inputs (Daunt *et al*. 2018). However, since this value has not yet been incorporated into the tool, the model assumption is likely extremely over-precautionary in

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
									this regard. The authors of the tool recommend that this be updated with the more recent parameter estimates (Searle *et al*. 2022). Results for sensitivity analysis for this parameter are presented here.
80. Strength of association between mass and survival (slope parameter) (Guillemot and razorbill) See model step 15.	Determines probability of winter survival	Inbuilt, species-specific	Derived from the literature (Erikstad, 2009)	1.03	1	C		C1	At the time of development of the seabORD tool, no data were available on the mass-winter survival relationship for adult guillemot and razorbill so the value for puffin was used (see row below). Daunt *et al*. 2018 found no statistical support for a relationship of mass with over-winter survival for Forth and Tay populations but provides point estimates and confidence intervals which can be used as alternative inputs. This was not tested for sensitivity; although the same relationship was tested for kittiwake (see above).
80. Strength of association between mass and survival (slope parameter) (Puffin) See model step 15.	Determines probability of winter survival	Inbuilt, species-specific	Derived from the literature (Erikstad, 2009)	1.03	1	C		C1	This parameter is used to assess to what degree deviation from average adult mass influences overwintering survival. The parameter value was taken from Erikstad *et al.* 2009, a study of a puffin population in northern Norway where puffins are generally larger (Anker-Nillson *et al*. 2018) and likely to experience more severe over-winter conditions (Daunt *et al*. 2018). Daunt *et al*. (2018) has found support for a relationship of mass with overwinter survival of Scottish puffins in the Forth and Tay region based on good sample sizes and data collected over a number of years. However, the slope was less steep than the Erikstad relationship suggesting that use of the Erikstad value may be over-precautionary. The authors of the tool recommend that this be updated with the more recent parameter estimates (Searle *et al*. 2022). This was not tested for sensitivity; although the same relationship was tested for kittiwake (see above).
2. Resolution of grid (grid cell size) (All species) See section 4.2	Determines the unit in space	User-defined via input maps, can be species-specific	Based on the resolution of the bathymetry data used in the original iteration of the model to simulate energy costs of diving. This step is excluded in more recent versions of the model.	1/120 degrees	6		B	B6	Grid cell size will likely affect the output of the model but is a necessary part of the modelling. There is no evidence that the authors of the tool have investigated the impact of or carried out proper optimisation on grid cell size to understand the effect that this has on model predictions. This was not tested for sensitivity.
6. Each adult is responsible for exactly 50% of the provisioning of its young and will not provide more than this, even if its partner is unable to meet the chick's requirements (All species) See section 4.2 and model step 13.	Determines adult energetic requirement from foraging and thus amount of time spent foraging versus other activities	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	This does not seem likely. There is evidence from a range of seabirds, including guillemot and razorbill, that parental contribution to both provisioning of chicks and attendance at the colony varies between sexes (Elliot *et al*., 2010; Grissot *et al*., 2019), suggesting that the mechanisms underlying the decision of how much investment to make in each activity are more complicated than implied here. Such mechanisms would be complex to model and no data appear to be available specifically for these species, therefore this seems a sensible simplification although we believe that it is conservative that a parent is constrained to provide a maximum of 50% of its chicks DER. This was not tested for sensitivity due to requiring in-depth code review to determine follow-on implications from this change.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
9. Excess time is divided equally between resting on sea and attending the colony (All species) See section 4.2	Determines how a simulated bird spends its time	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	Birds with active nests and a body mass of >90% of their starting mass are assumed to spend 50% of their time at the colony (parameter 6), 1 hour per 24 hours of time resting on sea (parameter 5) and the time required to reach their DER foraging (parameter 7). Given these assumptions, it seems a reasonable assumption that any additional time will be split between attending the colony and resting on sea. Daunt *et al*. (2002) found that chick rearing kittiwake on the Isle of May spent on average of 59% of their time at the colony and 16% of their time resting at sea (calculated by adding up approximate proportions presented in figure 3 in that reference). This assumption may be less valid for birds that have abandoned their breeding attempt or whose chicks have died. Sensitivity testing was not carried out for this assumption as would require code review to ensure changes were implemented appropriately.
10. Adults will not change their prioritisation of time spent at the colony depending on time spent by their partner. (Time spent at the colony is calculated independently of that of the partner). (All species) See section 4.2	Determines how a simulated bird spends its time	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	We do not believe that this is a well-founded assumption. For example, for kittiwake, we know that one parent remains with chick almost constantly for a period of several weeks post hatching (c.22 days - Cadiou and Monnat, 1996) and that the chick is subsequently left unguarded for increasingly long periods after this until it fledges (typically at c.45 days). Therefore, we believe that parents clearly do not act independently in real life, but rather will work together to ensure that the chick is protected during the early stages when it is most susceptible to mortality through exposure or predation. (Wanless and Harris 1989; Wanless and Harris 1992). This was not varied for sensitivity testing as would have required extensive changes to the model code.
14. Behavioural mode (apart from death) is based on initial mass at the beginning of the chick-rearing period rather than a population mean (i.e. assumes all birds are the same condition and can tolerate the same proportion of mass loss) (All species) See section 4.2	Determines the behavioural mode of the bird	Inbuilt, same across all species	No satisfactory justification provided	NA	6		B	B6	This does not account for the fact that variation in initial body weight might reflect condition at the beginning of the breeding season. Comparing to the population mean would do this, however, it would ignore the fact that birds vary in their intrinsic size (although this is also ignored when it comes to calculation of energetic requirements). This was not tested for sensitivity as changing this would require a re-work of the model code.
30. Assumes birds do not change their response to the offshore wind farm during the course of the chick rearing period (no	Used to model response of each individual to a wind farm	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	It seems likely that some birds would become accustomed to the wind farm and that displacement and barrier effects would therefore be reduced over time. However, no evidence was found indicating that the species included within the model do, or do not, habituate to the presence of anthropogenic activities in the marine environment (e.g. MMO, 2018). In the absence of any

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
habituation) (All species) See model step 5.									evidence on habituation it seems appropriate to assume no habituation and present this as a worst-case scenario. This was not included in sensitivity testing as this would include extensive changes to the model, and because relevant alternative information is available to guide alternative decisions in the model.
33. Prey distribution is fixed over the chick-rearing period (All species) See model step 7.	Used to calculate prey abundance at each grid cell	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	It is known that prey distributions do change temporally and it is very unlikely that the prey distribution remains static over the course of the season. However, there is not a good understanding of how prey distributions change. Even if this was well understood, incorporating them into such models would substantially increase the complexity of the model. It is considered, therefore, that an 'average' distribution is a necessary simplification and its reliability will be determined by the data underlying it. This was not incorporated in sensitivity testing as changing this assumption would require an extensive reworking of the model, and as mentioned above the reality to aim for is not well understood.
34. Prey distribution is uniform across the bounded area (All species) See model step 7.	Used to calculate prey abundance at each grid cell	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	If no prey distribution data are available, an assumption of uniform prey distribution is made (i.e. prey abundance is the same at every possible foraging location). It is known that in reality this is not the case. However, in the absence of good evidence regarding how prey distribute themselves (e.g. in relation to environmental covariates), this seems like a necessary simplification. Results for sensitivity analysis for this parameter are presented here.
37. Spatial distribution of foraging birds do not vary over time (All species) See model step 8.	Used to select foraging locations for adult birds at each time step	Inbuilt,	Simplification for model	NA	6		B	B6	Similar to prey distribution, it is known that foraging locations do change temporally. However, in the absence of a good understanding of how prey distributions change, an 'average' distribution is a necessary simplification and its reliability will be determined by the data underlying it. This was not incorporated in sensitivity testing as changing this assumption would require an extensive reworking of the model.
46. Size of footprint buffer (area birds are displacement to) (All species) See model step 9.	The area beyond the border into which birds are displaced	User-defined, could be species-specific	Default value from Steering Group of Searle *et al*. 2014	Default value is 5 km	6		B	B6	This is a user-definable parameter which is set to a default of 5 km as determined by the steering group for the Searle *et al.* 2014 project. This seems to be an arbitrary threshold - it does make sense that birds might be displaced to a local location upon first encounter with the wind farm although perhaps not for subsequent foraging trips even within a time step. Results for sensitivity analysis for this parameter are presented here.
53. Birds are aware of the location of the ORD and are able to find the most efficient path to their foraging location avoiding the ORD (All species)	Used to determine the flight path of barriered birds	Inbuilt, same across all species	Simplification for model	NA	6		B	B6	While birds are will not be aware of the offshore wind farm site and its extent when initially exposed to it, it can be assumed that birds frequenting the area would become familiar with the location and utilise more efficient routes around the offshore wind farm. The two pathfinding methods were compared in sensitivity testing and results are presented here.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
See model step 10.									
62. Adult birds are able to accurately assess the optimum number of foraging trips to make based on journey time and prey intake rate (All species) See model step 13.	Determines number of foraging trips made by birds	Inbuilt, same across all species	Assumption	NA	6		B	B6	It seems reasonable that birds are able to make decisions on the length of a foraging trip based on the rate at which they are catching prey. However, it is unclear how realistic this assumption is. This inherent assumption was not altered for sensitivity testing.
64. The proportion of the DER for a chick corresponding to 0 mass loss. See model step 14.	Determines chick mass	Inbuilt, same across all species	Simplification for model	0.6	6		B	B6	No evidence has been found to support this or otherwise. This was not altered for sensitivity testing.
65. Baseline chick death rate per time step. See model step 14.	Determines probability of chick survival	Inbuilt, same across species	This parameter is not referred to in documentation	0.05	6		B	B6	This parameter is not referred to in the reports that accompany the seabORD tool but is described in the code as the probability of death by flooding and other causes. It is not known whether direct data were used to inform this parameter or whether it was included to bring baseline chick death in line with empirical data, but a baseline level of chick death seems reasonable.
67. Relationship of predation risk with unattendance time (All species) See model step 14.	Determines probability of chick survival	Inbuilt, same across all species	Assumption	Increases linearly (probability of death = unattended time / maximum unattended hours)	6		B	B6	No data source is described for this assumption. As far as known there are no data available to support this or otherwise.
70. Threshold proportion of mass of an optimally fed chick at which a puffin chick leaves the burrow See model step 14.	Determines probability of chick survival	Inbuilt, puffin-specific	No justification provided	Presented as 0.8 in the documentation but scripted as 0.7 in MATLAB code for both versions 1.2 and 1.5.	6		B	B6	No evidence is provided to support this assumption (and the value provided in the 2014 and 2018 reports differ from that used in the MATLAB code). However, pufflings will leave the burrow to search for food when starving (as this is the typical fledging mechanism for this species). We have found no empirical data to support this value in particular (or the way in which this may change based on age) but we believe that this is a necessary component of the model and have no evidence to support or contradict the value chosen.
27. Percent population susceptible to displacement (Kittiwake) See model step 5.	Used to assign susceptibility status to each individual	User-defined, species-specific	Based on SNCB recommendations	30% used in Searle *et al.*, 2020	4		B	B4	This is a user-definable parameter and can therefor easily be updated based o on new evidence. The recommendation here is to use values determined by the regulators, based on expert opinion from knowledge of species-specific sensitivity to anthropogenic activity. We believe that there is good evidence to suggest that kittiwake enter rather than avoid operational wind farms (e.g. Krijgsveld et al., 2011; Walls et al., 2013). Results for sensitivity testing for this parameter are presented here.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
27. Percent population susceptible to displacement (Guillemot and razorbill) See model step 5.	Used to assign susceptibility status to each individual	User-defined, species-specific	Based on SNCB recommendations	60% used in Searle *et al*., 2020	4		B	B4	The recommendation here is to use values determined by the regulators, based on expert opinion from knowledge of species-specific sensitivity to anthropogenic activity. This parameter can be updated by the user to reflect any new evidence/guidance. MacArthur Green (2021) found little evidence of avoidance of the Beatrice offshore wind farm by either guillemot or razorbill and suggest that the 30 – 70% suggested displacement ranges are likely over-precautionary.
27. Percent population susceptible to displacement (Puffin) See model step 5.	Used to assign susceptibility status to each individual	User-defined, species-specific	Based on SNCB recommendations	60% used in Searle *et al*., 2020	4		B	B4	The recommendation here is to use values determined by the regulators, based on expert opinion from knowledge of species-specific sensitivity to anthropogenic activity. This parameter can be updated by the user to reflect any new evidence/guidance. MacArthur Green (2021) found that avoidance of wind farms by puffins did not appear to be strong, suggesting that the lower end of the suggested 30% - 70% suggested displacement rate might be appropriate for this species.
28. Percent population displaced also susceptible to barrier effects (All species) See model step 5.	Used to assign susceptibility status to each individual	User-defined, could be species-specific	Based on SNCB recommendations	Default: 100%	4		B	B4	Regulators recommend use of 100% here, i.e. all birds that are displaced will also not pass through the wind farm footprint. This is probably an over-estimate and should be presented as a worst-case scenario. However, no empirical evidence was identified to the contrary. This parameter can be updated by the user as new evidence comes to light. Results for sensitivity testing for this parameter are presented here.
45. Size of footprint border (additional displacement zone) (All species) See model step 9.	The area beyond the wind farm from which birds are displaced and barriered	User-defined, could be species-specific	Based on SNCB recommendations	Default value is 1 km, SNCBs requested 2km for SEANSE	4		B	B4	This is based on the SNCB recommendation of a 2km buffer zone for these species (SNCBs, 2022). As far as we know, there is no species-specific evidence to suggest that this is the area which will be avoided by displaced birds, but it does keep the modelling in-line with that carried out using the SNCBs matrix approach. Results for sensitivity analysis for this parameter are presented here.
66. Time spent unattended leading to chick death through exposure (All species) See model step 14.	Determines chick survival	Inbuilt, same across all species	Expert judgment	18 hours within a time step	4		B	B4	Based on expert judgement. No data have been found to support this or otherwise. Results for sensitivity analysis for this parameter are presented here.
69. Proportion of fully provisioned mass below which chick is assumed dead (All species) See model step 14.	Converts energy to grams of mass	Inbuilt, same across all species	Expert judgment	0.6	4		B	B4	This value was calibrated through the model such that chick mortality matched that observed from undefined sources. Results for sensitivity analysis for this parameter are presented here.
3. Length of time step (All species) See section 4.2	Number of hours considered to be	Inbuilt, species-specific	Described as biologically relevant. No supporting evidence provided.	Kittiwake: 36 hours; Guillemot: 24 hours;	3		B	B3	This parameter is species specific. The time step is simply a 24-hour period for auks which is a sensible length to use for diurnal behaviour. The reasoning for the longer time step for kittiwake is not explicitly provided but is described as

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
	within a biological "day"			Razorbill: 24 hours; Puffin: 24 hours					based on an "understanding of the behaviour of each species and the typical observed length of foraging trips" (Searle *et al*. 2014). Table B2 in Searle *et al*. 2018 suggests that kittiwake spend less time foraging and more time flying per 24-hour period than the three auk species, meaning that kittiwake would be expected to make fewer foraging trips per 24-hour period. However, it remains unclear why this was necessary as the model would allow for a lower average number of trips to be made within a 24-hour period (and also puffins seem comparable). No explicit consideration is given to night time in the model. We know that seabirds spend considerably less time foraging at night (Shoji *et al*. 2015; Dunn *et al*. 2020). However, the assumption of the model is that if a bird is prioritising achieving its DER over attendance at the colony then it will, with the exception of a mandatory hour in 24 spent resting on sea, spend the remainder of the time step foraging. This is a less precautionary approach than assuming lower foraging activity at night.
56. Maximum intake rate (All species) See model step 12.	Determines intake rate	Inbuilt, species-specific	Estimated from empirical data	Kittiwake: 4.369 g/min; Guillemot: 2.95 g/min; Razorbill: 3.066 g/min; Puffin: 3.293 g/min	3		B	B3	As the intake rate is estimated based on a relationship derived from empirical data it can be assumed that these intake rates are reasonable. However, it is not clear what species' intake rates were available as data on the study species was not available. It would be prudent for this method of intake rate estimation to be verified for species that do have empirical data. Results for sensitivity analysis for this parameter are presented here.
57. Prey level associated with reaching half of the maximum intake value (All species) See model step 12.	Determines intake rate	Inbuilt, species-specific	Determined during model calibration process (fixed so that baseline outputs matched empirical data)	Kittiwake: 900 g; Guillemot: 700 g; Razorbill: 600 g; Puffin: 1000 g	3		B	B3	Simulated based on maximum intake rate, so confidence in this is linked to that. The intake rate was calibrated such that the number of foraging trips and the mean and range of time foraging per day matched empirical data. The values used for the calibration are reported but their source(s) is not provided.
61. Adult birds make at least 1 and at most 6 foraging trips during each time step (All species) See model step 13.	Determines number of foraging trips made by birds	Inbuilt, same across all species	"The vast majority of empirical data suggest that most individuals complete between 2 and 4 foraging trips per time step"	NA	3		B	B3	The authors state that the vast majority of empirical data on these species suggest that most individuals complete between two and four foraging trips per time step so if this is accurate then six is a sensible value to use. However, it is expected that this assumption is violated frequently in reality.
73. Energy cost of flight (Razorbill and puffin) See model step 14.	Determines DER	Inbuilt, species-specific	Source cited as Enstipp *et al.* 2006 but this reference does not include these species.	Razorbill: 3581.34 kJ/day; Puffin: 3113.85 kJ/day	3		B	B3	The source for these values couldn’t be identified.
74. Energy cost of foraging (Razorbill and puffin) See model step 14.	Determines DER	Inbuilt, species-specific	Source cited as Enstipp *et al.* 2006 but this reference does not include these species.	Razorbill: 1421.45 kJ/day; Puffin: 974.97 kJ/day	3		B	B3	The source for these values couldn’t be identified.
75. Energy cost of resting at sea (Razorbill and puffin)	Determines DER	Inbuilt, species-specific	Source cited as Enstipp *et al.* 2006 but this reference does not include these species.	Razorbill: 646.15 kJ/day; Puffin: 461.24 kJ/day	3		B	B3	The source for these values couldn’t be identified.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
See model step 14.									
76. Energy cost of attending the colony (Razorbill and puffin) See model step 14.	Determines DER	Inbuilt, species-specific	Source cited as Enstipp *et al.* 2006 but this reference does not include these species.	Razorbill: 932.17 kJ/day; Puffin: 665.41 kJ/day	3		B	B3	The source for these values couldn't be identified.
11. Proportion of initial mass below which adult prioritises DER over attendance at the colony (All species) See section 4.2 and model step 13.	Determines the behavioural mode of the bird	Inbuilt, same across all species	Deduction from published data (see underlying assumptions column)	0.9 of own initial starting mass	2		B	B2	This is based on logic presented in Langton *et al.* 2014 which we have been unable to access. However, an example is given for guillemot, and the authors explain that 90% of initial body mass is well over starvation threshold and about 2/3 of the difference in mean initial mass and the minimum mass recorded in UK ringing data. This seems a reasonable assumption in the absence of data but there is high uncertainty associated with it. This parameter is applied across all species.
121. Proportion of initial mass below which adult abandons chick (All species) See section 4.2	Determines the behavioural mode of the bird	Inbuilt, same across all species	Deduction from published data (see underlying assumptions column)	0.8 of own initial starting mass	2		B	B2	This is based on the observation that 80% average starting body mass is below the minimum weight of UK ringing data, which is generally collected at breeding colonies. This seems a reasonable assumption, although the figures are only presented for guillemot so it is unclear whether this is true across all four species. Results for sensitivity testing for this parameter are presented here.
21. Initial adult body mass mean and standard deviation (Kittiwake) See model step 2.	Used to assign adult initial mass	Inbuilt, species-specific	Derived from published literature	Mean: 372.69 g, SD: 33.62 g	2		B	B2	Specific references are not provided for this and we have been unable to identify one specific source so it is difficult to assess data quality. However, the value used (372.69 g) is similar to the value cited by Enstipp *et al*. 2006 (361.64 g).
21. Initial adult body mass mean and standard deviation (Guillemot) See model step 2.	Used to assign adult initial mass	Inbuilt, species-specific	Derived from published literature	Mean: 920.34 g, SD: 57.44 g	2		B	B2	Specific references are not provided for this and we have been unable to identify one specific source so it is difficult to assess data quality. However, the value used (920.34 g) falls within those we identified within the literature (908.4 g (Thaxter *et al*. 2013), 836 g (Croll & McClaren 1993), 940 g (Birt-Friesen *et al.* 1989)).
21. Initial adult body mass mean and standard deviation (Puffin) See model step 2.	Used to assign adult initial mass	Inbuilt, species-specific	Derived from published literature	Mean: 392.8 g, SD: 21.95 g	2		B	B2	Specific references are not provided for this and we have been unable to identify one specific source so it is difficult to assess data quality. The value used (392.8 g) falls within those we identified within the literature although seems to be on the low side (311-730 g (Anker-Nilssen *et al*., 2018), mean chick rearing weight is 415 g, and higher in winter. Further, no birds lower than 425 g in body mass were recorded at Hornoy, with egg-laying weight closer to 510 g (Eilertsen 2008)).
24. Initial chick body mass mean and standard deviation (Kittiwake) See model step 4.	Used to assign chick initial mass	Inbuilt, species-specific	Baird 1994	Mean = 36 g, SD = 2.2 g,	2	B		B2	Specific references were not provided for this parameter, but we believe it was taken from Baird 1994, a review of kittiwake ecology from the US. Two references are presented with the value in the review, both of which are studies conducted in the US, published in 1983 and 1991 respectively. Although geographic and temporal relevance is low, we expect that values derived from studies far away and long ago, will be broadly correct

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
25. Chick DER (Guillemot) See model step 4.	Used to determine energetic requirement of a chick at each time step	Inbuilt, species-specific	Harris and Wanless 1985	221.71 kJ/day	2		B	B2	This was taken from Harris and Wanless 1985, a study about feeding rate in guillemot chicks on the Isle of May. We could not access this paper so cannot comment on sample size but the data are geographically relevant. It appears that DER must reflect feeding rate. However, the abstract states that this population did not seem to be food limited so its feeding rate may well exceed that required simply to offset DER.
25. Chick DER (Razorbill and puffin) See model step 4.	Used to determine energetic requirement of a chick at each time step	Inbuilt, species-specific	Harris and Wanless 1986	Razorbill: 195.67 kJ/day; Puffin: 325 kJ/day	2		B	B2	Harris and Wanless 1985 seems to be cited for all four chick DER values, but this reference seems to be specifically related to guillemot. We believe that the values for razorbill and puffin are calculated based on Harris and Wanless 1986, a study on daily food intake rates of chicks at the Isle of May.
32. Prey distribution map (All species) See model step 7.	Used to calculate prey abundance at each grid cell	User-defined, species- and colony-specific	Derived from the GAM model of bird distributions but excluding the effects of distance to colony	Map provided with tool	2	B		B2	The prey map provided with the application is derived based on the assumption that prey distribution mirrors distribution of seabirds once the effect of distance to colony has been removed. Species and colony-specific distribution maps were generated from tagging data that was used to generate a density surface model based on accessibility (proximity to colony and competition effects) and suitability (remaining patterns). The suitability part of the model was generated as an x-y smooth (no environmental covariates, as environmental covariates trialled did not adequately explain patterns) and is assumed to represent prey abundance so forms the prey distribution map. Sample sizes were fairly low (minimum six razorbill at Buchan Ness in a single year, maximum 53 kittiwake from Forth Islands over two years, Searle *et al*. 2014). Additional tracking data were used in the Searle *et al*. 2020 SEANSE study.
73. Energy cost of flight (Kittiwake and guillemot) See model step 14.	Determines DER	Inbuilt, species-specific	Enstipp *et al*. 2006	Kittiwake: 1400.74 kJ/day; Guillemot: 7361.72 kJ/day	2		B	B2	For guillemot and kittiwake, energy cost of the different behaviours are those reported in Enstipp *et al.* 2006. These values were derived by Enstipp *et al.* based on data from further literature. Results for sensitivity analysis for this parameter are presented here.
74. Energy cost of foraging (Kittiwake and guillemot) See model step 14.	Determines DER	Inbuilt, species-specific	Enstipp *et al*. 2006	Kittiwake: 1400.74 kJ/day; Guillemot: 1894.9 kJ/day	2		B	B2	For guillemot and kittiwake, energy cost of the different behaviours are those reported in Enstipp *et al.* 2006. These values were derived by Enstipp *et al.* based on data from further literature. Results for sensitivity analysis for this parameter are presented here.
75. Energy cost of resting at sea (Kittiwake and guillemot) See model step 14.	Determines DER	Inbuilt, species-specific	Enstipp *et al*. 2006	Kittiwake: 400.57 kJ/day; Guillemot: 810.28 kJ/day	2		B	B2	For guillemot and kittiwake, energy cost of the different behaviours are those reported in Enstipp *et al.* 2006. These values were derived by Enstipp *et al.* based on data from further literature. Results for sensitivity analysis for this parameter are presented here.
76. Energy cost of attending the colony (Kittiwake and guillemot) See model step 14.	Determines DER	Inbuilt, species-specific	Enstipp *et al*. 2006	Kittiwake: 427.75 kJ/day; Guillemot: 1168.91 kJ/day	2		B	B2	For guillemot and kittiwake, energy cost of the different behaviours are those reported in Enstipp *et al.* 2006. These values were derived by Enstipp *et al.* based on data from further literature. Results for sensitivity analysis for this parameter are presented here.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
78. Conversion from kJ fish to grams (All species) See model step 14.	Converts energy to grams of mass	Inbuilt, same for all species	Harris *et al*. 2008	6.1 kJ/gram	2	B		B2	This value is calculated from a table in Harris *et al.* 2008 (a study of the comparative quality of snakefish to sandeel and sprat as food for guillemot and puffin) and relates to the energy density of sandeels (n = 53).
1. Bounding box (All species) See section 4.2	Determines extent over which model runs	User-defined, can be species-specific	Based on foraging ranges of species being used	West: -4.1130, East: 1.0387, South: 54.5704, North: 58.9634	1		B	B1	If underlying foraging distributions are accurate then a bounding box based on a maximum foraging range should be suitable. Data source score is based on use of reliable literature such as mean maximum foraging ranges (+ 1SD) presented in Woodward *et al*., 2019. However, it should be noted that the default bounding box is applied across all species and includes a portion of sea on the west coast of Scotland which seems to get pulled in to calculations if distance decay is used with a large foraging range. For distance decay, the size of the bounding box will affect runtime with a larger box increasing the time taken for a run to complete. This was not varied for sensitivity testing.
13. Proportion of initial mass below which an adult is assumed dead (Guillemot) See section 4.2	Determines the state of a bird	Inbuilt, same across all species	Golovkin, 1963	0.6 of own initial starting mass	1		B	B1	This parameter is the same for all four species in the model. It is based on Golovkin 1963, who found that unfed guillemots in the southwest Barents Sea had lost approximately 60% of their body mass at death. We have been unable to access this article so are unable to comment on the data underlying this finding. The study also addresses kittiwake but no information is provided regarding the findings relating to kittiwake.
21. Initial adult body mass mean and standard deviation (Razorbill) See model step 2.	Used to assign adult initial mass	Inbuilt, species-specific	Derived from published literature	Mean: 582.9 g, SD: 26 g	1	B		B1	The specific reference for this is not given in the report, but the value matches that in Thaxter *et al.* 2013. This is based on a sample of 20 birds from the Isle of May across 2000, 2001 and 2004. Sample size is small and data are old, but multiple years are included and the birds are local.
22. Initial adult daily energy expenditure mean and standard deviation (Kittiwake) See model step 3.	Used to assign initial daily energy expenditure (DEE)	Inbuilt, species-specific	Derived from published literature	Mean = 802 kJ, SD = 196 kJ	1		B	B1	Kittiwake adult daily energy expenditure is taken from Humphreys, 2002, based on birds on the Isle of May. We have been unable to access this reference.
22. Initial adult daily energy expenditure mean and standard deviation (Guillemot) See model step 3.	Used to assign initial daily energy expenditure (DEE)	Inbuilt, species-specific	Derived from published literature	Mean = 1489.1 kJ, SD = 169.9 kJ	1		B	B1	Guillemot adult daily energy expenditure is taken from Montevecchi *et al*. 1990 which is an American study so less relevant to the region.
22. Initial adult daily energy expenditure mean and standard deviation (Razorbill and puffin) See model step 3.	Used to assign initial daily energy expenditure (DEE)	Inbuilt, species-specific	Derived from published literature	Razorbill: mean = 1231.89 kJ, SD = 95.3 kJ; Puffin: mean = 871.5 kJ, SD = 80 kJ	1		B	B1	Adult DEE for razorbill and puffin were taken from Brit-Friesen *et al*., 1989 which were based on a generic calculation using mass of each species for seabirds using flapping flight in cold water.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
23. Assimilation efficiency (proportion of available energy assimilated) (All species) See model step 3.	Used to calculate DER from DEE	Inbuilt, species-specific	Hilton *et al*. 2000	Kittiwake: 0.74; Guillemot: 0.78; Razorbill: 0.79; Puffin: 0.78	1	B		B1	This is taken from Hilton *et al.* 2000, a study comparing the energy content of food when it was eaten versus what was excreted by birds from Foula, collected in 1995. All four species were included in the study and the number of replicate measurements taken ranged between 9 and 11 depending on the species, so sample size was relatively low. Results for sensitivity testing for this parameter are presented here.
25. Chick DER (Kittiwake) See model step 4.	Used to determine energetic requirement of a chick at each time step	Inbuilt, species-specific	Humphreys 2002	Kittiwake: 525.71 kJ/day	1		B	B1	Harris and Wanless 1985 seems to be cited for all four chick DER values, but this reference appears to be specifically related to guillemot. Empirical values for the daily energy expenditure for chicks are available from Humphreys 2002 which is likely where this value came from (though the reference is not readily accessible).
18. Definition of moderate conditions for prey level calibration (percent adult mass loss and chick survival rates for auks/nest survival rates for kittiwake) (All species) See section 4.2 and model step 6.	Optimisation of prey availability inputs and also to predict over-winter survival rates under different conditions	Recommended by developers, species-specific	Harris, 1979; Harris and Wanless, 1988; Gaston and Hipfner, 2006; Nelson, 2013; Newell *et al*., 2016	Kittiwake: adult mass loss = 5 - 15 %, chick/nest survival = above 11 %; Guillemot: adult mass loss = 3.5 - 10.5 %, chick/nest survival = above 49 %; Razorbill: adult mass loss = 5 - 15 %, chick/nest survival = above 50 %; Puffin: adult mass loss = 5 - 15 %, chick/nest survival = above 50 %	1	B		B1	Moderate conditions are defined as the prey values within which the baseline model returns an adult body mass loss within specified lower and upper thresholds and a chick survival rate (or nest survival for kittiwake) above a specified lower threshold. These thresholds are based on empirical data (Harris 1979; Harris & Wanless 1988; Gaston & Hipfner 2006; Nelson 2013; Newell *et al*. 2016) regarding observed rates under 'moderate' environmental conditions. We note that the seabORD tool provides an assessment of whether or not each run classifies as moderate as an output, but that this assessment is based only on adult mass and does not incorporate chick survival rates, therefore cannot be used to inform model calibration.
36. Bird distribution map (All species) See model step 8.	Used to select foraging locations for adult birds at each time step	User-defined, species- and colony-specific	GAM modelling of seabird tracking data	Map provided with tool	1	B		B1	Species and colony-specific distribution maps were generated from tagging data that was used to model a density surface based on accessibility (proximity to colony and competition effects) and suitability (remaining patterns). It is unclear whether these data are based on the same dataset as in Searle *et al*. 2014, but if so, sample sizes were fairly low (minimum 6 RA at Buchan Ness in a single year, maximum 53 kittiwake from Forth Islands over two years). Additional data were included in the density surface modelling carried out the Searle *et al*. 2020 SEANSE study.
54. Bird flight speed (Guillemot, razorbill) See model step 11.	Used to calculate time spent travelling	Inbuilt, species-specific	Pennycuick, 1997	Guillemot: 19.1 m/s; Razorbill: 16 m/s	1	B		B1	The report cites Pennycuick 1997 but this actually refers uses data presented in Pennycuick 1987. Flight speed was estimated using ornithodolites. N = 178 for guillemot and N = 50 for razorbill. The data appear to be robust though more recent estimates of flight speed for kittiwake and puffin are lower than those presented in this reference (Skov *et al*., 2018; Bennison *et al*., 2019) so this method may over-estimate flight speeds.
54. Bird flight speed (Puffin) See model step 11.	Used to calculate time spent travelling	Inbuilt, species-specific	Pennycuick, 1997	Puffin: 17.6 m/s	1	B		B1	The report cites Pennycuick 1997 but this actually refers uses data presented in Pennycuick 1987. Flight speed was estimated using ornithodolites. N = 200 for puffin. The data appear to be robust but for an alternative value of 13.2 m/s exists for puffin, reported in Bennison *et al.* 2019.

Parameter/assumption (species)	**Role in model**	**User defined / inbuilt**	**Derivation**	**Value (if user-defined then default from worked example)**	**Score**				**Comments**
					DS	**DQ**	**OS**	**Final**	
71. Energy density of bird tissue (All species) See model step 14.	Converts energy to grams of mass	Inbuilt, same across all species	Representative of those available for guillemot in published literature	38 kJ/g	1		B	B1	This is based on Gabrielsen 1996 (a study on guillemots) and Montevecchi *et al*. 1984 (a study on gannets). Montevecchi states that "The energy equivalent of tissue was calculated by applying the conversion factors: 38 kJ/g lipid and 20 kJ/g lipid-free dry matter (Ricklefs 1974)." The factor for lipid is used in the seabORD model. We are unable to access the Ricklefs reference.
81. Baseline overwinter survival probability (All species) See model step 15.	Determines probability of winter survival	Inbuilt, species-specific	Freeman *et al*. 2014	Kittiwake: poor = 0.65; moderate = 0.80; good = 0.90; Guillemot: poor = 0.82; moderate = 0.92; good: 0.94; Razorbill: poor = 0.80; moderate = 0.90; good = 0.95; Puffin: poor = 0.85; moderate = 0.90; good = 0.95	1		B	B1	The report that the values originate from is not available for investigation. However, these values match broadly with regional and local annual survival rates (we assume very little adult mortality during the breeding season). For example, Isle of May rates fall between moderate and good for kittiwake, puffin and guillemot and between poor and moderate for razorbill.
29. Assumes birds cannot be barriered but not displaced (All species) See model step 5.	Used to assign susceptibility status to each individual	Inbuilt, same across all species	Logical assumption	NA	6		A	A6	We have not found empirical evidence to support this, but it seems to be a sensible assumption during the chick-rearing season – for a given bird that is assumed to be deterred from passing through a wind farm on the way to a suitable foraging location, it seems sensible to assume that the same bird will also not forage within one. It is possible to imagine a scenario in which birds would change their path to another location to avoid the wind farm as an obstacle but, being motivated by a good food source within the wind farm, would be more likely to investigate further and make a decision to forage in between turbines, but the lack of evidence and the difficulty parameterising such behaviour is prohibitive to including it within the model.
47. Birds are able to re-distribute themselves according to prey density (All species) See model step 9.	Used to determine foraging locations chosen by displaced birds	Inbuilt, same across all species	Assumed	NA	6		A	A6	This seems to be a reasonable assumption given that there is strong selection pressure on seabirds to be able to detect shifting prey resource.
49. Birds travel directly to their foraging locations if possible (All species) See model step 10.	Used to determine travel distance	Inbuilt, same across all species	Assumed	NA	6		A	A6	This seems a sensible assumption as birds will presumably seek to minimise the amount of energy consumed travelling to and from forage locations. Most seabird species, most of the time during the breeding season, transit fairly directly to the area in which they commence foraging.
50. Birds do not travel over land, but navigate around it according to A* pathfinding (All species)	Used to determine travel distance	Inbuilt, same across all species	Assumed	NA	6		A	A6	Seabirds do not generally fly over land so this seems to be a sound assumption.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
See model step 10.									
55. Intake rate follows a type II functional response. (All species) See model step 12.	Determines intake rate	Inbuilt, same across all species	Assumed	NA	6	A	A	A6	A type II functional response is described as expected by expert opinion for prey consumption (intake rate increases with prey density until a maximum is reached). However, the authors note that some experts also suggest a type III functional response (intake rate increases more slowly at low prey density and then accelerates more rapidly, reflecting decreased handling time/switching as the prey source becomes more abundant) instead (Middlemas *et al.*, 2006; Enstipp *et al.*, 2007). This was not used due to the higher complexity and additional data requirements. The type II response is a reasonable assumption, especially given that complexities such as switching among prey type are not incorporated into the model.
79. Relationship between mass and survival is linear on a logit transformed scale (All species) See model step 15.	Determines probability of winter survival	Inbuilt, same across all species	Assumption	NA	6		A	A6	The logistic relationship assumed between mass and overwinter survival is expected to be reasonable. However, it is surprising that the authors believe that it is impossible to check the validity of this assumption using currently available information given several seabird colonies possess long timeseries of capture recapture datasets.
20. Fraction of population to run (All species) See model step 1.	Determines number of birds to simulate (and used later to determine intraspecific competition effect)	User-defined, could be species-specific	NA	Default: 0.25	4		A	A4	The model is described as relatively insensitive to this parameter (since it is accounted for in competition calculations) (Mobbs *et al*. 2018). However, as large a proportion as possible is recommended to allow accurate quantification of uncertainty. Where less than 100% of the population is modelled, any absolute metrics (such as number of mortalities) must be scaled up to represent the total expected for the full population. However, other metrics, such as percent additional mortality are calculated based on the total population size and do not require scaling.
41. Proportion of birds within foraging range (All species) See model step 8.	Used in distance decay function	User-defined, species-specific	Recommended to be from expert judgement	Developers suggest the value might be between 0.9 and 0.999	4		A	A4	This is a user-defined parameter advised to be based on expert judgement on how many birds will forage within the selected foraging range. If using mean maximum foraging range + 1 standard deviation as recommended proportions of birds beyond that distance are going to be very close to 1. There should therefore be high confidence in this parameter if expert opinion follows on from the use of the Woodward *et al*. 2019 foraging ranges. The exact value is going to be unclear but does not affect the outcome of the distance decay curve very much at all.
4. Number of steps per season (Length of chick rearing period/daylength) (All species) See section 4.2	Number of biological "days" determined to be within a chick-rearing season	Inbuilt, species-specific	Dependent upon the length of the time step such that the product of this parameter and the time step should be equal to the chick-rearing period for that species. No supporting evidence for the length of the chick-rearing period is provided.	Kittiwake: 30 steps (fledging period length of 45 days); Guillemot: 21 steps (fledging period length of 21 days); Razorbill: 21 steps (fledging period length of 21 days);	3		A	A3	Season lengths are consistent with those presented in the literature (e.g. Robinson, 2005; Coulsen and White, 1958 (kittiwake, 42.7±4.4 days, n = 116); Hedgren, 1981 (guillemot, 20 days), Harris and Wanless, 1989 (razorbill, 19.1±4.4, n = 73)) but the value itself depends on definition of the time step. Note that the industry guidance for defining seasons does not include a definition of the chick-rearing period (i.e. excluding incubation), therefore more general references must be used here.

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
				Puffin: 40 steps (fledging period length of 40 days)					
72. Calculation of adult body mass at a given time step from its mass in the previous time step, the energy it gained, its DER and the energy density of its tissue (All species) See model step 14.	Determines mass change	Inbuilt, same across all species	Langton *et al*. 2014	NA	3		A	A3	This is stated as following Langton *et al*. 2014. We have been unable to access this report but this approach makes seems reasonable.
63. Maximum possible mass gain for chicks (All species) See model step 14.	Determines mass change	Inbuilt, species-specific	Estimated from observations of chick mass change from hatching to fledging (UKCEH unpublished data; Harris and Wanless, 2011)	Kittiwake: 11 g; Guillemot: 9 g; Razorbill: 7 g; Puffin: 6 g	2		A	A2	While the publications that these values are derived from are not accessible, it can be assumed that for seabirds that nest in accessible colonies such as the four species included here, there are likely to be abundant data from repeat weight measurements of chicks.
19. Colony size (All species) See model step 1.	Determines number of birds to simulate	User-defined, species- and colony-specific	User to define from published sources	Guillemot: 17753 (Boddam to Collieston), 37277 (Fowlsheugh), 19891 (Isle of May), 29079 (St. Abb's Head); Razorbill: 4883 (Fowlsheugh), 3467 (Isle of May), 1262 (St. Abb's Head); Kittiwake: 12542 (Boddam to Collieston), 9388 (Fowlsheugh), 3766 (Isle of May), 4314 (St. Abb's Head); Puffin: 52291 (Isle of May)	1	A		A1	All parameters relating to the colonies (size, name, spatial location and population size) are user-defined within an input spreadsheet – the values listed here are the defaults within the software. Colony size will be species-specific and should be based on the most recent colony count data available. This is a parameter that can potentially change rapidly over time and even if it were up to date, may not reflect the size of the population that will be present when a wind farm becomes operational. This was not varied for sensitivity testing as it should be based off the best possible information at each site.
40. Foraging range (All species) See model step 8.	Used in distance decay function	User-defined, species-specific	Recommended to be from literature e.g. Thaxter *et al*. 2012	Kittiwake: 120 km; Guillemot: 135 km; Razorbill: 95 km; Puffin: 200 km	1		A	A1	Foraging range is a user-defined parameter and will be determined by regulators. Currently it is advised to use the mean max foraging range plus one standard deviation with the values taken from Woodward *et al*. 2019. This is a thorough literature review of foraging range which we have high confidence in. This was not varied in sensitivity testing as there was high confidence in this parameter.
48. Location of SPAs (All species) See model step 10.	Used to create distribution of birds and to calculate	User-defined, species-specific	Mid-point of defined colonies	Buchan Ness to Collieston Coast: 57.4333, -1.8000, Fowlsheugh: 56.9191, -2.1978,	1		A	A1	Mid-points of SPA colonies are used to determine the distance to the colony and to create flight paths. These are based on known colony locations (although some colonies may extend along the coastline meaning that individual birds may actually have quite different starting points).

Parameter/assumption (species)	Role in model	User defined / inbuilt	Derivation	Value (if user-defined then default from worked example)	Score				Comments
					DS	DQ	OS	Final	
	foraging distances			Isle of May: 56.1833, -2.5567, St Abbs to Fast Castle: 55.9251, -2.1437					This was not varied in sensitivity testing as a result of there being little uncertainty surrounding colony locations.
31. Prey distribution type (All species) See model step 7.	Determines which input type is used	User-defined, could be species-specific	Determined by available data	Uniform or map	NA			NA	This determines whether a density map or an assumption of a uniform distribution is used to model prey distribution. This parameter is determined by available data with a map generated from real-world data being preferred and a uniform distribution option available if such a map does not exist. Results for sensitivity testing for this parameter are presented here.
35. Bird distribution type (All species) See model step 8.	Determines which input type is used	User-defined, could be species-specific	Determined by available data	Distance decay or map	NA			NA	This determines whether a density map or a distance decay function is used to select foraging locations for birds. This parameter is determined by available data with a map generated from real-world data being preferred and a distance decay relationship option available if such a map does not exist. Results for sensitivity testing for this parameter are presented here.
44. Wind farm footprints (All species) See model step 9.	The location of the wind farms	User-defined, same for all species	Based on data from developers	Default is four arbitrary shapes created for demonstration purposes	NA		0	NA	The wind farm footprint is user-defined and should represent the area up to the outermost turbines. (The displacement border will add an additional margin within which birds may still experience displacement). Results for sensitivity analysis for this parameter are presented here.
51. Barrier navigation method (All species) See model step 10.	Used to determine the flight path of barriered birds	User-defined, could be species-specific	Truth likely to be somewhere between the two.	Either Perimeter or A* pathfinding	NA			NA	This is a user-defined parameter and determines the way in which barriered birds pass around the footprint of the offshore wind farm. An A* navigation path (identified using an algorithm which finds the shortest path between two locations) is more energy efficient and more likely for birds that have previously experienced the ORD whereas a perimeter approach may be more representative of birds encountering the OWF for the first time. Results for sensitivity analysis for this parameter are presented here.

Source: Natural Power

6. Sensitivity analysis

6.1. Aims

The aim of the sensitivity analysis was to determine which parameters are the main drivers of predicted mortality rates output by the model, within the realistic range that those parameters might be expected to take. Sensitivity analysis was prioritised according to the confidence index presented in Table 5.1, with those parameters with highest uncertainty being tested first. In many cases, testing sensitivity of assumptions would have involved re-writing of the model code whilst ensuring the elimination of any unintended knock-on effects for other steps in the model. Since a prohibitive amount of time would be required to carry out a full code review, it was not considered that such updates could be made without a degree of uncertainty as to how exactly the changes might have impacted upon the overall logic underlying the model. For this reason, sensitivity of these assumptions was not tested, meaning that several elements of the model remain unexamined.

6.2. Methods

Sensitivity analysis was carried out by varying individual parameters within a single "default" scenario, selected to be consistent with analysis carried out by Searle *et al*. 2020. In this case, the effects of a single wind farm footprint were considered. The footprint selected was identical to the footprint labelled "OWF_4" in Searle *et al*. 2020. The seabORD tool was used to test the effects of displacement and barrier effects from this hypothetical wind farm footprint upon kittiwake at the St. Abb's Head to Fast Castle Special Protection Area (SPA), since this was the SPA for which the largest impacts were predicted.

It should be noted that due to the complexity of the model, the sensitivity of any given parameter is likely to vary depending on the other inputs used. As a simple illustration, the impact of the proportion displaced will vary depending on the density of birds predicted to occur within the wind farm footprint, the total number of birds as determined by colony size, the size of the border and buffer, and the prey distribution within the buffer region. As another example, in our specific scenario, no effect of the mass at which adults abandoned their chicks on chick survival was found, up until a threshold value at which point chick survival started to decline. Until that threshold value, chick mortality was likely driven either by predation or exposure resulting from its parents spending less time at the colony, or by starvation, both of which are governed by a separate suite of parameters and assumptions.

Two sets of sensitivity tests were carried out. The first set used the downloaded seabORD application (running version 1.3 of the seabORD model) and tested sensitivity to user-definable input parameters. Use of the application does not require the user to have the MATLAB licenses required to run the underlying code. The second set used the MATLAB code provided for version 1.2 of the seabORD model, and tested sensitivity to parameters that cannot be edited using the seabORD application. The differences among the two versions of seabORD (v1.2 and v1.3) are minimal. The documentation for version 1.3 described only two differences between the two versions (Mobbs et al. 2018). The first is that the method for reading in shapefiles in version 1.3 has been updated to allow for missing data fields which were required in version 1.2 but were not used by the model, and the second is a change to the way the "zones map" (one of the maps displayed during a model run) is displayed. These changes do not affect the way in which the model runs so it would not be expected to cause substantial differences among the two outputs. In order to test this, the default scenario was run in both version 1.2 (run within MATLAB) and version 1.3 (run through the GUI) and compared the predicted mortality rates. Chick mortality rates were almost identical among the two methods. Adult survival was slightly lower, and there was more variability in replicate runs when using version 1.3 implemented within the GUI than version 1.2 implemented within MATLAB (Table 6.2, row 1).

The methodology used for sensitivity testing was identical for all parameters. The default scenario was run initially to determine a default estimate to which subsequent runs could be compared. For each subsequent scenario, a single parameter was varied at a time whilst all other parameters remained constant. For example, to determine the sensitivity of the model to the proportion of birds that are barriered, this value was varied while all others remained the same as those used in the default. For several parameters for which the new values resulted in altered baseline chick mortality and/or end-of-season adult mass metrics, a second set of sensitivity analyses were run in which prey values were recalibrated so that the baseline chick survival and adult mass matched, as closely as possible, those of the baseline in the default model, to allow sensitivity to be assessed in the context of the real world usage of the model.

Alternative values used for sensitivity testing were based on the literature review described in Section 5 such that all values could be considered to fall within the biologically plausible range. Where no information existed to inform alternative parameter values, these values were varied by 10% either way with the exception of energy costs which were varied by 5% either way.

The seabORD tool allows the user to specify a "seed" value which causes stochastic processes in the model to remain fixed among runs, meaning that they can be directly compared. This feature was used to reduce the number of runs that were needed to be able to identify the effect of the changes made. For each value of a parameter, the model was run 5 times specifying each of 5 pre-selected seed values which were chosen haphazardly.

The values used in the default runs are outlined in Table 6.1.

Runs were conducted with a small proportion (10%) of the total population simulated (Table 6.1). In trial runs during which proportions of the population ranging from 5% to 20% were simulated, it was found that point estimates were more or less consistent. For example, the average point estimate for adult additional mortality in a "good" year varied non-directionally between 0.93 - 1.31% for estimates based on between 5 and 20% of the population simulated and estimates were well within one another's 95% confidence limits. Therefore, it was deemed that modelling a low proportion of the population was a suitable approach to reduce run time and allow assessment of a greater number of parameters. The developers of seabORD recommend simulating as large a proportion of the population as is feasible (Searle *et al*. 2018); however, the default value within the software remains 25%. While this does increase confidence in point estimates, the main reason to maximise the proportion simulated when running the tool for assessments is that it allows for a better quantification of uncertainty. During trial runs, uncertainty around point estimates decreased with increasing percentages of the population that were simulated, for example standard errors reduced from 3.13 when 5% of the population was simulated, down to 0.67 when 20% of the population was considered.

When the tool is used in the real world, prey density is provided as an upper and lower bound defining the range of prey densities that generate "moderate" survival outcomes in the baseline runs to which the impact scenarios will be compared. This is to allow simulation of the range of outcomes expected under these conditions, as the model is highly sensitive to the prey density parameter (Searle *et al*. 2018). However, incorporating a range of prey values would require multiple runs to be carried out per parameter, value and seed combination which would have dramatically increased the amount of time required to test each parameter. Therefore, we set the upper and lower bounds as the same value, the mid-point of the values used in the seabORD worked example (Mobbs *et al*. 2018), which generates a "moderate" baseline scenario using our default parameters.

Default parameters were based on those used in Searle *et al*. 2020 (Table 6.1).

Table 6.1: Parameters used for the default model

Parameter	Value used
Colony data file	Default data downloaded with the seabORD application (birds from all four colonies were included in the simulations)
Species	Kittiwake
Site selection method	Map
Underlying bird distribution map	Default kittiwake density data downloaded with the seabORD application (Figure 4.1)
Probability of being displaced	0.3
Probability of being barriered	1.0
Barrier avoidance method	Perimeter
Offshore wind farm footprint	“OWF_4” from Searle *et al*. 2020
Border (km)	2
Buffer (km)	5
Prey distribution type	Map
Prey distribution map	Default kittiwake prey density data downloaded with the seabORD application (Figure 4.1)
Upper prey density	166 grams per unit volume
Lower prey density	166 grams per unit volume
Proportion of population(s) simulated	0.1
Number of matched pair runs	1
Starting random number seed	52,19873,1990, 999, 124155

Source: Natural Power

To assess sensitivity of the model to variations in parameters, three metrics were used to compare among runs. Additional chick mortality (expressed as a percentage of the total number of chicks) was used to assess the impact to chicks, and additional adult mortality assuming a ‘good’ and a ‘moderate’ winter (as a percentage of the total population size) were used to assess the impact on adults. Metrics relating to a ‘moderate’ winter would usually be used for assessment. All outputs relate to the colony at St. Abb’s Head SPA, as this colony experienced the greatest predicted impact in the scenario tested. It is important to note that additional mortality from the seabORD model is not directly comparable to the mortality rates used in the displacement matrix as they do not relate to the subset of birds that are present within the wind farm footprint during a “snapshot” (see Section 4.4).

In order to get an indication of the potential implications of parameter sensitivity on predicted snapshot mortality rates, the snapshot functionality was used to calculate the mortality rate for displaced birds occurring within snapshot surveys, similar to that used in the displacement matrix with the number of birds observed in the simulated snapshots to derive the simulated additional mortality rates. This was carried out for the interference coefficient parameter. Snapshots could not be carried out with the wind farm footprint “switched off” as described in the user guide as the tool does not allow snapshot days to be selected under those conditions, so runs were carried out in “multiple mode” with the wind farm footprint switched on. Since the P2 metric and the metrics included in the sensitivity testing are based on the same underlying mortality rates, the sensitivity of the metrics (in terms of percentage change) will be similar (but not identical since P2 includes birds from all colonies, whilst those used for sensitivity testing relate only to birds from St Abbs Head).

6.3. Results

Results of the sensitivity testing are presented in Table 6.2 and an overview of the results in Figure 6.1, Figure 6.2 and Figure 6.3.

Use of the snapshot functionality of the model for the interference parameter demonstrated a huge range in predicted mortality rates among parameter values (from 1% to more than 50% when the interference coefficient was varied between 0.01 and 0.04, Table 6.3).

Table 6.2: **Results of sensitivity testing, showing percentages of additional mortality (AM) for chicks and adults in a "good" year (when baseline adult survival matxches that expected in a year with conditions most conducive to survival – see parameter 81) as well as percent change in this metric from the default model. Estimates derived from the default parameter values are indicated with bold text. Numbers in brackets are standard errors.**

	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
Parameter	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	Comments
Software baselines	MATLAB running v1.2	GUI running v1.3		**5.1 (1.3)**	**0.0**	**5.1 (0.9)**	**0.0**			**1.6 (0.3)**	**0.0**	**1.9 (0.5)**	**18.8**			**1.2 (0.2)**	**0.0**	**0.9 (0.3)**	**-19.8**			Chick survival is almost identical among the two methods of implementing the seabORD model. Adult survival differs when running the GUI versus the MATLAB code.
5a. Minimum time spent resting on sea (All species) (MATLAB)	0.5	**1.0**	2.0	0.7 (0.4)	-86.2	**5.1 (1.3)**	**0.0**	9.5 (0.9)	86.4	1.2 (0.2)	-28.4	**1.6 (0.3)**	**0.0**	0.1 (0.5)	-92.6	0.8 (0.2)	-32.5	**1.2 (0.2)**	**0.0**	0.2 (0.4)	-80.8	These parameter values were chosen as they are considered to be within the biologically plausible range of values. The minimum time spent resting on sea appears to be a sensitive parameter, with a decrease of half an hour per 24 hours leading to a decrease in additional chick mortality of 86%, due to the increased amount of time available to the adults for foraging, and an hour increase leading to an 86% increase due to the reduced amount of time adults had available to forage. Both scenarios resulted in lower predicted additional adult mortality.
5b. Minimum time spent resting on sea (All species) – calibrated prey (MATLAB)	0.5	**1.0**	2.0	5.22 (1.11)	2.4	**5.1 (1.3)**	**0.0**	6.3 (0.5)	22.7	1.5 (0.3)	-6.8	**1.6 (0.3)**	**0.0**	1.1 (0.5)	-6.8	1.16 (0.2)	-3.3	**1.2 (0.2)**	**0.0**	1.5 (0.4)	25.8	When calibrated, sensitivity of this parameter decreases. There is little impact of reducing the minimum time spent resting on sea by half an hour but increasing it by an hour does increase both chick and adult mortality rates in a good year as the adult has less time to dedicate to foraging.
12. Proportion of initial mass below which adult abandons chick	0.72	**0.80**	0.88	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.8 (0.8)	13.7	1.6 (0.3)	0.0	**1.6 (0.3)**	**0.0**	1.5 (0.4)	-6.8	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.0 (0.3)	-10.3	As no alternative parameter values were available, this parameter was varied by 10% either way of the default. This parameter is not sensitive at the low to intermediate level because chick death is occurring before the adult reaches these thresholds (either due to

Parameter	Parameter value low/ 1	Parameter value mid/ 2	Parameter value high/ 3	Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
				AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
(MATLAB)																						exposure/predation or to chick starvation). If the threshold is increased, chick mortality increases as would be expected. Adult mortality reduces if the adult abandons the chick at a higher threshold of its initial starting weight.
13. Proportion of initial mass below which adult is assumed dead (MATLAB)	0.54	**0.6**	0.66	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	0.0	1.6 (0.3)	0.0	**1.6 (0.3)**	**0.0**	1.6 (0.3)	0.0	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	Parameter values were selected based on 10% variation in either direction. Varying this value had no impact on estimates. This is because in this scenario, adult mortality is entirely driven by over-winter survival which is determined by a different set of parameters. Adult mortality is usually extremely low during the chick-rearing period in nature (Searle *et al.* 2018). Calibration is not required for this parameter since there is no change to the baseline.
16. Prey quantity (GUI)	158	**166**	170	6.7 (1.0)	32.0	**5.1 (0.9)**	**0.0**	1.2 (0.7)	-77.3	0.0 (0.2)	-100	**1.9 (0.5)**	**0.0**	1.9 (0.3)	0.0	-0.1 (0.4)	-112.9	**0.9 (0.3)**	**0.0**	1.3 (0.3)	42.0	This range covers all prey values resulting in a "moderate" baseline scenario for kittiwake at St. Abb's Head. As has been observed by Searle *et al*. (2014; 2018) this parameter is extremely sensitive to the point that it must be calibrated prior to running an assessment. Within the moderate range, chick mortality decreases with increasing food abundance as would be expected. Adult mortality is highest at the highest prey quantity. (See discussion in section 7.2).
23. Assimilation efficiency (MATLAB)	0.67	**0.74**	0.81	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	0.0	1.6 (0.3)	0	**1.6 (0.3)**	**0.0**	1.6 (0.3)	0.0	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	Parameter values tested were selected based on 10% variation in either direction. This parameter determines how efficiently a bird converts the energy present within food into energy that it can access. This should be a

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
																						sensitive parameter but appears to do nothing within this range. However, if reduced as far as 0.5 then baseline chick deaths increase dramatically.
27. Percent population susceptible to displacement (GUI)	10%	20%	**30%**	1.6 (0.3)	-68.2	3.0 (0.6)	-40.8	**5.1 (0.9)**	**0.0**	0.5 (0.3)	-75.3	1.3 (0.6)	-31.2	**1.9 (0.5)**	**0.0**	0.5 (0.2)	-50.5	0.9 (0.2)	0.0	**0.9 (0.3)**	**0.0**	Parameter values tested here are considered to be within the range of biologically plausible values – the default 30% displacement rate is considered to be high for this species (see confidence score for parameter 27). This parameter can be edited by the user and recommendations are regularly reviewed and updated based on new evidence. The value is also the same as that used within the displacement matrix. Therefore, this is not a key priority for the sensitivity analysis. As expected, mortality of both adults and chicks decrease when displacement rate is decreased.
28. Percent population displaced also susceptible to barrier effects (GUI)	90%	95%	100%	5.3 (1.1)	4.7	3.3 (1.3)	-36.3	**5.1 (0.9)**	**0.0**	1.7 (0.3)	-6.5	2.0 (0.1)	5.9	**1.9 (0.5)**	**0.0**	0.9 (0.3)	0.0	1.2 (0.2)	24.7	**0.9 (0.3)**	**0.0**	100% is a conservative value and can be updated by the user as new evidence arises. Between 90 and 100% barrier effect there is not a linear relationship with mortality for either adults or chicks. Testing more broadly, additional chick mortality increases almost linearly from 0% to 80% (results not shown).
31a. Prey distribution type (GUI)	Uniform	Map		0.9 (0.3)	-81.8	**5.1 (0.9)**	**0.0**			0.1 (0.4)	-93.5	**1.9 (0.5)**	**0.0**			-0.1 (0.2)	-112.9	**0.9 (0.3)**	**0.0**			In this scenario, mortality rates are lower for both chicks and adults under the assumption of uniform prey compared to use of a density map derived from modelled GPS data. This is likely because the windfarm lies between the colony and the highest densities of prey (see Figure 4.1). This means that when the prey map is used, displaced birds will be more likely to be

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
																						displaced away from the colony and beyond the wind farm such that they will travel further and may also experience barrier effects reaching their new foraging location. Conversely, uniform prey distributions result in higher baseline mortality but lower additional mortality in this scenario. This relationship will depend entirely on the map being used for prey. In the hypothetical scenario where prey is high in the wind farm buffer, the effects of competition resulting from displacement will be reduced. If it is assumed that the prey distribution maps within the Forth and Tay region are an accurate representation, using uniform prey distributions does not seem to be an appropriate assumption for this scenario.
31b. Prey distribution type – with calibrated prey (GUI)	Uniform	**Map**		1.9 (0.7)	-63.5	**5.1 (0.9)**	**0.0**			0.9 (0.4)	-50.0	**1.9 (0.5)**	**0.0**			0.4 (0.2)	-62.4	**0.9 (0.3)**	**0.0**			When the model including a uniform prey density is calibrated, sensitivity is reduced but this input is still extremely influential. The uniform prey distribution results in greatly reduced additional mortality than the distribution map. In practice, a uniform prey distribution will generally be used with a distance decay function rather than a prey map. (See below for additional mortality with distance-decay and uniform prey).
34a. Bird distribution type (GUI)	Distance decay and prey map	Distance decay and uniform prey map	Map	0.0 (0.0)	-100.0	0.0 (0.0)	-100.0	**5.1 (0.9)**	**0.0**	0.4 (0.3)	-81.2	-0.1 (0.3)	-106.5	**1.9 (0.5)**	**0.0**	0.2 (0.3)	-75.3	-0.1 (0.1)	-111.1	**0.9 (0.3)**	**0.0**	Using the distance decay function option lowers mortality in this case. However, this pattern will depend on the location and proximity of the offshore development relative to seabird colonies as well as the nature of the underlying map. Assuming that the GPS maps are a good

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
																						representation of prey within the Forth and Tay area for this scenario, the distance decay function does not seem to be an appropriate assumption.
34b. Bird distribution type – with calibrated prey	Distance decay and prey map	Distance decay and uniform prey	Map	0.0 (0.0)	-100.0	2.1 (0.3)	-58.8	**5.1 (0.9)**	**0.0**	0.0 (0.1)	-100.0	0.5 (0.2)	-75.3	**1.9 (0.5)**	**0.0**	0.0 (0.1)	-100.0	0.2 (0.2)	-96.1	**0.9 (0.3)**	**0.0**	Calibrating the prey values for the distance decay model results in an even greater decrease in adult mortality than when run with the GPS maps in this case. In the real world, the distance decay function will be used in conjunction with the assumption of uniform prey rather than using a prey distribution map. When run in this way, mortality rates are still lower than the default scenario but are significantly higher than when using the prey map.
44. Wind farm footprints (MATLAB)	North	**Default location**	West	4.9 (1.0)	-4.5	**5.1 (1.3)**	**0.0**	6.5 (1.7)	27.5	1.3 (0.4)	-21.0	**1.6 (0.3)**	**0**	2.0 (0.7)	21.6	1.0 (0.2)	-10.3	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	The shapefile for the windfarm was nudged by 5km to the North and West to determine how sensitive results were to wind farm placement. In this case, these relatively small changes in position did affect mortality estimates. However, the sensitivity of this parameter will be determined by the location of the wind farm relative to prey sources and the colony in question.
45. Size of footprint border (additional displacement zone) (GUI)	0.05	1.00	**2.00**	2.6 (0.9)	-50.0	4.6 (1.3)	-9.0	**5.1 (0.9)**	**0.0**	1.4 (0.3)	-25.3	1.5 (0.4)	-18.8	**1.9 (0.5)**	**0.0**	0.6 (0.2)	-37.6	0.9 (0.2)	0.0	**0.9 (0.3)**	**0.0**	As expected, the wider the border from which birds are assumed to be displaced, the greater the additional mortality for both chicks and adults.
46. Size of footprint buffer (area	4.5	**5.0**	7.0	5.8 (1.0)	13.7	**5.1 (0.9)**	**0.0**	6.5 (1.1)	27.5	1.6 (0.4)	-12.9	**1.9 (0.5)**	**0.0**	1.4 (0.5)	-25.3	1.0 (0.2)	11.8	**0.9 (0.3)**	**0.0**	1.2 (0.4)	24.7	Both increasing and decreasing the size of the buffer into which birds can be displaced resulted in increased

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
Parameter	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	Comments
birds are displaced to) (GUI)																						chick survival and adult survival in a god year and decreased adult survival in a moderate year. The implications of this parameter for survival rates are complicated and appear to be unpredictable.
51. Barrier navigation method (GUI)	A* path-finding	**Perimeter**		3.9 (0.8)	-22.7	**5.1 (0.9)**	**0.0**			1.3 (0.4)	-31.2	**1.9 (0.5)**	**0.0**			0.9 (0.2)	0.0	**0.9 (0.3)**	**0.0**			Use of the more efficient A* pathfinding barrier navigation method to avoid he windfarm footprint decreases chick additional mortality and adult additional mortality in a moderate year compared with perimeter navigation. Model runtime increases considerably when the A* pathfinding algorithm is used due to the computationally intensive nature of the algorithm so there are practical considerations associated with selecting this option for full runs.
54a. Bird flight speed (MATLAB)	8.71	10.8	**13.1**	0.0 (0.0)	-100.0	0.0 (0.0)	-100.0	**5.1 (1.3)**	**0.0**	-0.4 (0.4)	-121.6	-0.1 (0.1)	-107.4	**1.6 (0.3)**	**0.0**	-0.1 (0.3)	-110.3	0.1 (0.2)	-89.7	**1.2 (0.2)**	**0.0**	The lowest value tested here represents a more defensible value from the literature and an intermediate value has also been tested. Intuitively, the faster the flight speed, the lower the mortality should be (since energy costs would be assumed to be the same so time is the limiting factor). However, here, the opposite is true. For chicks, this is because flight speed has a large impact on the baseline model (not shown) such that there are no chicks left to contribute to additional mortality associated with the development. Adult mortality also reduces, probably also due to the changes in the baseline relative to the impact scenarios. (See Section 7.2)
54b. Bird flight speed	8.71	10.8	**13.1**	4.9 (1.1)	-4.5	5.8 (1.1)	13.7	**5.1 (1.3)**	**0.0**	2.2 (0.5)	35.8	1.6 (0.8)	0.0	**1.6 (0.3)**	**0.0**	1.4 (0.3)	15.8	0.9 (0.4)	-22.5	**1.2 (0.2)**	**0.0**	The mid scenario (10.8 m/s average flight speed) should be considered with care here, as simulations would not

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
(MATLAB) – with calibrated prey																						complete for two seeds for unknown reasons and estimates are therefore based on 3 seeds only. It is unclear why these seeds did not complete. Flight speed becomes much less sensitive when the model is calibrated.
56. Maximum intake rate (MATLAB)	3.932	**4.369**	4.806	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	0.0	1.6 (0.3)	0.0	1.6 (0.3)	0.0	**1.6 (0.3)**	**0.0**	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	Parameter values tested represent a 10% increase and decrease from the default value. Altering the maximum intake rate appears to have no effect on additional mortality estimates.
59a. Interference coefficient (m) (MATLAB)	0.01	**0.02**	0.04	2.1 (0.8)	-59.0	**5.1 (1.3)**	**0.0**	8.4 (1.2)	63.7	1.9 (0.3)	14.8	**1.6 (0.3)**	**0.0**	0.6 (0.4)	-64.2	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	0.4 (0.3)	-69.8	Interference competition appears to be a highly sensitive parameter determining chick survival and, especially at higher values, adult mass at the end of the chick-rearing season. The derivation of this parameter is vague (see comments for parameter 59) and the model documentation suggests that during model development, the intake rate was parameterised to match observed numbers and lengths of foraging trips within the time step periods prior to incorporation of competition effects into the algorithm. Therefore, there is low confidence in this parameter.
59b. Interference coefficient (m) – with calibrated prey (MATLAB)	0.01	**0.02**	0.04	5.1 (0.9)	0.0	**5.1 (1.3)**	**0.0**	4.4 (0.8)	-13.5	1.6 (0.3)	0.0	**1.6 (0.3)**	**0.0**	1.7 (0.2)	7.4	1.2 (0.3)	0.0	**1.2 (0.2)**	**0.0**	1.0 (0.3)	-10.3	With calibrated prey, the interference coefficient becomes much less sensitive. This is unsurprising as increasing prey quantity should counter the effects of increasing competition.
66. Time spent unattended leading to	14	**18**	20	6.3 (1.0)	22.7	**5.1 (1.3)**	**0.0**	4.6 (1.3)	-9.0	1.9 (0.5)	14.8	**1.6 (0.3)**	**0.0**	1.6 (0.3)	0.0	1.3 (0.2)	10.3	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	Values here were chosen because they are considered to be biologically plausible. Chick survival is sensitive to this parameter, which not only

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
chick death through exposure (MATLAB)																						determines the absolute threshold resulting in death, but also the slope of the relationship between unattendance and death. Since chicks appear to die of exposure or predation rather than adult abandonment of the breeding attempt, this parameter will also affect the sensitivity of other parameters that are currently not sensitive.
69. Proportion of fully provisioned mass below which chick is assumed dead (MATLAB)	0.54	**0.60**	0.66	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	0.0	1.6 (0.3)	0.0	**1.6 (0.3)**	**0.0**	1.6 (0.3)	0.0	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	Values tested for this parameter are 10% either side of the default value. There was no effect of changing this threshold within the range of values tested.
73a. Energy cost of flight (MATLAB)	1330.70	**1400.74**	1470.78	3.5 (0.5)	-31.8	**5.1 (1.3)**	**0.0**	7.9 (0.7)	54.7	1.7 (0.4)	7.4	**1.6 (0.3)**	**0.0**	1.6 (0.5)	0.0	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	0.8 (0.2)	-30.2	Values for this parameter are 5% either side of the default value. The energy cost of flight appears to be a sensitive parameter, with additional mortality of chicks raising by approximately 2% of the population with each 5% increase in the parameter.
73b. Energy cost of flight (MATLAB) – with calibrated prey	1330.70	**1400.74**	1470.78	3.5 (0.5)	-31.8	**5.1 (1.3)**	**0.0**	6.3 (0.7)	22.7	1.7 (0.4)	7.4	**1.6 (0.3)**	**0.0**	1.6 (0.4)	0.0	1.2 (0.2)	0.0	**1.2 (0.2)**	**0.0**	1.04 (0.1)	-13.3	Calibration reduces sensitivity at the higher value but not at the lower value.
74a. Energy cost of foraging (MATLAB)	1330.70	**1400.74**	1470.78	2.6 (0.6)	-50.0	**5.1 (1.3)**	**0.0**	9.3 (0.8)	82.0	2.0 (0.2)	21.6	**1.6 (0.3)**	**0.0**	1.0 (0.4)	-35.8	1.3 (0.3)	10.3	**1.2 (0.2)**	**0.0**	0.8 (0.2)	-30.2	The costlier foraging is, the higher the chick mortality rate, as the adult will have a higher DER to achieve each day. Since deficit is split 50:50 between the chick and the adult, the chick will receive less food for the same overall energy gained if the adults DER is

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
																						higher. Adult mortality rate decreases, probably due to the changes in the baseline relative to the impact scenarios. (See Section 7.2)
74b. Energy cost of foraging (MATLAB) – with calibrated prey	1330.70	**1400.74**	1470.78	4.87 (1.3)	-4.5	**5.1 (1.3)**	**0.0**	7.19 (1.1)	40.9	1.9 (0.4)	14.8	**1.6 (0.3)**	**0.0**	1.6 (0.2)	0.0	1.16 (0.1)	-3.3	**1.2 (0.2)**	**0.0**	1.04 (0.2)	-13.3	The signal of sensitivity is similar to **74a** with uncalibrated prey, albeit with change to the magnitude of sensitivity. Lower costs of foraging result in a moderate reduction in additional chick mortality, whereas increasing the cost of foraging results in a considerable increase in additional chick mortality.
75a. Energy cost of resting at sea (MATLAB)	380.54	**400.57**	420.60	5.8 (0.5)	13.7	**5.1 (1.3)**	**0.0**	5.3 (0.8)	4.7	1.7 (0.5)	7.4	**1.6 (0.3)**	**0.0**	1.4 (0.4)	-14.2	1.16 (0.2	-3.3	**1.2 (0.2)**	**0.0**	0.93 (0.2)	-22.5	Sensitivity to this parameter within this range is relatively low. This is unsurprising as adults spend relatively little time resting on sea.
75b. Energy cost of resting at sea (MATLAB) – with calibrated prey	380.54	**400.57**	420.60	5.8 (0.5)	13.7	**5.1 (1.3)**	**0.0**	5.34 (0.8)	4.7	1.7 (0.5)	7.4	**1.6 (0.3)**	**0.0**	1.4 (0.4)	-14.2	1.16 (0.2	-3.3	**1.2 (0.2)**	**0.0**	0.93 (0.2)	-22.5	Changing the energy cost associated with resting on sea did not alter the baseline conditions so these results are identical to those above.
76a. Energy cost of attending the colony (MATLAB)	384.97	**427.75**	470.52	1.2 (1.2)	-77.3	**5.1 (1.3)**	**0.0**	8.6 (0.8)	68.2	2.0 (0.2)	21.6	**1.6 (0.3)**	**0.0**	1.3 (0.5)	-21.0	1.0 (0.3)	-10.3	**1.2 (0.2)**	**0.0**	0.7 (0.3)	-39.7	Chick mortality is strongly affected by changing the energy cost associated with attending the colony, with higher additional mortality associated with higher energy costs.
76b. Energy cost of attending the colony (MATLAB) – with calibrated prey	384.97	**427.75**	470.52	5.57 (1.0)	9.2	**5.1 (1.3)**	**0.0**	6.03 (1.2)	18.2	1.5 (0.4)	-6.8	**1.6 (0.3)**	**0.0**	1.9 (0.4)	14.8	0.93 (0.2)	-22.5	**1.2 (0.2)**	**0.0**	1.3 (0.2)	6.7	Calibrating the model reduces the sensitivity of this parameter to chicks but adult additional mortality increases with increasing energy costs associated with attending the colony.

Parameter	Parameter value			Additional chick mortality during the chick-rearing season						Additional adult mortality in a moderate year						Additional adult mortality in a good year						Comments
				low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		low/ 1		mid/ 2		high/ 3		
	low/ 1	mid/ 2	high/ 3	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	AM	% of default	
77. Energy cost of food warming (MATLAB)	0.00	**34.15**	35.86	0.2 (0.4)	-95.5	**5.1 (1.3)**	**0.0**	6.5 (1.6)	27.5	1.2 (0.4)	-28.4	**1.6 (0.3)**	**0.0**	1.6 (0.3)	0.0	1.0 (0.3)	-10.3	**1.2 (0.2)**	**0.0**	1.2 (0.2)	0.0	The energy cost of food warming was tested at 5% above the default value and at 0 (because this cost may already be incorporated in the energy cost of foraging). The model is very sensitive to removing the cost of food warming with both chicks and adults doing better if this parameter is removed.
80a. Strength of association between mass and survival (slope parameter) (MATLAB)	0.00218	0.02009	**0.03800**	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	**0.0**	0.0 (0.1)	-100	0.7 (0.3)	-56.8	**1.6 (0.3)**	**0.0**	0.0 (0.1)	-100.0	0.2 (0.3)	-80.8	**1.2 (0.2)**	**0.0**	The relationship between the slope parameter for overwinter survival and adult mortality appears sensible, with steeper slopes resulting in higher additional adult mortality. Chick survival is unaffected as this parameter is only involved in calculation of adult survival rates.
80b. Strength of association between mass and survival (slope parameter) (MATLAB) – with calibrated prey	0.00218	0.02009	**0.03800**	5.1 (1.3)	0.0	**5.1 (1.3)**	**0.0**	5.1 (1.3)	**0.0**	0.0 (0.1)	-100	0.7 (0.3)	-56.8	**1.6 (0.3)**	**0.0**	0.0 (0.1)	-100.0	0.2 (0.3)	-80.8	**1.2 (0.2)**	**0.0**	The overwinter survival slope is used by the model at the end of the season, and therefore does not impact the metrics used to calibrate the prey levels (chick survival and adult mass loss during the chick-rearing period). These results are therefore identical to the above.

Source: Natural Power

Source: Natural Power

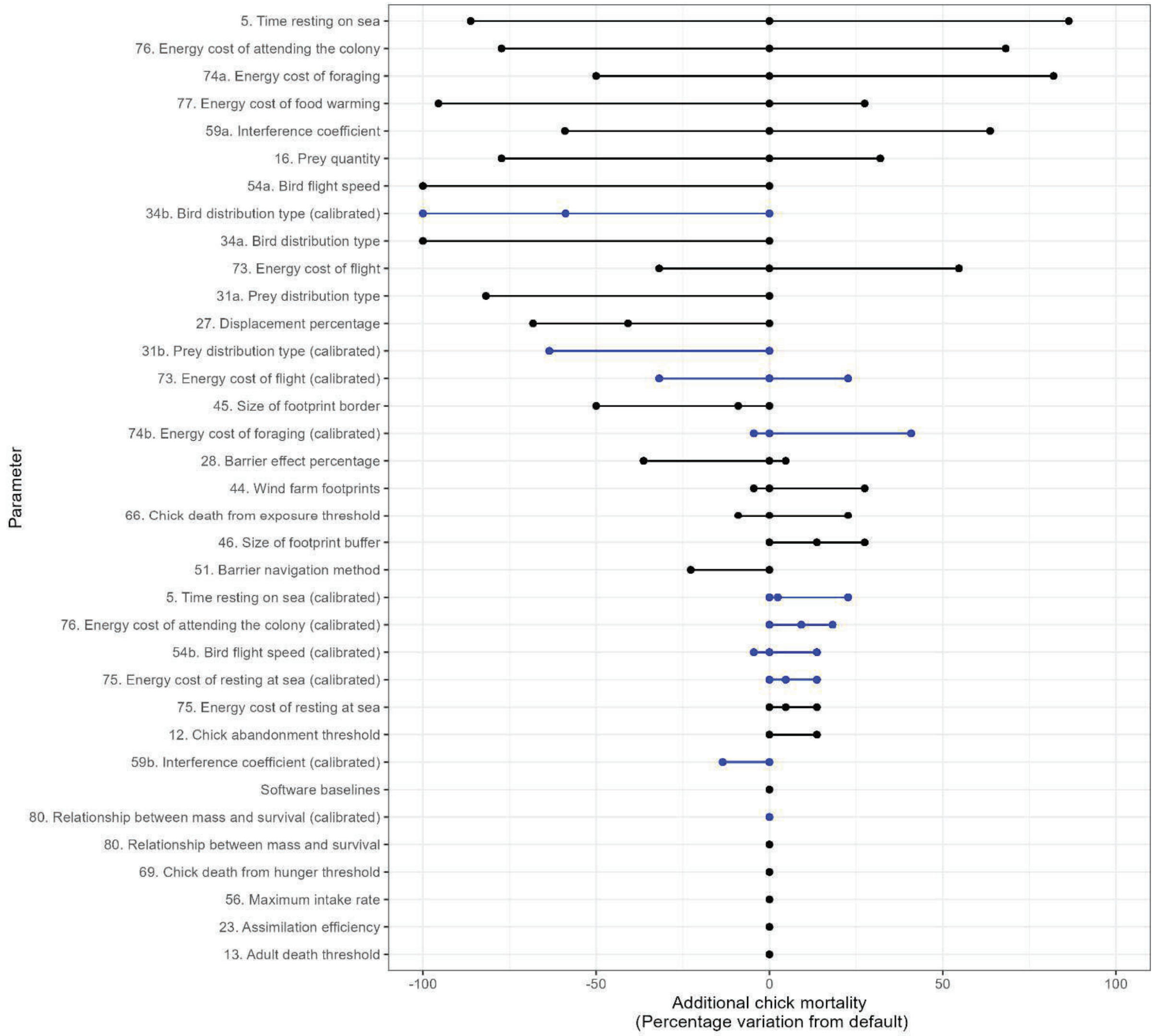

Figure 6.1: Change in additional mortality of chicks for parameters and parameter values tested during sensitivity analysis. Blue lines indicate analyses for which prey density has been calibrated for each input value. Detailed results per parameter are presented in Table 6.2

Source: Natural Power

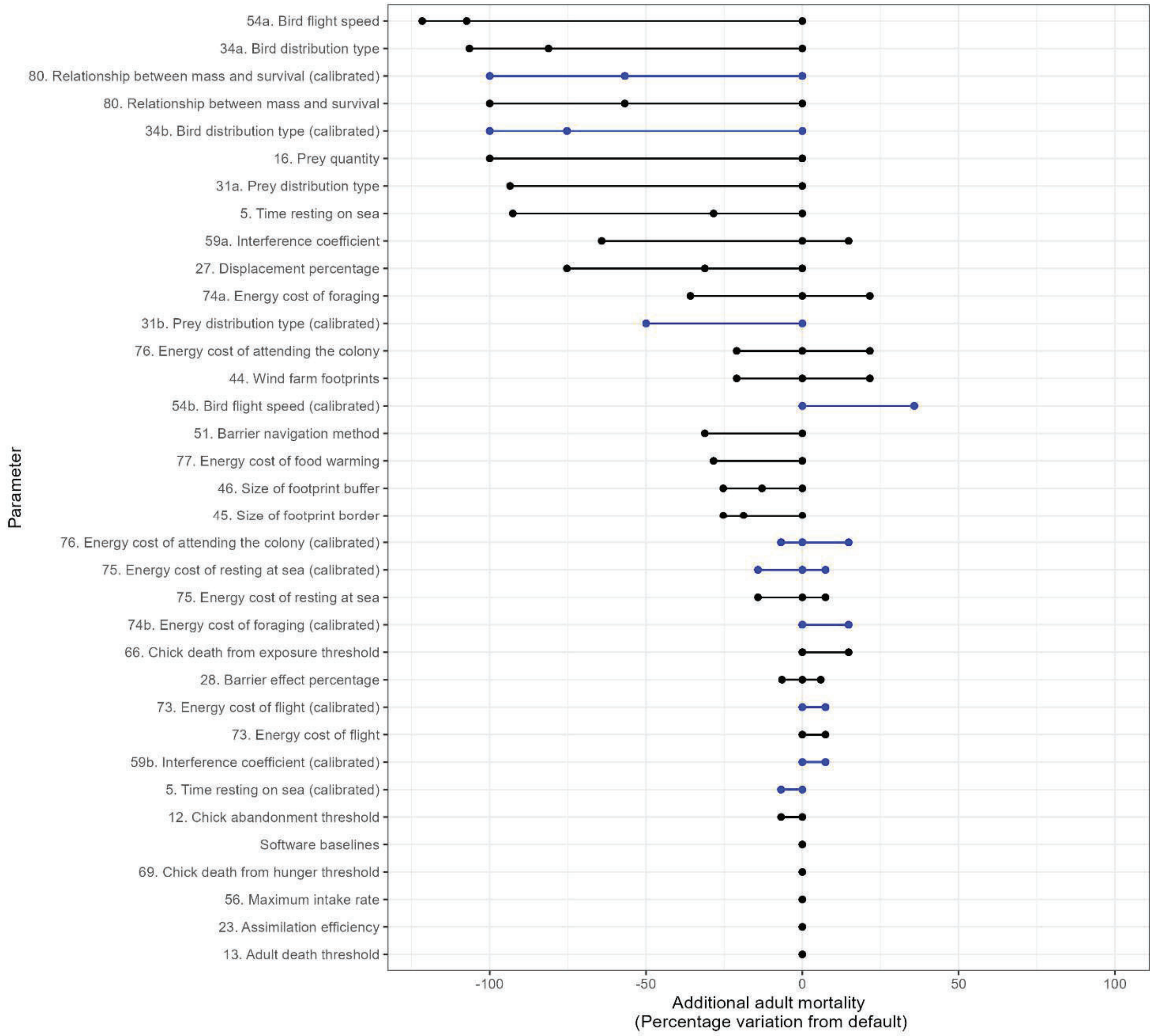

Figure 6.2: Change in additional mortality of adults assuming a "moderate" winter for parameters and parameter values tested during sensitivity analysis. Blue lines indicate analyses for which prey density has been calibrated for each input value. Detailed results per parameter are presented in Table 6.2

Source: Natural Power

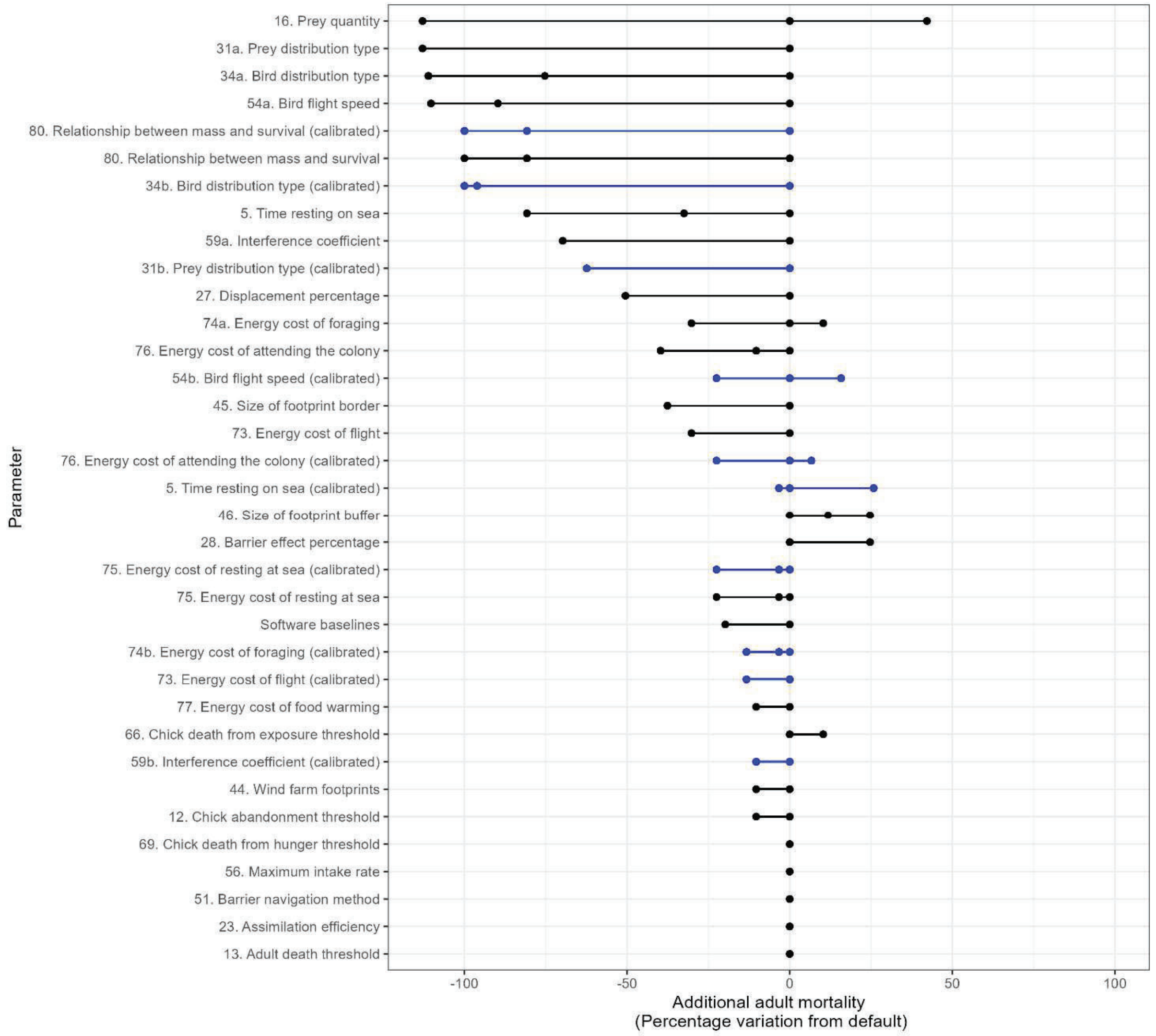

Figure 6.3: Change in additional mortality of adults assuming a "good" winter for parameters and parameter values tested during sensitivity analysis. Blue lines indicate analyses for which prey density has been calibrated for each input value. Detailed results per parameter are presented in Table 6.2

Table 6.3: Mortality rates predicted from snapshot surveys. P2 is calculated as the total mortality with the wind farm minus the total mortality without the wind farm divided by the number of birds in snapshot. (Note that mortality includes all colonies whereas numbers presented in Tables above relate only to St Abbs Head)

Parameter value	Birds in snapshot	P2 metric	Displacement rate	Mortality rate
Low impact of competition (interference coefficient = 0.01)	91.0	0.00	0.30	0.01
Default model (interference coefficient = 0.02)	92.3	0.15	0.30	0.51
High impact of competition (interference coefficient = 0.04)	93.3	0.16	0.30	0.54

Source: Natural Power

7. Validity and applicability of seabORD tool for offshore wind farm assessment

7.1. Use of precaution within the model

The modelling approach underlying the seabORD tool has been extensively developed with the aim of predicting the potential effects of displacement and barrier effects from offshore wind farms upon the survival of seabirds at colonies of interest. There has been considerable thought put in to trying to replicate the processes underlying the energetics of the species covered and parameterising these appropriately, and the model provides a framework to understand how these factors may interact to cause different effects on the individuals and populations affected by the development of offshore wind farms. The model is based around the principals underlying the ecology and behaviour of seabirds and where possible, parameter values are taken from publicly available literature or from data accessible to the authors. However, the model necessarily incorporates a number of simplifications in order to keep the run-time down and a number of assumptions where evidence to support a more refined mechanism is unavailable. Where simplifications or assumed parameters are used, a precautionary approach is generally taken. This occurs at a number of points during the modelling process, for example:

- that adults do not change their feeding location within time steps even if the foraging conditions are poor
- that habituation or learned avoidance of the wind farm area at a large spatial scale, i.e. a change in forage location choice based on having previously encountered the wind farm, is assumed not to occur
- that birds are not able to accrue more energy within a time step than is required to replace the energy used in the previous timestep, i.e. no adult mass gain
- that adults are not able to compensate for time unattended, or deficit in energy provided to their chick by their partner

Coupled with precaution in the user-defined parameter values recommended by regulators and their advisors, for example, for displacement rates and the proportion of displaced birds barriered, this will result in an accumulation of precaution such that while each individual assumption may make a small impact on the outcomes of the model, the cumulative impact of these simplifications will be much greater. We note that the assumption that birds are equally likely to spend time foraging at any time within a 24-hour period will favour survival over a more realistic assumption that birds do not spend as much time foraging at night. However, the level of precaution in the model overall will almost certainly outweigh this source of reduced conservatism.

The way in which "cumulative precaution" is treated has been a recurring topic of concern in the assessment of impacts of offshore wind farms due to the understanding that such conservatism can become an unnecessary barrier to developments. The more complex the modelling approach used to make such assessments, the more opportunities there are for accumulation of conservatism, and an understanding of the magnitude and potential impacts of this conservatism on model outputs is necessary context with which to view the results.

7.2. Factors determining adult survival in the model

The matrix approach to displacement assessment focuses solely on predicting mortality of breeding adults arising from displacement and barrier effects. In the scenario that was selected for the sensitivity analysis of the seabORD model presented here, adult mortality appeared to be entirely driven by the mass of each bird at the end of the chick-rearing period and the relationship between that and over-winter survival, rather than by direct adult mortality during the chick-rearing period. Parameters determining this relationship (the slope parameter and the baseline over-winter survival probabilities) are therefore key in determining overall adult mortality levels. There is a lot of uncertainty around the slope parameter, highlighted by a recent and more applicable study which suggested that the slopes of these relationships are a lot shallower than those assumed in the published seabORD model, and that the association between mass and survival may be weak for guillemot, razorbill and kittiwake, at least for the Forth and Tay region (Daunt *et al*. 2018; Figure 7.1). Indeed, one of the key recommendations of the authors for future improvement of the seabORD tool is incorporation of these updated parameter values (Searle *et al.* 2022). In the scenario tested here, additional adult mortality reduced to zero using the updated slope parameter and by more than 80% using an intermediate value, suggesting that uncertainty around this parameter severely reduces confidence in the adult mortality predicted. Since the prey value calibration is based on adult mass at the end of the chick-rearing season rather than final survival rates, calibration is not required to allow comparison among different values. The sensitivity of the model to this parameter strongly supports the recommendation by Searle *et al*. 2022 that this parameter be updated within the model. Uncertainty surrounding the survival rates is difficult to assess since the report from which the adopted baseline survival rates originate was not accessible. These rates were calculated based on populations from the Isle of May so may be representative for the Forth and Tay, but their applicability outside of this region is less certain. A recent study has indicated that breeding colonies of guillemot and razorbill around the Scottish coastline over-winter in distinct locations (Buckingham *et al*. 2022) suggesting that over-wintering conditions may vary significantly. Since, baseline values for these parameters are likely to be extremely site-specific depending on the local abundance of food, climatic conditions and presence of other sources of mortality, the relationship between adult mass and over-winter survival may therefore differ for birds breeding on the East coast of Scotland versus those in the North or West.

Source: Natura Power

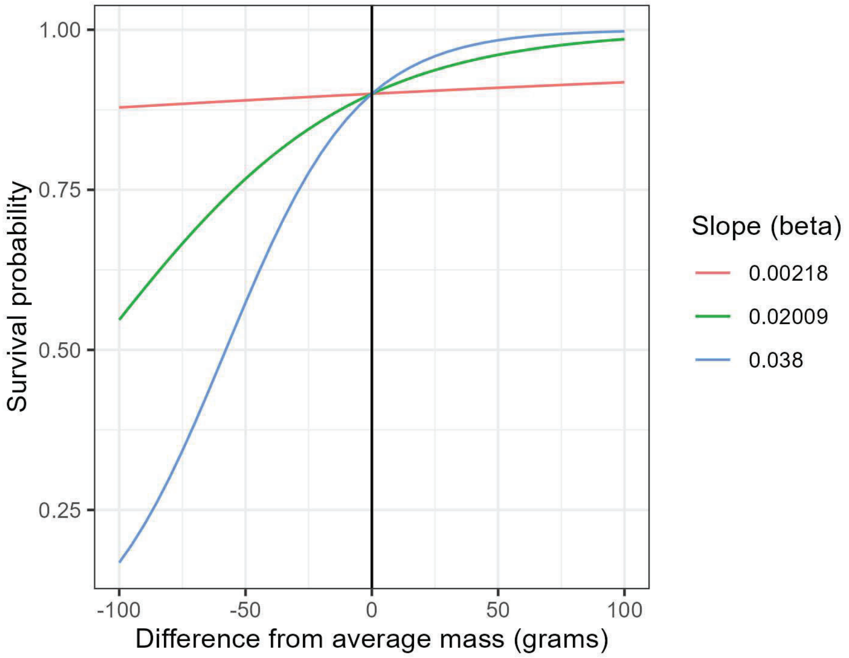

Figure 7.1: **Relationship linking the difference in an adult's end-of-season body mass and the average end-of-season body mass to its over-winter survival probability in a 'good' year. The blue line represents the relationship as implemented in seabORD, and the red uses the updated parameter from Daunt *et al*. 2018. The green line is the intermediate value used in the sensitivity testing.**

Sensitivity testing carried out without re-calibration tended to result in a reduction in additional adult mortality regardless of what parameter value was used, even if the parameter value should theoretically be more conducive for survival than the default value. This is because, as mentioned previously, additional adult mortality was driven by over-winter survival. Over-winter survival probability for each individual is determined as a function of the difference between the mass of each individual at the end of the chick-rearing season and the mass of the average individual in the baseline scenario at the end of the chick-rearing season (see Figure 7.1). The relationship between adult mass and prey value is a reverse sigmoidal curve (Figure 7.2) demonstrating that there is a minimum and maximum possible adult mass loss inherent in the system. The maximum is likely related to the fact that adults cannot achieve more than their target DER per time step. The minimum appears to occur before the point at which adult mass drops below the threshold proportion of their initial mass at which they are assumed to die, since no adult mortality was observed during the chick-rearing season in our simulations. When adding an impact to the model, the curve is shifted to the right (Figure 7.2) meaning that the difference between the two curves (representing the value used in the over-winter survival relationship) is greatest at intermediate prey values and there is no difference at the extremes (Figure 7.3). When the values of input parameters are varied without recalibration to standardise the adult mass loss in the baseline among runs, the baseline will change to a greater or lesser extent with the same effect as shifting the prey input level either to the left or right, explaining why additional mortality may often be lower for parameter values that should promote survival.

Source: Natural Power

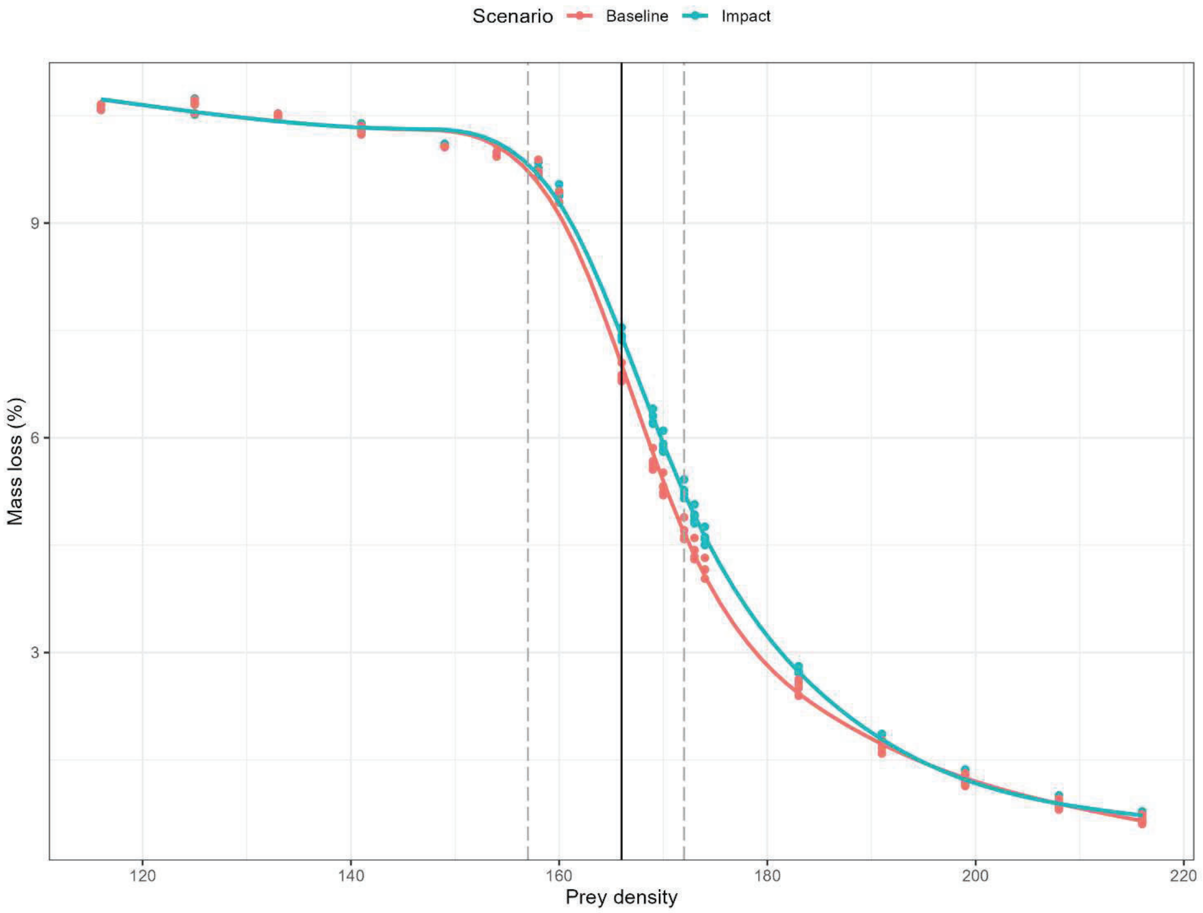

Figure 7.2: **Percent mass loss at the end of the chick-rearing season at different prey densities for the baseline and the impact scenarios. The solid black line represents the prey value used in the default model for sensitivity testing and the dotted lines indicate the 'moderate' range used in prey calibration. Points represent the results for the different seeds run and coloured lines are indicative smooths fit to the data.**

Source: Natural Power

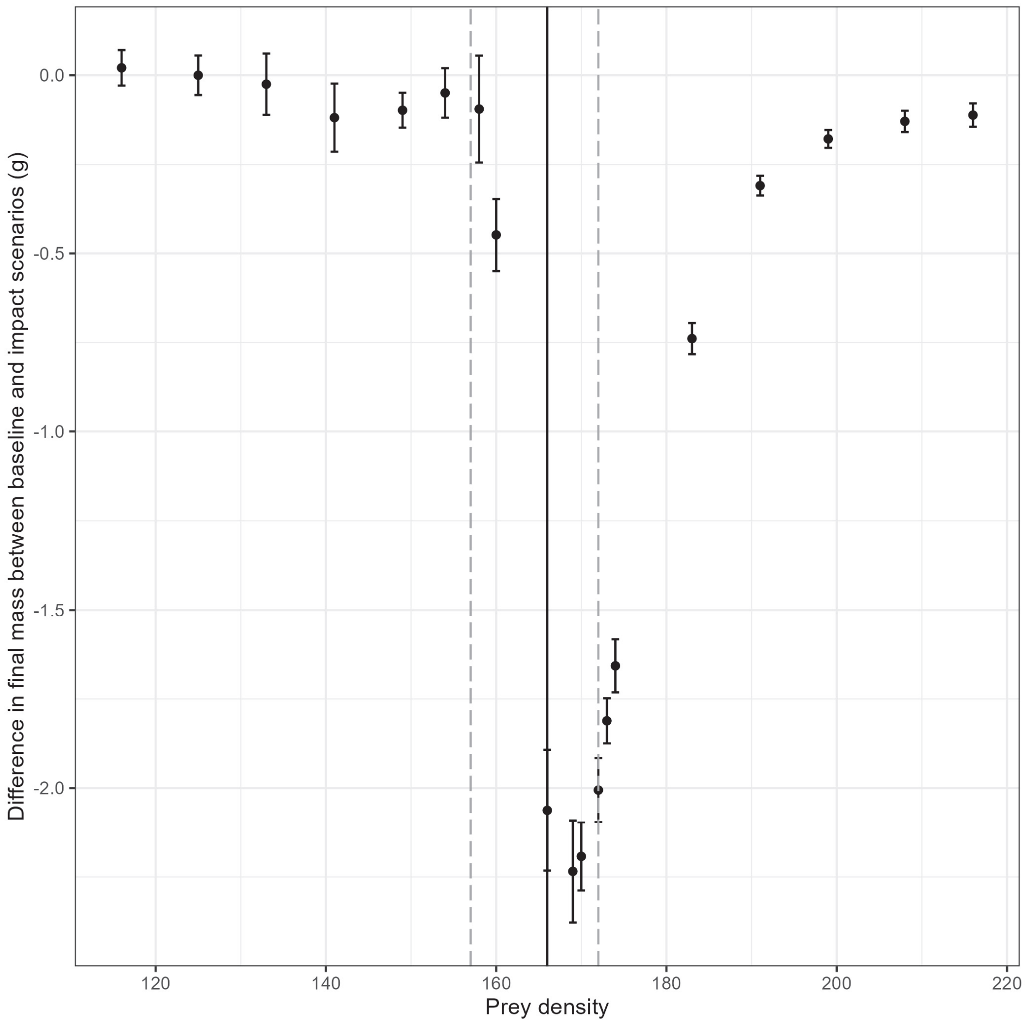

Figure 7.3: **The difference average mass between the baseline and impact scenarios at different prey levels. The solid black line represents the prey value used in the default model for sensitivity testing and the dotted lines indicate the 'moderate' range used in prey calibration**

This explains patterns in additional mortality, but it was noted that baseline mortality also peaks at an intermediate prey value, which is unexpected since mortality for individuals in the baseline is relative to the average value for the baseline. The overwinter survival relationship is described by a logistic curve linking the difference in an individual's mass at the end of the breeding season from the population average to its probability of survival. An individual with a mass equal to the average mass of all simulated birds at the end of the relevant baseline run would survive with a probability equal to the baseline survival parameter (parameter 81) and the survival probability of other individuals follows the relationship shown in Figure 7.1. As mentioned previously, the over-winter survival relationship is based on baseline survival probabilities published in Freeman et al., 2014 for good, moderate and poor years. For kittiwake, these probabilities are 0.9, 0.8 and 0.65 respectively. However, in our default scenario, baseline over-winter survival was substantially lower than this (at 0.78, 0.63 and 0.51 respectively). This suggests that the nature of this relationship is pulling down the population-level survival rate due to the steeper slope to the left of 0 compared to the right (see Figure 7.1) and the effect is greater at intermediate prey values (Figure 7.4). It appears then that the structure of the model is not achieving what was intended, since population-level over-winter survival rates calculated from simulated birds are significantly lower than those expected for these species in the Forth and Tay in reality. In this scenario at least, we therefore have evidence of over-estimation of adult mortality rates. This effect would likely be reduced by the use of the updated mass-survival relationships presented in Daunt et al., 2018, as recommended in Searle *et al*. 2022, because the relationship is more linear within the range of values that are likely to be represented by differences in mass (Figure 7.1). One possibility is that the shape of this relationship also explains why adult mortality is highest in the moderate range since variation around the average mass will be greater in the middle of the prey curve than at the edges where birds are at the extremes of the mass loss possible within the model (as is suggested by Figure 7.4).

Source: Natural Power

Figure 7.4: **Baseline adult over-winter survival predicted by seabORD at different prey densities. Points represent different seeds and dotted lines represent survival rates from Langton *et al.* 2014 for good (red), moderate (green) and poor (blue) years.**

7.3. Model sensitivity to parameters derived from expert judgement

Several parameters built into the model are based on expert judgement including

- the interference coefficient (the strength of the effect of competition upon the intake rate of a foraging bird)
- the amount of time chicks remain unattended within a time step before they are assumed to have died (also determining the slope of the relationship between unattendance and probability of mortality)
- the threshold of fully provisioned mass below which a chick is presumed to have died.

The need for sensitivity analysis on these parameters has been highlighted by Searle *et al*. but had not been possible for them to complete within the timeframe of their project (Searle *et al*. 2018; 2022). Here the sensitivity of these parameters has been assessed. There was a strong effect of varying the interference coefficient on chick mortality rates representing approximately 60% change in additional mortality when the coefficient is halved or doubled compared to the default model. This effect was reduced by calibrating the prey level such that there was no change when the parameter was halved and a 14% reduction in additional mortality when doubled. The calibration process is therefore effective at mediating much of the sensitivity associated with this parameter. That prey level and the competition effect counteract one another is unsurprising as these parameters will have exact opposite effect on accessibility of food resource to the simulated birds. As expected, chick mortality was sensitive to the amount of time chicks are unattended before they are assumed to be dead, though this sensitivity was not as strong as many of the other parameters tested. There was no effect of changing the threshold of fully provisioned mass below which chicks are presumed to have died due to chick death being assumed as a result of other components of the model prior to this threshold being reached.

7.4. Calibrated parameters

As has been noted previously (Searle *et al*. 2018), the default scenario was extremely sensitive to the prey quantities specified, even when these fall within the range of values that result in a "moderate" baseline scenario. During the sensitivity testing, additional chick mortality predicted ranged from no additional mortality to 32% higher mortality than the default scenario and additional adult mortality was always lower than the default model, by up to 113% (at which adults did better in the impact than the baseline at the lowest prey abundance level due to higher chick mortality rates). The sensitivity of the model to prey abundance is understandable since prey availability will be a key determinant of adult mass loss and reproductive success in any given year. However, it is problematic, due to the need to conduct lengthy calibration runs prior to running final models to identify prey values that will result in "moderate" baseline scenarios. The parameter acts as a correction factor, such that the impact of changing underlying parameters relating to foraging energetics are dampened. On one hand, this can be seen as a strength of the model, since, if run as intended, it will be robust and less sensitive to poor/incorrect specification of other parameters determining foraging success, many of which are linked to substantial levels of uncertainty. On the other hand, the model has been carefully parameterised to attempt to reflect the mechanisms underlying foraging energetics in the real world. However, the way that all of these parameters interact can change substantially "under the hood" if the prey density parameter is used to fix baseline model output metrics, therefore it is difficult to determine exactly what is driving observed effects, and whether or not these are reasonable under any given scenario. The fact that the model must be re-run for each colony to be included in the model with prey values re-calibrated for that colony reduces confidence in the extent to which the tool is able to replicate the real-world conditions experienced by the birds, as in reality birds from all colonies will experience the same set of conditions.

The intake rate parameter determining prey depletion was also calibrated by the tool authors during the model development and it is important to note that if parameters or assumptions within the model were updated by the authors, this parameter would likely be recalibrated which would further alter the dynamics of the model and the sensitivities of the other parameters (Searle et al., 2022).

7.5. Bird and prey density maps

It has been noted that mortality rates predicted by seabORD for displaced individuals vary significantly depending on the underlying data used in the modelling (e.g. ICOL, 2018; King, 2021). For example, the additional adult mortality predicted for guillemot at St Abbs Head for scenario 3 in the SEANSE study was -0.13% using distributions derived from at-sea data and 0.53% using GPS data, with the confidence intervals around these values not overlapping (Table 12 in Searle et al., 2020). This highlights the need for data that accurately reflect reality, particularly regarding the underlying bird and prey distribution, as these will, both in the model and in the real world, have significant impacts on mortality levels. Unfortunately, it is very difficult to generate accurate seabird distributions and even more difficult to derive prey distributions. Moreover, we know that these are not static over time and may change substantially from year-to-year and over the course of the chick-rearing period, as demonstrated in Bogdanova *et al*. 2022 based on the at-sea distribution of the four species included in the seabORD model from tracked birds from the Isle of May (presented in Appendix 3 of Bogdanova *et al*., 2022). For bird density maps, large amounts of data would be required over multiple years and throughout the chick rearing season to be confident that average mapped bird distributions used as inputs appropriately capture this variation. The initial model developed by Searle *et al*. 2014 was based on bird distributions derived from low sample sizes, especially for some combinations of species and colonies, collected within a short portion of the chick-rearing season and over just a few years. New maps have been generated based on larger sample sizes for recent iterations of the model (Searle *et al*. 2020) but there is a large degree of variation among these maps, demonstrating that there is substantial uncertainty associated with them. This is the situation for the Forth and Tay, where there is a comparative wealth of suitable data. Outside of the Forth and Tay region, such detailed analyses would be impossible based on current data availability. Since prey density maps are currently derived from modelled bird distributions, these sources of uncertainty are also true for the prey distributions but with the additional complexity that the way in which prey has been modelled (as the remaining variation once effects of distance to colony and competition effects have been accounted for) may have a tendency toward generating prey maps that will predict smaller prey quantities closer to the colony and larger prey quantities at greater distances from the colony. The uncertainty around the data underlying these two inputs is acknowledged by the authors of the tool (Searle *et al*., 2020; Searle *et al*. 2022) and further work has been carried out and is ongoing to provide more robust bird and prey density data for the Forth and Tay region (Searle *et al*, 2020; Searle *et al*. 2022). However, in the meantime, it seems that use of the existing outputs for decision making is not easily defensible given the fact that predictions may change substantially with use of more robust datasets.

Where data to derive distribution maps are not available, or have not been modelled, an alternative approach can be implemented in which a distance decay function is used to model the distribution of bird foraging locations and a uniform (even) prey distribution used to feed into the intake rate at any given foraging location and determine new foraging locations of displaced birds. The distance decay function applied within the tool generates surfaces that are very different to the GPS maps generated for the same area (Figure 4.1). With distance decay, the majority of birds are predicted to forage close to the colony. This will often result in much lower predictions of the effects of offshore wind farms than would be expected to be generated using a density map, as most wind farms will not be built in very close proximity to seabird colonies, and because the distance-decay relationship cannot account for the effect of prey abundance which will generally cause hotspots of bird density beyond those where they would be expected to be when only considering distance to the colony (acknowledged in Searle *et al*. 2018). One of the main benefits of the seabORD model is that it does not rely on data collected on site, for which assumptions must then be made in relation to connectivity with individual populations of interest. However, with the distance decay assumption this benefit becomes obsolete as it is based on the same assumptions generally used to attribute birds to colonies but without the additional information provided by the data collected within the site. At this point, the number of birds on site derived from site-specific data seems far more suitable to investigate the potential impacts of displacement than the predicted foraging sites predicted by the distance decay function. The distance decay method will likely be required for most commercial wind farm assessments, as the colony-specific tracking data required to generate appropriate bird distribution maps for use with seabORD are either not available or not accessible to wind farm developers. Given the uncertainty surrounding how well distance decay maps approximate the realised distribution of foraging seabirds and the sensitivity associated with this assumption – with calibrated distance decay/uniform prey additional mortality estimates 59% and 96% lower than estimates using distribution maps for chicks and adults respectively – we do not consider that seabORD is an appropriate method for predicting the impacts of displacement and barrier effects using the distance decay relationship.

7.6. Use of mortality rates derived from seabORD

As noted previously, outputs from seabORD are being used as a basis to inform SNCB advice on displacement mortality rates for use with the matrix approach (SSE, 2022; Searle *et al*. 2020). In order to generate such mortality rates, there must be a method of linking seabORD outputs with the at-sea snapshot survey data used to generate displacement matrices.

The bird density maps underlying the seabORD tool could be used with population size data to predict the number of birds using the site in the baseline scenario, but they cannot be used to predict number of birds that would be present within a snapshot unless an assumption is made about the proportion of birds that will be at sea at any given point in time. SeabORD therefore incorporates the ability to simulate snapshot at-sea surveys like those generally used as a basis for the displacement matrix approach (see Section 4.4). This functionality should be useful to validate predictions of spatial bird distributions derived from the seabORD model against actual survey data although does not seem to have been used in this way to date, and provides an approach for deriving mortality rates that are similar to those used in the displacement matrix in an independent way (as opposed to simply by comparing seabORD predictions directly to predictions from existing displacement matrices based on at-sea survey data).

Though these derived "matrix-comparable" mortality rates will vary more or less proportionately to the other metrics produced by seabORD (see Section 4.4), the rates themselves will be much larger due to the relatively small number of birds detected within the simulated snapshot surveys. All other seabORD metrics relate mortality to the total population size which is very large in comparison to the number of birds in snapshot. In the example presented here, a relatively small reduction in the interference coefficient parameter gives rise to a change in estimated "matrix-comparable" adult mortality rate from 50% to just over 1%, which represents a considerable range.

Moreover, there are a number of considerations which mean that mortality rates derived from the seabORD simulated snapshot surveys are not directly comparable to those that should be used with the at-sea survey abundances that feed into the displacement matrix. These are:

- according to Searle et al. 2018 (Appendix E) seabORD snapshots relate to birds within the footprint of the offshore wind farm suggesting that this does not include the 2km displacement buffer used to calculate abundances from at-sea survey data for displacement matrices. This would underestimate the number of birds in snapshot leading to over-estimation of mortality rate.
- seabORD generates it's P2 metric based on the average number of birds across the simulated snapshots, rather than the peak as is used for the displacement matrix, again resulting in lower predicted birds in snapshot and higher derived mortality rates.
- only those colonies included in the seabORD model will be available to be present within the windfarm, and it is likely that it will not generally be possible for all colonies from which birds may originate can be included in the seabORD modelling due to the increased amount of run-time associated with modelling additional colonies. There is also no consideration of any non-breeding birds that may pass through the site. This will also lead to underestimating the number of birds within the footprint.
- SeabORD focuses only on the chick-rearing season whereas the comparable displacement matrix covers the whole of the breeding season.
- the seabORD predicted mortality rate includes over-winter survival, but for the matrix approach, over-winter survival is assessed in a separate model. This means that any conclusions drawn from seabORD regarding appropriate mortality rates must be considered in the context of the mortality predicted across the full year by the displacement matrix rather than just making comparisons with the breeding season matrix.

7.7. Cautions for sensitivity testing

Due to the complex nature of the model, absolute sensitivities cannot be assigned to individual parameters and assumptions. The sensitivity of a single parameter is highly dependent upon the values of the other parameters. In this study, we have investigated the sensitivity of each parameter within a single scenario. However, it is clear from our outputs that these sensitivities would be very different if other parameters were to change. For example, the impact of the threshold mass at which an adult abandons its chick will vary depending on the value of other parameters determining chick survival – in the scenario tested here, chicks had already died by the time the adult reached this threshold, meaning that there was no effect of further reducing the threshold. The result of the complex nature of these interactions is that if data came to light that would cause one of the input parameters to vary, this could potentially have knock-on effects to the impact of several other parameters. Since sensitivity is specific to the input parameters being used in the modelling, sensitivity testing might be required for every situation in which the model is used, if the mechanisms underlying, and key parameters determining the observed outputs in that particular scenario are to be understood. In the latest version of seabORD (version 1.5) the developers have built in the possibility to carry out sensitivity testing on a wider range of parameters. However, there are still several values which cannot be varied within this framework. In addition, the extremely long runtime associated with the modelling means that such sensitivity testing would not be practical. However, it is recommended that similar work be carried out for other species and scenarios in order to support a more comprehensive understanding of the behaviour of the model in a range of representative situations.

7.8. Incorporation of uncertainty within the model

Impact metrics generated by seabORD include a measure of uncertainty surrounding them. This uncertainty captures the intrinsic stochastic variability within the model and the uncertainty associated with specification of the prey density values. The former includes the various stochastic processes determining the state and behaviour of simulated individual birds, and the latter represents the variation around simulations run at different prey levels resulting in "moderate" baseline conditions. We note that the latter captures uncertainty around what may happen in a moderate year but does not consider good or poor prey scenarios (as does the part of the simulation relating to winter), thus under-representing uncertainty even within this parameter. A range of additional sources of uncertainty also remain unquantified, including the uncertainty associated with parameter estimation, the structural uncertainty associated with the model, and the uncertainty associated with the spatial distributions of birds and prey (Searle *et al*. 2018; 2022). As recognised by the model developers, these sources of uncertainty are likely to be large. The true uncertainty associated with the model will be much higher, and the total uncertainty inherent within the model is not accurately represented by the output. It is impossible to predict the magnitude of this under-estimate without explicitly incorporating these sources of uncertainty into the modelling process meaning that this cannot be accurately assessed by users of the model. Therefore, despite openness regarding this issue, confidence intervals provided are misleading and may provide false confidence when comparing scenarios against one another. The authors of the tool state that treatment of uncertainty should be extended in future iterations of the tool to incorporate a wider range of parameters than currently considered but also note that in many cases, uncertainty around assumptions for which direct information is not available cannot be defensibly quantified (Searle *et al*. 2022).

7.9. General comments

The seabORD model has been promoted as a favourable alternative to the displacement matrix due to the simplicity of the matrix model relative to the process that it represents, the difficulty in determining connectivity of birds within a wind farm footprint to different colonies, and the reliance of the matrix approach upon expert judgement for mortality rates. Whilst the matrix model is extremely simplistic and does not allow incorporation of our increasing understanding of the specifics of seabird behaviour, it does provide mortality estimates in a straightforward and transparent format that provides an indication of likely mortality rates given our current understanding, and in a way that allows ease of interpretation by industry and academia alike. This is in contrast to the seabORD model which is extremely complex and opaque in terms of which factors are driving predicted additional mortality, meaning that critical evaluation of the outputs is extremely difficult. The seabORD model is attractive in that it provides a mechanistic approach to predicting adult mortality and can predict reproductive consequences as well. Indeed, our seabORD simulations (as well as other situations in which seabORD has been used for all species except puffins, for which chick survival rates are presumably improved by the protection afforded by burrows e.g. ICOL, 2018; Searle *et al*. 2020) indicated that displacement has a larger impact on reproductive success than adult survival, as might be expected for long-lived seabird species. However, the sensitivity of the model to some key parameters suggests that the outputs are unlikely to be any more reliable than those from the matrix model with the added disadvantage that the sources and magnitude of uncertainty are not transparent. Finally, for the matrix approach, a single, but key parameter, the proportion of displaced birds expected to result in a mortality, is based on expert judgement. In the seabORD model there are a vast range of parameters and assumptions, many of which are listed here, which are based on little or no real-world evidence but rather on simplifications, calibration or expert judgement. The seabORD model is an excellent model with which to understand the mechanisms by which displacement and barrier effects may impact upon seabird populations. However, given the uncertainty and sensitivity associated with many of the key parameters and assumptions used in the model, and the suite of recommended modifications listed by the authors that are not yet incorporated into the model (Searle *et al*. 2022), it does not seem to be the correct tool to provide the concise, transparent and comparable predictions required for general use for impact assessment at this time.

7.10. Conclusions

This work has qualitatively assessed the assumptions underpinning the seabORD model, and quantitatively assessed the sensitivity of model parameters to variation in an illustrative scenario. Several of the key findings are summarized as follows:

- The seabORD model incorporates a vast range of parameters and assumptions, many of which are based on little or no real-world evidence but rather on simplifications, calibration or expert judgement.
- Several assumptions underlying the model are precautionary such that combined with precautionary displacement and barrier rates, impacts may be substantially over-estimated.
- Model outputs relating to adult survival are very sensitive to parameters determining over-winter survival. The slope parameters used in the published version of the model almost certainly result in significant over-estimation of adult mortality.

- Over-winter survival rates predicted by the seabORD model for the baseline appear to be significantly lower than those that would be expected in reality. This appears to be a structural issue with the model that will result in over-estimation of adult mortality rates.
- Calibration of the prey level input values is required to run the model and serves to fix the end of chick-rearing season baseline chick mortality and adult mass loss within an expected range of values. This calibration reduces the sensitivity of most parameters but may alter the way in which the underlying parameters are interacting in a way that cannot readily be understood. Sensitivity testing without calibration generally results in lower predicted additional adult mortality rates compared to the default scenario used as the difference in mass loss between the baseline and impact scenarios which determines adult over-winter survival is highest at intermediate prey values.
- The output of the model is extremely sensitive to the prey distribution and bird density maps underlying the algorithms thus it does not seem appropriate to rely on simplifications such as the distance-decay assumption and the assumption of uniform prey. Outputs generated using of the existing bird and prey distribution maps should also be treated with caution due to the level of uncertainty associated with these inputs and the fact that no attempt is currently made to incorporate an estimate of this uncertainty into the model.
- The snapshot functionality of the tool, designed to provide a mechanism for translating at-sea survey data from offshore wind farm footprints into population-level demographic consequences as predicted by seabORD, does not currently accurately reflect the method used to derive the numbers that feed into the displacement matrices and would over-estimate mortality rates to be used in the displacement matrix if used as is.
- The model is still under development, with work currently ongoing to better understand key input parameters and several improvements and refinements suggested by the authors not yet implemented. It therefore seems inappropriate to draw strong conclusions from the outputs at this stage.
- Although a measure of uncertainty is provided with the model, this only reflects a small portion of the total uncertainty inherent within the modelling process. Additional sources of uncertainty, such as uncertainty associated with parameter estimation, the structural uncertainty associated with the model, and the uncertainty associated with the spatial distributions of birds and prey are not incorporated, thus providing outputs that inaccurately represent the true uncertainty associated with the modelling process. While the authors are clear that this is the case, the outputs are misleading and suggest a lot more confidence than can truly be attributed.
- The seabORD model is a complex and intricate model for which it is currently impossible to assess correct levels uncertainty, to derive generally applicable sensitivities or to understand the specifics of the interplay of the different components giving rise to the outputs for any given scenario. However, it is clear that the model is associated with a large amount of uncertainty and that the model can be highly sensitive to certain key input parameters. Given this, it does not seem to be the correct tool to provide the concise, transparent and comparable predictions required for general use for impact assessment at this time.

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