Study to Examine how Seabird Collision Risk, Displacement and Barrier Effects Could be Integrated for Assessment of Offshore Wind Developments

June 2022

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Final Report – July 2020

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Published by Marine Scotland Science

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UK Centre for
Ecology & Hydrology

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Client Ref: [ITQ-0246]

Date 21/07/2020

Title	Study to examine how seabird collision risk, displacement and barrier effects could be integrated for assessment of offshore wind developments
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Client reference	ITQ-0246
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Date	21/07/2020

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Study to Examine how Seabird Collision Risk, Displacement and Barrier Effects Could be Integrated for Assessment of Offshore Wind Developments (ITQ-0246)

Final Report – July 2020

Kate Searle[1], Adam Butler[2], Deena Mobbs[1], Mark Trinder[3], Ross McGregor[4], Aonghais Cook[5], Aly McCluskie[6], Bruno Caneco[7], and Francis Daunt[1].

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1 Executive summary

Collision and displacement/barrier impacts for seabirds interacting with offshore wind farms (OWFs) are currently assessed using separate modelling methods. This means collision mortality is estimated separately from displacement and barrier effects, and the effect sizes are subsequently combined. However, there is concern with this approach because the parameters used in both assessments are not equivalent, making integration subject to error. Secondly, there is concern about double counting of mortalities: an individual seabird is potentially vulnerable to displacement and collision, yet it cannot be vulnerable to both simultaneously.

Accordingly, the objective of this project was to develop a framework within which collision, displacement and barrier effects can be aggregated into a single overall assessment of combined impacts in a way that is internally consistent, scientifically defensible, and practically useful.

Collision impacts with wind turbines are assessed using collision risk models (CRM). These are relatively simple mechanical models that combine estimates of the number of flights through a wind farm with an estimate of the likelihood that a bird of a specified size and speed will collide with a rotating turbine of a specified size and speed (Band 2012; further developed in Masden 2015, McGregor et al. 2018).

Displacement impacts during the breeding season are currently assessed using two general methods; individual-based simulation models, and simple

deterministic ‘matrix’ approaches involving expert elicitation of likely displacement and mortality rates combined with estimates for the density of birds within footprints. Individual-based models predict the time/energy budgets of individual animals and translate these into projections of demographic rates, such as adult annual survival and productivity (e.g. Searle et al. 2014, Warwick-Evans et al. 2017, Searle et al. 2018). Matrix approaches (JNCC, 2017) use a more simplistic method, multiplying the observed number of individuals within a proposed wind farm site by the percentage expected to be displaced and the percentage of those displaced then expected to suffer mortality as a consequence.

The first stage of this project involved a workshop that brought together experts from research, government and conservation bodies to discuss how best to implement combined modelling of displacement and collision risks from OWFs for breeding seabirds. Current methods for estimating collision and displacement risks separately in assessments were discussed, with a following session on the extent to which the inputs, parameters and assumptions used in the different methods are consistent with each other. Finally, there was a session on how to combine collision and displacement risks into a single assessment of risk from both displacement and collision.

Building upon outcomes from the expert workshop, we developed a methodological framework for simultaneously quantifying the impacts of displacement and collision by adapting an individual-based mechanistic model of seabird movement, behaviour, demographics and OWF interactions (SeabORD) to be able to simultaneously estimate mortalities related to collision, barrier and displacement effects. We implemented an initial version of this framework that used output from the stochastic CRM (sCRM) (McGregor et al. 2018) as an input to a modified version of SeabORD – we do this by translating the current population-level sCRM calculations into corresponding calculations at the individual level, and then embedding these within SeabORD.

We demonstrate the integration of sCRM output with the individual based simulation model, SeabORD, by running the models using data for black-legged kittiwakes (*Rissa tridactyla*) at Forth Islands SPA.
We conclude with recommendations for future research to advance the integration of collision and displacement/barrier assessments. Primarily, we recommend research aimed at developing a more powerful and flexible approach by merging the functionality of individual-based models such as

SeabORD, and the sCRM into a single model and software product. We also recommend research to develop a year-round individual-based simulation model to extend current methodologies beyond the chick-rearing period; efforts to obtain empirical data for validation of key mechanisms with both displacement/barrier and collision risk models. Finally, we recommend research to improve quantification of uncertainty within the modelling approaches, to better inform the level of appropriate precaution in assessments.

2 Introduction

The Scottish Government has set a target to generate 50% of Scotland's overall energy consumption from renewable sources by 2030 and to have decarbonised the energy system almost completely by 2050. The marine environment offers considerable potential for renewable energy, through wind, wave and tidal stream energy generation. The Scottish Government has a duty to ensure that offshore renewable developments (ORDs) are achieved in a sustainable manner, by protecting the natural environment from adverse impacts in accordance with the Marine Strategy Framework Directive (2008/56/EC), the Habitats Directive (92/43/EEC) and the Birds Directive (2009/147/EC). To help achieve this, they are required, under the Precautionary Principle, to ensure that decisions are informed by the best available scientific evidence and make reasonable effort to address any gaps in knowledge. Crucially, offshore renewable developments have the potential to impact on seabird populations that are protected by the EC Birds Directive, notably from collisions with turbine blades and through displacement from important habitat (Drewitt & Langston 2006; Larsen & Guillemette 2007; Masden et al. 2010; Grecian et al. 2010, Langton et al. 2011).

The process whereby seabirds collide with wind turbines is assessed using collision risk models (CRM). These are relatively simple mechanical models that estimate the likelihood of a bird of a specified size and speed colliding with a rotating turbine of a specified size and speed (Band 2012). These data are combined with densities of birds in flight and their flight height, which are estimated from baseline characterisation surveys of proposed wind farm projects and from generic datasets (particularly for flight heights). The first offshore CRM (Band 2012) was deterministic and provided monthly predictions of species-specific collision mortality for four model options. Two model options (Options 1 and 2) use the ‘basic model’ and make the assumption that seabirds were evenly distributed across all heights of the wind turbines, Option 1 using a site-specific estimate of the proportion of birds at collision height and Option 2 a generic estimate derived from analysis of a pooled dataset (Johnston et al. 2014). This assumption is known to be incorrect, because the relative frequency of flight densities declines with increasing height. This is important because the risk of collision is not the same for all distances from the rotor hub and therefore varies with flight height, even within the rotor-swept zone. The third model option (Option 3) takes account of this predictable decline in flying densities with increasing height, but uses the generic flight height distributions in Johnston et al. 2014. Option 4 allows the use of site specific flight height distributions, but is otherwise identical to Option 3. In order to improve on the deterministic outputs from this model subsequent stochastic versions of the Band model (2012) have been developed (Masden 2015, McGregor et al. 2018). These models translate the uncertainty and variability in the input values through to outputs that provide predictions, together with associated probability distributions or confidence intervals. Part of the Band (2012) and McGregor (2018) model incorporates a correction for differences between observed and predicted collision rates. This correction factor is usually called the 'avoidance rate' because it is assumed that the majority of this difference is due to the avoidance behaviour of birds in relation to the presence of the wind farm, wind turbines and turbine blades (because model input data are collected prior to windfarm construction and, therefore, do not include any potential displacement or avoidance effects). However, as this correction factor is derived from a collision rate predicted from the Band (2012) model in the absence of avoidance behaviour, it also incorporates model error (currently estimated at ± 20%) arising as a result of simplifications within the model (Band 2012). A key source of this error is likely to relate to how the flux rate is calculated, which means that a greater number of birds may be exposed to the risk of collision than is realistic (Masden *et al.* in prep). As a consequence, it is important that any avoidance rate used by the Band (2021) model corrects for this simplification in how the flux rate is estimated.

At present, the avoidance rate is a species, but not site, specific value. The overall avoidance rate is often calculated from three different spatial scales of behaviour: macro-avoidance (birds avoid entering the wind farm at all), meso-avoidance (birds enter the wind farm, but avoid entire turbines) and micro-avoidance (birds approach turbines but avoid colliding with the moving blades). Macro-avoidance behaviour has been assumed to be comparable to displacement behaviour, but there are subtleties in the assumptions and interpretation of how these processes are represented by parameters within alternative modelling methods, and in how they are applied to data. Not least, macro-avoidance behaviour only applies to birds in flight, while displacement also applies to birds on the water.

Displacement impacts during the breeding and chick-rearing seasons are currently assessed using two general methods; individual-based simulation models, and simple matrix approaches. Individual-based models predict the time/energy budgets of individual animals and translate these into projections of demographic rates, such as adult annual survival and productivity (e.g. Searle et al. 2014, Warwick-Evans et al. 2017, Searle et al. 2018). These models simulate foraging decisions of individuals under the assumption that they are acting in accordance with optimal foraging theory. Foraging behaviour of individuals is driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of conspecifics. Impacts of displacement and barrier effects arising from specific OWFs can be assessed using such models by comparing baseline scenarios with scenarios containing one or more OWFs. The models can estimate the change in productivity and adult survival between the baseline and OWF scenarios, the latter process resulting from estimates of adult mass at the end of the breeding season. The most comprehensive model available for estimating the population level consequences of displacement and barrier effects for seabirds is the SeabORD model, developed as part of Marine Scotland's project "Finding out the Fate of Displaced Birds (CR/2015/19)" (Searle et al., 2014, Searle et al. 2018; Mobbs et al. 2018). Although this model was developed within the context of assessing displacement impacts of OWFs during the chick-rearing period, it is a very general model of seabird foraging and provisioning behaviour, and time-energy budgeting. This flexibility, and its ability to track individual birds, makes it ideal for integrating mortalities arising from the different risk types – collision and displacement.

The second method for quantifying impacts of displacement is the Displacement Matrix (JNCC, 2022). This takes a more simplistic approach by multiplying the observed population within a proposed wind farm site by the percentage expected to be displaced and the percentage of those expected to suffer mortality as a consequence of displacement. These percentages are currently most often derived from expert opinion (JNCC 2015, JNCC 2022). Displacement in this context is an integrated estimate of displacement (loss of access to habitat) and barrier effects (additional flight costs incurred flying around OWFs), but the method does not separate out rates or mortality consequences into these two categories. In acknowledgement of the uncertainty in both these percentages, a wide range of displacement mortality values is typically presented in impact assessments, potentially using a matrix form with 0-100% displacement along one axis and 0-100% mortality along the other, although in practice the range for each axis is much less than 0-100% (JNCC 2015; JNCC 2022)

The matrix approach and SeabORD have different data requirements, and currently are applicable to different suites of seabird species. SeabORD is more data intensive, requiring utilisation distributions (UD) for each breeding colony and a prey availability map, and is currently only parameterised for four seabird species (common guillemot, razorbill, Atlantic puffin and black-legged kittiwake). The matrix method requires estimates of densities of birds within footprints only (not a full UD), and is applicable to any species for which these data are available. Both modelling approaches require users to specify rates of displacement from footprints, usually derived from expert elicitation, and rarely from empirical studies as very few suitable studies have been completed. The matrix approach also requires users to input a mortality rate for displaced birds, derived from expert opinion, whereas this is a model output for SeabORD.

Currently, collision mortality is estimated separately from displacement and barrier effects, and the effect sizes are combined in assessments of effects of OWFs on seabird populations for those species where both effects are assessed. However, there is concern with this approach because the parameters used in both approaches are not equivalent, which means the resulting estimates are not based on an internally consistent set of assumptions. For instance, the collision model parameter for macro-avoidance appears to be aimed at capturing the same process as the displacement rate parameter in displacement models; however, due to the inclusion of the avoidance rate correction in collision models, it is not clear that these two parameters are in fact directly comparable. Second, there is concern about double counting: an individual seabird is potentially vulnerable to displacement and collision, yet it can’t be vulnerable to both simultaneously. There is, therefore, a concern that assessments may be overestimating effects on demographic rates due to double counting — that is, counting the death of an individual bird twice due to a failure to separate collision and displacement effects.

Accordingly, the objective of this project was to develop a framework within which collision, displacement and barrier effects can be aggregated into a single overall assessment of combined impacts in a way that is internally consistent, scientifically defensible, and practically useful (*sensu* Humphreys et al. 2015).

3 Background: Displacement risk modelling

Displacement effects can be defined to be:

*Displacement mortality = Baseline exposure * Displacement rate * Mortality rate for displaced birds* (**Equation 1**)

“Baseline exposure” represents the number of birds that are estimated to use the wind farm footprint (plus any appropriate buffer to represent the distance to which birds may be affected outside of the windfarm footprint) using data on the baseline spatial distribution of birds - which may either be at-sea survey data or GPS tracking data. The “displacement rate” represents the proportion of birds that are susceptible to displacement – i.e. the proportion of birds that will undertake displacement behaviour if they encounter a wind farm. The “mortality rate for displaced birds” represents the proportion of displaced birds that die as a result of being displaced – note that this represents the mortality rate for birds that are both exposed and susceptible to displacement. Some methods also include an impact of displacement effects on chicks via changes to the productivity rate or breeding success of adults (e.g. individual based models such as SeabORD), whilst other methods, such as the displacement matrix only consider impacts on survival.

Two approaches are currently used for the estimation of displacement effects within Scottish waters. The ‘Displacement Matrix’ approach involves calculating baseline exposure from site-based density estimates, and then calculating effects for pre-specified values of the “displacement rate” and “mortality rate for displaced birds”. The Displacement Matrix often involves calculating displacement risk for a range of values of the latter two inputs, but we focus here upon running it for a single, ‘best estimate’, of each rate.

SeabORD (Searle et al. 2014, 2017) is a mechanistic individual-based model of seabird foraging, energetics, demographics and OWF interactions, providing an alternative to the Displacement Matrix approach. SeabORD takes a map of baseline spatial distribution of birds from the breeding colonies of interest, and the footprint(s) for the OWFs of interest and produces an estimate of displacement and barrier effects - the increase in mortality (as a percentage of population size) associated with displacement or barrier effects caused by the OWFs, for both breeding adults and chicks. Displacement and barrier rates are entered in to the model by the user, specified as a proportion of the breeding adult population that are displacement or barrier susceptible, and therefore impacted by OWFs should they interact with footprints during the course of the chick-rearing period. These rates are set in consultation with statutory agencies. This creates sets of birds in three categories: 1. Non-susceptible birds that are unaffected by OWFs; 2. Displacement susceptible birds that will not forage within an OWF, but will fly directly through it; and 3. Displacement *and* barrier susceptible birds that are both barriered by an OWF and will not forage within it. In practice, SeabORD is most often set up such that only Categories 1 (unaffected) and 3 (displacement & barrier susceptible) are used. SeabORD predicts the time/energy budgets of breeding seabirds during the chick-rearing period and translates these into projections of adult annual survival and productivity. The model simulates foraging decisions of individual seabirds under the assumption that they are acting in accordance with optimal foraging theory. Each individual selects a suitable location for feeding during each foraging trip from the colony based on bird density maps derived from a range of methods, and the subsequent behaviour of birds is then simulated, incorporating realistic assumptions and constraints derived from observed behaviour. Fundamentally, the model assumes that the foraging behaviour of individual seabirds is driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of conspecifics. Barrier effects are implemented within the model by susceptible birds flying around OWFs to reach foraging grounds, and displacement effects are incorporated by causing susceptible birds to re-select foraging locations out-with the OWF should an initial foraging location within the OWF be selected. The resulting outputs for adult mass at the end of the breeding season are then translated into an estimate of population level adult survival for each colony, with and without one or multiple OWFs present. Impacts on chick mortality are also included within the model, with provisioning and attendance by both parents affecting chick growth and probability of mortality within simulations. The model provides individual and population level estimates for the change in adult mortality and breeding success for individual colonies affected by one or more OWFs, providing a direct link from observed or estimated spatial foraging patterns of breeding birds through to population demographics. The model also enables the behaviour and fate of individual birds to be tracked and summarised in a range of different ways. This permits a direct quantification of the demographic consequences of displacement for individual birds (for full details of SeabORD model specification see **Appendix A**). SeabORD does not directly use Equation 1 in calculating displacement risk, but because it does require users to specify both baseline exposure (via a bird utilisation distribution map) and the displacement rate, it is straightforward to express SeabORD outputs using Equation 1. Specifically, Equation 1 can be rearranged to give:

*Mortality rate for displaced birds = Displacement mortality / (Baseline exposure * Displacement rate).*

which is directly comparable to the ‘mortality rate for displaced birds’ used within the Displacement Matrix approach.

Expressing it in this way illustrates that the fundamental difference between SeabORD and the Displacement Matrix lies in the way that the mortality rate for displaced birds is calculated. SeabORD calculates this using a mechanistic model, whereas the Displacement Matrix approach currently derives these rates from expert judgement. The Displacement Matrix approach also uses a particular way of visualising and summarising uncertainty (via the ‘Matrix’), which is not currently used when applying SeabORD, but the connection between the approaches described here shows that this could also potentially be used in conjunction with SeabORD. Presentation of uncertainty in SeabORD is currently limited to that resulting from variation in prey availability across good, moderate and poor environmental conditions and its impact on adult and chick mortality. However, uncertainty in the displacement rate used within SeabORD could also be expressed using something similar to the visualisation used in the matrix method – running simulations with different displacement rates and tabulating or graphing the resulting uncertainty in model outputs.

Equation 1 can be used to calculate mortality rates for either adults (i.e. survival) or chicks (i.e. productivity). Note that SeabORD considers both of these, but impacts on chicks are usually ignored within the Displacement Matrix approach.

4 Background: Collision risk modelling

Collision Risk Modelling is a multistage calculation that results in a predicted number of birds killed per month and per year by a proposed wind farm. The first stage calculates the activity of birds in the air within the proposed wind farm development footprint. This flight activity is calculated from the aerial density of birds (from site-based surveys of the proposed wind farm), the heights at which those birds fly (from either site-based survey information or from previously collated and analysed survey data from multiple wind farms across all seasons) and the number of hours per day (24 hour period) during which birds are thought to be active.

These data are used to calculate the number of transits of birds through the rotors of the proposed wind farm.

$$Bird\ transits\ = bird\ flux\ \times proportion\ at\ collision\ height$$

Bird flux is estimated from the aerial density of birds (i.e. those birds in flight), bird flight speed, bird daytime and night-time activity and the size of each turbine and the total number of turbines:

$$Bird\ flux = (v\frac{D_a}{2R})\ (T\pi R^2)\big(t_{day} + f_{night}t_{night}\big)$$

Where:

v bird flight speed (ms^{-1})
D_a Bird density per unit area (birds/km^2)
R Rotor radius (m)
T Number of turbines
t_{day} hours of daytime in each month
f_{night} proportion of time at night when birds are active
t_{night} hours of time at night in each month

Based on the relative size and speed of a bird in flight of a known size, and a turbine in motion of a known size, the probability of a bird being struck by a blade is calculated, termed the probability of collision (‘p.coll’).

The first step in this calculation is to determine the probability of collision of passage through any one point in the rotor. This probability of a bird being struck during a transit of a rotor is multiplied by the transits of birds through the rotor to estimate the number of birds predicted to be struck per month.

There are four model options that use different assumptions and data on the vertical distributions of birds in relation to the rotors of the turbines. These options are divided into two "basic" options and two "extended" options. The basic options (Option 1 and 2) assume that there is an equal probability of birds occurring at any point within the vertical range of the rotor of the turbine. These options use different data to determine the proportion of birds flying at rotor height. Option 1 uses site-based data collected during surveys of the proposed development area and a suitable buffer. Option 2 uses published information on the proportion of birds at collision risk height collated from multiple boat-based surveys of proposed OWFs around the UK (Johnston et al. 2014). The extended models do not make the assumption that seabirds will be equally distributed across all parts of the turbine rotor. Option 3 uses generic flight height distributions of seabirds (usually from Johnston et al. (2014)), where birds are predicted to be at greater densities in the lower part of the turbine rotor with densities declining with increasing height. Due to the relative size and speed of the turbine blades, collision risk varies across the rotor surface, generally being lower at the outer edge of the rotor, increasing towards the middle of the surface. Thus Option 3 tends to result in fewer predicted collisions than Option 2. Option 4 is identical to Option 3 but uses site-based flight height distribution information. To date Option 4 has only rarely been applied in OWF assessments in the UK; it has been used by developers in their applications, but has yet to be used in the final assessment figures – i.e. those used for the Appropriate Assessment by the Competent Authority (for Scotland: Scottish Ministers).

The predicted collisions are based on the density of birds in the air before the wind farm is constructed and do not account for the behaviour of birds in relation to the wind farm, the individual wind turbines and to the moving blades. Overall, these behaviours are assumed to be captured by an 'avoidance rate' parameter that is used to adjust the predicted collision from the model. The avoidance rate can be calculated by combining avoidance behaviour at three scales: macro-avoidance, meso-avoidance and micro-avoidance. The total avoidance rate is calculated by:

$$Total\ avoidance = 1 - (1 - Macro)\ \times (1 - Meso)\ \times (1 - Micro)$$

Micro-avoidance has been defined as the last second change in flight path a bird takes to avoid being struck (Cook et al. 2014). Cook et al. (2014) considered this to occur within 10 m of the turbine blades. Those authors defined meso-avoidance as all the behavioural responses that occur more than 10 m from the turbine blades, but within the wind farm itself. However, in practice, meso- and micro-avoidance are typically combined as "within-windfarm avoidance" and calculated by comparing observed and predicted collision rates. As different model options will produce different predicted collision rates, the avoidance rates used must differ between model options. Macro-avoidance is the overall avoidance of the whole wind farm. It is important to note that macro-avoidance applies to birds in flight only, as it is used to adjust the predicted mortality of birds flying through the turbine rotors. Macro-avoidance therefore has similarities with displacement, but it is not identical. Displacement usually refers to both birds in flight and birds on the sea. There are greater similarities with barrier effects, where birds fly around the wind farm rather than through it.

Several versions of the Band model (2012) are generally available and used for predicting collision risk mortality to seabirds from OWFs, within the UK. A deterministic model was produced in 2012 by the Strategic Ornithological Support Services (SOSS) group, funded by The Crown Estate enabling actions fund (Band 2012). This is implemented in Microsoft Excel but is unable to incorporate uncertainty and variation in the input parameters to produce a prediction with associated confidence intervals. This was recently addressed in an update to the model created by Band (2012), funded by Marine Scotland, by adapting and updating an existing version of the CRM in R (Masden 2014). This stochastic collision risk model (sCRM) is able to incorporate uncertainty and variation in the input parameters to produce a predicted collision mortality with a variety of suitable measures of confidence (McGregor *et al*. 2018).

5 A framework for integrated modelling of displacement and collision

To simultaneously quantify the impacts of displacement, barrier and collision effects we propose using an individual-based mechanistic model of seabird movement, behaviour, demographics and OWF interactions. This approach avoids the possibility of double counting, helps to ensure that the outputs of these processes are quantified in directly comparable ways, and provides a framework that could be refined to allow for direct interactions between collision-related, displacement-related and barrier-related processes.

As SeabORD already provides an individual-level mechanistic model of seabirds and seabird-OWF interactions, as shown in Figure 1., we have developed an integrated model of collision and displacement and barrier effects by integrating the sCRM calculations within the SeabORD model. This approach involves translating the current population-level sCRM calculations into corresponding calculations at the individual level, and then embedding these within SeabORD.

In this initial project we have extended SeabORD so that it can incorporate collision risk using the outputs produced by the existing sCRM. However, ultimately a more powerful and flexible approach could be obtained by merging the functionality of SeabORD and the sCRM into a single model and software product that would apply to species at risk from both sources of impact. For other species not at risk from both collisions and displacement/barrier effects separate approaches will be needed.

5.1 Integrated modelling of displacement and collision – initial approach

The approach to integrating displacement and collision risk calculations we have developed within this project involves extending SeabORD so that it incorporates collision-related, as well as displacement-related, mortality, but doing this in such a way that the inputs to the collision-related part of the extended SeabORD model can be derived using outputs from the existing sCRM.

5.2 Extending SeabORD

SeabORD already simulates the amount of time in hours, T, that each adult breeding bird, within each simulation run, will spend foraging and flying within the OWF footprint on each day, when an OWF is present. A proportion of birds within the population, D, are assumed to be "displacement-susceptible", and for these birds the amount of time spent within the OWF footprint, once the OWF is present, will always be zero; for the remaining birds, the amount of time spent in the OWF footprint after construction of the OWF is assumed to be identical to that which would have been obtained in the “baseline” (i.e. if no OWF were present).

We have extended SeabORD by allowing users to specify whether collision-related mortality should be considered, or not. If users opt **not** to consider collision-related mortality, SeabORD will operate as in the current version (Marine Scotland (MS) Fate of Displaced Birds project, Searle et al., 2018). If users opt to include collision-related mortality, the model assumes that each bird has a probability $p(T)$ of dying due to collision on each day, which will depend on amount of time T the bird spends undertaking collision-related behaviours (foraging, flying) on the day in question. Whether or not a bird actually dies, on any particular day, is decided by simulating a binary variable (1 = die, 0 = survive) from a binomial distribution with sample Size 1 and probability $p(T)$. If a bird is simulated to die, the chick associated with the bird is also assumed to die, and the partner of the bird is assumed to no longer be required to attend the nest.

The daily probability of collision-related mortality, $p(T)$, is assumed to be equal to:

$$p(T) = 1 - \left(1 - \frac{Q}{1 - D}\right)^{T/720}$$

where Q represents the collision probability per bird-month and D represents the proportion of displacement-susceptible individuals within the population (an input to SeabORD). The derivation of this formula is given in **Appendix B.**

This implies that $p(T)$ increases with time spent in the footprint, with individual birds accumulating risk as they utilise the habitat within the OWF. However, to note that SeabORD does not currently operate at the scale of individual turbines, birds simply interact with each OWF footprint as a whole, meaning any displacement behaviour within the OWF footprint, nor the potential influence of turbine density on displacement rates is captured by the model. Similarly, turbine density is not relevant to current versions of the sCRM – this model calculates collision risk for a single turbine, then multiplies by the number of turbines in the footprint regardless of turbine space. Turbine density could have an impact on displacement rates, but this has not currently been applied in assessment frameworks.

We define the collision probability per bird-month, Q, to be:

“The probability that a single bird would die through collision for every month [720 hours] that it spends within the OWF footprint in the baseline.”

Although this seems a rather difficult quantity to interpret, it is a crucial quantity, because it represents a way of converting the current sCRM output into a format that can be used to quantify collision risk within an individual-based mechanistic model.

The value of Q can be calculated from the current sCRM, for each month within the chick-rearing period, by either:

a) dividing the number of mortalities within the sCRM output by (bird density * footprint area); or, equivalently,
b) running the sCRM with a bird density equal to (1 / footprint area).

This step is needed because SeabORD performs calculations for each individual separately, and it is therefore necessary to transform the sCRM output so that it relates to an individual bird, rather than the population; this is achieved by scaling the sCRM output by the mean number of birds within the footprint (which is, in turn, equal to bird density * footprint area).

These values are then averaged across the months of the sCRM, and the resulting values are inputted to SeabORD. Separate values need to be provided by users for each OWF footprint included within SeabORD simulations. Note that the averaging across months implies that the collision rate is assumed to be identical for all months within the chick rearing period, and is necessary in this implementation because it is assumed that collision risk does not vary over the chick-rearing period in this version of SeabORD.

The sCRM produces multiple simulations of mortality, representing uncertainty and variability, with a large number of simulations (1000) typically being used. SeabORD also uses multiple simulations to represent uncertainty, but as SeabORD is highly computer intensive to run, the number of simulations is much lower, and in this initial project we have used ten simulations. Users may, therefore, specify that SeabORD selects up to ten values of Q for each OWF footprint; these values are derived within the model by randomly selecting ten values from the sCRM output for each footprint, which is uploaded to SeabORD at the start of a simulation.

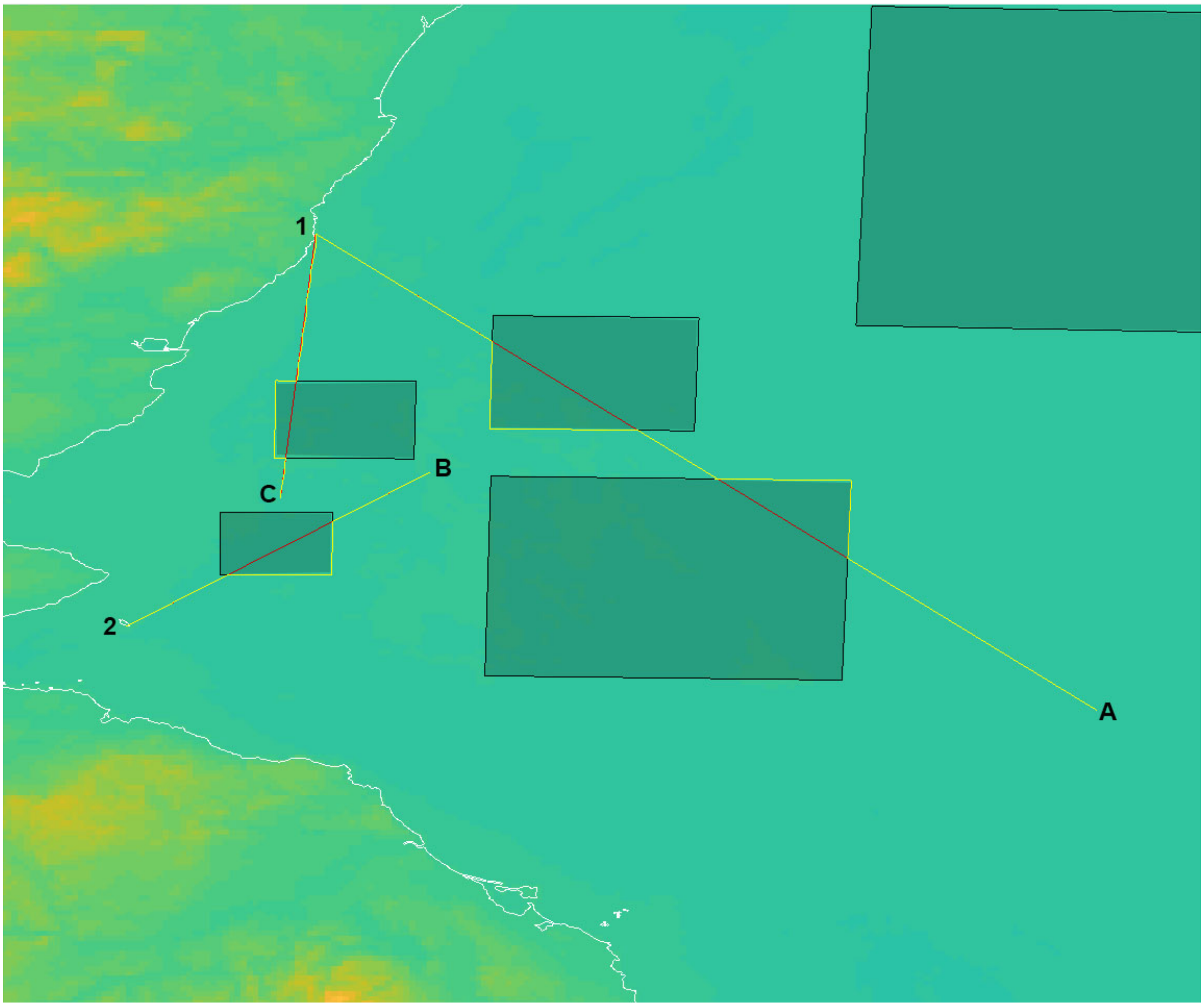

Figure 1: Example flight paths from two colonies (1 = Fowlsheugh, 2 = Forth Islands) to three forage locations (A, B, C). Yellow paths show the route taken by a bird susceptible to displacement or barrier effect (using the ‘perimeter’ flightpath methods within SeabORD. Red lines represent flights of birds within OWF footprints for birds not susceptible to displacement or barrier effects, used within the model to estimate time spent within footprints to use in collision risk calculations.

5.2.1 Case study for integrating sCRM outputs within SeabORD: Black-legged kittiwakes from the Forth Islands SPA

We demonstrate the integration of sCRM output with the individual based simulation model, SeabORD, by running the models using data for black-legged kittiwakes at the Forth Islands SPA. We used the same data and model outputs for the sCRM as were generated in the MS ‘SEANSE’ project (Searle et al, 2019). In the MS SEANSE project, five notional OWFs were assessed in terms of collision risk using a stochastic implementation of the Band (2012) collision risk model (M. Trinder, MacArthur Green) with bird densities generated from local GPS tracking data (Figure 2). These provided a set of simulated collision risk estimates for each of the five notional OWF footprints, from which ten values were selected to use within the SeabORD model to combine with displacement and barrier effects

(Table 2, Figure 3).

The rates used within the SEANSE project varied across species in terms of the displacement rate used in both SeabORD and the matrix approach, and the mortality rate of displaced birds (matrix approach only) (Table 1).

Table 1

sCRM outputs derived from output in SEANSE case study for black-legged kittiwakes from the Forth Islands SPA. The values relate to collision probability per baseline bird month within footprint. Table gives the mean of 1000 simulated values, and the ten randomly selected values that were used within the SeabORD model to combine collision risk with displacement and barrier effects.

			Random samples from sCRM output										
OWF	**Number of turbines**	**Density of turbines**	**mean**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
OWF_3	64	0.13	0.032	0.033	0.031	0.026	0.035	0.026	0.029	0.031	0.031	0.039	0.029
OWF_2	64	0.52	0.082	0.071	0.101	0.086	0.086	0.086	0.082	0.077	0.072	0.084	0.077
OWF_1	35	0.45	0.082	0.074	0.09	0.095	0.084	0.084	0.103	0.084	0.072	0.081	0.087
OWF_4	235	0.19	0.031	0.036	0.03	0.037	0.028	0.031	0.032	0.036	0.034	0.034	0.032
OWF_5	300	0.06	0.015	0.018	0.015	0.012	0.016	0.016	0.013	0.015	0.015	0.014	0.016

Table 2

Rates used within the SEANSE project to parameterise the individual-based model, SeabORD, and the calculations within the matrix approach. Note within this report only black-legged kittiwake is considered (in bold). B = breeding, NB = non-breeding.

Species	Displacement rate	Mortality rate of displaced birds	Season for assessments
Atlantic puffin	60%	2%	Breeding
Common guillemot	60%	1%	Breeding and non-breeding
Razorbill	60%	1%	Breeding and non-breeding
Black-legged kittiwake	**30%**	**2%**	**Breeding**
Gannet	80%	0.5% (B) 0.25% (NB)	Breeding and non-breeding

Figure 2: Locations and size of exemplar Offshore Wind Farm (OWF) footprints used in Scenario 3 in the MS SEANSE project. Pink: OWF_1, Yellow: OWF_2, Red: OWF_3, Grey: OWF_4; Brown: OWF_5.

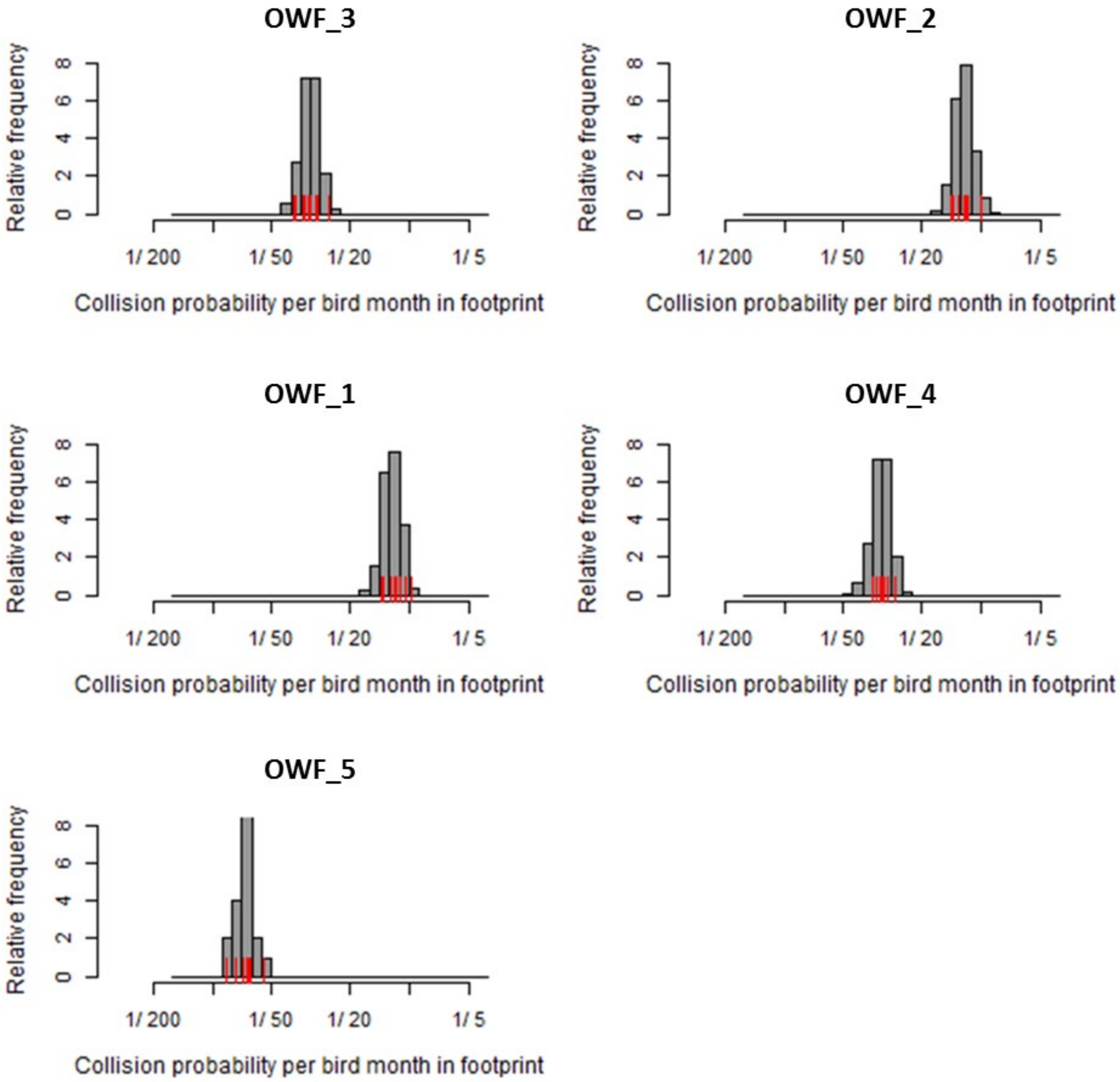

Figure 3: Summary of collision probabilities per bird per month spent in footprint for each of the five notional OWFs used within the MS SEANSE project. All values refer to black-legged kittiwakes from the Forth Islands SPA. The histograms show the distribution of the 1000 simulated values produced by the sCRM, and the red lines show the ten random values, selected from the wider set of simulated values, that are used within SeabORD.

Results and conclusions

We integrated collision risk probabilities into the individual-based model, SeabORD, using parameter settings and inputs from the MS SEANSE project (Searle et al, 2019). This set up SeabORD to simulate black-legged kittiwakes from the Forth Islands SPA during chick-rearing, with the potential for interactions with five notional OWFs (note that birds from other Forth-Tay colonies were also included in model runs to account for inter-colony competition – St Abbs Head, Buchan Ness and Fowlsheugh. SeabORD was modified to keep track of the time spent by individuals within each of the notional OWFs, based on flight lines, flight speed, and foraging times (Figure 1). Only 30% of each SPA population was included in the simulations to reduce processing time.

SeabORD determined collision risk based on output from the sCRM and the cumulative time each individual spent within an OWF footprint on each day of the simulation. For illustration, the table below (Table 3) shows, for each SPA, summary information for the number of individual birds that were exposed to some collision risk (by spending time within one or more footprints) on 0, 1, 2, or more days (‘Days with a collision risk’) during the model run for an entire chick-rearing period (note that zero days means the individual never entered an OWF). This shows that in this model run, 460 individuals from Fowlsheugh SPA were exposed to collision risk on 10 days during the chick-rearing period (value highlighted in red in Table 3). In all, 4689 individuals from Buchan Ness to Collieston Coast SPA (hereafter Buchan Ness) were exposed to collision risk on at least one day, followed by 4089 individuals from Fowlsheugh SPA, 2953 individuals from St Abb’s Head to Fast Castle SPA (hereafter St Abb’s Head), and 1962 individuals from Forth Islands SPA (Table 3). Across all four SPAs, 13,693 individual black-legged kittiwakes were simulated to experience collision risk on at least one day during the chick-rearing period. Note that these numbers are based on simulations with only 30% of each SPA breeding population included, such that values for the full SPA population would be greater.

Table 3

Summary for one SeabORD run for the entire chick-rearing period of the number of individual kittiwakes from each of the four SPAs that were exposed to collision risk, by spending time within one or more OWF footprints, on 0, 1, 2, or more days during the season. Note that only 30% of each SPA population was included in simulations. Values for zero days are birds that never entered an OWF during the simulation. The value highlighted with an asterisk is referred to in the text above to explain the values in the context of bird-OWF interactions.

Days with a collision risk (out of 30)	Buchan Ness	Fowlsheugh	Forth Islands	St Abb's Head	Total
0	**2201**	**1705**	**836**	**1255**	**5997**
1	467	2		2	471
2	883			1	884
3	1090	5		4	1099
4	973	8	1	7	989
5	695	16		30	741
6	351	67	3	75	496
7	152	101	6	148	407
8	58	238	29	267	592
9	15	339	49	383	786
10	4	460*	99	449	1012
11	1	573	145	427	1146
12		582	215	388	1185
13		502	269	334	1105
14		454	311	202	967
15		336	252	126	714
16		196	228	60	484
17		125	156	22	303
18		47	102	23	172
19		30	47	5	82
20		8	35		43
21			9		9
22			6		6
Total with collision risk	**4689**	**4089**	**1962**	**2953**	**13693**

As described above in the methods, the time birds spent in OWF footprints is combined with output from the sCRM to estimate the number of birds suffering mortality through collision. When averaged across ten simulations, this resulted in a mean of 43.5 total collisions across all four SPAs, with an average of 18.2 birds colliding from Fowlsheugh, 12.3 from St Abb's Head, 8.4 from Forth Islands, and 4.6 from Buchan Ness (Table 4). Across all SPAs, the notional OWF_4 resulted in the most collisions (16.9), followed by OWF_2 (9.7 collisions), OWF_3 (8.3 collisions), OWF_1 (5.7 collisions), and OWF_5 (2.9 collisions). Note that all these numbers were obtained from simulations with only 30% of each SPA population.

Table 4

Summary of the mean number of collisions (averaged across ten simulations) for black-legged kittiwakes from each SPA per notional OWF footprint. Note all numbers are based on runs with 30% of each SPA population included in simulations. 'no collisions' refers to the mean number of birds that entered a footprint at some point during model simulations that did not suffer a collision with turbines.

OWF	Buchan Ness	Fowlsheugh	Forth Islands	St Abb's Head	Grand Total
OWF_3	1.0	4.6	1.5	1.2	8.3
OWF_2	1.3	5.9	1.6	0.9	9.7
OWF_1	0.2	2.1	2.3	1.1	5.7
OWF_4	0.7	4.3	3.0	8.9	16.9
OWF_5	1.4	1.3		0.2	2.9
(no collisions)	6885.4	5775.8	2789.6	4195.7	19646.5
Total collisions	**4.6**	**18.2**	**8.4**	**12.3**	**43.5**

Finally, we combine the collision mortality with the mortality arising from displacement and barrier effects, to estimate the total combined additional mortality for Forth Islands black-legged kittiwakes (Table 5). We first compare the estimated additional mortality and reduction in productivity between the original SeabORD run (Table 5); top row 'Displacement risk: original SeabORD') and an identical run using the new modified SeabORD, but without collision modelling turned on within the simulations (Table 5); second row 'Displacement risk: revised SeabORD'). The results show that the estimated impacts are very close, and only differ by a few decimal places, which is to be expected because the matching of stochastic events within the revised version of SeabORD is no longer the same as in the previous version, before collision was added (Table 5). Once collision was turned on (Table 5); last row 'Combined risk: revised SeabORD'), the estimated additional adult mortality increased by 0.134%, from 0.879% (95% CI: 0.153-1.606) with only displacement and barrier effects simulated, up to 1.112% (95% CI: 0.480-1.743) with both displacement, barrier and collision effects simulated (Table 5). Similarly, chick productivity reduced by an additional 0.515% when collision was included in the simulations, from 5.561% (95% CI: 0.326-10.797) with only displacement and barrier effects, to 6.076% (95% CI: 1.047-11.104) when collision was also included in model runs (Table 5).This combined estimate using the integrated model (last row, 'Combined risk: revised SeabORD') is broadly similar to the additive estimate of displacement and collision from separate models (fourth row, 'Combined risk: additive') calculated from separate models in the MS SEANSE project. When modelled separately in SEANSE, the combined additional adult mortality was estimated as 1.05%, compared to an increase in mortality of 1.11% using the integrated models used here (Table 5, rows 4 and 5). The risk from collision only (Table 5, 'Collision risk: sCRM') was approximately 0.19% additional mortality.

Table 5

Summary of population level effects for additional adult mortality (mean, SD, 95% CI) and reduction in productivity (mean, SD, 95% CI) for black-legged kittiwakes from the Forth Islands during the chick-rearing period, in relation to displacement/barrier risk, collision risk and the combined risk of collision and displacement/barrier effects. Displacement/barrier risk is calculated using either the older version of SeabORD without collision risk added (as used in the SEANSE project) or the revised version produced within this project, collision risk is calculated using the sCRM (as used in the SEANSE project), and combined risk is calculated either by adding displacement/barrier and collision risk (as in the SEANSE project) or by using the revised SeabORD model that includes the facility for collision modelling. Note that SDs and confidence intervals for the "Additive" combined risk estimate are approximate, and derived under assumptions of independence and normality.

Run	**Model scenario**	**Additional mortality %, mean**	**Additional mortality %, SD**	**Additional mortality % lower confidence interval**	**Additional mortality % upper confidence interval**	**Productivity % reduction mean**	**Productivity % reduction SD**	**Productivity % reduction LCI**	**Productivity % reduction UCI**
Displacement risk	Original SeabORD	0.861	0.267	0.229	1.494	5.354	2.103	0.365	10.342
	Revised SeabORD	0.879	0.306	0.153	1.606	5.561	2.207	0.326	10.797
Collision risk	sCRM	0.186	0.010	0.168	0.205	0	0	0	0
Combined risk	Additive	1.047	*0.267*	*0.523*	*1.571*	5.354	2.103	0.365	10.342
	Revised SeabORD	1.112	0.266	0.480	1.743	6.076	2.119	1.047	11.104

5.3 Integrating collision risk models with the Displacement Matrix approach: case study

The overall combined impact of collision and displacement on mortality is usually estimated in practice by using the displacement matrix approach to estimate displacement risk and the sCRM to estimate collision risk, and then summing the results together (an “additive” approach).

Aside from any limitations and caveats associated with estimating each of the constituent risks (displacement and collision) in this way – the limitations of the displacement matrix approach have been discussed extensively elsewhere (Searle et al, 2019) - there appear to be two main issues involved in combining the estimated mortalities from the two sources of risk in an additive way: a) the potential for double counting, and b) potential inconsistencies in the displacement/avoidance rates used in the calculations.

5.3.1 Potential for “double-counting” of mortalities

Concern has been expressed about the potential for ‘double-counting’ of mortalities arising from collision or displacement within assessments. This refers to a potential error whereby assessments count deaths of individual birds more than once, for instance assigning an individual to die from both displacement impacts and from collision, potentially resulting in an over-estimation of mortality impacts. Individual-based models that explicitly account for both possible causes of deaths - such as the new, revised version of SeabORD - circumvent this issue by explicitly modelling the behaviour of each bird at each point in time, and by removing birds from the simulation as soon as they have died.

Additive population-level approaches - e.g. calculating annual collision mortality using the sCRM and annual displacement mortality using the Displacement Matrix or original version of SeabORD and then summing these together – are, however, potentially susceptible to double counting. Unless OWF effects on mortality are extraordinarily large, however, simple probability calculations suggest that the rate of double counting is likely to be very low, relative to the estimated sizes of collision and displacement effects. If, for example, the annual probability of mortality due to displacement is 1% (i.e. 0.01) and that due to collision is 3% (i.e. 0.03) then, if collision and displacement occur independently, the probability of double counting will be 0.01 * 0.03 = 0.0003 = 0.03%. In this example the actual overall risk due to collision and mortality would therefore be 3.97%, whereas the assumed risk, if we ignored double counting and simply added the two sources of mortality, would be 4%.

In practice, displacement and collision are very unlikely to be independent – because birds that are susceptible to displacement cannot, by definition, be simultaneously susceptible to collision, we might expect negative dependence between the probability of collision and the probability of displacement, and this is likely to further reduce the rate of double counting. In the most extreme case, if birds were to remain either collision-susceptible or displacement-susceptible through the entire year or season (as SeabORD assumes, for example) then double counting would be impossible, and in that case it would be correct to simply sum the collision and displacement-related mortality rates.

5.3.2 Potential inconsistencies in avoidance and displacement rates

The displacement matrix approach and sCRM both require an input parameter that captures ‘macro-avoidance’ in some form – the percentage of birds seen in the footprint pre-construction that would be displaced entirely from the area and not enter the footprint post-construction. However, there are important inconsistencies in how these parameters are specified and used within the two modelling approaches, which potentially limit the defensibility of combining the outputs from these approaches to estimate the overall (combined) mortality rate associated with an OWF:

- The displacement rate in the matrix approach applies to all birds observed within an OWF footprint (in flight and on the water); whilst the avoidance rate in sCRM approaches is applied only to birds in flight

- The avoidance rate used in sCRM calculations encompasses three different scales of avoidance: micro, meso and macro. However, the displacement rate used within the matrix approach is intrinsically assumed to capture only macro-avoidance (birds not entering the OWF footprint at all). The extent to which these different rates can be compared (‘macro’ versus ‘macro, meso and micro’) is yet to be established. On the face of it, we might expect the avoidance rate used in sCRM models (macro, meso, micro) to be a higher percentage than the displacement rate used in the matrix approach (macro only) because it also accounts for birds that having entered the OWF, avoid individual turbines via meso- and micro-avoidance. It is also not currently possible to separate avoidance rates out into their three components (macro, meso and micro) for most seabird species, or indeed as a first step, into two components representing macro-avoidance versus ‘micro- and meso-’ avoidance.

- The avoidance rate used within sCRM models incorporates a correction to account for model error (e.g. in relation to how flux rate is estimated). However, as avoidance rates are estimated by comparing observed and predicted collision rates, there is a need to consider macro-avoidance separately. Macro-avoidance can be accounted for by adjusting density of birds within the wind farm area pre-construction by the proportion expected to not enter the wind farm once it is constructed. Consequently, the macro-avoidance rate can be used within displacement modelling approaches – the assumption is that macro-avoidance is the sum of displacement and barrier effects, and therefore appropriate for use within models that estimate both processes. However, this requires a separation of avoidance into at least two, potentially three components (‘macro’ and ‘meso plus micro’; or ‘macro’, ‘meso’ and ‘micro’), which is not currently available for most seabird species. It is also problematic that the avoidance rate used within sCRM models includes correction for multiple factors leading to discrepancies between calculated collision rates and actual collision rates, further complicating separation into different scales of displacement behaviour (Bowgen & Cook 2018).

To address these issues, the next step is to undertake research and model development to split the overall avoidance rate used in sCRM models into its critical components – macro-, meso- and micro-avoidance, or potentially as a first step, macro- and micro- + meso-avoidance). Displacement rates used within the matrix approach may then be specified to be equivalent to macro-avoidance. Because avoidance rates also include a ‘correction factor’ for other causes of differences between calculated and actual collision rates, the ‘correction factor’ element could be estimated only in relation to the micro- and meso-avoidance components of the sCRM model, meaning the macro-avoidance rate and the displacement rate would be directly equivalent. If this is the case, then the number of birds simulated to die from collision in the sCRM will not include displaced birds, and because the mortality rate used in the Matrix approach relates directly to displaced birds, the number of mortalities from each method may simply be summed to find the total mortality associated with both collision and displacement.

This will require interrogation of existing empirical data, or collection of new empirical data to facilitate better estimation of displacement (macro-avoidance) rates across the three scales for seabird species. It would also require some model development within the sCRM to split out the application of the correction factor such that it only affects meso- and micro-avoidance. Alternatively, refinements to sCRM models to better reflect observed collision rates would reduce the need for a correction factor to be applied, or would minimise its contribution to avoidance rates (Bowgen & Cook 2018).

6 Discussion

Here, we first summarise outcomes from an initial project workshop to explore approaches for combining displacement, barrier and collision assessment approaches. We then identify a series of future research priorities for integrating modelling methods for collision and displacement/barrier impacts. Finally, we present a set of wider recommendations to facilitate and advance approaches for combined estimates for collision and displacement/barrier impacts on seabirds.

6.1 Workshop on combining displacement, barrier and collision assessment methodologies

The project held an initial workshop that brought together experts from research, environmental consultants, government and conservation bodies to discuss how best to implement combined modelling of displacement, barrier and collision risks from OWFs for breeding seabirds. The aim was to discuss how current methods are used to estimate collision and displacement risks separately in assessments, with a following session on the extent to which the inputs, parameters and assumptions used in the different methods are consistent with each other. Finally, there was a session on how to combine collision and displacement risks into a single assessment of risk. For full reporting of workshop discussions and conclusions see **Appendix C**. The main recommendations arising from the workshop were as follows:

6.1.1 General recommendations from workshop

By bringing together experts in collision risk and displacement modelling, we were able to summarise the key challenges in integrating collision risk and displacement, and agree an approach for integrating sCRM outputs (collision) into SeabORD or with the matrix method (displacement and barrier) in this project, using black-legged kittiwake (to illustrate practical combining of the sCRM with the individual-based model, SeabORD), and a more general discussion for combining the sCRM + matrix approaches

In using GPS tracking data there is a need to integrate outputs from hidden Markov models (HMMs) by BTO to partition movement data by behaviour (Thaxter et al. 2019), thereby allowing behaviour-specific bird utilisation distributions to be used within models;

Flight height should consider commuting and foraging flight separately when applied to an individual-based model; for some species (e.g. black-legged kittiwake) flight speeds should also be estimated and modelled separately for commuting and foraging; if birds use distinct areas for commuting and foraging, then using an average flight height may overestimate collision risk in commuting areas and under-estimate collision risk in foraging areas (assuming birds fly higher when foraging) (Cleasby et al. 2015). Given different locations/size/layouts etc. of wind farms, it’s probably not reasonable to assume the two biases would cancel each other out.

There is a need to incorporate 3D flight movements, based on the latest GPS tracking data (available for gannet and kittiwake, more planned for both species at more locations; e.g. Thaxter et al. 2017);

There is a need for further empirical data and validation of inputs and outputs of sCRM, matrix approach and SeabORD;

Further model developments must consider the growing relevance of cumulative in-combination effects across multiple OWFs. Some progress has been made but more will be needed.

6.1.2 Specific sCRM recommendations

There is a need to parallelise sCRM to increase its speed to levels obtained when using the underlying code;

There is a need to incorporate an observed distribution of flight speeds in sCRM (a truncated normal distribution with a mean and standard deviation is currently used);

6.1.3 Specific SeabORD recommendations

There is a need to speed up running time for model, and include automated calibration to handle application with new data more efficiently.

6.2 Future research priorities for integrated modelling of displacement and collision

6.2.1 Unifying models and inputs

We have developed a framework for simultaneously estimating collision and displacement effects, from either a single OWF or multiple OWFs, using an individual-based mechanistic model of seabird movement, foraging and demographics coupled with output from the sCRM. In the initial implementation of this framework, we have used outputs from the existing sCRM model to provide information on collision-related mortality rates, which are then used to simulate collision events within an extended version of SeabORD.

This integration has highlighted some key complexities around some of the model parameters, notably the need for methods to empirically estimate macro-avoidance to improve the realism of parameters used within the new combined model and consistency in assumed rates of displacement. A further key issue for future work is to develop methods which would enable GPS data to be used to estimate flux within collision risk models.

It would ultimately be preferable to unify the two models into a single model, by embedding the sCRM calculations within SeabORD so that the Band model calculations of collision risk would effectively be performed for each bird on each day. Unifying the models would improve usability and reduce the potential for users to run the two models in ways that are inconsistent with each other (e.g. by providing inputs with inconsistent values).

The key advantage of unifying the models using an individual-based modelling approach, however, would be the potential to refine the model processes to improve the realism of the biological assumptions of both models. This would include, for instance, changes to simulate 3D flight paths for individual birds within OWFs, and more realistic (non-straight line) foraging paths outside of OWFs, as well as potentially separating out collision risk into specific behaviours, such as commuting flight and foraging flight. The key advantage in modelling individual flights within OWFs is that the model would automatically separate out the three types of avoidance – macro (displacement/barrier), meso (>10 m movements to avoid individual turbines), and micro (<10 m ‘last second’ flight adjustments close to individual turbines). It would also be desirable to extend the SeabORD model to include the incubation period, as well as the chick-rearing period within model simulations.

However, it is important to note that not all species need both collision and displacement to be modelled simultaneously. For some species, statutory advice has so far been that collision risk modelling is not needed, primarily due to the flight height distribution of birds (e.g. shearwaters, auks), while for some species collision risk is important, but displacement appears not to occur (e.g. large gulls or other species with very large foraging ranges such as northern fulmar and northern gannet, in Scotland only). An integrated model will be of most value to those species where the likely impacts from displacement and/or barrier effects and collision risk are both considered important (e.g. black-legged kittiwake and northern gannet). In addition, stand-alone collision risk modelling will continue to be useful for determining the worst-case scenario within the design envelope of the proposed OWF.

6.2.2 Better methods for incorporating non-breeding birds at risk of collision and displacement within modelling approaches, and new research needed to extend modelling to include immature and sabbatical birds (non-breeders), and to potentially deal with birds breeding in other countries

New science is needed to extend individual-based models such as SeabORD to cover the whole of the breeding season (but see van Kooten et al 2019 for initial work in this area). At present, for each of the four species currently parameterised within SeabORD, the model only simulates OWF impacts over the chick-rearing period. Currently, a full extension to the whole of the breeding season (pre-breeding attendance, incubation, chick-rearing, post-fledging attendance) may not be possible for all seabird species at risk of OWF impacts due to a lack of data on individual movements, behaviour and other ecological processes. This development would require several key stages: 1. Identification, collation and processing of relevant data, 2. Theoretical model development to incorporate new behaviours and processes out-with the chick-rearing period, 3. Implementation of new developments within the model code and subsequent testing, and 4. Model validation, QA and sensitivity analysis.

In order to fully reflect ecological reality, it is important that impacts on all life-history stages are considered, including those on non-breeding birds (e.g. immature birds and those taking a sabbatical). Estimates of the proportion of immature birds within the population could be obtained by examining digital aerial images (for species where plumage differs recognisably between age classes), while estimates of the proportion of birds taking a sabbatical year could be determined through the analysis of ringing and colour-ringing datasets where available. In order to better apportion impacts back to the appropriate protected sites, a clearer understanding of the movements of birds between colonies, both in the UK and elsewhere, is needed (Black & Ruffino 2018; Ruffino et al. 2020). Previous large scale-analysis of GPS tracking data has highlighted the partitioning of birds from different colonies at sea (e.g. Wakefield et al. 2014). Given the rapid expansion of GPS tracking studies, similar analyses should be considered for other species in order to gain a clearer understanding of how birds from different colonies may interact with particular developments.

Other methods for estimating impacts on non-breeding birds should also be explored, such as more empirical work aimed at quantifying the proportion of non-breeders associated with SPA populations, movements between SPA colonies, and the relative abundance of non-breeders or birds from non-UK colonies observed at sea.

There are important differences in the approaches needed for undertaking impact assessments for different legislation. EIA legislation is intended to protect the environment as a whole, while Habitats Regulations Appraisal (HRA) is intended to protect specific populations that utilise and are supported by a network of designated sites. Thus, EIA needs to apply to whole populations of seabirds at regional and national/international levels and includes all birds regardless of their age or breeding status. HRA needs to apply only to impacts that affect the conservation objectives of the site. Overarching objectives tend to focus on maintaining the designated population size. In the case of SPA designated seabird colonies those populations are breeding adults. While it is important to consider impacts on other demographic elements (e.g. sabbatical birds, immature birds, etc.) it is only where these are relevant to maintain the designated population size of adult birds that they need to be included in the impact assessment. Thus, current individual based models are much more useful to the HRA than to the EIA, as the population is well defined and individuals that are part of the qualifying population of a site are a suitable unit of assessment. HRA is also intended to be a higher hurdle to development with the potential to do harm, reflecting the greater conservation importance on species and populations within designated sites.

7 Wider recommendations

We have identified six main areas for wider recommendations for future research to facilitate robust and defensible estimation of combined collision and displacement/barrier effects for seabirds:

- Requirements for validation of individual-based models;
- Improvements to incorporation of uncertainty in individual-based models;
- The potential for making collision risk modelling an agent-based approach;
- Better unification of the behavioural definitions used within current individual-based models (SeabORD) and those derived from at-sea survey data;
- Potential for combined modelling of displacement and collision risks throughout the whole year;
- Potential for assessing in-combination and cumulative effects of multiple OWFs.

7.1 Requirements for validation of individual-based models

Fundamentally, validation of the mechanisms within individual-based models such as SeabORD requires empirical data on the behavioural response of individual birds to OWFs, and the consequences of those behavioural responses in terms of changes to body condition and demography. These data are best acquired through GPS tracking of individual breeding birds before and after construction, with simultaneous measurements of individual condition, breeding success and survival.

7.2 Improvements to incorporation of uncertainty in individual-based models

Most of the model parameters in SeabORD, even when derived from empirical data, are currently utilised within the model as a single value, such as the mean of a sample of empirical data, or as a single value derived from expert judgement. Primarily, this is due to a lack of empirical data with which to test some of the key mechanisms within the model to do with bird behaviour and responses to OWFs, such as intake rates of individuals in relation to prey availability, competition effects of conspecifics on individual intake rates, probabilities of chick mortality arising from adult unattendance, and other such mechanisms. Before such empirical data become available for parameterising some of these mechanisms, the model could use simulated values across a range of plausible values derived from expert elicitation for these unknown parameters to better incorporate uncertainty in model processes within the simulations. This would require improving model processing time efficiency, to allow for a large number of simulations to be run, and to allow for an initial model sensitivity analysis to be conducted to identify key model parameters having the greatest impact on model output. Then, as empirical data is collected, it can be used to refine parameter estimates in the model, thereby reducing uncertainty in model outputs.

7.3 The potential for making collision risk modelling an agent-based approach

Developing individual-based models for collision risk modelling would improve estimates for collision mortality by allowing more nuanced simulations of the response of individual birds to OWFs and turbines, and facilitating better quantification of avoidance behaviours at the three main scales (macro, meso and micro). This could be achieved by developing 3D movement models derived from GPS tagging data, allowing for simulations of individual bird flights to be performed within models. This would also allow a full integration of displacement, barrier and collision risk modelling within a single modelling framework, reducing the need for harmonising parameters across alternative modelling approaches, minimising error, and facilitating quantification of uncertainty. This development would also allow for a better representation of bird movements in relation environmental parameters (e.g. wind speed and direction) and diurnal patterns. This will require the collection of high frequency GPS tagging data of individuals interacting with operating OWFs, preferably across many individuals and multiple colonies to appropriately capture individual variation in behavioural responses.

7.4 Better unification of the behavioural definitions used within current individual-based models (SeabORD) and those derived from at-sea survey data

The SeabORD model simulates a range of individual behaviours, with individuals at-sea potentially performing commuting flight, foraging or resting at sea. These behaviours are identifiable from GPS tracking data, particularly when coupled with other technology such as TDRs or accelerometers (e.g. Thaxter et al. 2019). However, at-sea survey data tends to only be classified into individuals in flight or on the sea surface (though some other behaviours may be observed, such as multi-species aggregations of birds), meaning that estimating utilisation distributions (UDs) from at-sea survey data cannot currently provide foraging-specific UDs, and also requires the use of apportioning methods to generate UDs for specific breeding colonies. Other behaviours that are of interest in understanding the use of a proposed wind farm can be obtained from at sea survey data, but not from GPS tagging data (such as density surface models of all birds using the space, or the spatial occurrence of multi-species feeding assemblages). The estimation of behaviour-specific UDs to facilitate modelling methods such as individual-based models, or indeed to refine estimates used in sCRM or the matrix approach, is therefore best approached through the use of GPS tagging. However, at-sea survey data can be used to provide context for GPS tagging data. It is important to recognise that to date GPS tagging tends to sample breeding adults, but assessments require knowledge about all of the birds present in the areas of OWFs (all age classes and non-breeders). At present, at-sea surveys are best placed to provide this categorisation of individuals.

7.5 Potential for combined modelling of displacement and collision risks throughout the whole year

Sub-lethal effects of offshore renewable energy developments on seabirds during the non-breeding season are currently poorly understood, poorly estimated, high in uncertainty and low in defensibility. We, therefore, recommend research to develop a new individual-based model of birds in the non-breeding season, parameterised with at-sea survey data and tracking data on winter distribution and activity budgets of birds from multiple colonies. A similar approach to that of the breeding season model SeabORD could be developed, whereby a simulation model predicts the time/energy budgets of seabirds during the non-breeding period and translates these into projections of adult annual survival and productivity.

There are critical differences between the constraints and behaviours within which seabirds operate in the non-breeding season, compared to the breeding season. In the non-breeding season, adult birds are independent of offspring and mates, and are not typically operating out of a central place such as a breeding colony. Some species undertake partial or full migration in winter, and winter places higher energetic costs upon birds. However, birds are constrained during the non-breeding season by a number of mechanisms, for instance they may be spatially constrained because of high flight costs or physiological changes such as moulting and may be temporally constrained by shorter day lengths. Some progress has been made in developing year-round models for assessing displacement effects of OWFs; van Kooten et al. (2019) developed modelling methods to consider effects for the full life cycle of several seabird species in the North Sea, focusing on the wider population in the region, rather than on specific breeding colonies. Whilst representing an important step forwards, this approach does not yet include reproduction or density dependent effects arising from reduced carrying capacity as individuals are displaced into smaller areas; and was also restricted to conducting separate simulations for the breeding and non-breeding seasons in species present in the region year-round (van Kooten et al. 2019).

Some of the key research priorities for developing such a model include advancing estimates for the extent of interaction between birds of known provenance (SPAs) and OWF footprints during the non-breeding season (GPS tagging); developing methods for defensible estimates of mortality rates of displaced birds during winter (energetic models and changes in mass and survival), and the incorporation of carry-over effects from winter displacement or barrier effects on subsequent breeding efforts.

There is currently the strongest potential for developing such an individual-based model for common guillemots, although this species is thought to be less affected by collision due to the majority of its flight occurring below rotor height. In this species, there exists year-round data from GLS (light-level global location sensor/gelocator) tagging on their wintering distribution, activity budgets and energetics, and subsequent changes in body mass. Other species should also be prioritised by developing GLS deployments in new species to build baseline individual-based models, as well as GLS deployments in new species to estimate interactions with OWF developments.

It is, however, important to understand the legal frameworks in which impact assessment for OWF occurs. These individual based models are likely to be of great utility to estimating year-round impacts on birds from important breeding colonies designated as SPAs. While this fulfils the requirement to assess impacts under the Habitats Regulations (referring to marine SPA sites), it is also necessary for OWF developments to assess their impacts under the relevant EIA legislation. To undertake an EIA the applicant must address impact to all birds potentially affected by the development, not just those that can be tracked as breeding adults from SPA colonies.

7.6 Potential for assessing in-combination and cumulative effects of multiple OWFs

Through the use of individual-based models, in-combination cumulative impacts of multiple OWFs are easily quantified, because the interaction of each individual bird with each OWF is captured within the modelling process. By embedding collision risk models within individual-based models, in-combination assessments are easily made, with no risk of double counting of collision mortalities arising from turnover of observed birds within different footprints.

8 Acknowledgements

This research was funded by the Scottish Government: Marine Scotland - Marine Planning and Policy. We particularly wish to thank the members of the Project Steering Group and expert attendees at the project workshop: Tom Evans (MSS), Janelle Braithwaite (MS), Alex Robbins (SNH), Julie Black (JNCC), and Lise Ruffino (JNCC).

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9.1 Summary of key mechanisms and assumptions within the SeabORD model

Here we summarise the key SeabORD model mechanisms, assumptions and their impact on demographic output for assessing effects of OWFs on breeding seabirds. The model can be condensed into a series of sub-models associated with different stages of simulation (Figure 4: e.g. estimating spatial distribution of birds, simulating foraging behaviour and provisioning, estimating survival from mass change of adults). The following is taken from the Marine Scotland 'Fate of Displaced Birds' project report (Searle et al. 2019).

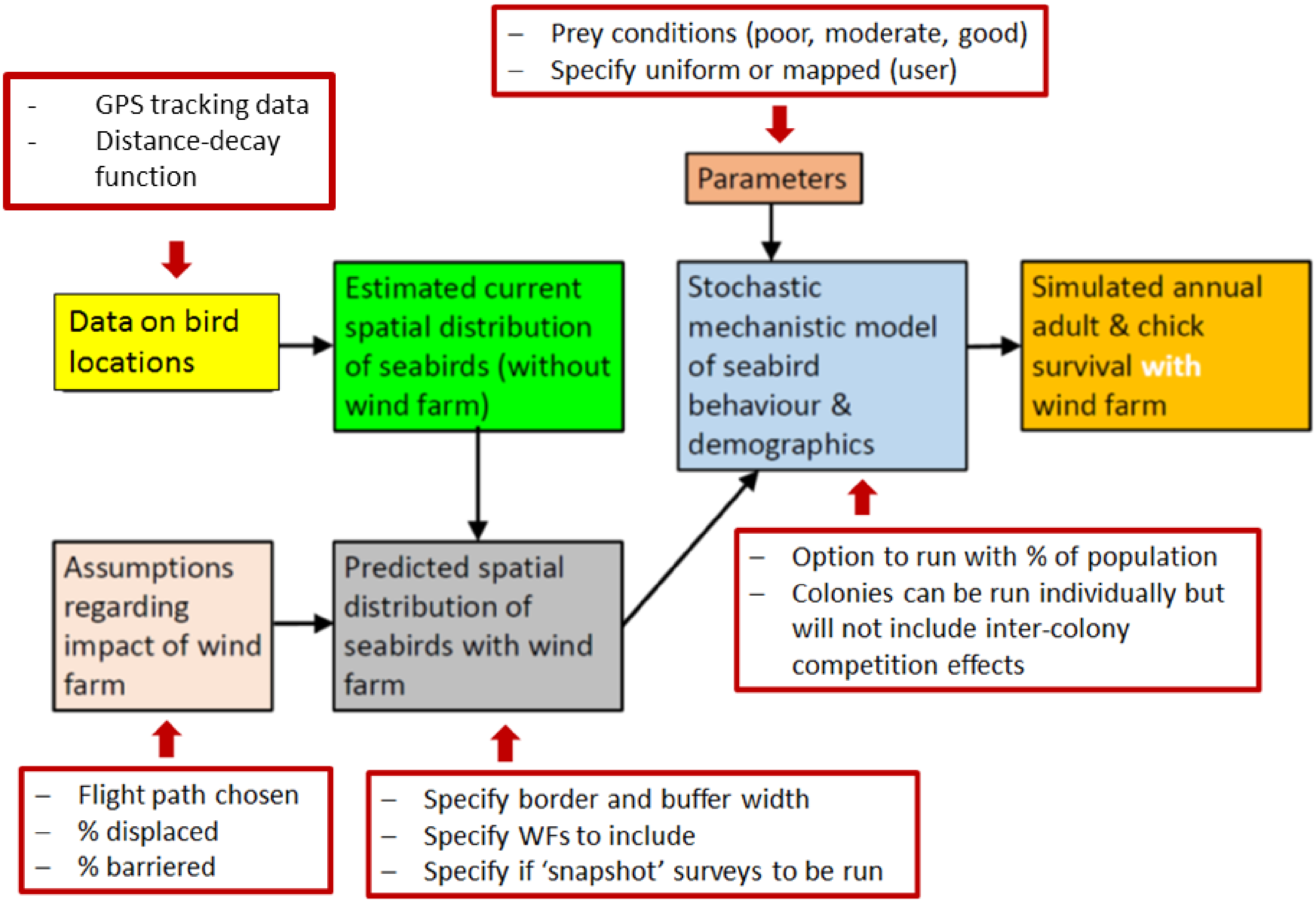

Figure 4: Schematic of model structure and data and user-specified inputs. Reproduced from Searle et al. 2019.

The specific mechanisms within the model are based upon the best available evidence or expert opinion for how breeding seabirds are likely to behave in terms of time-activity budgets and specific behaviours relating to their own energy acquisition, provisioning of energy for chicks, and breeding behaviours such as attendance at nests. Below we summarise all of the main mechanisms within the model, listing their assumptions and stating the likely impact of each on subsequent model output for demographic parameters (Table 6).

Table 4

Summary of mechanisms, assumptions and likely effect in demographic output for all processes operating within the model (SeabORD) for estimating the impact of OWFs on breeding seabirds. Reproduced from Searle et al .2019.

Process	Mechanism	Assumptions	Likely effect on demographic output
Bird Foraging locations:			
Local GPS maps	Birds from each colony choose a foraging location in proportion to the intensity of usage estimated using a GAM model of GPS points. Importantly, there is no assumption that birds attempt to meet an ideal free distribution (IDF). The IDF has restrictive assumptions, including that birds have perfect information of resource supply and distribution of conspecifics, and that there are no constraints to patch choice. The first two assumptions are clearly unrealistic, and the third is likely to be violated when central place foraging occurs, as for breeding seabirds. Furthermore, the balance between competition and facilitation in foraging seabirds is not properly understood. Finally, several studies have shown that seabird and prey distribution seldom conform with IDF predictions (e.g. see Fauchald 2009).	Foraging locations are chosen independently at each simulated time step with no influence of site fidelity. The order of individuals choosing foraging locations is random at each time step so the likelihood of an individual choosing a location with high or low bird density is also random. The available GPS data provide an accurate and unbiased estimate of the underlying spatial distribution of foraging birds utilised by birds from the colonies of interest.	Bird location influences demographic output through determining distance travelled, interspecific competition and potential encounter with OWFs (displacement and barrier effects). The relationship between the spatial distribution of birds and the impact of the OWF upon survival is potentially very complicated, so it is not straightforward to anticipate the likely sign or magnitude of effects that would arise from altering the spatial distribution.

Distance-decay	Intensity of usage declines exponentially with distance from colony according to pre-specified parameters by the model user. It is the responsibility of the user to best determine that simulated bird distributions match those expected in reality. Birds from each colony choose a foraging location in proportion to the predicted intensity of usage from the distance-decay algorithm. Importantly, there is no assumption that birds attempt to meet an ideal free distribution (IDF). The IDF has restrictive assumptions, including that birds have perfect information of resource supply and distribution of conspecifics, and that there are on constraints to patch choice. The first two assumptions are clearly unrealistic, and the third is likely to be violated when central place foraging occurs, as for breeding seabirds. Furthermore, the balance between competition and facilitation in foraging seabirds is not properly understood. Finally, several studies have shown that seabird and prey distribution seldom conform with IDF predictions (e.g. see Fauchald 2009).	The spatial distribution of birds is unaffected by either environmental heterogeneity or competition. Foraging locations are chosen independently on each simulated time step with no influence of site fidelity. The order of individuals choosing foraging locations is random at each time step so the likelihood of an individual choosing a location with high or low bird density is also random.	Bird location influences demographic output through determining distance travelled, interspecific competition and potential encounter with OWFs (displacement and barrier effects).

Prey availability			
Median prey density	The user specifies a median prey density across cells in the region of interest which is used to specify the overall available prey density per grid cell in the model.	Adults protect their own survival to safeguard future reproduction (via a threshold in acceptable mass loss in relation to provisioning of chicks and abandoning the breeding attempt) over that of their chick's survival	This trade-off between current reproduction and future survival means that relative effects on adult survival and productivity will depend on prey level in complex ways. As prey levels decline, the effect will initially be stronger on adult survival as they safeguard current reproduction, but with further declines the effect on productivity will strengthen and those on adult survival stabilise as individuals abandon breeding. Yet further declines in prey levels are then likely to affect both demographic rates simultaneously.

Uniform spatial distribution of prey	Prey is uniform throughout the available foraging area	All locations have equal prey availability	Prey availability at each bird location influences demographic output through determining intake rates, and therefore the required time spent foraging to achieve a set energy requirement. Model output under uniform prey is likely to be less variable than that under prey derived from local GPS data because all birds encounter the same prey availability at their chosen foraging location.
Local GPS spatial distribution of prey	Prey is estimated from a GAM model of bird GPS locations assuming that once the accessibility (distance from source colony) and competition (distance from next nearest colony) effects are accounted for, the remaining spatial distribution in the intensity of usage is due to prey availability.	No knowledge of empirical prey distribution and density is assumed, prey is derived solely from bird locations. Locations far from the source colony with high densities of birds assume high prey availability. Foraging locations simulated by SeabORD are determined by bird densities (see above section) and are not related to prey directly (i.e. no assumption of Ideal Free Distribution)	Prey availability at each bird location influences demographic output through determining intake rates, and therefore the required time spent foraging to achieve a set energy requirement. Model output under uniform prey is likely to be less variable than that under prey derived from local GPS data because all birds encounter the same prey availability at their chosen foraging location.

Displacement and barrier effects			
Displacement effects	The user defines a proportion of the total population that are susceptible to displacement effects. Displacement susceptible birds are displaced from the OWF footprint (footprint + border) when their chosen foraging location lies within this region. Upon displacement, birds select a new foraging location within the buffer area around the OWF in proportion to the modelled bird density within the buffer area. It is assumed that birds fly straight to the new foraging location from the colony (i.e. they do not attempt to first fly to the displaced location). As a result birds may either incur additional flight costs due to the new location being on the far-side of the OWF (and due to barrier effects if the individual is also barrier-susceptible), or may have reduced flight costs because their new foraging location in located on the near-side of the OWF in relation to the source colony.	The user must set the displacement rate for each modelled species. This defines the proportion of the total population that are susceptible to displacement. Individual birds are randomly assigned to the displacement-susceptible category until this proportion is met at the population level. As a result all individuals in the displacement susceptible category will always seek a new foraging location in the OWF buffer zone when their chosen foraging location lies within the OWF footprint or border region.	Displacement effects can be both positive and negative in terms of their impact on demographic output. If a bird is displaced closer to the source colony it will have lower flight costs and shorter flight times, subsequently benefitting from displacement both energetically and in gaining more time for other activities (foraging or time at the nest). If a displaced bird is displaced into a part of the buffer zone where prey availability is higher (after taking into consideration the interference effects of other birds foraging at that location), it will benefit from a higher intake rate allowing it to more rapidly meet its energetic costs, therefore benefitting energetically and in gaining more time to devote to other activities (time at nest).

			If a displaced bird is displaced to a location further from the source colony it will incur increased flight costs and flight time, negatively affecting its energy budget and reducing the time available for other activities (foraging and time at nest). If a displaced bird is displaced into a part of the buffer zone where prey availability is lower (after taking into consideration the interference effects of other birds foraging at that location), it will suffer reduced intake rate, thereby negatively affecting it energetic budget through increased time spent foraging, potentially affecting its ability to meets its energetic requirements and devote time to attending its nest.

Barrier effects	Because the model assumes barrier-affected birds must also be displacement-susceptible (it is likely not plausible for a bird to not be prepared to fly within an OWF footprint, but to be prepared to forage within an OWF footprint) all barrier-affected birds are also assigned to the displacement-susceptible category. The proportion of the population in the barrier-affected category is set by the user when setting the barrier rate. This proportion may only be as great as the displacement rate proportion set above (because all barrier-affected birds must also be displacement-susceptible). Should a barrier-affected bird choose a foraging location obstructed by the OWF footprint it incurs additional flight costs determined by the barrier flightpath method (‘perimeter’ or ‘A-star’).	The user must set the barrier rate for each modelled species. This defines the proportion of the total population that are susceptible to barrier effects. Individual birds are randomly assigned to the barrier-affected category until this proportion is met at the population level. As a result all individuals in the barrier affected category will always fly around the OWF footprint + border zone when their straight-line path to the chosen foraging location is obstructed.	Barrier effects are negative, unless they cause a bird’s chick to suffer mortality from unattendance or low provisioning as a result of its partner giving up the breeding attempt when an OWF is present, releasing both adults from restrictive central place foraging conditions resulting in the bird that did not reach the mass loss threshold losing less mass over the course of the breeding season. When a bird is obstructed by the OWF it incurs extra flight costs (energy and time) due to avoiding the OWF footprint + border. This will negatively affect the individual’s energy budget and will reduce time available for other activities (foraging and time at nest). Some individuals may choose to reduce the number of foraging trips made per simulated time step to reduce the time

			costs associated with the extra flight distance. However, due to the optimisation procedure within the foraging component of the model, birds will never benefit from reducing the number of trips in relation to their time-energy budget in the paired baseline run within an OWF present.
Intake rate and number of trips			
Intake rate	Intake rate is determined by prey availability at the bird's foraging location, whereby a Type II functional response returns the estimated intake rate after accounting for effects of interference competition arising from the number of additional birds also foraging at that location during the simulated time step. Prey depletion occurs, determined by the shape of the Type II functional response curve for each species.	The effects of conspecifics foraging at the same location is assumed to create interference competition, reducing the intake rate of each forager in relation to the total number of other birds foraging at that location over the duration of the simulated time step. No facilitation by conspecifics is assumed to occur. Each individual experiences prey depletion whereby their intake rate drops with time spent foraging at a location, determined by the shape of the Type II functional response. Prey depletion occurs during each foraging trip, but prey is then replenished to the	Intake rate is strongly and directly related to provisioning of food to chicks, and changes to adult and chick body mass over the chick-rearing period. Higher intake rates (due to greater prey availability or the presence of very few conspecifics) result in birds being able to meet their energy requirements more quickly, thereby increasing the amount of time available for other activities (time at nest).

		original level before any further foraging is undertaken. This means that each time a bird visits the same location within a simulated time step it is assumed that it encounters the same initial prey availability, and therefore experiences the same initial intake rate each time.	
Number of trips	Birds optimise the number of foraging trips to make during each simulated time step based on the prey availability at their chosen foraging location and the associated flight time accrued travelling between the foraging location and the source colony. If birds are able to meet their required DER at the chosen foraging location they select the number of trips that minimises the total time requirement (foraging + flying) required to meet the DER. If birds are unable to meet their required DER at the chosen foraging location (because prey availability is sufficiently low that the realised intake rate does not allow the bird to reach its DER within the time available) then the bird selects the number of trips that leads to the greatest total prey intake by the bird (i.e. that which minimises their shortfall in	The mechanisms underlying the selection of the number of trips to make per simulated time step assume that birds attempt to meet their DER within the shortest amount of time, thereby maximising nest attendance. If birds are unable to do meet their DER, the model assumes that they select the number of trips which minimises the energy deficit (i.e. the difference between DER and daily energy intake)	The model selected number of trips affects demographics by determining the time-energy budgets of each adult bird, and therefore its change in mass per simulated time step, and the change in mass of its chick. The 90% adult mass threshold that triggers a shift in behaviour when selecting the optimum number of trips to allow unattendance of chicks has a strong and direct impact on chick survival. Raising this threshold would increase unattendance and subsequent chick mortality, but would also allow adults the opportunity to better protect their

	intake relative to the DER). Bird state (adult mass) also plays a role in determining the number of trips when the adult’s DER cannot be met. If the adult’s mass is >90% of its initial mass at the onset of chick rearing, it will avoid non-attendance of its chick, and will select the number of trips that minimises its energy deficit. However, if an adult’s mass is >80% but <90% of its initial mass, it will fail to attend its chick, and will therefore select the number of trips that either allows it to meet its DER within the simulated time step (by increasing foraging time and unattending its chick), or that which minimises its energy deficit (by increasing foraging time and unattending its chick – although still not having sufficient time in the time step to meet its DER).		own survival by minimising mass loss through additional energy gained by unattending chicks; lowering it would have the reverse effect.
Allocation between adult and chick			
Daily Energetic Requirements and provisioning	If an adult successfully collects all the food it needs (its DER plus half its chick’s DER) then it provides exactly one half of what the chick needs to the chick during the simulated time step. If an adult is not able to collect enough food to satisfy its own DER plus half of its chick’s DER then the intake of both chick and adult will be	Adults do not take in to account the state (body mass or age) of their chick when deciding how to adjust their time-energy budgets to best meet energetic requirements and successful rearing of their chick. Adults do not account for the provisioning or unattendance of their	The acquisition of DER and subsequent provisioning to chicks directly affects both the mass change of adults and chicks, and therefore their subsequent survival. The lack of compensation between adults in a

	reduced so that each reach the same percentage of their energy requirements. If a bird is only simulated to receive 50% of the total energy needs for itself and (half of) the chick at a particular time step, for example, then the adult will receive only 50% of its DER, and the chick will receive 50% of one half of their DER (the other parent may still be able to provide 100% of its contribution to the chick's DER, it which case the chick would actually receive 75% of its total DER that time step, but this will not always be the case).	partner when making decisions regarding time-energy budgets to best meet their own energetic requirements and successful rearing of their chick. Nor do adults take into account the provisioning of their chick by their mate when determining how much food to collect, therefore there is no compensation within a pair where one adult can acquire more food for the chick to compensate for its mate not being able to collect enough food.	breeding pair means that any deficit in DER for the chick arising from one parent failing to capture enough food cannot be mitigated by the other parent, should that parent have additional time available for foraging (after all other activities, including attendance at nest). This means the effect of an OWF on the foraging of one parent cannot be compensated for by the other parent, increasing the negative impact of an OWF upon chick survival over a model where such compensation is allowed to occur. It would be possible to change this mechanism within the model so that, for instance, the adult always attempts to provide 100% of one half of the chick's DER before provisioning itself. However, due to the lack of empirical data on which to parameterise this process, the division of acquired energy is simply split equally

			between the parent and the chick.
Bird states and consequences			
Unattendance and abandonment of breeding attempt	When an adult's body mass is greater than 90% of its starting body mass at the onset of chick-rearing (based on empirical data) it will avoid unattending its chick, even if it had not met its DER during the simulated time step. If an adult's body mass is between 90% and 80% of its initial mass it will favour its own needs over those of its chick, and will leave its chick unattended in order to achieve its required DER. Adults with a body mass of less than 80% of their starting mass abandon the breeding attempt. This necessarily means that their partner also gives up the breeding attempt, resulting in chick death. Finally, if an adult's body mass falls below that deemed critical for survival (60% of its initial body mass at the onset of chick-rearing), the adult is assumed to have died and is removed from the simulation. This causes its partner to abandon the breeding attempt for the remainder of the simulation.	Adults do not take in to account the state (body mass or age) of their chick when deciding how to adjust their time-energy budgets to best meet energetic requirements and successful rearing of their chick. Adults do not account for the provisioning or unattendance of their partner when making decisions regarding time-energy budgets to best meet their own energetic requirements and successful rearing of their chick. The model assumes adults will prioritise their own survival (by protecting their energy gain and minimising mass loss over the chick-rearing period) over that of their chick. However, the model also assumes that adults avoid unattendance when their mass is still reasonably high (>90%) in comparison to their starting mass at the onset of chick-rearing.	The rules governing unattendance and abandonment of the breeding attempt have a strong and direct impact on chick survival, as well as on energy acquisition by adults and consequently their body condition and survival prospects. The effect of unattendance is to increase the risk of chick death through exposure or predation. The risk of chick death increases linearly with time unattended, until reaching a certainty after 18 consecutive hours of unattendance. Both the thresholds for mortality from unattendance (18 hours) and abandonment of the breeding attempt (adult body mass <80% of initial mass at onset of chick-rearing) has a strong impact on demographic output from the model. Raising the unattendance

			threshold (e.g. from 18 hours to 24 hours) would decrease overall chick mortality, and would lower the impact of an OWF on chick mortality as fewer chicks would die from a result of unattendance. A similar effect would be seen on model output if the adult mass threshold for abandonment (<80% of initial mass) were lowered.
Chick death	Chick death occurs when the chick's mass reaches 60% of that of an idealised chick provided with its total DER on each time step of the simulation up to the current point in time.	The model assumes that chick's DER do not change with age or body mass.	Varying the mass threshold (60% of idealised chick's body mass) at which mortality occurs has a direct and strong impact on chick survival of the population. A lower threshold would reduce the impact of an OWF on chick survival because chicks would be able to buffer a greater reduction in provisioning (and therefore mass loss) before dying. Chick death is also linked to adult body condition and survival prospects because of behavioural changes that occur to adult foraging when freed from

			provisioning for offspring.
Mass Change			
Adults	Adult birds update their body mass at the end of every simulated time step in response to the balance between the energy expended and gained during the time step. When the bird’s DER is met, it loses no mass. When the bird’s DER is not met, it loses body mass according to a linear relationship with the ratio of the energy deficit to the energy density of the bird’s tissue (parameter value set a priori). The upper limit to adult mass loss is set by this ratio between the energy deficit and the energy density of tissue.	The model assumes adults may only remain at the same weight as they enter the chick-rearing period, or lose mass over the chick-rearing period – it is assumed to be impossible for them to gain weight	Adult mass loss over the chick-rearing period determines both its own subsequent survival, as well as affecting its behavioural decisions affecting the survival of its chick through provisioning and unattendance.
Chicks	The model assumes a simple linear function for daily mass change of chicks in relation to food provisioned by its parents. If a chick receives its total DER from its parents its mass changes by the maximum possible mass gain (g/day; parameter value set a priori). If a chick receives only a proportion of its total DER, its increase in mass declines linearly with the decrease in total DER provided by its parents.	The model assumes chicks may not lose mass during the model simulation, however if insufficient energy is provided by its parents it will fail to gain mass at the rate required to maintain good health, and eventually die from starvation.	Mass change in chicks is strongly and directly related to provisioning of food to chicks, and is the ultimate determinant of chick survival over the chick-rearing period and, therefore, the chick survival of its parents. Chick death is also linked to adult body condition and survival prospects because of behavioural changes that occur to adult foraging

	The model contains a threshold parameter (set a priori) that represents the proportion of the chick's DER provided at which zero growth occurs.		when freed from provisioning for offspring.
Mass-Survival relationship			
Converting adult mass at end of chick-rearing into subsequent survival	For each individual adult bird the model assumes a logistic relationship between the adult mass at the end of the breeding season and the probability of over-winter survival. The logistic model contains two unknown parameter values: in the way we have parameterized the models these parameters quantify (a) the "baseline" survival and (b) the slope associated with the impact of a change in adult mass upon the change in logit(survival probability).	The model assumes: a) that the shape of the relationship between adult-mass and over-winter survival can be described by a logistic curve; b) that the baseline survival probability has been specified correctly; and c) that the mass-survival slope parameter has been specified correctly. The value of the baseline survival probability is fixed to be the mean value across sites with observed data on annual adult survival.	The impact of OWFs upon adult survival will be directly related to the value of the slope parameter – the two quantifies are related in a strong but nonlinear way. The value of the baseline survival probability is also likely to be moderately strongly linked to OWF effects; the nonlinearity of the logistic curve means the impacts of the slope parameter vary depending on the level of baseline survival. The estimates of OWF effects are not likely to be strongly related to the assumption that the curve has a logistic shape.

Appendix B

9.2 Derivation of $p(T)$

Formula

SeabORD calculates the probability of collision-related mortality for any particular bird on any particular day to be:

$$p(T) = 1 - \left(1 - \frac{Q}{1-D}\right)^{T/720}$$

where T denotes the amount of time (in hours) that SeabORD simulates this bird to spend in displacement-susceptible behaviours on this day (this will be zero for birds that are displacement-susceptible), D represents the proportion of displacement-susceptible birds in the population, and Q represents the collision mortality rate per bird-month. Q is the average, across months within the chick-rearing period, of (predicted number of collisions from sCRM / (density of birds in footprint * footprint area)) – i.e. the probability of collision mortality per month spent in the footprint.

Derivation

Step 1. The value of Q relates to the entire population of birds that use the OWF footprint *within the baseline period* – i.e. in the absence of an OWF. This will include birds that are displaced by the OWF, and so are never actually susceptible to collision risk. We need to translate this into the collision risk associated with birds actually spending a month within the OWF – i.e. which are not displacement-susceptible, and so are actually susceptible to collision. This rescaling gives us the collision risk associated with a bird spending an entire month [720 hours] in the footprint *once the OWF is there*:

$$P(720) = \frac{Q}{1-D}$$

Step 2. Our model assumes that the mortality rate per unit time is unrelated to the length of the period of time, which implies that the time to mortality follows an exponential distribution. Let $S(t) = 1 - P(t)$ denote the probability of *not* dying due to collision during a period of length t; it follows immediately from the properties of the exponential distribution that $S(t) = S(1)^t$.

Step 3. From Steps 1 and 2 it follows that:

$$p(T) = 1 - \left(1 - P(720)\right)^{\frac{T}{720}} = 1 - \left(1 - \frac{Q}{1-D}\right)^{\frac{T}{720}}$$

Appendix C

9.3 Full Workshop Report

Marine Scotland

Combining collision and displacement in ornithological offshore renewable energy assessments

Workshop
Victoria Quay 10 December 2019

Attendees

Marine Scotland
Tom Evans, Janelle Braithwaite, Elaine Douse
UK Centre for Ecology & Hydrology
Francis Daunt, Kate Searle
BioSS
Adam Butler
MacArthur Green
Mark Trinder
BTO
Aonghais Cook
RSPB
Aly McCluskie
HiDef Aerial Surveying
Ross McGregor
DMP Statistics
Bruno Caneco
SNH
Alex Robbins (phone)
JNCC
Julie Black, Lise Ruffino

Purpose of workshop

This workshop brought together experts from research, government and conservation bodies to discuss how best to implement combined modelling of displacement and collision risks from offshore wind farms (OWFs) for breeding seabirds. The aim was to discuss how current methods are used to estimate collision and displacement risks separately in assessments, with a following session on the extent to which the inputs, parameters and assumptions used in the different methods are consistent with each other. Finally, there was a session on how to combine collision and displacement risks into a single assessment of risk from both displacement and collision.

Agenda

Times		Details
9:30	9:50	Reception & registration
9:50	10:00	Welcome and introductions
10:00	11:00	Presentations: estimating collision and displacement in assessments • Methods of estimating collision effects (HiDef/DMP) • Methods of estimating displacement effects (CEH) • Combining effects: possible approaches (BioSS)
11:00	11:15	Tea & coffee
11:15	12:45	Combining effects: consistency of inputs (plenary) • Avoidance vs displacement rates: detailed discussions • flight speeds
12:45	13:15	Lunch
13:15	14:45	Combining effects: consistency of assumptions (plenary) • time periods and life stages • risk by behaviours • variation and uncertainty
14:45	15:00	Tea & coffee
15:00	16:00	Final plenary: integration

Collision Methods Summary

Collision risk modelling (CRM) involves three broad types of data:

1. Wind farm data (turbine specs, latitude, site dimensions etc.);
2. Site specific seabird data (densities and flight heights);
3. Generic seabird data (biometrics, nocturnal activity, avoidance rates, flight speed and flight height).

More specifically, these include data on the following key parameters:

- Bird biometrics: length, wingspan, flight speed, flight type (flapping versus gliding);
- Aerial densities of birds in flight by month (from site surveys);
- Flight height distribution (proportion at collision risk height);
- Avoidance rates – see Cook et al. 2018 for further details;
- Wind farm characteristics (location, number of turbines);
- Turbine characteristics (blades, rotation, radius, hub height, blade width, pitch, % time operational for turbine);
- Hours of daylight (derived from latitude);
- Flux (derived within CRM - see below).

Flux (mean traffic rate, expressed as birds s^{-1} m^{-2}) – based on bird flight speed and density (Band, 2012). This is then used to work out the number of bird flights through the rotor over any given time period, by scaling up based on the duration of the time period concerned and, the total area occupied by turbine rotor sweeps. More specifically, these calculations are used to estimate the proportion of the wind farm which is rotor swept, i.e.: Flux x prop rotor swept x prop at rotor height, which gives the number of at risk flights (rotor transits), which is then multiplied by p.collision (‘PColl’: wrong place wrong time) and then by avoidance rate.

Monthly total mortality (all birds derived from):

- Number of transits through the rotor (= flux x proportion at flight height);
- Collision probability (physical bird and turbine factors);
- Wind farm collisions (transits x collision probability x proportion of time operational)
- Overall avoidance rate = 1 – ((1 – macroAR) x (1 – mesoAR) x (1 – microAR))

Notes on equivalency of parameters within collision risk modelling and displacement/barrier effects modelling:

- Macro-avoidance although capturing displacement and barrier effects, refers only to birds in flight, not birds on the water;
- Area affected by displacement tends to include a border, but there is no border in collision risk modelling; but there is evidence for avoidance of up to 2km if not further from OWF perimeter;
- The matrix method does include buffer for displacement.

Displacement Methods Summary

The following parameters were identified as key inputs to displacement risk modelling when using the individual based model SeabORD:

- Bird Utilisation Distributions from GPS or at-sea survey data (site data typically not appropriate);
- Median prey availability in model region;
- Colony locations and sizes;
- Apportioning (if at-sea data; known if GPS);
- Bird behavioural parameters based on empirical data and in accordance with optimal foraging theory;
- Location, shape and size of OWF footprint(s);
- Displacement and barrier rate;
- ‘buffer width (km) to be added for OWF footprints (within which displacement and barrier effects are assumed to occur; note this is called the ‘border’ within SeabORD); and
- ‘displacement foraging buffer’ width (km) to be added to OWF footprints (area into which birds are displaced during foraging).

Key questions:

- Q: Potential for prey redistribution around OWFs – can SeabORD account for this? A: this could be accounted for by altering the prey maps that are used within SeabORD between the baseline and the impact scenarios, but this has not been done before.
- Importance of thinking about birds that are displaced but not barriered – because there is evidence for birds flying through footprints but not foraging within them, so this category is probably quite important. Whereas there is no evidence for the converse (birds that are barriered but not displaced);

however it may be that individuals are prepared to invest in a short detour to avoid turbines, but not to cease all access to a key foraging area, so this behavioural response is likely to be more complex than can be captured with simple rules.

- Q: Should this vary for an individual over time? Martin Perrow's work on terns shows changes in displacement propensity over time whereby birds fly through OWFs during chick rearing but not pre-breeding season and incubation – interpreted as birds being more constrained, and therefore less risk averse, during chick-rearing when energetics demands are higher? A: Yes, this could be included within the model with a re-working of some of the mechanisms and constraints assumed at different periods of the season, in order to develop a model capable of simulating over the full breeding season, not just the chick-rearing period.
- Also worth thinking about potential "shadow" effects – e.g. birds no longer using the area directly beyond a wind farm, thereby creating a loss of habitat – we (BTO) have some (as yet) unpublished data on this in Sandwich Terns. It shows flights between the breeding colony & OWF going right up to the OWF edge, with birds diverting round it. The area on the far side of the OWF from the colony is then not used by birds.

Summary of bird-related inputs and other processes required for model runs:

Inputs	**sCRM**	**Matrix**	**SeabORD**
Bird behaviour (flight and on water)	Flight only	Both	Both
Timescales	Monthly	Seasonal	Seasonal (chick-rearing)
Buffer	No buffer	Buffer	Buffer
Bird distribution & density	Site data	Site data	GPS or at-sea-based UDs
Displacement rate	Population level	Population level	Population level
Apportioning required?	No	No	To colony

Methodology for Integration Summary

- Habitats Regulations have to deal with the population in protected sites, not just colonies (unless the whole colony is within the SPA). So both the sCRM and SeabORD need to work at the SPA level, not only individual colonies.
- To inform the consenting process, the potential impacts of the key effects associated with developments are assessed through an Environmental Impact Assessment (EIA) in relation to baseline populations at site, local, regional and national levels. When preparing applications for Nationally Significant Infrastructure Projects (NSIPs) in England or Wales, or for equivalent national developments or major developments in Scotland and Northern Ireland, developers are legally required to consider if the project is likely to affect European sites by providing a Habitats Regulations Assessment or Appraisal (HRA). HRA is an iterative process and the emphasis is on understanding no Likely Significant Effects (LSEs) and demonstrating no Adverse Effects on Site Integrity (AESI) on relevant SPAs. If no LSEs on features of a European site, either alone or in combination with other plans or projects, cannot be ruled the HRA report provided with the application should enable the competent authority to then carry out an Appropriate Assessment (AA). The purpose of the AA is to ascertain whether there is no AESI on the relevant sites. Under the EC Birds Directive [2009/147/EC], sites are classified as Special Protection Areas (SPAs) based on the relative size of the population of a species, or suite of species, that they hold and must be maintained in a favourable condition.
- Currently, the expectation is that both the sCRM and SeabORD will be maintained as separate models, and this project will add the facility to use sCRM outputs within SeabORD.
- SeabORD applies to breeding adults from specific colonies, not all birds from everywhere; however, the input to the sCRM includes all birds seen flying in the footprint, including non-breeders, and potentially birds from colonies not modelled within SeabORD, when suing site-specific data from at-sea surveys.
- How to combine collision and displacement during the rest of the year needs to be considered because SeabORD currently only operates over the chick-rearing period.

Consistency of Inputs Summary

- Key is understanding the different types of avoidance assumed in the models: avoidance versus displacement rates, and the effects of the buffer;

- Important to consider the differences in input density information; e.g. all birds (sCRM) versus only breeding adults (SeabORD) or specific age classes; and all birds (displacement) versus only birds in flight (CRM);
- Need to consider flight behaviour – flapping and gliding (for collision probability the current guidance is assume everything is flapping), commuting and foraging, flight height;
- SeabORD could model meso-avoidance if each shapefile represented one turbine; however, this has not been attempted before; and
- The four most sensitive parameters in sCRM are flight height, flight speed, bird density, avoidance rate.

Avoidance and Displacement Rates Summary

- SeabORD models both displacement and barrier effects;
- Macro-, meso-, and micro-avoidance are all one parameter in the sCRM, although there is some empirical evidence for some species for differences between these. Crucially, overall avoidance estimates are partitioned into the three types for most species (Cook et al. 2018), however current values advised by SNCBs do not partition. We can then use the macro-avoidance rate in SeabORD; however, note that currently macro-avoidance rates and advised displacement rates may not be the same;
- This project should focus on black-legged kittiwakes (BLKI) and northern gannets (NOGA) because they are at collision and (in some jurisdictions) displacement risk. There are estimates for macro-avoidance from empirical work for both species;
- For other species would be good to lay out what sort of information you would need to estimate empirical macro-avoidance;
- Using Option 3 in the sCRM is better for integration because there are fewer things to correct – this is because it includes the relative distribution of flight height but still uses an adjustment to some extent (at present, Option 3 still uses the same flight speed adjustment as Options 1 and 2 - but there’s the potential to update this given all the GPS tracking data available);
- Where and how do we take the adjustment part of the sCRM into account? This mostly comes into the micro and meso aspects of avoidance, so perhaps not relevant to the macro-avoidance rate that is required by SeabORD?
- A correction factor is applied in sCRM, but it can only be applied to meso- and micro-avoidance, so macro-avoidance is not affected by the correction. This means that the macro-avoidance rate can be used within SeabORD – the assumption is that macro-avoidance is the sum of displacement and barrier

effects, and, therefore, appropriate for use within SeabORD which models both processes.

Input density information

- Differences between EIA and HRA were discussed (see notes above) – however, SeabORD is not always relevant for EIA because it is a model that operates at the scale of individual breeding colonies (although multiple colonies may be run at once). However, note that if the only source of birds is a single SPA colony then EIA is equal to HRA, for sites that are close to colonies during the breeding season. A single SPA may incorporate multiple breeding colonies, so this is relevant for HRA.
- Consideration needs to be given to ‘All birds’ versus ‘breeding adults’.
- Including a buffer around a wind farm footprint within the collision risk modelling inputs is achievable because this is a specified input to the sCRM, therefore it can be adjusted to be the same as within SeabORD to ensure consistency between the two methods.
- sCRM only uses birds in flight at sea; however, the displacement matrix uses all birds seen at sea.
- The combined displacement rate and barrier rate must equal ‘macro-avoidance’ for the sCRM to be equivalent with both the matrix method and SeabORD – this is a critical assumption.
- SeabORD is only chick-rearing period so cannot be used in the non-breeding season.
- Consensus that we should be building the collision risk model into SeabORD, but need to convert data into flux in order to do that, estimate proportion of time in area and proportion of time in distance/area, needed in the collision calculations.
- The current sCRM uses the density of birds in flight – then ‘PColl’(the probability of collision when a bird is in the rotor swept area) is multiplied by the number of birds passing through the rotor sweep over a given time period and the proportion of those birds at collision risk height (N.B. – applies to basic model only, not the extended model) – Q: can we plug ‘PColl’ into SeabORD? It is straightforward to extract ‘PColl’ from the Band (2012) model. A: Yes – this is straightforward, PColl is typically in the region of ~10% - but note that this applies to the Basic model only. For the extended model, need to use the collision integral, which accounts for the fact that, bird density, probability of interacting with rotor & probability of colliding all vary with flight altitude.
- SeabORD would ideally need a probability of collision per bird per time unit.

- Tagging data can estimate flux much better than at-sea survey data, we need a much better understanding of how birds move at sea. This could be achieved using radar and/or GPS. The current assumptions of a basically constant conveyer belt of birds moving through the wind farm are far too simplistic. This would reduce the need for the avoidance rate to be used as a correction factor. At present, estimates of the avoidance rate combine both avoidance behaviour and model error. Avoidance rates are estimated by comparing observed and predicted collision rates (Cook et al. 2018). The predicted collision rate will be derived from estimates of the total number of birds exposed to collision risk which are largely determined by the flux rate. Consequently, by being able to better estimate the flux rate, we will reduce its contribution to model error and, reduce the need for the avoidance rate to be seen as a correction factor (Masden et al. in prep.) A valuable future goal would be to document how GPS data can be used to estimate flux.
- If we can solve flux this gets at a lot of the bird behaviour issues as well, although not flight height.

Assumptions

- Are there differences in time periods used within the models? – for instance, nocturnal activity is incorporated in the sCRM (albeit coarsely), and nocturnal activity is also included in SeabORD but done in a different way (by setting the number of hours during a 24 hours period in which birds are assumed to be able to forage);
- Seasonal differences – SeabORD is chick-rearing but sCRM calculations are done monthly all year;
- SeabORD includes effects on chicks, but the sCRM does not – Q: would this make a big difference? A: Yes, over the lifespan of a OWF it could. Note that because the mortalities are typically plugged into a PVA, this would actually only be important if the collision occurred during the chick-rearing period: if the PVA is post-breeding census, adults must survive to breed and breeding happens instantaneously – so if a bird dies prior to breeding no offspring will survive, but if the bird survives the breeding period then it may have a successful breeding attempt (or may not, depending on the provisioning achieved by it and its partner);
- Note that SeabORD could be modified to cover the wider breeding season, for instance including incubation, but this would require a substantial amount of work to develop and parameterise different behavioural mechanisms during this time;
- sCRM can kill the same birds in different months over and over again;

- Assumption is usually that all age classes have same collision probability – however, it is likely that immatures differ quite strongly from adults in flight and foraging behaviour in many species;
- Foraging versus commuting flight could be included in the sCRM – e.g. by using different flight height and speed for different behavioural modes.
- The sCRM assumes 50% of birds are upwind and 50% are downwind, and that split affects collision risk;
- Flight speeds also different upwind/downwind – flux doubles with doubling of flight speed, but PColl only changes by about 2%; and
- Birds appear to show less strong avoidance of turbines that aren't spinning – this is implicitly included in the sCRM via the use of operational time in calculations; however, there is some evidence that birds may collide with static objects, and this potential is not currently included within the sCRM.

Variation and uncertainty

- The Matrix method doesn't include variation unless you vary the density of birds;
- sCRM: Typically there are data for 24 months of surveys, thus two surveys per calendar month, one from each of two years. Average density in each month is used, or if stochastic CRM then bootstrap of data from both months;
- Displacement matrix: average in each month (from the two surveys) but then for the season value, the highest of the individual month average values is used ('peak mean') – so if the period is Jan-Mar and you have average densities of 3, 7, 2 in those months (from raw values of 2+4, 5+9, 0+4 for the months) the seasonal displacement would be calculated using 7;and
- However, this means that the more you split the season (e.g. into more months) then the higher the risk is (because peak seasonal mean is used), which is illogical;
- Ideally would feed in the distribution of collision probabilities from the sCRM for SeabORD to use within the simulations; however, can only currently run SeabORD for 10s of simulations due to long processing times; it may be more appropriate to pick simulations and feed these into SeabORD rather than taking a mean and SD and using this to derive inputs because collision probabilities tend not to have unimodal distribution.

Integration

- Important to separate out what we want to achieve in this project, and what the larger objectives are for future work and recommendations;

- We should have a case study using black-legged kittiwake (BLKW) which integrates SeabORD and the sCRM. This should consider:

  Behavioural split in SeabORD – SeabORD can partition out time in footprint into foraging and commuting, so should these different behaviours have different collision risks?

  BTO project on commuting versus foraging flights using HMMs may be useful here?

  It is likely that birds spend considerably more time foraging in footprints than flying through them, so potentially important to capture differences in collision risk?;

- There should be a northern gannet case study using the matrix method and the sCRM:

  Important to explore available data for macro-avoidance rates to use in both approaches (e.g. Cook et al report)

  Which mortality rate should be used in the matrix method? Same as in the SEANSE project?

  Also should consider the Dierschke et al Biological Conservation paper on displacement.

Conclusions and recommendations

The workshop was extremely useful. By bringing together experts in collision risk and displacement modelling, we were able to summarise the key challenges in integrating collision risk and displacement, and agree an approach for integrating sCRM outputs into SeabORD in this project, using kittiwake and gannet as case study species;

Report should set out a vision for a combined model, covering the whole year;

Report should discuss what is needed to validation of individual based models, and give some advice on empirical data needed to do this in the future;

Report should discuss how better classification of uncertainty can be incorporated into IBMs, and that this should decrease as empirical data is used to better estimate key processes;

Report should discuss cumulative impacts (in-combination); and

Future needs were discussed:

- Need to parallelise sCRM to speed it up to the speeds that are obtained when using the underlying code;
- Need to integrate outputs from HMM models by BTO to partition by behaviour;
- Need to incorporate a distribution of flight speeds in sCRM (fixed rates currently used);
- Flight height should consider commuting and foraging flight separately;
- Need to incorporate 3D flight movements, based on the latest GPS tracking data (available for gannet and kittiwake, more planned for both species at more locations);
- Need further empirical data and validation of inputs and outputs of sCRM, matrix and SeabORD; and
- Further developments must consider the growing relevance of cumulative impacts. Some progress has been made but more will be needed.

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gov.scot

This publication is available at **www.gov.scot**

Any enquiries regarding this publication should be sent to us at

The Scottish Government
St Andrew's House
Edinburgh
EH1 3DG

ISBN: 978-1-80435-220-5 (web only)

Published by The Scottish Government, June 2022

Produced for The Scottish Government by APS Group Scotland, 21 Tennant Street, Edinburgh EH6 5NA
PPDAS1034550 (06/22)