OFFSHORE RENEWABLES JOINT INDUSTRY PROGRAMME (ORJIP) FOR OFFSHORE WIND

CARBON TRUST

Quantification of mortality rates associated with displacement (QuMR)

Final Report

May 2025

working to accelerate offshore consenting

ORJIP Offshore Wind

The Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind is a collaborative initiative that aims to:

- Fund research to improve our understanding of the effects of offshore wind on the marine environment.
- Reduce the risk of not getting, or delaying consent for, offshore wind developments.
- Reduce the risk of getting consent with conditions that reduce viability of the project.

The programme pools resources from the private sector and public sector bodies to fund projects that provide empirical data to support consenting authorities in evaluating the environmental risk of offshore wind. Projects are prioritised and informed by the ORJIP Advisory Network which includes key stakeholders, including statutory nature conservation bodies, academics, non-governmental organisations and others.

The current stage is a collaboration between the Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Power (UK) Limited, RWE Offshore Wind GmbH, Shell Global Solutions International B.V., SSE Renewables Services (UK) Limited, TotalEnergies OneTech, Crown Estate Scotland, Scottish Government (acting through the Offshore Wind Directorate and the Marine Directorate) and The Crown Estate Commissioners.

For further information regarding the ORJIP Offshore Wind programme, please refer to the [Carbon Trust website](), or contact Ivan Savitsky (ivan.savitsky@carbontrust.com) and Žilvinas Valantiejus (zilvinas.valantiejus@carbontrust.com).

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- Natural England
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- NatureScot
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Abbreviations

Term	Description
CEF	Climate Engagement Fund
CEH	Centre for Ecology & Hydrology
DM	Displacement Matrix
DMR	Displacement Mortality Rate
EE	Expert Elicitation
EIA	Environmental Impact Assessment
GPS	Global Positioning System
GU	Common Guillemot
HRA	Habitats Regulations Appraisal
KI	Black-legged Kittiwake
ORD	Offshore renewable development
ORJIP	Offshore Renewables Joint Industry Programme
OWF	Offshore wind farm
PU	Atlantic Puffin
PVA	Population Viability Analyses
RA	Razorbill
SD	Standard Deviation
SE	Standard Errors
SNCB	Statutory Nature Conservation Bodies
SPA	Special Protection Area
UD	Utilisation distributions
WP	Work package

General summary

Offshore renewable developments (ORDs) have the potential to affect seabirds, through displacement from important at-sea foraging habitat. The estimation of displacement mortality rates is a critical component of the assessment process for estimating impacts on seabirds arising from ORDs, with large influence upon resulting predicted ORD impacts for affected populations.

The project first reviewed existing information on the displacement mortality rates used to determine the mortality of six seabird species displaced by ORDs in the UK. This revealed no empirical evidence for the mortality of seabirds that have been displaced from offshore windfarms. Given the paucity of empirical evidence, an Expert Elicitation workshop was then run to elicit mortality rates for these six species in the context of displacement from ORDs in both the breeding and non-breeding seasons. Broadly, the experts' estimates revealed that displacement mortality rates for adults (breeding or non-breeding season) were typically thought to fall below 10% additional mortality. Estimates relating to chicks in the nest revealed less agreement amongst experts in comparison to estimates for adult, however, overall, the displacement mortality rate for chicks in the nest was estimated as being substantially greater than for the adults.

Displacement mortality rates may also be estimated using predictive models. SeabORD is an individual-based model of how the movement, behaviour, energetics and demography of seabirds are potentially altered in response to offshore renewables in the breeding season. The model simulates impacts of displacement and barrier effects during the chick-rearing period upon three key quantities: (a) chick mortality, (b) adult mass loss over the chick-rearing period, and (c) over-winter adult mortality, which is derived from adult mass loss over the chick-rearing period. In this project, we ran SeabORD for three species (common guillemot *Uria aalge*, black-legged kittiwake *Rissa tridactyla* and razorbill *Alca torda*) at four SPAs under a range of windfarm scenarios, to understand the relationship between the proportion of individuals that are displaced and the predicted impacts on adult and chick mortality, and adult mass loss. The results of the SeabORD runs were then used within an application of a statistical emulator to understand if specific characteristics of ORDs or foraging environments were strongly related to the model's estimated impacts. This work suggests that the estimated impacts of ORDs on mortality and mass loss in SeabORD are relatively strongly driven by the proportion of simulated individuals that are experiencing displacement within the model.

The mass-survival relationships currently used by SeabORD (Oro & Furness 2002 and Erikstad et al. 2009) suffer from three main challenges: firstly, they are not based on populations that are very geographically relevant to UK offshore renewables and thus may have contrasting behaviour; secondly, they are based on only a few years of data, in some cases involve only one year of measurement; and finally, the analyses have not considered various important aspects in the modelling used such as age effects, uncertainty in body mass measurement and observation, and most importantly a rigorous consideration of year to year changes in survival probability unrelated to body mass. The results of the sensitivity analysis conducted in this study revealed that in general, the sensitivity of estimated survival to body mass is larger when ORD impacts on mass are larger.

In summary, the displacement mortality rates generated via expert elicitation and SeabORD/emulation cannot be used within the Displacement Matrix tool currently used in many UK assessments, because of the differences in definition between the alternative approaches. In particular, the Displacement Matrix uses seasonal peak estimates of abundance derived from at-sea survey data to quantify the number of individuals at risk of displacement, which is difficult to relate to the definitions of the number of individuals at risk used in the expert elicitation and SeabORD/emulation. **Our belief is that it is not appropriate to use the displacement mortality rates arising from the EE or SeabORD/emulation within the Displacement Matrix in its current form unless adjustments are made to account for this discrepancy. Our key recommendations are therefore for further work to understand site fidelity, and the impact of this upon**

displacement risk, to understand whether there is a potential for under-estimation of effects within the Displacement Matrix in relation to this process.

Technical summary

Offshore renewable developments (ORDs) have the potential to affect seabirds, through displacement from important at-sea foraging habitat. The estimation of displacement mortality rates is a critical component of the assessment process for estimating impacts on seabirds arising from ORDs, with large influence upon resulting predicted ORD impacts for affected populations.

Displacement mortality rates form a key input to assessment tools such as the Displacement Matrix, as well as comprising part of predicted outcomes from other assessment tools such as Individual Based Models (e.g., SeabORD, Searle et al. 2018). However, there is very little empirical evidence upon which these rates may be based. This project aimed to critically review the displacement mortality rates for seabirds used to determine the mortality of birds displaced by offshore windfarms in the UK offshore wind assessment process. And, where feasible, to provide updates to species-level estimates of mortality rates, with a clear indication of current supporting evidence and associated uncertainty. The project also sets out high-level recommendations for future empirical and analytical work addressing key knowledge gaps.

The project first reviewed existing information on the displacement mortality rates used to determine the mortality of birds displaced by ORDs in the UK. The review focused on six key species considered to be at greater potential risk of displacement and displacement mortality in future offshore windfarm development in the UK: Black-legged kittiwake *Rissa tridactyla*; Common guillemot *Uria aalge*; Razorbill *Alca torda*; Atlantic Puffin *Fratercula arctica*; Red-throated diver *Gavia stellata*; and Northern Gannet *Morus bassanus*. These reviews found no empirical evidence of the mortality of seabirds that have been displaced from offshore windfarms. It appears likely that this has not been studied to date, rather than not reported.

An Expert Elicitation workshop was then run to elicit mortality rates for these six species in the context of displacement from ORDs in both the breeding and non-breeding seasons. Given the uncertainty associated with displacement mortality in general, and for these species in particular, the workshop sought to address the knowledge gaps related to the excess mortality rates for these species, for both individual birds and their inter-dependents. The purpose of eliciting experts' judgements regarding these knowledge gaps was to gain a better understanding of the biological context in which displacement mortality may occur, and to provide information of relevance to the implementation of current assessment methodologies (Joint-SNCB 2022). Broadly, the bulk of belief for the Displacement Mortality Rates (DMR) for individuals (breeding or non-breeding season) was on values below 10%. There was, however, notable variance in the estimated upper bounds, meaning disagreement and overall uncertainty in what would be a plausible upper limit to the effects of OWF in terms of DMR. In terms of the effects on dependents (chicks in the nest), there was markedly less agreement and certainty indicated by the experts' responses. However, overall, the DMR for dependents was estimated as being substantially greater than for the mature individuals. Experts also discussed which aspects of seabirds' interactions with offshore windfarms had not been considered in estimates, and identified key areas requiring future research:

- The importance of capturing displacement impacts on seabird productivity.
- Potential effects of habituation.

- That the values currently used in the assessments for the size of the populations that might be affected by DMR are noted as being under-estimates, being based on snapshots, perhaps limited to OWF footprints and near surrounds.

- Other classes of bird not considered in the EE may undergo differing displacement effects, including "Sabbatical" adults and juveniles.

- Other species were noted as being of potential importance.

- Currently the cumulative effect of multiple windfarms is done in a simplistic additive fashion, and more research is needed in how to better capture cumulative impacts from multiple ORDs.

An alternative way of quantifying displacement mortality rates is via simulation from a mechanistic model. SeabORD provides an individual-based model of movement, behaviour, energetics and demography in response to offshore renewables. SeabORD simulates impacts of displacement and barrier effects during the chick rearing period upon three key quantities: (a) chick mortality, (b) adult mass loss over the chick-rearing period, and (c) over-winter adult mortality, which is derived from mass loss over the chick-rearing period. SeabORD is primarily designed to quantify population-level impacts, although it does this via simulation of individuals, in such a way as to incorporate inherent stochasticity. SeabORD does not use a "displacement mortality rate" as such, but such rates can be estimated using the model outputs. Complications arise because there are multiple possible ways to define such rates within the context of SeabORD. We consider two such definitions here: (a) rates that are defined in relation to the number of individuals displaced per timestep, and (b) rates are defined relative to the number of individuals displaced at any point during the chick rearing period. We ran SeabORD for three species (common guillemot *Uria aalge*, black-legged kittiwake *Rissa tridactyla* and razorbill *Alca torda*) at four SPAs, under a range of windfarm scenarios, to understand the relationship between the proportion of individuals that are displaced (per timestep, and over the entire season) and the impacts on mortality and mass loss. The slopes of these relationships, which we can estimate via statistical modelling (emulation), provide model-based estimates of the displacement mortality rate. The emulation approach allows us to quantify uncertainty in these estimates, and to identify sources of variation in the rates. Where sources of variation are explainable in terms of colony and windfarm characteristics it also provides a basis for extrapolating displacement mortality rates to new scenarios, and thereby to estimating the population-level displacement risk under those scenarios. The results of the SeabORD runs and emulation suggest that the impacts on mortality and mass loss in SeabORD are relatively strongly driven by the proportion of individuals that are experiencing displacement, and there is no clear evidence for non-linearity in this relationship, when expressed in terms of the individuals experiencing displacement per timestep. However, the results suggest that the relationships can vary quite substantially between SPAs - more SeabORD runs would be required to understand the cause of this variation, and thereby to produce a version of the emulator that can infer the rates to use for additional SPAs. When the proportion of individuals experiencing displacement is relatively low the results are also relatively noisy – the SeabORD runs considered here only spanned higher levels of displacement for timestep for black-legged kittiwake, so for common guillemot and razorbill more runs, covering scenarios with higher levels of encounter with windfarms, would also be needed in order to reliably infer rates.

The displacement mortality rates generated via expert elicitation and SeabORD/emulation cannot be used within the Displacement Matrix, because of the differences in definition between the different approaches. In particular, the Displacement Matrix uses seasonal peak estimates of abundance derived from at-sea survey data to quantify the number of individuals at risk of displacement, which is difficult to relate to the definitions of the number of individuals at risk used in the EE and SeabORD/emulation. Further research on site fidelity and turnover is needed in order to understand these differences.

Our belief is that it is not appropriate to use the displacement mortality rates arising from the EE within the Displacement Mortality in its current form unless adjustments are made to account for this discrepancy. Our key recommendations are therefore for further work to understand site fidelity, and the impact of this upon displacement risk, to understand whether there is a potential for under-estimation of effects within the Displacement Matrix.

This work would involve:

- Interrogation of GPS tracking data to estimate rates of fidelity in seabird species, including influence of environmental variation and seasonal variation.
- Examination of seabird time-activity budgets to understand influence of partitioning of behaviour between at-sea and colony behaviours and how this might be used to adjust at-sea survey data.
- Tracking of individual birds to link observed interactions with operational offshore windfarms (barrier effects and displacement) with subsequent demographic rates (breeding success and survival).

Introduction

Offshore Renewable Developments (ORDs) can make a significant contribution to the UK Government's target to generate 50% of overall energy consumption from renewable sources by 2030 and to have decarbonised the energy system almost completely by 2050. However, the Scottish Government has a duty to ensure that ORDs are delivered in a sustainable manner, in accordance with the requirements of the Marine Strategy Framework Directive (EC/2008/56), the Habitats Directive (EC/92/43) and the Birds Directive (EC/79/409), as transcribed into UK law. Offshore renewable developments have the potential to affect seabirds, through displacement from important at-sea foraging habitat (Drewitt & Langston 2006; Masden et al. 2010; Scottish Government 2011). The UK Joint SNCB Interim Displacement Advice Note provides advice on how to present assessment information on the extent and potential consequences of seabird displacement from ORDs (Joint SNBC 2022). This advice requires assessments to use published indices of disturbance (e.g., Furness et al. 2013, Wade et al. 2016) to assign a range of displacement levels for each species individually, with consideration of modifications arising from emerging new evidence and discussions with SNCBs to agree appropriate levels of likely adult mortality associated with particular displacement levels, for each species individually (acknowledging that data are very limited at this time). Assessments should then use these two metrics (displacement rate and displacement mortality rate) to compile a 'Matrix Approach' table (i.e., representing proportions of birds potentially displaced and/or dying as a result of ORDs). The advice specifies that this table should be presented from 0-100%, in 10% increments for displacement levels. Percentage increments for mortality should also be presented between 0-100% but including smaller increments at lower values (e.g., 0%, 1%, 2%, 5%, 10%, 20%, etc). The estimation of displacement mortality rates is therefore a critical component of the assessment process, with large influence upon resulting ORD impacts for affected populations. However, there is very little empirical evidence upon which this rate may be based.

In this project we critically reviewed the displacement mortality rates used to determine the mortality of birds displaced by offshore windfarms in the United Kingdom. The overall aim of the project was to update species-level estimates of mortality rates, where feasible, with a clear indication of current supporting evidence and associated uncertainty, and to set out high-level recommendations for future empirical and analytical work addressing key knowledge gaps.

The project is divided into six work packages:

WP1: Review of mortality rates

In the first work package we reviewed existing information (availability and quality) and tools/methods for estimating mortality rates of species affected by displacement from offshore wind developments in the UK. This included a review of published literature to identify and assess the consequences of displacement from offshore windfarms on vital rates; a review of the key factors that may have an influence on the mortality of populations affected by displacement impacts; a review of the available approaches to collecting, analysing and modelling the demographic consequences of displacement; collation of the available relevant displacement and mortality information used in the examination, determination, and appropriate assessments of offshore windfarm consent applications in the UK; and collation of the available information that could be used to estimate empirical values for the demographic consequences of displacement.

WP2: Expert elicitation

We conducted an expert elicitation workshop to fill knowledge gaps related to the potential displacement mortality rate of seabirds in response to the presence of offshore windfarms. Expert elicitation is a formal, structured process designed to obtain experts' opinion and knowledge while reducing heuristics and biases. Based on the review in WP1, the workshop focused on the estimation of the potential displacement mortality rates affecting common guillemot, razorbill, Atlantic puffin, black-legged kittiwake, northern gannet and red-throated diver. The purpose of eliciting experts' judgements regarding these knowledge gaps was to gain a better understanding of the biological context in which displacement mortality may occur, and to provide information of relevance to the implementation of current assessment methodologies (e.g., Displacement Matrix, Joint-SNCB 2022). More specifically, the workshop was intended to elicit information from the experts on the biological processes relevant to the "mortality rate of displaced birds"; the timescales over which the mortality rate of displaced birds are estimated; and the precise definition of the "mortality rate of displaced birds".

WP3: Displacement tool simulation

Building upon WPs 1&2, we identified suitable species for modelling in WP3. Based upon discussion with the project steering group and expert panel, the selected displacement tool was the individual based model developed through a series of Scottish Government Projects – 'SeabORD', which models energetics of individuals during the chick-rearing period for four species (black-legged kittiwake, razorbill, common guillemot and Atlantic puffin) and their interactions with ORD, developed by Searle et al. (2014, 2018). SeabORD predicts the time/energy budgets of breeding seabirds during the chick-rearing period and translates these into projections of population level 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. In the model, foraging behaviour of individual seabirds is driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of conspecifics. The model estimates productivity and adult survival, the latter resulting from estimates of adult mass at the end of the breeding season and published relationships between adult mass and subsequent survival (Oro and Furness 2002, Erikstad et al. 2009). Baseline scenarios are compared with scenarios containing one or more ORDs, allowing us to estimate the excess mortality resulting from the ORDs – i.e., the number of birds killed when the ORD(s) are present minus the number of birds killed in the baseline. Estimates of excess mortality can be converted into estimates for the displacement mortality rate by dividing the estimated excess mortality by the product of the displacement rate and the estimated abundance within the windfarm.

Using SeabORD, we estimated mortality rates of displaced birds across a range of scenarios encompassing the likely range of characteristics resulting from seabird and ORD interactions in UK waters. It is not feasible to run SeabORD for all of the scenarios of interest, for computational reasons, therefore we employed a constrained set of scenarios, and used these to develop a statistical emulator of SeabORD that can be used to estimate displacement mortality rates for three species (common guillemot, razorbill and black-legged kittiwake). Emulator methods use a statistical model to link the predicted model output (e.g., SeabORD displacement mortality rate) to the set of model inputs (e.g., windfarm and population characteristics). We then summarise the ability of the statistical emulator to estimate a range of SeabORD outputs using simple predictor metrics for ORD, colony and bird distribution inputs.

We also conducted a sensitivity analysis for how estimates of changes in adult survival from the mass-survival relationships used with SeabORD (Oro and Furness 2002, Erikstad et al. 2009) vary in relation to uncertainty around the parameters in these functions.

WP4: Mortality rate estimation

In this work package we used SeabORD and the associated emulator to estimate model-based displacement mortality rates of adults and chicks - we use the term model-based to highlight that the definition of rates used is not identical to that used in the Displacement Matrix, to avoid any ambiguity. We define model-based displacement mortality rates in relation to displacement per timestep and displacement over the entire season (chick rearing period).

We define the model-based displacement mortality rates as the ratio of the population-level windfarm impacts to the proportion of individuals displaced (either per timestep or over the whole season). The "per timestep" rates provide a useful proxy of the windfarm impacts, because (WP3) they show a relationship with impacts on both adult and chick mortality that are strong, positive and approximately linear. The "per timestep" rates are also the closest comparison that we can derive here from SeabORD to the displacement mortality rates used in the Displacement Matrix. The "per season" rates, in contrast, provide the closest comparison that we can derive here from SeabORD to the rates used in the Expert Elicitation.

We produce estimates of both types of rates (per timestep and per season) for both adults and chicks, for each species, and provide both overall estimates and SPA-specific estimates. We present rates that have been derived directly from SeabORD outputs, but also present rates derived from the emulator – the latter approach is possible because the emulators in WP3 were explicitly formulated so that their parameters relate to model-based displacement mortality rates, and to variations in these rates. The emulator-based results provide an estimate of uncertainty, in the form of standard errors.

WP5: Assessment of mortality rates

In WP5, we provide a summary based upon outcomes from WPs 1 to 4, assessing the evidence for the robustness of mortality rates for displaced seabirds, with associated uncertainty, where feasible.

This project has considered three distinct sources of evidence regarding the mortality rates of displaced birds ('displacement mortality rates'):

1. The rates recently used in UK assessments within the Displacement Matrix (presented in offshore windfarm consent application assessments).

Mortality rates for displaced birds used within the Displacement Matrix, as presented in offshore windfarm consent application assessments, have tended to vary between 1-10% for most of the species considered here, with the exception of Northern gannet (1-5%) and Black-legged kittiwake (1-2%, Table. 2, summarised from Table 1 in WP1 Report).

1. An expert elicitation of displacement mortality rates.

The majority of estimates for the Displacement Mortality Rates (DMR) for individuals (breeding or non-breeding season) is on values below 10% (WP2 report). There was, however, notable variance in the estimated upper bounds, meaning disagreement and overall uncertainty in what would be a plausible upper limit to the effects of OWF in terms of DMR. In terms of the effects on dependents (chicks in nest), there was markedly less agreement and certainty indicated by the experts' responses (WP2 report). However, overall, the DMR for dependents was estimated as being substantially greater than for the mature individuals.

2. Model-based estimation of displacement mortality rates via SeabORD and a statistical emulator.

The maximum levels of mean impact (per scenario) on population-level mortality rates in the simulated model runs were highest for black-legged kittiwake (an increase of 0.079 in the mortality rates for chicks and 0.005 in the mortality rate for adults), followed by razorbill (0.007 chicks, 0.003 adults) and then common guillemot (0.006 chicks, 0.001adults). These numbers should be interpreted very cautiously, as they depend heavily on the scenarios selected (e.g., for razorbill and common guillemot the maximum proportion of bird distribution map with a footprint was lower than for black-legged kittiwake, and that is likely to be at least one reason for the population-level impacts being lower), but they do, at least for black-legged kittiwake (where the scenarios span the widest range of displacement levels) give an indication of the magnitudes of impact that are possible within SeabORD.

Overall, this work undertaken in this project revealed that it was not possible to provide suggestions for how mortality rates currently advised for use within the Displacement Matrix could be revised as a result of outcomes from this project, specifically relating to estimates of mortality rates from the expert elicitation and the Individual-Based Model, SeabORD. This was due to discrepancies in definitions used within the Displacement Matrix, the expert elicitation and available estimates from the Individual-Based Model, SeabORD.

However, for the three species examined in the project, displacement mortality rates arising from the Individual-Based Model SeabORD varied consistently in relation to the proportion of the bird utilisation distribution within ORD footprints suggesting that future work could potentially develop an emulation approach to estimating such impacts more rapidly than is possible using the full SeabORD model.

We conclude by identifying key knowledge gaps and future research (both empirical data collection and analytical methods) that would facilitate more accurate quantification of mortality rates for displaced seabirds, and application of project results within the Displacement Matrix tool.

WP6: Project validation

In the final work package, Prof Jason Matthiopoulos (MacArthur Green Consulting & Glasgow University), provided an independent review of the project and its outputs. This report includes edits arising from his review (see Appendix E). The independent review includes high-level future recommendations for adapting the methodology used to estimate displacement mortality rates for seabirds to make it more robust (see Appendix E).

Summary of WP1: Review

We reviewed of existing information (availability and quality) and tools/methods for estimating mortality rates of species affected by displacement from offshore wind developments in the UK. This involved:

- Reviewing published literature to identify and assess the consequences of displacement from offshore windfarms on vital rates.
- Reviewing the key factors that may have an influence on the mortality of populations affected by displacement impacts.
- Reviewing the available approaches to collecting, analysing and modelling the demographic consequences of displacement.
- Collating the available relevant displacement and mortality information used in the examination, determination, and appropriate assessments of offshore windfarm consent applications in the UK.
- Collating the available information that could be used to estimate empirical values for the demographic consequences of displacement.

We focused on six key species considered to be at greater potential risk of displacement and displacement mortality in future offshore windfarm development in the UK:

- Black-legged kittiwake,
- common guillemot,
- razorbill,
- Atlantic puffin,
- red-throated diver Gavia stellata, and
- Northern Gannet *Morus bassanus*

These reviews found no empirical evidence of the mortality of seabirds that have been displaced from offshore windfarms. It appears likely that this has not been studied to date, rather than not reported.

There are two primary approaches used for the assessment of displacement mortality for offshore windfarm Environmental Impact Assessment (EIA) or Habitats Regulations Appraisal (HRA) in the UK: the matrix approach and SeabORD.

The matrix approach is a simple matrix of estimated number of birds predicted to be displaced from the windfarm being assessed across a range of displacement rates from 0% to 100%. This is compared with a range of subsequent mortality levels from 0% to 100%. Guidance on the use of the matrix approach, including the values used to parameterise the matrix has been provided by the UK SNCBs (SNCBs 2022). Input to the metric is the "mean seasonal peak population estimates based on several years data", though typically there is not more than two seasons of survey data. The mean peak population estimate is based on the abundance of birds both on the water and in flight in the windfarm and a suitable buffer around the windfarm (which is species specific). Assessments are completed for the breeding season and non-breeding season separately. It is important to note that to date the displacement rate and mortality rate have been based on recommendations from SNCB's based on the indices described above and not on empirical measures of displacement or mortality, largely because these have been lacking.

SeabORD is a tool to estimate the cost to individual seabirds, in terms of changes in adult survival and productivity, of displacement and barrier effects resulting from offshore windfarms (Searle et al. 2018). It was developed for common guillemot, razorbill, Atlantic puffin, and black-legged kittiwake in the Forth and Tay region of Scotland during the chick-rearing period. SeabORD is the only current means of estimating mortality from empirically derived inputs (with the exception of the displacement rate; and noting that several parameters within the model have been estimated through expert opinion where data are lacking) and thus provides a more defensible estimation of mortality for any given displacement rate than the matrix approach, at least as these methods are applied to impact assessments in the UK.

The full report is available in Appendix A.

Summary of WP2: Expert elicitation

This workshop was focused on using expert elicitation to fill knowledge gaps related to the potential displacement mortality rate of seabirds in response to the presence of offshore windfarms. Expert elicitation is a formal, structured process designed to obtain experts' opinion and knowledge while reducing heuristics and biases.

When considering the effects of offshore wind in the UK, there are currently six main species of concern: the common guillemot (*Uria aalge*), razorbill (*Alca torda*), Atlantic puffin (*Fraturcula arctica*), black-legged kittiwake (*Rissa tridactyla*), northern gannet (*Morus bassanus*) and red-throated divers (*Gavia stellata*). Two additional species are also of concern, Sandwich tern (*Thalasseus sandvicensis*) and lesser-black backed gull (*Larus fuscus*), but were not considered here due to needing to restrict the number of questions and parameters for which experts were asked to provide estimates. Given the uncertainty associated with displacement mortality in general, and for these species in particular, the workshop detailed in this report sought to address the knowledge gaps related to the excess mortality rates for these species, for both individual birds and their inter-dependents. With the exception of the red-throated divers, displacement mortality was also considered separately in the breeding and non-breeding season.

The workshop focused on the estimation of the potential displacement mortality rates affecting the common guillemot, razorbill, Atlantic puffin, black-legged kittiwake, northern gannet and red-throated divers. The purpose of eliciting experts' judgements regarding these knowledge gaps was to gain a better understanding of the biological context in which displacement mortality may occur, and to provide information of relevance to the implementation of current assessment methodologies (Joint-SNCB 2022). More specifically, the workshop was intended to elicit information from the experts on:

- the biological processes relevant to the "mortality rate of displaced birds",
- the timescales over which the mortality rate of displaced birds is estimated, and
- the precise definition of the "mortality rate of displaced birds".

As noted in the discussion with the experts, the scope of the workshop was limited to eliciting the displacement mortality rate related to an individual's interaction with a single offshore wind facility in either the breeding or non-breeding season. The cumulative effects of individuals interacting with multiple windfarms are accounted for separately within the assessment process (through the summation of individual impacts) and were considered beyond the scope of the workshop. Furthermore, the workshop sought to elicit the best biological estimates of displacement mortality, rather than seeking to build a definition that was consistent with current approaches used within assessments (the Displacement Matrix for OWF consenting processes, and individual-based models such as SeabORD). How the experts' elicited values might be integrated into the assessment process was not a focus of the workshop.

The workshops were held virtually on 5th, 13th, 17th of May and 10th of June 2022. A list of workshop participants, expert statements and a copy of the agenda can be found in Appendices **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**.

The experts were asked to provide a set of values that would answer the following questions:

> *The excess mortality rates (as an absolute %) for an individual bird that would have used the area of influence of the OWF and associated infrastructure if there had been no OWF, but which is displaced away from the area during construction and/or operation.*

The excess mortality rates (as an absolute %) for dependent birds that would have used the area of influence of the OWF and associated infrastructure if there had been no OWF, but which is displaced away from the area during construction and/or operation.

Although there is substantial detail and information within the results of each question posed to, and answered by, the experts (see Appendix B), some broad observations can be made:

- The bulk of belief for the Displacement Mortality Rates (DMR) for individuals (breeding or non-breeding season) is on values below 10%. There was, however, notable variance in the estimated upper bounds, meaning disagreement and overall uncertainty in what would be a plausible upper limit to the effects of OWF in terms of DMR.

- In terms of the effects on dependents, there was markedly less agreement and certainty indicated by the experts' responses. However, overall, the DMR for dependents was estimated as being substantially greater than for the mature individuals.

At the end of the workshop, experts were asked to consider what aspects of seabirds' interactions with offshore windfarms had not been considered, particularly as it relates to the effects of displacement. The following summarises these points, along with topics emphasized by the panel during the entire workshop process.

The following research topics were highlighted by experts:

- Displacement effects of OWF go beyond simple mortality as being captured by DMR in this elicitation, for example impact on productivity was identified. The effects of habituation were discussed and were noted as potentially important but poorly known. Habituation was noted as being potentially positive in terms of sub-lethal effects (lower stress) and potential influences on collision rates.

- The values currently used in the assessments for the size of the populations that might be affected by DMR are noted as being under-estimates, being based on snapshots, perhaps limited to OWF footprints and near surrounds. The panel was clear that in reality much larger numbers will be interacting with OWF and subject to effects, e.g., different birds are passing through over time. While the numbers of birds expected to be affected by OWF were not a direct focus of the elicitation process, the DMR figures are likely to be combined with estimates of the number of birds influenced by an OWF for overall impact estimates. These estimates of numbers of birds will themselves be based on survey data, and therefore subject to the noted underestimation. Improved methods for estimating the number of birds subject to OWF influence was therefore identified as warranting research.

- Mature breeding birds and their dependents were considered here. It was noted that there are other classes of bird that might undergo differing displacement effects. "Sabbatical" adults and juveniles being two that were identified. Further research would be warranted for a more holistic view of displacement effects on a population.

- There were six species considered as part of this EE process. The scope was limited to a priority list for good logistical reasons, but other species were noted as being of potential importance. Further research of displacement effects for other species is warranted.

- Currently the cumulative effect of multiple windfarms is done in a simplistic additive fashion, i.e., calculations are done for individual windfarms, then treated as independent by performing what is effectively a summation. The consequence of this is not clear, but overly simplistic: on one hand there will be double-counting of effects in some circumstances (e.g., a bird that dies at one windfarm cannot die at another), while on the other hand there is the potential to underestimate effects on an individual level (e.g., accumulated stress from interacting with multiple windfarms may increase exponentially, not linearly, as assumed by the summation). This was noted a complex issue warranting research for a deeper understanding and improved approaches for its treatment.

The following information to improve assessments was identified by experts:

- When considering displacement mortality rate (DMR), it was deemed important to consider the effects on dependents, not just the mature animals who are directly displaced. This is of principal importance within the breeding season. The importance of this is evidenced in the expansion of the initial elicitation scope from 11 questions to 16 to include the DMR for dependents – meaning an additional question for each of Atlantic puffin, common guillemot, black-legged kittiwake, gannet and razorbill. The experts noted that this difference between individuals and their dependents should be applied generally when determining DMR for OWF developments.

- More realistic estimates of the numbers of birds within the influence of an OWF, compared to those thought to be currently employed, are needed.

The full report is available in Appendix B.

Summary of WP3: Tool simulation

When empirical data are lacking, predictive models can be used to estimate impacts of pressures on wildlife populations. One such model for quantifying displacement mortality rates, and sources of variation in these rates, is via the mechanistic model, SeabORD (Searle et al. 2014, 2018). Simulations from the mechanistic model can be used to estimate the mortality rates associated with different scenarios of offshore windfarm development.

We used SeabORD (Searle et al. 2014, 2018), an individual-based model of seabird behaviour, energetics, demography and windfarm interactions, to estimate the levels of displacement mortality associated with different colonies under different windfarm scenarios. SeabORD includes two main mechanisms of windfarm interaction: displacement effects (a switch in foraging location as a result of a windfarm) and barrier effects (increased flight distances, and hence energetic costs, to reach foraging locations when birds avoid flying over windfarms). We refer to all mortality arising from the windfarm – mortality arising directly from displacement or barrier effects, or indirect mortality arising from displacement of other individuals leading to increased competition – as "displacement mortality". SeabORD can consider either a single windfarm, or the simultaneous effects of multiple windfarms, and considers impacts on both chicks and adults. SeabORD directly simulates the impact of windfarms on chick mortality. For adults, SeabORD simulates the impact on windfarms on the change in body mass over the course of the breeding season and then translates this into impacts on annual adult survival via published mass-survival relationships. SeabORD only considers the impacts of windfarm interactions during the chick rearing period within the breeding season and is parameterized for four species: black-legged kittiwake, common guillemot, razorbill and Atlantic puffin.

Foraging locations within the model are driven by the use of a spatially explicit foraging distribution for each breeding colony. Birds from the colony select a foraging location with a probability proportionate to the probability density of use of each cell located in the foraging distribution map. The selection of foraging locations is independent between foraging trips and between model timesteps. Birds are assumed to navigate around all land in the foraging area, flying around the coastline rather than crossing directly over land to reach ultimate foraging locations. The number of foraging trips per day and the duration of each individual foraging trip are derived for each individual bird based on an optimality assumption of seeking to maximise energy gain whilst minimising time away from the nest (unattendance). When the presence of an OWF in an impact run causes a bird to be displaced from its chosen foraging location in the baseline (i.e., when no OWFs are present), it selects a new foraging location within the 'displacement zone', which in all cases for the runs used in this project was set to be within a 5km area of the OWF causing the displacement event. Foraging locations within the displacement zone are selected based on the probability density within that zone derived from the foraging distribution map for the colony. The displaced bird travels directly to this new foraging location in the impacted runs (i.e., when OWFs are present), incurring altered travel costs associated with the new distance flown to reach the new, displaced foraging location relative to the original baseline foraging location. In all simulations runs used in this project, the quantity of prey available was assumed to be homogeneous across the entire foraging area. Therefore, costs associated with displacement to a new foraging location may also incur additional reductions in energy gain associated with the number of conspecific birds also foraging at that location during the relevant timestep (reflecting increased competition for prey). Mortality of chicks occurs via several mechanisms: through insufficient provision of food by parents; through unattendance leading to predation or exposure-related death; or through one or more of the parents giving up the breeding attempt due to insufficient acquisition of energy for themselves. Mortality of adult birds can occur during model simulations if the body mass of adults falls below a critical threshold. However, in practice, this occurs very rarely (reflecting empirical observations), so the vast majority of adult mortality arises via the mass-survival calculation applied to the adult body mass outputs of the model in which subsequent over-winter survival of adults is estimated.

Emulation provides a framework for using statistical models to approximate mechanistic models. It uses a "training set" of mechanistic model inputs and outputs to build a general model for the relationship between the mechanistic model inputs and outputs, and, as such, provides an approximation to the mechanistic model. Emulation is typically designed to approximate computationally intensive models using much less computationally intensive models, so that the emulator can then be used, predictively, as a rapid but approximate substitute for the mechanistic model.

We focused upon using SeabORD, and an emulator of SeabORD, to produce estimates of displacement mortality for three species – black-legged kittiwake, common guillemot and razorbill – under to a range of SPAs and windfarm scenarios, and to identify sources and levels of variation in these mortality rates within each species. For each species we focus upon attempting to build an emulator of SeabORD windfarm impacts that could be applied to all UK SPAs, and, for each SPA, to all windfarms whose footprints are in the CEF Data Store and that lie within the foraging range of the SPAs. This represents an exceptionally large number of scenarios, so we build the emulator using a much smaller training set of SeabORD model runs for each species. For pragmatic purposes, we focus upon three SPAs per species and use colony-specific bird distribution maps derived from the maps of Wakefield et al. (2017) and upscaled to SPA level within the CEF. Since the vast majority of possible windfarm scenarios involve extremely low levels of interaction between windfarm footprint and SPAs, and practical interest lies in situations in which there is a fairly substantial interaction with windfarms, we develop the training set using windfarm scenarios whose interaction with an SPA (as defined using '*total_p_ud_in_ord*') exceeds a minimum threshold, and thereby consider the effects of between 6 and 11 windfarm scenarios per SPA per species.

For reference, the SeabORD simulation runs ranged from about two hours for the smallest populations (~6000 pairs) up to ~10 hours for the larger populations (~47,000 pairs). Run times for impacted runs (i.e., including OWFs) increased by up to 40-50% compared to baseline runs with no OWFs present.

We use the SeabORD training runs to build an emulator for each species, in which we relate the SeabORD impacts on adult and chick mortality, and adult mass loss over the chick rearing period, to a range of metrics that summarize the characteristics of the windfarm footprint(s), SPA and spatial interaction between SPA and windfarm(s). We use this emulator to identify the percentage of variation in impacts that can be explained by these characteristics, and to identify the key characteristics that influence the simulated impacts for each species.

The emulator is framed in relation to displacement mortality rates, so provides a straightforward mechanism for predicting the levels of displacement mortality across a much wider set of SPAs and windfarm scenarios than those used in developing the emulator. The simplest version of the emulator that we consider assumes that population-level displacement mortality from SeabORD increases in direct proportion to the proportion of individuals that are assumed to experience displacement at each timestep, which is itself equivalent to the displacement rate multiplied by the proportion of the bird distribution that lies within any footprint (or within 2km of a footprint). The slope of this relationship represents the increase in mortality that arises from an increase in the number of individuals displaced and so can be interpreted as one form of displacement mortality rate – to distinguish it from the differing definitions of rates considered in the EE and the Displacement Matrix, we term it a model-based displacement mortality rate.

This very simple emulator assumes that the same slope applies across all SPAs and scenarios, which corresponds to an assumption that the same model-based displacement mortality rate can be applied in all situations. Within this model, prediction to other SPAs and scenarios is therefore trivial - the same rate is simply assumed to apply in all situations. Within this model the model-based displacement mortality rate can be converted, under any scenario, in a prediction of impact on population-level mortality rates by multiplying the model-based displacement mortality rate by the displacement rate and the proportion of bird distribution contained within any footprint (plus 2km).

We consider alternative emulation models that allow the model-based displacement mortality rates (for chicks and adults) to vary in relation to a range of characteristics of the ORDs and ORD-SPA interactions, and that allow the model-based displacement mortality rate to vary in relation to the proportion of birds displaced (corresponding to a quadratic relationship between proportion of birds displaced and the impacts on population-level displacement mortality). These alternative models use characteristics that can readily be calculated for any scenario, and so also provide a straightforward basis for predicting model-based displacement mortality rates under other scenarios.

We can also consider SPA characteristics within this approach. A key practical challenge, however, is that it has only been feasible here to consider a relatively small number of SPAs per species (3 or 4), with the result that relationships in relation to SPA characteristics may not be sufficiently well estimated to be transferrable to other SPAs. In order to evaluate the potential for transferability we also consider an emulator that assumes a separate model-based displacement mortality rate for each SPA – if this model has better empirical performance than the other emulation models this suggests that the relationships are not transferrable, since this model does not allow prediction to SPAs other than those used to develop the emulator.

The results of the emulation provide relative strong and consistent evidence for a positive relationship between the proportion of birds displaced per timepoint for all three species, and for all three response variables of interest (impacts on adult mortality, chick mortality and adult mass loss). These relationships also appear to be relatively well approximated by a linear relationship, although (a) there is high level of noise, so even if non-linear effects existing it may be difficult to detect them and (b) there is some evidence, at least visually, that the relationships may be becoming non-linear as the upper end of the relationship (i.e., as we move into the scenarios with the highest levels of displacement).

These results suggest that a model that assumes the same model-based displacement mortality rate (i.e., the same slope) in all situations can provide a moderately good approximation to the SeabORD outputs. However, there is consistent evidence that a better approximation to the SeabORD outputs can be obtained by considering models that allow this rate to vary. There is some evidence that there may be variations in relation to ORD characteristics, but also evidence for variation in relation to SPA characteristics. The results vary substantially between species and populations but the model that most commonly has reasonable performance is the model obtained by allowing there to be a separate rate for each SPA, suggesting that there is tentative evidence against the model being transferrable to other SPAs.

It is likely that these variations could be explained, or characterised probabilistically (e.g., via a random slope), but this would require SeabORD runs from a wider set of SPAs. The results of the work must therefore be interpreted cautiously, so we conclude by outlining the key limitations and caveats underpinning the work and describing the potential for future work in this area (including work that is already planned to take place within the ECOWINGS project). We finally conclude by examining the wider implications of the work.

The full report is available in Appendix C.

Summary of WP4: Mortality rate estimation

The individual-based model SeabORD can be used to produce metrics that relate to 'displacement mortality rates´. Because 'displacement mortality rate' is not defined within SeabORD itself, rather a range of potentially relevant metrics are produced by the model, and subsequent derivations of quantities related to displacement mortality rates may be obtained, whose interpretations are dependent on the definition used. The emulator developed in WP3 can also be used as a mean of calculating metrics that relate to the displacement mortality rate and provides a natural framework for quantifying variations in these metrics between colonies, scenarios and individual model runs.

We have focused on two definitions of model-based displacement mortality rates (the term model-based is used to highlight that the rates produced are not directly comparable to those used in the Displacement Matrix), in relation to the number of individuals displaced per timestep and the number of individuals ever displaced within the chick rearing period. In Work Package 5 we will consider how these definitions relate to those used in the expert elicitation (WP2) and in the Displacement Matrix.

We have quantified the values of these metrics for black-legged kittiwake, common guillemot and razorbill using two different approaches – direct calculation of the metrics from SeabORD, and calculation of them via the parameters of the emulation model.

The ratio of impacts relative to 'proportion of birds ever displaced during the season' are consistently much lower than the ratio of impacts relative to 'proportion of birds displaced per timepoint (day)'. This simply reflects the fact that, at least within the assumptions of SeabORD, the proportion of birds that are ever displaced within the season is always much higher than the proportion of birds displaced at any particular timepoint (day). Moreover, such a definition does not include birds that may not be displaced from foraging locations by the windfarm but are barriered by the windfarm in their journeys to other foraging locations. SeabORD predicts demographic impacts for both birds that are directly displaced by a windfarm, and for birds that are not directly displaced but suffer barrier effects on their way to other foraging locations. SeabORD can also predict impacts on birds that are neither displaced nor barriered, but forage in the vicinity of a windfarm and are subject to increased levels of competition from displaced birds. Therefore, the input to the Displacement Matrix (peak abundance in the windfarm footprint and buffer), and any adjustment made using only the proportion of the utilisation distribution (UD) within this area, will always be a lower estimate of the number of birds whose demographics may be altered in the presence of a windfarm(s) within SeabORD.

Estimates of this ratio based on SeabORD outputs typically show relatively high levels of variation, with ranges that often include very large outliers, whilst the emulator-based ratios show lower levels of variation. This arises because the ratio can become very unstable when the mean proportion of birds within a footprint is very small – at this point, small, stochastic, variations in mortality can be magnified up into very large impacts divided by the mean proportion of birds within the footprint. The emulator avoids this issue, by using a statistical model to explicitly allow for the possibility of noise in the level of displacement mortality seen in each SeabORD run. The emulator is therefore the preferable approach for the calculation of such rates (although this may not be true under alternative definitions of 'displacement mortality rate': for example, focusing on the fate of subgroups of affected birds within SeabORD would also avoid the issue of instability because the same stochasticity would apply in both the numerator and denominator). The results of WP3 indicate that the rates are likely to vary between SPAs and windfarm scenarios and additional SeabORD runs would therefore be needed in order to produce rates that could be generalised to SPAs other than those used in the SeabORD runs considered here. The results outlined here should be interpreted cautiously, given that the training set of SeabORD runs is relatively small (especially in relation to the number of SPAs), and the emulator methods used are relatively simple. The low signal to noise ratio when levels of displacement are relatively low also suggests that SeabORD runs with relatively high levels of displacement need to be included when fitting the emulator in order to be able to obtain reliable results – of the three species considered here, relatively high levels of displacement only occurred for black-legged kittiwake within the scenarios considered, so further runs that include high levels of displacement are also needed in order to produce reliable emulation results for common guillemot and razorbill. Overall, the results suggest that it may be possible to approximate outputs from SeabORD using a simpler method relating to the proportion of the population's utilisation distribution that falls within an ORD footprint. However, the development of such an approach would require application of many more model runs across a wider range of ORD impacts to adequately assess how a simpler method based on emulation could be used to robustly replicate model outputs. We also note that such an approach still relies upon use of GPS tracking data to provide an appropriate estimate of the proportion of time each population is likely to spend within an ORD footprint, which cannot currently be obtained from site-based at-sea survey data.

The full report is available in Appendix D.

Mass-survival relationship sensitivity analysis

The individual-based model, SeabORD, uses two published relationships to convert mass of adults at the end of the breeding season into subsequent over-winter survival. The procedure for converting individual adult mass values into an overall estimate of adult survival for each simulation run is essentially based on the two previously published studies (Oro and Furness 2002, Erikstad et al. 2009) where the general assumption is that mass and survival are linked through the equation:

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \log\left(\frac{s_o}{1-s_o}\right) + bm_{ij}$$

where m_{ij} denotes the standardised mass of individual i in run j and p_{ij} denotes the (annual winter) survival probability of this individual. The value of b quantifies the strength of the relationship between mass and survival, and the value of s_0 denotes the 'baseline' survival (i.e., the survival rate that would be associated with a bird of average mass in the absence of an ORD). The overall survival rate for a simulation run, P_i is simply assumed to be the average (mean) of the survival probabilities for all of the individuals within it, so that:

$$P_i = \frac{1}{n}\sum_{i=1}^{n} p_{ij}$$

(where n denotes the total number of individuals).

The validity of this approach will depend primarily upon the validity of the values that are selected for b (the strength of the relationship between mass and survival) and s_0 (the 'baseline' survival - the survival rate that would be associated with a bird of average mass in the absence of an ORD). As used within SeabORD, the value of the baseline survival, s_0, is assumed to vary between species – the specific values are based upon the results of the population modelling performed by CEH for Scottish Government (Freeman et al. 2014) and are given in Table 1.

Table 1. Baseline survival probabilities for birds in baseline conditions (no ORDs present) under poor, moderate and good prey availability (Freeman et al. 2014). The level of prey availability is determined by the percent mass loss of adult birds over the chick-rearing season (see Worked Example for more details).

	Poor	Moderate	Good
Kittiwake	0.65	0.80	0.90
Puffin	0.85	0.90	0.95
Guillemot	0.82	0.92	0.94
Razorbill	0.80	0.90	0.95

The strength of the relationship between mass and survival, *b*, is determined using values given in the published literature (estimated values for *b* are 1.03 in Erikstad *et al*., 2009; and 0.038 in Oro & Furness 2002). For black-legged kittiwake the value of *b* is based on the value given in Oro & Furness (2002), and for all other species it is based on the value given in Erikstad *et al*. (2009). Published values do not exist for razorbill or common guillemot, so we assume that these species have the same value as that estimated for Atlantic puffin in the Erikstad *et al*. (2009) paper. The black-legged kittiwake study was undertaken on a population in Shetland experiencing low food abundance, and the Atlantic puffin study was based on a population in northern Norway. Both populations may have differed in terms of adult body mass and relationships between condition and survival from populations in the other regions. Furthermore, mass/survival relationships in common guillemot and razorbill may differ from those observed in Atlantic puffin.

Given these uncertainties, we tested the sensitivity of predicted survival in relation to seabird body mass to variation in *b* (strength of the relationship between mass and survival), s_0 (baseline survival - the survival rate that would be associated with a bird of average mass in the absence of an ORD), and the assumed impact of ORD on adult mass at the end of the breeding season.

We varied *b* (strength of the relationship between mass and survival) over a range representative of the 95% confidence intervals reported in each of the two papers (Erikstad *et al*., 2009, Oro & Furness 2002). For black-legged kittiwake we varied this parameter over -20% to +20% (Figure 1, y-axis), with the 95% confidence interval represented as horizonal blue lines in Figure1. For Atlantic puffin, common guillemot and razorbill we varied this parameter over -60% to +60% (Figures 1 & 2, y-axis) with the reported 95% confidence intervals represented as horizontal blue lines in Figure 1 (common guillemot), and Figure 2 (razorbill and Atlantic puffin).

We varied the ORD impact on mass for Atlantic puffin, common guillemot and razorbill using the assumed impacts of the ORD on standardised mass, varying this quantity from 0 to -2 (Figure 1, common guillemot; Figure 2, razorbill and Atlantic puffin; x-axis), representing variation across 2 standard deviations (SD). We therefore tested the sensitivity to a range representing variation from no impact (zero) to the lower bounds of expected natural variation in mass of birds at the end of the breeding season (-2SD). For black-legged kittiwake, we varied the ORD impact on mass as the impact of ORDs on absolute mass based on variation around the observed SD of mass of this species at the start of the breeding season based on empirical data from the Isle of May (SD=33.6g). Therefore, we varied mass by up to 2SD (or 60g) for black-legged kittiwake to match the approach taken for the other three species (Figure 1, black-legged kittiwake, KI; x-axis).

Finally, we assessed sensitivity over these two parameters (*b* and ORD impact on mass) for three different values of s_0, baseline survival - the survival rate that would be associated with a bird of average mass in the absence of an ORD. These are represented for all four species in Figures 1 & 2 in the three panels for each species and correspond to the reported values for 'poor', 'moderate' and 'good' seasons in Table 1.

The results of the sensitivity analysis reveal that in general the sensitivity of estimated survival to body mass is larger when ORD impacts on mass are larger – this is shown in Figures 1 & 2 for all 4 species, whereby there is greater variation in predicted survival (see Figure legend) on the left-hand side of all plots where estimates for the largest impacts of ORDs in mass are displayed (x-axis). This is particularly true in the case of Atlantic puffin, razorbill and common guillemot where for a given ORD impact on mass (e.g., -2.0 SD), predicted change to survival varied by as much as 0% to -70% with variation in the parameter *b* (strength of the relationship between mass and survival) (Figures 1 & 2). This is likely a reflection of the fact that the mass-survival equation for Atlantic puffin (Erikstad *et al*., 2009), also used for razorbill and common guillemot, had considerably more uncertainty reported in the published study than that reported in the black-legged kittiwake analysis (Oro & Furness 2002), as can be seen by the depiction of the 95% confidence intervals in Figures 1 & 2 (horizontal blue lines). Results also showed that variation in baseline survival had only marginal impact on the output of the mass-survival relationships for all four species, although there was more variation for black-legged kittiwake than for the other three species (Figure 1).

The ranges of simulated mean mass loss values within the scenarios considered in WPs 3 and 4 are very narrow compared to the ranges shown on these graphs: absolute mass change for kittiwake range from -1.32g to +0.15g, whilst standardised mass changes for guillemot range from -0.01 to 0.01 and for razorbill from -0.03 to 0.01.

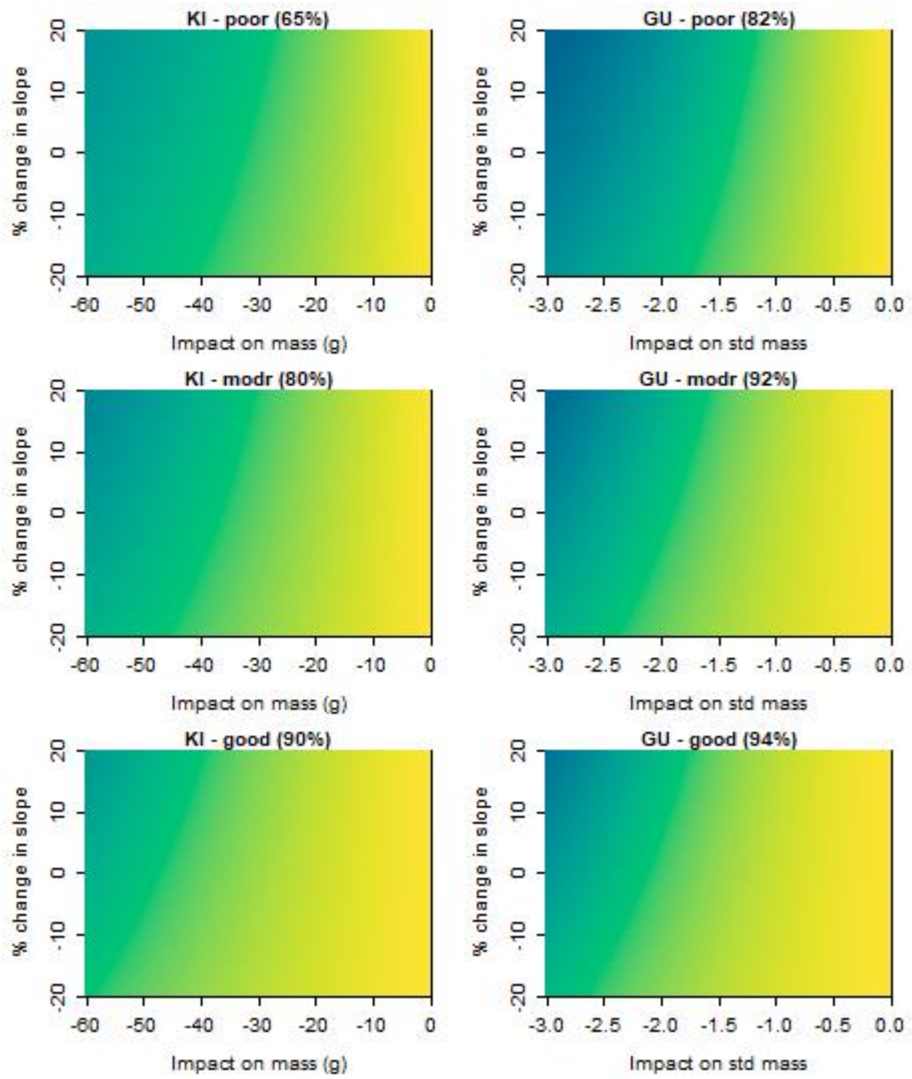

Figure 1. Summary of sensitivity analysis outputs for black-legged kittiwake (KI) and common guillemot (GU) in relation to the mass-survival relationships used within the individual-based model SeabORD. Variation in adult overwinter survival is shown in colour (see legend for decrease in adult survival rate ranging from no change, '0', to a decrease of 77%, '-77'). Each set of three vertical panels shows how survival is affected by variation in the ORD impact on mass (x-axis) and the percentage change in the mass-survival slope parameter (y-axis), for three baseline survival rates representing poor (top panel), moderate (middle panel) and good (lower panel) average conditions.

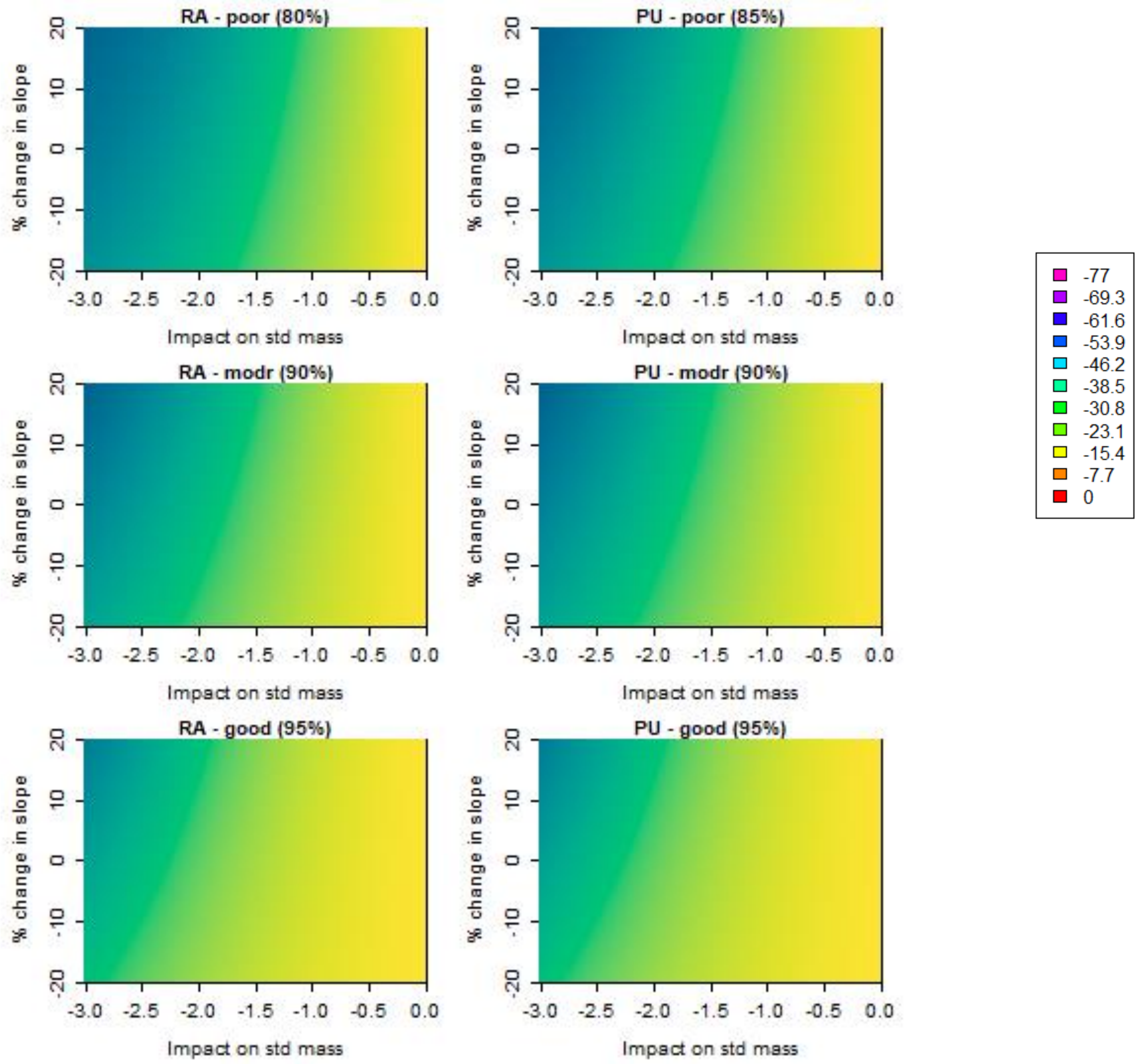

Figure 2. Summary of sensitivity analysis outputs for razorbill (RA) and Atlantic puffin (PU) in relation to the mass-survival relationships used within the individual-based model SeabORD. Variation in adult overwinter survival is shown in colour (see legend for decrease in adult survival rate ranging from no change, '0', to a decrease of 77%, '-77'). Each set of three vertical panels shows how survival is affected by variation in the ORD impact on mass (x-axis) and the percentage change in the mass-survival slope parameter (y-axis), for three baseline survival rates representing poor (top panel), moderate (middle panel) and good (lower panel) average conditions.

Recommendations

The mass-survival relationships currently used by SeabORD (Oro & Furness 2002 and Erikstad et al. 2009) suffer from three main challenges: firstly, they are not based on populations that are very geographically relevant to UK offshore renewables and thus may have contrasting behaviour; secondly, they are based on only a few years of data, in some cases involve only one year of measurement; and finally, the analyses have not considered various important aspects in the modelling used such as age effects, uncertainty in body mass measurement and observation, and most importantly a rigorous consideration of year to year changes in survival probability unrelated to body mass.

More recently, Daunt et al., (2020) used data from the Isle of May to produce empirical estimates of mass-survival relationships for the four species currently considered within SeabORD: common guillemot, razorbill, Atlantic puffin and black-legged kittiwake. As part of long-term monitoring, adult birds are caught during the breeding season and individually marked, and a proportion are weighed. This protocol has been undertaken over multiple years in these four species, allowing the relationship between body mass and survival to be estimated. A sophisticated statistical modelling framework was used, which accounted for the effects of age and inter-annual variability and provided a full quantification of uncertainty. Incorporating the estimated relationships from Daunt et al. (2020) into SeabORD, in place of the current mass-survival relationships, would overcome two of the key issues: that the current relationships are based on populations, and often species, that are not directly related to the populations and species to which SeabORD is being applied, and the fact that uncertainty in the mass-survival relationship is not currently accounted for. The incorporation of uncertainty is key, because, in practice, assessments are designed to be precautionary and hence need to consider the /range of uncertainty associated with the estimated annual effect. Representing the range of uncertainty in effects on annual survival will, by including quantiles of estimated effects within SeabORD output, allow stakeholders to assess the plausible upper limit of values for estimated displacement effects.

Importantly, there are substantial caveats with the current relationships used in SeabORD, and many of these would remain with the revised relationship. The estimated relationships between body mass and survival are derived from naturally occurring between-individual variation in survival, not imposed differences driven by restrictions on access to feeding ground, and it is an untested but essentially unavoidable assumption that the associated estimates of the mass-survival relationships are applicable to estimate variation in survival due to ORD impacts. For a more comprehensive review of the new mass-survival relationships please see Daunt et al. (2020)[1], and for their potential use within SeabORD, please see Searle et al. (2022)[2].

[1] https://data.marine.gov.scot/dataset/improving-estimates-seabird-body-mass-survival-relationships

[2] https://www.gov.scot/publications/study-examine-feasibility-extending-seabord-entire-breeding-season/pages/1/

Overall assessment of mortality rates rising from whole project

In WP5, we provide a summary based upon outcomes from WPs 1 to 4, assessing the evidence for the robustness of mortality rates for displaced seabirds, with associated uncertainty, where feasible. This project has considered three distinct sources of evidence regarding the mortality rates of displaced birds ('displacement mortality rates'):

1. The rates recently used in UK assessments within the Displacement Matrix (presented in offshore windfarm consent application assessments)

2. An expert elicitation of displacement mortality rates; and

3. Model-based estimation of displacement mortality rates via SeabORD and a statistical emulator

In this Work Package we summarise the key findings of the project regarding each of these sources of evidence and then consider the extent to which the second and third sources of evidence can be used to provide information for updating the rates recommended for use in the Displacement Matrix. We conclude with recommendations, including around additional research.

Summary of currently used rates in Displacement Matrix

Mortality rates for displaced birds used within the Displacement Matrix as presented in offshore windfarm consent application assessments have tended to vary between 1-10% for most of the species considered here, with the exception of Northern gannet (1-5%) and Black-legged kittiwake (1-2%, Table. 2, summarised from Table 1 in WP1 Report).

Table 2. Mortality rates for displaced birds used within the Displacement Matrix (see table 1 in WP1 report for full details)

Species	Range of displacement mortality rates used	Demographic rate	Season
Black-legged kittiwake	1-3%	Mortality rate of displaced adults	Breeding Non-breeding
Northern gannet	1-5%	Mortality rate of displaced adults	Breeding Non-breeding
Common guillemot	1-10%	Mortality rate of displaced adults	Breeding Non-breeding
Razorbill	1-10%	Mortality rate of displaced adults	Breeding Non-breeding
Atlantic puffin	1-10%	Mortality rate of displaced adults	Breeding Non-breeding
Red throated diver	1-10%	Mortality rate of displaced adults	Non-breeding

Summary of rates elicited by experts

The majority of estimates for the Displacement Mortality Rates (DMR) for individuals (breeding or non-breeding season) is on values below 10% (WP2 report). There was, however, notable variance in the estimated upper bounds, meaning disagreement and overall uncertainty in what would be a plausible upper limit to the effects of OWF in terms of DMR.

In terms of the effects on dependents, there was markedly less agreement and certainty indicated by the experts' responses (WP2 report). However, overall, the DMR for dependents was estimated as being substantially greater than for the mature individuals.

Summary of mortality rates arising from SeabORD and emulation

SeabORD was run for between 25-35 scenarios, corresponding to 3-4 SPAs, for each species. Scenarios were specifically designed to cover a range of plausible single-windfarm and in-combination effects, and in particular to characterise the behaviour or SeabORD across a range of impact levels to capture those combinations of windfarms that lead to the highest levels of in-combination effects.

Mean impacts per scenario on chicks in the nest and adult mortality rates are summarised in

Figure 4. The maximum levels of mean impact (per scenario) on population-level mortality rates are highest for black-legged kittiwake (an increase of 0.079 in the mortality rates for chicks and 0.005 in the mortality rate for adults), followed by razorbill (0.007 chicks, 0.003 adults) and then common guillemot (0.006 chicks, 0.001 adults). These numbers should be interpreted very cautiously, as they depend heavily on the scenarios selected (e.g., for razorbill and common guillemot the maximum proportion of bird distribution map with a footprint was lower than for black-legged kittiwake, and that is likely to be at least one reason for the population-level impacts being lower), but they do, at least for black-legged kittiwake (where the scenarios span the widest range of displacement levels) give an indication of the magnitudes of impact that are possible within SeabORD. Across the simulations, black-legged kittiwake experienced the highest levels of displacement and barrier interactions (Figure 3). It is particularly notable that black-legged kittiwake experienced greater barrier interactions than the other two simulated species, likely leading to the larger impacts arising from simulated OWF impacts for this species (Figure 3). Razorbill experienced very low levels of displacement or barrier interactions (Figure 3), which is why predicted model impacts were negligible for this species. Similarly, although common guillemot experienced some displacement and barrier interactions, the higher density of birds closer to colonies (maps not shown) likely meant that displacement tended to result in birds choosing to forage closer to the colony when an OWF(s) was present, resulting in reduced travel costs potentially offsetting any competition-mediated displacement impacts in the model runs for this species. Coupled with the relatively low occurrence of barrier interactions for common guillemots, this likely drove the low impact sizes in this species across the simulated model runs.

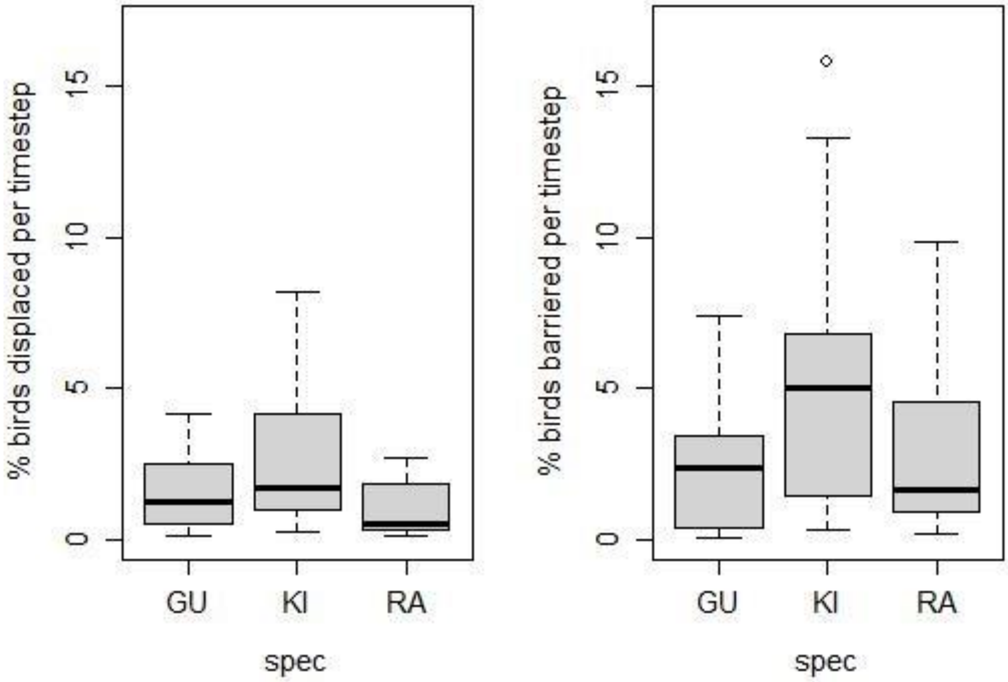

Figure 3. Summary of the percentage of birds displaced per timestep (left panel) and percentage of birds barriered per timestep (right panel) for the three seabird species simulated using the Individual-Based Model, SeabORD. Data are shown as median (thick black line), quartiles (grey boxes), minimum and maximum (whiskers) and outliers (dots).

There is considerable noise in the results, but the magnitude of the population-level impacts for all three species for both chicks and adults appears to be related to the mean proportion of birds that are experiencing displacement at each timepoint, although the relationship is much clearer for black-legged kittiwake than for common guillemot and razorbill. This quantity is, in turn, simply derived from multiplying the displacement rate by the proportion of the bird distribution that lies either within a footprint or within 2km of a footprint. We term the magnitude of slope in these relationships the 'model-based displacement mortality rate per timestep'.

Emulation provides a statistical framework for estimating this rate, and identifying the uncertainty and variability associated with it. Model selection via the emulator provides very variable results but indicates that rates are likely to vary in relation to SPA and windfarm characteristics. In Figure 5 we show the fitted SPA-specific emulation models, and in Table 3 summarise the model-based displacement mortality rates per timestep that these imply, and the uncertainty associated with these.

Because there is evidence of variation between SPAs in the model-based displacement mortality rates, and because it has not been possible to run SeabORD here for sufficient SPAs to be able to explain these variations, the emulators that have been developed cannot defensibly be applied to SPAs other than those for which SeabORD runs are already available.

We can also use the emulator to derive an estimate of the 'model-based displacement mortality rate over the entire season' (Figure 6). This rate increases as the level of displacement increases, all else being equal, because as the level of displacement becomes high there is, at least within SeabORD, an increase in the frequency of displacement for displaced birds as well as an increase in the number of displaced birds, which is not captured by focusing only on the number of individuals that ever experience displacement.

The ‘model-based displacement mortality rate over the entire season’ derived from SeabORD outputs via the emulator is relatively comparable to the displacement mortality rate defined by the experts within the expert elicitation. In particular, both relate to the set of birds that are displaced across an entire season, rather than at a specific timepoint, both can be defined for either adults or chicks, and both are defined in terms of impacts on demographic rates rather than in terms of impacts on absolute numbers of individuals. One key difference is that the EE definition included all birds that experience any form of displacement-related impact, including barrier effects or indirect effects, whereas the definition used in the SeabORD emulator did not.

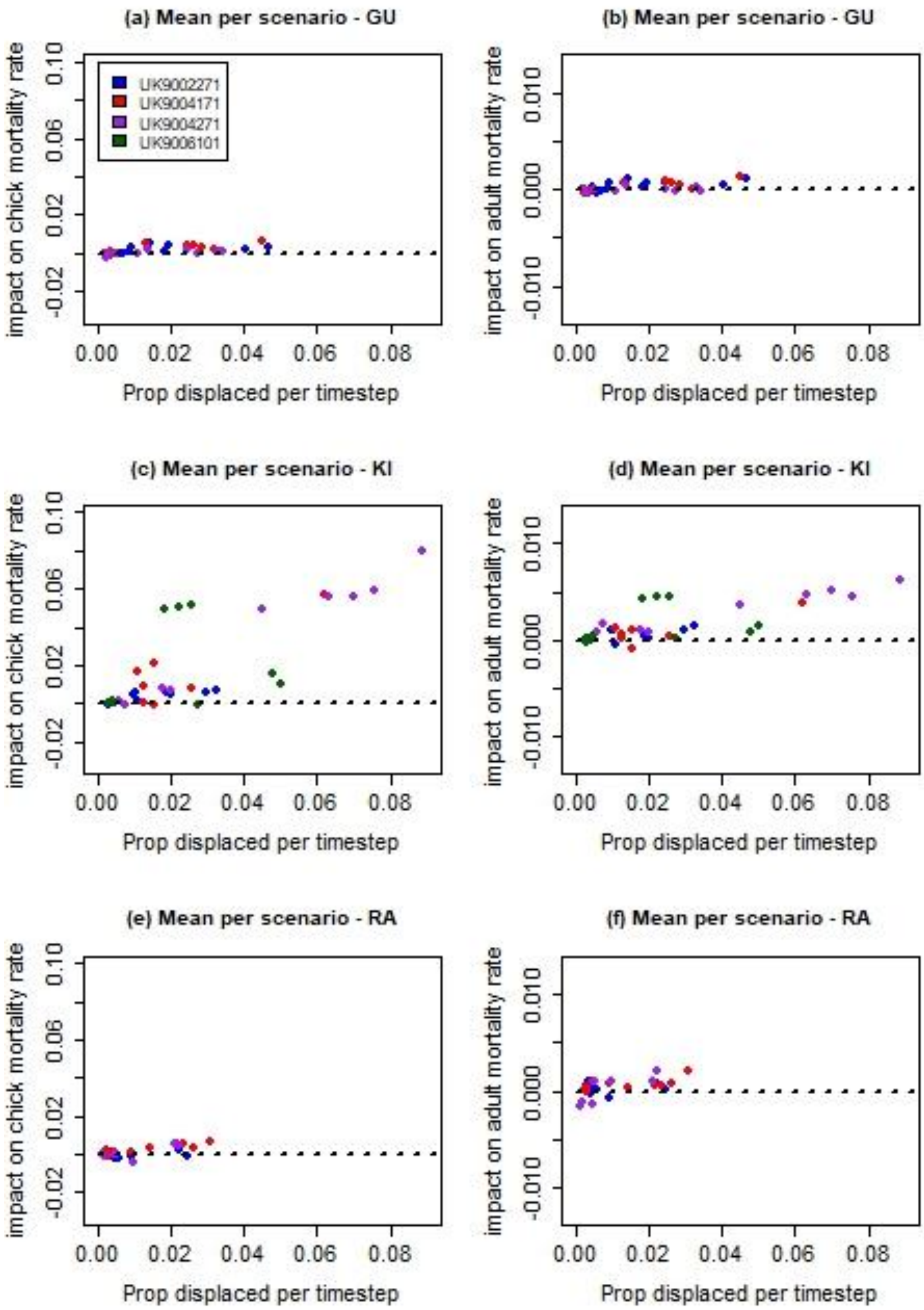

Figure 4. Scatterplots of proportion of birds displaced per timestep (ptdisp) against simulated SeabORD impacts (mean impact per scenario) on chick (a, c and e) and adult (b, d, and f) mortality for each species (GU = common guillemot; KI = black-legged kittiwake; RA = razorbill), with different colours representing different SPAs. The dashed black line represents an impact of zero.

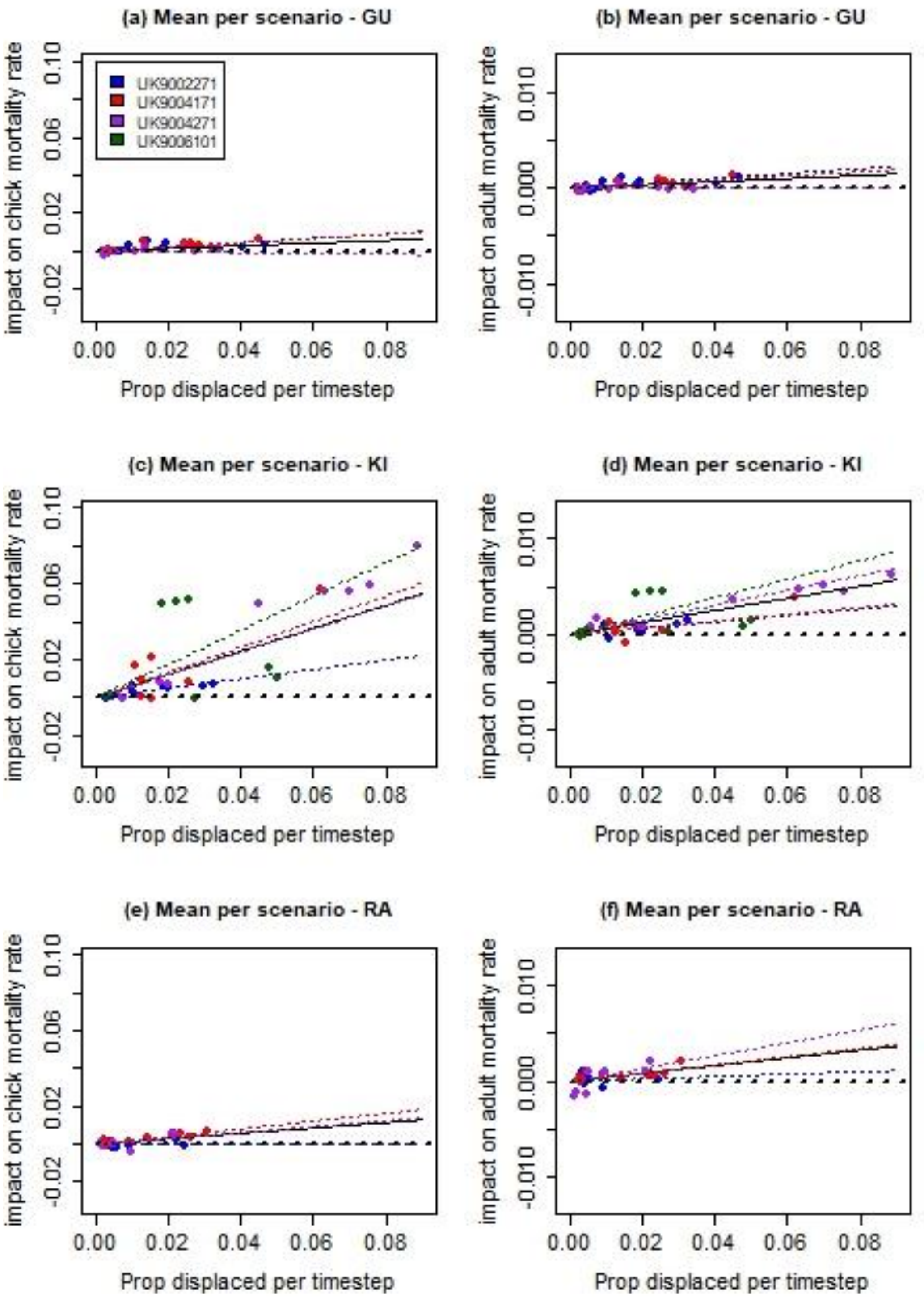

Figure 5. Scatterplots of proportion of birds displaced per timestep (ptdisp) against simulated SeabORD impacts (mean impact per scenario) on chick (a, c and e) and adult (b, d, and f) mortality for each species (GU = common guillemot; KI = black-legged kittiwake; RA = razorbill), with different colours representing different SPAs, and with fitted emulators based on models with common slope (black) or SPA-specific blocks (dotted coloured lines). The dashed black line represents an impact of zero.

Species	SPA	Chicks		Adults	
		Estimate	SE	Estimate	SE
GU	UK9002271	0.088	0.021	0.018	0.004
	UK9004171	0.127	0.021	0.024	0.004
	UK9004271	0.024	0.025	0.006	0.005
KI	UK9002271	0.240	0.253	0.008	0.025
	UK9004171	0.793	0.189	0.050	0.019
	UK9004271	0.845	0.088	0.060	0.009
	UK9006101	0.650	0.165	0.051	0.016
A	UK9002271	0.004	0.054	0.022	0.024
	UK9004171	0.204	0.035	0.031	0.015
	UK9004271	0.155	0.058	0.052	0.025

Table 3. Estimated model-based displacement mortality rates per timestep, for chicks and adults, as derived from an emulator of mean SeabORD impacts per scenario. The emulator assumes separate rates for each SPA for each species (GU = common guillemot; KI = black-legged kittiwake; RA = razorbill). Estimates and standard errors (SEs) are shown.

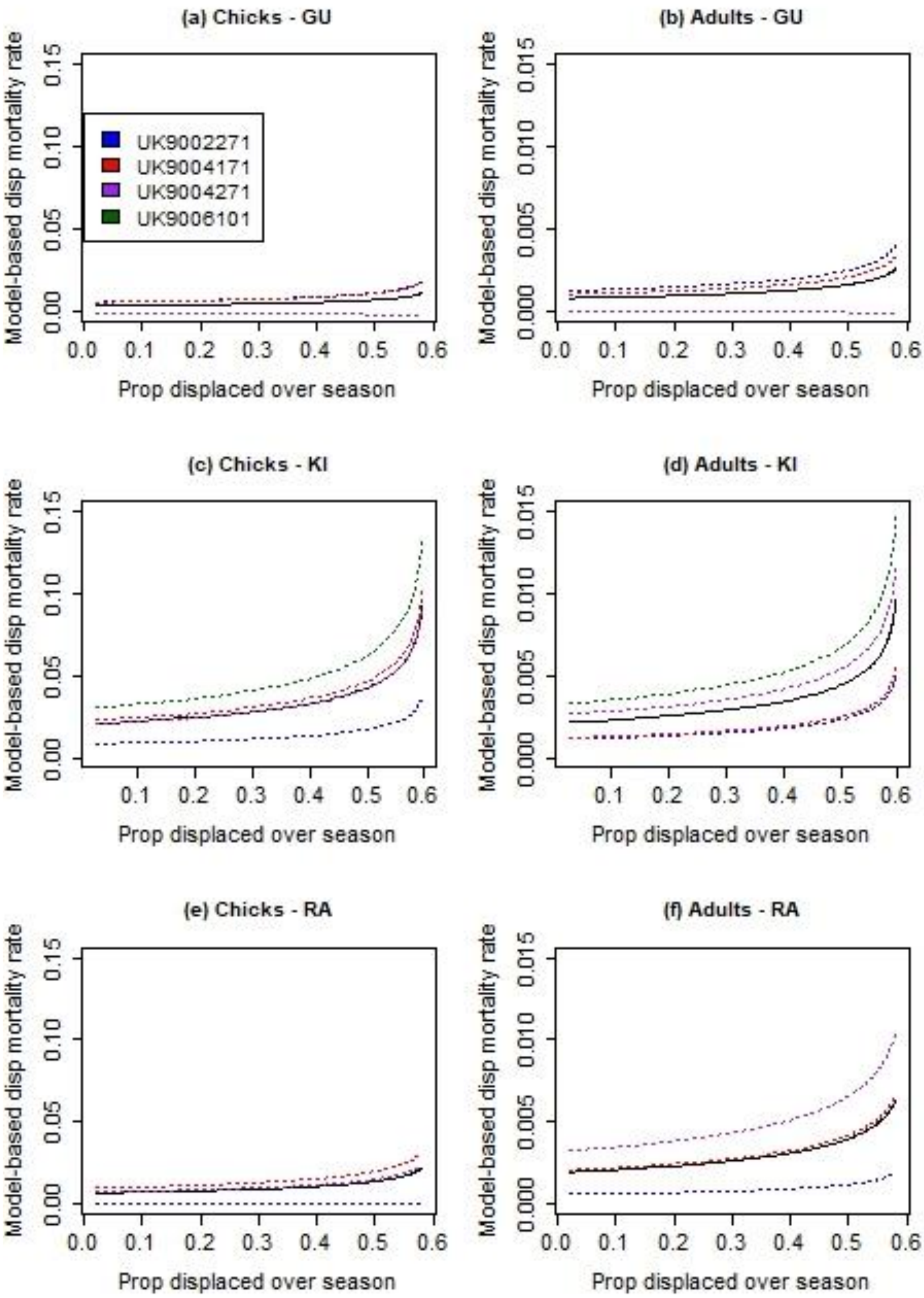

Figure 6. Estimated model-based replicate mortality rate across whole season, as derived from an emulator of impacts using multiple regression that allows a separate rate per SPA (colour) and an emulator that has a common rate for all SPAs (black) for each species (GU = common guillemot; KI = black-legged kittiwake; RA = razorbill).

Using expert elicitation results in the Displacement Matrix tool for assessments

In this section we provide recommendations on the usage of the expert elicitation results for the mortality rate of displaced birds (hereafter '*displacement mortality rate*') within the main tool that is currently used in assessing risk from displacement – the "Displacement Matrix", which requires this parameter as an input to the tool.

A very broad operational definition of the displacement mortality rate is that it is equal to the ratio of the absolute level of displacement mortality from a windfarm to the number of individuals experiencing displacement by a windfarm, so that the absolute level of displacement mortality from a windfarm is equal to the number of individuals experiencing displacement by a windfarm multiplied by the displacement mortality rate. The number of individuals experiencing displacement by a windfarm can itself, in general, be calculated to be equal to the baseline number of individuals using the windfarm footprint area prior to construction multiplied by the proportion of these individuals that would experience displacement if there were a windfarm (the "displacement rate"). The absolute level of mortality is therefore equal to:

*Absolute level of displacement mortality from a windfarm = Baseline number of individuals using windfarm * Displacement rate * Displacement mortality rate*

[Equation 1]

The current Displacement Matrix approach, which is extensively used in assessments, performs this calculation for a pre-specified set of values for the displacement rate and displacement mortality rate. A range of values for both of these parameters are used to provide a visual means of examining the consequences arising from the uncertainty associated with both rates. Within the current Displacement Matrix approach the baseline number of individuals using the windfarm is defined in a specific way -- as the maximum monthly estimated baseline abundance within the windfarm footprint within the season of interest, as estimated using at-sea survey data. The current approach focuses only on individuals that use the windfarm and so does not account for indirect effects on individuals that do not use the windfarm but may be impacted by it – e.g., in particular, it does not account for indirect effects on chicks driven by displacement impacts on breeding pairs.

There is currently no direct empirical evidence regarding the displacement mortality rate (see WP1 report), leading to considerable uncertainty in the appropriate parameter values to use within the Displacement Matrix tool. The expert elicitation (EE) within this project used expert judgement to assign values to the displacement mortality rate, for six species in breeding and non-breeding seasons. The displacement mortality rate is a key input to the Displacement Matrix approach, so the results of the EE have clear relevance to the way that the Displacement Matrix is used and should be considered in relation to updating SNCB guidance for this approach. However, there are a number of important issues that need to be taken into account when using the results of the EE within the Displacement Matrix approach:

1. The way in which the EE accounts for uncertainty and variability.

2. The way in which baseline abundance is estimated within assessments, and how this relates to the biological interpretation of seabird space use of windfarm footprints developed by the experts and used to frame displacement mortality rate estimation within the EE.

3. The fact that the EE produced separate estimates for indirect displacement effects on chicks as well as for direct effects on adults.

Issue 1: the approach that the EE uses to account for uncertainty and variability

The current Displacement Matrix approach uses pre-specified ranges of values (defined by the regulator and their advisors) for the displacement rate and displacement mortality rate. The EE results differ from this in two important ways:

1. They provide a probability distribution, rather than a discrete set of fixed values.
2. They provide a separate distribution for each expert, rather than providing a single overall distribution or range.

These differences have consequences for the potential use of elicited values for displacement mortality rates within the current UK assessment framework. It is generally recommended that the distributions for individual experts are used, rather than pooling these distributions, to retain the uncertainty from the EE that arises from differences between individual experts. A simulation-based approach could be used to capture uncertainty both within and between experts: within each of a large number of simulations, a random expert is first selected, and a value of the displacement mortality rate is then simulated using the probability distribution for this expert. The simulated rates therefore capture both sources of uncertainty – uncertainty associated with the estimate provided by each expert, and uncertainty arising from variation in estimates across all experts involved in the EE.

The Scottish Government CEF project has developed a simulation-based approach to propagate uncertainty between individual assessment tools and provides the functionality for a set of simulated displacement mortality rates to be provided. Each rate is then converted into absolute displacement mortality, using Equation 1, and this is propagated through the subsequent stages of modelling (e.g., Population Viability Analysis) using the simulation-based approach. This functionality could allow for the uncertainty captured in the EE to be used within the assessment process via the CEF (both in terms of differences between experts, and within the probability distribution resulting from each individual expert's judgements). This simulation-based approach for propagating uncertainty should, in principle, allow the current approach, of applying precaution at each modelling step within the assessment process, to be avoided: by propagating uncertainty through the whole process, the simulation-based approach should allow precaution to only be considered at the final step in the chain of models, because the uncertainty at this final step has incorporated individual components of uncertainty from each earlier step in the assessment process.

A practical challenge, however, is that the extent to which uncertainty is quantified currently varies considerably between tools and steps in the assessment process. In the context of the Displacement Matrix, a key challenge lies in how the probabilistic quantification of uncertainty in the Displacement Mortality Rate arising from the EE can be combined with the way that uncertainty is accounted for in the Displacement Rate. Because uncertainty in the Displacement Rate is currently dealt with in a non-probabilistic way, and it is difficult to combine uncertainties obtained using probabilistic and non-probabilistic approaches, this requires further research, such as a meta-analysis of existing studies estimating displacement rates, or expert elicitation to quantify the uncertainty associated with displacement rates.

Issue 2: definition of baseline bird abundance for use in the Displacement Matrix

The current Displacement Matrix approach defines the baseline number of individuals using the windfarm to be the maximum monthly estimated baseline abundance within the windfarm footprint in the season of interest, estimated from at-sea survey data. This quantity can be calculated directly from data that are routinely collected, so is in operational terms, straightforward to use.

However, during the EE the experts considered whether it was possible to provide judgements on the displacement mortality rate in the context of the way in which baseline bird abundance is currently estimated in Displacement Matrix approach. The experts concluded that this was not possible because the definition of baseline abundance currently used is broadly incompatible with a biological understanding of seabird space use patterns over time, including biological processes such as turnover, fidelity in space use, and behavioural patterns associated with breeding pairs and attendance of offspring.

The experts in the EE therefore defined the Displacement Mortality Rate using a biological, rather than operational, definition of the extent to which seabirds use the windfarm footprint, which then allowed them to meaningfully provide judgement on the values of the displacement mortality rate. The specific definition that was adopted related to any:

"Individual bird or their dependents and inter-dependents that would have used the area of influence of the offshore windfarm and associated infrastructure if there had been no offshore windfarm."

hence, the elicited mortality rates were specifically defined as:

"The excess mortality rates (as an absolute %) for an individual bird or their dependents and inter-dependents that would have used the area of influence of the offshore windfarm and associated infrastructure if there had been no offshore windfarm, but which is displaced away from the area during construction and/or operation."

This definition implicitly assumes that the displacement mortality rate applies to all individuals that experience displacement at any point during the season of interest. This, in turn, implies that the baseline abundance that is effectively being used in defining the displacement mortality rate is the **total number of individuals that utilise the windfarm footprint, during the baseline period, at any point during the season of interest**. The experts stated that this definition was likely to result in very different numbers of birds than the one used in the current assessment process based on at-sea surveys.

The level of baseline abundance used in the EE definition of the displacement mortality rate is, therefore, likely to be substantially different to that used in the current Displacement Matrix approach. The baseline abundance level used in the EE definition might be expected to be both systematically and potentially substantially larger than that used in the current displacement matrix approach. This systematic difference arises because the EE definition accounts for turnover in space use of birds at sea, whereas the current Displacement Matrix definition does not. The EE definition considers all individuals that *ever* use the windfarm footprint during a particular season, whereas the Displacement Matrix definition focuses only on the number of individuals using the footprint at a particular point in time (albeit that with high abundance, amongst the points at which surveys occurred).

Our belief is that it is not appropriate to use the displacement mortality rates arising from the EE or SeabORD/emulation within the Displacement Matrix in its current form, unless adjustments are made to account for this discrepancy. We consider a simple example to demonstrate the potential variation in mortality levels arising from this mismatch, in which the baseline abundance is 200 individuals based on the definition in the current Displacement Mortality approach (e.g., from at-sea surveys), versus a value of 800 individuals according to the definition used in the EE (e.g., all *individual birds or their dependents and inter-dependents that would have used the area of influence of the offshore windfarm and associated infrastructure if there had been no offshore windfarm*). If we assume the EE estimated a single displacement mortality rate of 1%, then when this EE displacement mortality rate is used in combination with the baseline abundance value from the current method for the input to the Displacement Matrix (at-sea surveys) the resulting mortality level will be just 25% (e.g., 100 * [200/800]) of the value arising from the application of the definition used in the EE process. To adjust for this discrepancy, the baseline abundance from the current Displacement Matrix could either be multiplied by the ratio of the baseline abundances (800/200=4) before combining it with the displacement mortality rate from the EE, or, equivalently, the displacement mortality rate from the EE could be multiplied by this ratio prior to combining it with the baseline abundance from the current Displacement Matrix approach. However, we currently lack an agreed methodology for how these conversions could be applied, and the precise way in which conversion values should be calculated.

This adjustment or conversion fundamentally relies on estimating **turnover** in space use of seabirds at sea:

"The ratio of the number of birds that ever use the windfarm footprint at any point during the season of interest to the number of birds estimated using the peak monthly at-sea survey data."

In undertaking assessments of potential impacts of offshore wind farms on seabirds, interest lies in estimating the number of birds that will be present in a particular area of sea (e.g., the footprint of a proposed offshore wind farm) at a particular time, relative to the total number of birds that will use that area of sea at any point during the breeding season. This relative use of an area at a given time in relation to the rest of the breeding season is termed 'turnover', relating to the turnover of individual birds using a particular area over time. Estimating turnover is important because estimates of the number of birds that may be affected by offshore renewable energy developments typically involve a limited series of at-sea surveys of fixed areas (potential wind farm footprints). These surveys effectively provide a snapshot estimate of the number of birds using that area at different times during the breeding season. Therefore, there is a need for better understanding of the extent to which these snapshot estimates underestimate the total number of birds using the area over the entire breeding season.

Turnover is influenced by site fidelity (e.g., from individuals choosing to similar foraging locations over time), but is also affected by daily time budgets, particularly in breeding pairs in which attendance of chicks is critical to chick survival. This is because even if individuals always forage in the proposed windfarm location, they will still spend only a proportion of their time in the windfarm area (and therefore be available to be counted within at-sea surveys) because they must engage in other activities such as returning to the nest to attend their chicks and relieve their breeding partner. Turnover cannot be estimated using at-sea survey data because at-sea surveys do not track the extent to which the same individuals are observed in different surveys, so needs to be estimated using other data sources. GPS tracking data can provide a way of estimating turnover values because it tracks specific individuals over time. There are, however, challenges in using GPS tracking data for this purpose, such as datasets tending to focus on a subset of the population and typically tracking individuals for part of a season over relatively short time periods. Expert elicitation could provide another possible approach for estimating turnover rates in the absence of sufficient GPS tracking data for each species and location of interest, as turnover is likely to vary in both space and time depending on environmental characteristics and lifecycle phase.

A previous project funded by Scottish Government considered processes relating to, and estimates of turnover for some seabird species in one region of the North Sea (Searle et al. 2015), providing recommendations for how turnover could be estimated, and the potential extent to which it could affect estimates of the number of individuals using a discrete area of space derived from at-sea survey data. Key inference from this project was as follows:

- The turnover values calculated could, in principle, provide a basis for scaling the abundance estimates of breeding individuals obtained during bird surveys of a particular area (such as a windfarm footprint) up to estimates of the number of breeding birds that are using that area during the entire breeding season. However, there were three key reasons why considerable caution needs to be taken in trying to do this:

- The results were contingent upon particular scenarios regarding the level and spatial scale of site fidelity, which is currently unknown for most species of interest. The results therefore provide a guide to assess how the level of turnover changes with site fidelity behaviours and patterns, and with the spatial scale of windfarm footprints, but they cannot provide specific estimates of turnover until further data on both the level and spatial scale of site fidelity of these species become available.

- The literature review in the project highlighted the considerable variability in seabird foraging ranges and foraging trip characteristics both within and between species, and within and between years – all of which will affect estimates of turnover. This variation may translate into among-population and inter-annual differences in turnover of individuals at sea that should be considered when assessing the potential impacts of offshore renewable energy developments on breeding seabirds.

- Current methods for surveying seabirds at-sea cannot achieve a complete census of all birds within an area the size of most windfarm footprints. At-sea surveys will, therefore, generally be a sample, rather than a complete census, and will typically take place over a longer time period rather than at an instantaneous snapshot. In order to scale actual survey data (e.g., at-sea surveys) up to the total number of birds in the area it is necessary to use statistical adjustments to account for factors other than turnover, such as non-detection. In addition, at sea survey estimates cannot distinguish between breeding and non-breeding individuals, nor assign birds to specific colonies. An additional step is required to adjust the at-sea estimate by the proportion of non-breeding birds and to assign remaining birds to the appropriate colony or population of interest.

Issue 3: Impacts on chicks

Implementing the EE estimates for impacts of displacement on breeding success of affected adults is in principle straightforward, as it produces a change in breeding success for affected birds which may be used within a PVA in the same way that any change in adult mortality is implemented. However, such an implementation encounters the same challenge described above, namely the discrepancy between how inputs for the Displacement Matrix are currently calculated and the definition assumed within the EE of impacts on adults and chicks – how to reliably estimate the number of adult birds that would have used the area of influence of the offshore windfarm and its associated infrastructure at any time during the season of interest. Consideration would also have to be given to the breeding state of individuals observed in at-sea surveys when making this adjustment for impacts in the breeding season. For many species it is not possibly to separate breeders from non-breeders (e.g., adults from immatures, or to identify adults that are not breeding but still in using the area around a breeding colony) in aerial survey data. As with the previous recommendation, both GPS tracking data and expert elicitation could be used to estimate the adjustment needed to convert estimates of all birds observed within at-sea surveys to estimate the number of breeding birds likely to be using the area of sea at any point during the breeding season. This will require further research to develop a standardised and reliable method.

Using SeabORD emulation results in the Displacement Matrix tool for assessments

The emulator is designed to provide a rapid approximation to SeabORD via a statistical model. Together, SeabORD and the emulator provide two possible approaches to estimating the model-based displacement mortality rate – by calculating this directly from within each run of SeabORD using an appropriate metric, or by estimating it via the emulator from a set of SeabORD runs. The latter approach provides a relatively straightforward way to explicitly examine variations in displacement mortality rates – effectively by analysing the relationship between SeabORD inputs and outputs as if these were data, to understand how variations in the outputs of SeabORD relate to variations in the inputs. We have applied an emulator to SeabORD output to estimate model-based displacement mortality rates. The SPA-specific displacement mortality rates per timestep are summarised in Table 3.

The adult model-based displacement mortality rates per timestep shown in this table share much in common with displacement mortality rates used in the Displacement Matrix: both are effectively defined as the value that is needed to translate the number (or proportion) of individuals that are experiencing displacement at a particular point in time, to the number (or proportion) of individuals in the population that die as a result of displacement. They differ primarily in the way that "time point" is defined – within SeabORD this is tied to the timestep used in the model, and in the Displacement Matrix this is tied to the use of at-sea survey data to provide a snapshot of abundance, which is then aggregated to seasonal level by taking peak abundance. However, these two quantities cannot be readily translated to each other, because any translation depends on a detailed understanding of site fidelity. SeabORD also makes internal assumptions about site fidelity, which may not be compatible with any assumptions that are made to translate abundance values from at-sea survey data into rates that are defined at the same scale.

The key limitation in relating the emulation and SeabORD results to the values of the displacement mortality rate used in the Displacement Matrix therefore arises, as with the EE, from the need to better understand turnover and site fidelity. The seasonal peak estimates of abundance used in the Displacement Matrix are liable to systematically under-estimate the number of birds utilising the footprint(s), and therefore being at risk from displacement, in part because of patterns of nest attendance sharing within breeding pairs, and particularly if site fidelity is anything other than very high. Moreover, observations of birds in at-sea survey data within the footprint area and associated buffer will not capture birds utilising foraging areas beyond the windfarm footprint which may not suffer displacement but will be potentially affected by barrier effects. Therefore, either these seasonal peak estimates themselves, or the resulting displacement mortality rate, would need to be adjusted to address this underestimation. In contrast, the results obtained using SeabORD are most likely to be useful in situations of low site fidelity, given that the model (currently, in the absence of other information) assumes independence in foraging locations between timesteps, and thereby a low level of fidelity. In situations of high fidelity the results obtained using SeabORD may not be realistic, although the direction of any bias is potentially complicated because, all else being equal, low fidelity will lead to a larger number of birds interacting with the windfarm(s) but with a relatively lower frequency of visit per birds, whereas high fidelity will lead to a smaller number of birds interactive but with a higher frequency per bird. For these reasons, the rates that have been derived here via SeabORD and the emulator cannot be used in the Displacement Matrix.

The concept of a `displacement mortality rate' is ultimately a simplification of the processes captured within SeabORD. One way in which this manifests itself is in the impact of the displacement "susceptibility" rate. The Displacement Matrix approach implicitly assumes that the displacement mortality rate and displacement susceptibility rate can be varied independently of each other, but this is unlikely to reflect reality, and is not the case within SeabORD – the displacement susceptibility rate is an input to SeabORD, whereas the displacement mortality rate is an output, so the value for the displacement mortality rate will be inherently linked to the value that was used for the displacement susceptibility rate. A wider suite of SeabORD runs would be needed to understand the nature of this relationship – by considering "proportion of birds displaced per time point" rather than "proportion of bird distributions within footprint" as the explanatory variable in the emulator is structured in such a way that it could potentially be generalisable to different displacement susceptibility rates, but only if impacts from SeabORD are a linear function of the displacement mortality rate. It requires further work to investigate whether this is a reasonable assumption.

An emulator of SeabORD can, in principle, be used to predict the population-level displacement risk associated with a new scenario and/or population for which SeabORD has not yet been run. The emulators that we have used here are structured in terms of model-based displacement mortality rates - either a common overall rate, SPA-specific rates, or rates that are modified by the effects of explanatory variables. Prediction of displacement mortality rates to new populations/scenarios is therefore trivial, since the displacement mortality rates are themselves parameters within the emulator, and so the relevant rate simply needs to be applied to the new scenario. These rates can be translated into predictions of the population-level mortality rates that would be generated by SeabORD via a model-based Displacement Matrix approach, in which:

*Impact on population level mortality = Model-based displacement mortality rate * Displacement susceptibility rate * Proportion of population-specific bird distribution using a footprint or 2km around a footprint at each timestep*

This differs from the Displacement Matrix itself because of the final part of the equation, which uses the proportion of the population-specific bird distribution that lies within the footprint (or within 2km of it), a quantity readily derived from GPS tracking data but not from at-sea survey data. In contrast, the Displacement Matrix uses seasonal peak abundance within the footprint+2km, as derived from at-sea survey data.

In practice, the emulation results considered here show potential differences in model-based displacement mortality rates between SPAs, which limit their transferability – the SPA-specific emulation models, which are in a number of cases preferred by the model selection process as providing the best fit to the SeabORD outputs relative to their complexity, can be used to generate predictions for new windfarm scenarios within the SPAs already considered, but not to extrapolate predictions to new SPAs. In reality there are likely to be many sources of variation in rates between SPA and windfarm scenarios, with the analysis used here lacking the power to detect more subtle effects, but the apparent differences between SPAs merit further investigation, and more detailed modelling (using SeabORD outputs from a larger set of SPAs) to understand the extent to which these variations can be described in terms of predictable characteristics of the SPA and associated bird distribution map.

Fundamentally, SeabORD does not explicitly use, or generate, a displacement mortality rate - it produces an extensive set of detailed outputs, from which various metrics relating to displacement mortality can be extracted, and some of these metrics can be interpreted as estimates of the 'displacement mortality rate', and this lack of equivalence complicates translation between SeabORD and the Displacement Matrix.

One obvious limitation of using SeabORD (and the emulator) to estimate displacement mortality rates is that it is a model – any rates estimated using SeabORD will therefore correspond to properties of the model, rather than being direct empirical estimates of displacement mortality. In the absence of empirical data, however, mechanistic models such as SeabORD can nonetheless provide valuable information to consider alongside expert judgements and can be used to explore the emergent properties implied by the biological assumptions that underpin the model. Perhaps the most important assumption to be aware of when considering displaced mortality in SeabORD is that it assumes independence in chosen foraging locations by individual birds between timesteps, thereby implying a low level of site fidelity in foraging sites. As a result, displacement mortality rates within SeabORD are very different depending on whether they are calculated in relation to a 'snapshot' of the number of birds observed within a windfarm, or in relation to the total number of birds ever interacting with a windfarm at any point within the chick rearing period.

Aside from the underlying biological assumptions, two other key limitations on the use of the quantitative results from SeabORD and emulator are:

1. That the number of runs, and particularly the number of SPAs, used is relatively small, which limits our ability to generalise the results – in particular, the ability to tease apart variations that can be explained by identifiable SPA/ORD characteristics from unexplained variation.

2. That these results are based on runs generated by a development version of SeabORD-R that has not yet been fully tested and benchmarked.

Despite these key caveats, the work has demonstrated the potential to estimate displacement mortality rates, and variation in these rates, via SeabORD and emulation, and highlighted a range of broader issues. In particular, the work has identified that displacement mortality rates may vary across SPAs and windfarm scenarios and has tentatively identified some explanatory variables that are potentially of value in explaining (e.g., proportion of UD in footprint), and ideally in future predicting, variations between SPAs and windfarms (these appear to vary between species, and between the impact metric considered). The work has also highlighted the potential to use emulation to predict population-level displacement in situations where either the data or computational requirements of SeabORD make it infeasible to use.

Despite the various caveats and limitations, one key advantage of using a model like SeabORD to investigate displacement mortality is that it makes the modelling assumptions explicit. Exploration of these assumptions has helped to highlight a crucial point regarding the Displacement Matrix: that it is not meaningful to consider whether the displacement mortality rate used within it is correct in isolation, because even if the quantitative value used for the rate were correct, the results of the displacement matrix calculation would be incorrect if the quantities being considered within it were defined in ways that were not directly comparable. A key broad issue raised is therefore whether the displacement mortality rate values used in the Displacement Matrix are directly comparable to the other inputs to the Displacement Matrix, especially as more information on the values of the other inputs becomes available – and, in particular, to the estimate of bird abundance. If empirical evidence regarding patterns of nest attendance within pairs and for site fidelity implied that an adjustment was needed to the abundance estimates used in the Displacement Matrix to account for turnover of birds, then the Displacement Mortality Rates would also need to be updated to reflect this new biological knowledge, or there would be a risk of inconsistency between the different inputs used. Similarly, because the Displacement Matrix does not explicitly consider mortality impacts arising from barrier effects, if such effects were to be included in the Displacement Matrix calculations adjustments would be required to both correctly identify the number of birds likely to be subjected to barrier effects, and the subsequent mortality of those affect individuals. It is this inter-relationship between the different inputs to the Displacement Matrix, and the difficulty of translating the estimates of abundance used in the EE and SeabORD/emulator to the estimates used in the Displacement Matrix, that make it difficult to translate between displacement mortality rates used in the EE, SeabORD/emulator and Displacement Matrix, and means that the displacement mortality rates estimated from the EE and SeabORD/emulator cannot be used within the Displacement Matrix.

Overall summary of recommendations arising from project

Modification of advice on displacement mortality rates to use within assessments.

It is not currently possible to use the EE or emulation results to recommend displacement mortality rates within the DM because the Displacement Matrix defines displacement mortality rates in relation to a specific estimate of the number of individuals at risk from displacement – the seasonal peak abundance, as derived from monthly at-sea surveys. In contrast, the EE defined the number of individuals at risk to include all individuals that are impacted by displacement, either directly or indirectly, at any point during the season. SeabORD, and hence the emulator, can refine displacement mortality rates in a range of different ways, but none of these provides a direct link to the definitions used in the DM, in large part because SeabORD assumes independence over time (and hence low site fidelity), whereas the appropriateness of the DM method largely depends on an assumption of high site fidelity (so that the peak seasonal abundance provides a good estimate of the number of individuals at risk from displacement).

Research recommended to facilitate use of the EE and emulation outputs within the Displacement Matrix, and to improve estimates of displacement mortality rates.

Our belief is that it is not appropriate to use the displacement mortality rates arising from the EE or SeabORD/emulation within the Displacement Matrix in its current form unless adjustments are made to account for this discrepancy. Estimates for the mortality rate of displaced birds from the EE were variable, reflecting the uncertainty associated with this quantity, however, in many cases experts' median estimates and weight of belief (lower and upper quartiles) during the breeding season included high levels of mortality, on the order of 10-15% (see WP2 Report). Previous UK assessments have tended to use mortality rates for displaced birds of around 2-5%, increasing to 10% in a few cases. Although these rates fall within the same range as those arising from the EE, there is an important discrepancy between the interpretation of these rates within the two sets of approaches. This discrepancy between the mortality rates used within the Displacement Matrix and those arising from the EE and IBM relates to the inputs to the different methods – i.e., the identification of the population at risk from displacement. The baseline abundance level used in both the EE definition, and the number of birds estimated to be affected by ORDs within the SeabORD IBM, are expected to be both systematically and potentially substantially larger than that used in the current Displacement Matrix approach. This systematic difference arises because the EE definition and the SeabORD IBM account for turnover in space use of birds at sea, whereas the current Displacement Matrix definition does not. Both the EE definition and the mechanisms within SeabORD consider all individuals that ever use the windfarm footprint during a particular season, as well as individuals that may be affected indirectly, whereas the Displacement Matrix definition focuses only on the number of individuals using the footprint at a particular point in time (albeit that with high abundance, amongst the points at which surveys occurred). As such, whilst the EE results provide tentative evidence that displacement mortality rates could be substantially higher than is often currently assumed. **Our key recommendations are therefore for further work to understand site fidelity, and the impact of this upon displacement risk, to understand whether there is a potential for under-estimation of effects within the Displacement Matrix in relation to this process**. This work would involve:

- Interrogation of GPS tracking data to estimate rates of fidelity in seabird species, including influence of environmental variation and seasonal variation.

- Examination of seabird time-activity budgets to understand influence of partitioning of behaviour between at-sea and colony behaviours and how this might be used to adjust at-sea survey data.

- Tracking of individual birds to link observed interactions with operational offshore windfarms (barrier effects and displacement) with subsequent demographic rates (breeding success and survival).

These recommendations relate to research that is needed to provide underpinning evidence upon which a decision to use the elicited displacement mortality rates or predicted mortality rates from emulation within the Displacement Matrix approach could be based (via a conversion for the number of birds likely to be using the area of interest over the course of each month and/or season). At present, we believe we do not have the required research evidence to estimate robust site fidelity or turnover values that could be used to convert abundance estimates and thus enable the direct application of the mortality rates generated by the EE process or emulation within the Displacement Matrix. Whilst these research outputs would enable this conversion of at-sea survey counts to allow for the use of the elicited or emulated rates in the Displacement Matrix, it is likely that uncertainty around the form and magnitude of this conversion will persist.

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+44 (0) 20 7170 7000

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