

OFFSHORE RENEWABLES JOINT INDUSTRY
PROGRAMME (ORJIP) FOR OFFSHORE WIND



Quantification of mortality rates associated with displacement (QuMR)

Appendix – D

May 2025



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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Abbreviations

Term	Description
GU	Common Guillemot
KI	Black-legged Kittiwake
ORD	Offshore renewable development
ORJIP	Offshore Renewables Joint Industry Programme
OWEZ	Offshore Windpark Egmond aan Zee
OWEC	Offshore Wind Evidence and Change
OWF	Offshore wind farm
SD	Standard Deviation
SE	Standard Error
SPA	Special Protection Area
WP	Work Package

1. Introduction

Displacement mortality rates are challenging to quantify empirically and currently lacking empirical literature to provide evidence (WP1). Expert elicitation suggests that there are high levels of uncertainty regarding the values of these rates, but that they could potentially encompass values representing large changes to demographic rates (see WP2).

An alternative method for quantifying displacement mortality rates, and sources of variation in these rates, is via a mechanistic model. Simulations from the mechanistic model can be used to estimate the mortality rates associated with different scenarios. Within Work Package 3 we used SeabORD (Searle et al. 2014, 2017), an individual-based model of seabird behaviour, energetics, demography and windfarm interactions during chick-rearing, to estimate the levels of displacement mortality for breeding adults and their dependents, and for mass change in breeding adults, associated with different colonies under different wind farm scenarios, for three species (black-legged kittiwake, common guillemot and razorbill). However, SeabORD is a computationally intensive model to run, and so to provide a framework for approximating the outputs that SeabORD would have provided under other scenarios, we developed a statistical emulator – a statistical model that is designed to approximate a mechanistic model. Emulation 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 that can be used to predict the likely outputs that the mechanistic model would have produced under alternative scenarios (e.g., in this context, for alternative SPAs and/or wind farm scenarios).

Within WP3 a “training set” was generated by running SeabORD for each of three species (guillemot, kittiwake and razorbill) at three SPAs, and a range of windfarm scenarios. These runs were then used to build emulators, which aimed to capture the key characteristics of the SeabORD runs, and thereby to predict the results that would be obtained by running SeabORD at SPAs/windfarms that were not included in the training set. Emulators were constructed in relation to three key outputs from SeabORD: chick mortality (per nest), adult mortality (as a proportion of breeding adults) and percent mass loss over the chick-rearing season. In each case, the response variable used for the emulator was the difference between these values under a windfarm scenario and the values obtained under the baseline. The emulator links these response variables to a range of explanatory variables that summarise key characteristics of the SPA, windfarm and SPA-windfarm interaction.

The results of the emulation work in WP3 need to be interpreted cautiously because they are based on a relatively small training set of SeabORD runs, but the key findings from the work were that the impacts of windfarm scenarios on adult mass loss and adult and chick mortality over the course of chick rearing all show a very strong positive relationship to the proportion of birds displaced at each time point (“ptdisp”). This proportion is simply the multiple of the displacement rate with the proportion of the bird distribution that lies within any footprint (“totalpinords”). There was no clear evidence for non-linear effects, or for effects of other explanatory variables, but there was evidence in almost all cases that the magnitude of the relationship varied between SPAs.

The SeabORD outputs focused on are simulations of overall changes in adult mass and adult and chick survival rates within the entire breeding population being simulated within SeabORD. In contrast, displacement mortality rates focus on the excess mortality rate experienced by a subset of the whole population – i.e., those birds *that have been displaced*. The exact definition varies by context: the expert elicitation exercise, in particular (WP2 report), defined the adult mortality rate in relation to *any* adult birds

that are affected by displacement, including those affected indirectly rather than directly, and defined an impact rate for chicks as well as adults.

Displacement mortality rates are of interest for two key reasons:

1. Displacement mortality rates are a key input to the Displacement Matrix, were a focus of the literature review (WP1) and expert elicitation exercise (WP2) and are the main focus of this project.
2. Displacement impacts on birds subjected to displacement effects are likely to be more generalisable across scenarios and colonies than population level impacts on overall mortality, since the latter will be heavily influenced by the level of baseline spatial interaction with the wind farm footprints.

In this WP we consider ways in which the outputs from SeabORD and the associated emulator from WP3 can be used to provide information on displacement mortality rates. SeabORD does not directly use a “displacement mortality rate”, and the main outputs from it relate to population-level outcomes, but a range of other metrics can also be extracted from SeabORD, and some of these are related to the “displacement mortality rate”. In particular, the emulator within WP3 was explicitly constructed in a way that allows the parameters of it to be interpreted in relation to displacement mortality rates.

In this work package we define “model-based displacement mortality rates” in two possible ways and calculate these using the SeabORD outputs and estimated emulator parameters from Work Package 3. We use the phrase “model-based displacement mortality rates” to make it explicit that the rates we define using SeabORD outputs are not directly comparable to the “displacement mortality rate” used in the Displacement Matrix – we outline the connection between the different definitions of “displacement mortality rate” considered in the Displacement Matrix, Expert Elicitation and SeabORD/emulator in WP5, and the challenges in translating between these. The key advantage of using the emulator, as well as the SeabORD runs themselves, is that the emulator provides a natural framework for investigating variability and uncertainty in rates.

We quantify mean rates and variability in the resulting “model-based displacement mortality rates” for each of the three species.

2. Methods

2.1 SeabORD outputs

SeabORD evaluates the impacts of windfarms by comparing outputs for scenarios that involve windfarms against a “baseline” scenario in which there are no windfarms. The key metrics of impact from SeabORD outputs considered in WP3 were therefore overall metrics of population-level impact:

- *Windfarm effect on adult mortality = (Simulated adult mortality rate with windfarm(s) – Simulated adult mortality rate under baseline)*
- *Windfarm effect on chick mortality = (Simulated chick mortality rate with windfarm(s) – Simulated chick mortality rate under baseline)*
- *Windfarm effect on adult mass loss = (Simulated mean proportional adult mass loss over the chick rearing period with windfarm(s) - Simulated mean proportional adult mass loss over the chick rearing period under baseline)*

These represent differences between the windfarm(s) and the baseline, so these values will be positive if the windfarms lead to an increase in survival/mass relative to the baseline, and negative if they lead to a reduction in survival/mass relative to the baseline. The impacts operate on population-level rates, rather than absolute numbers of birds: if baseline mortality is 0.2 (20% of birds dying per year), if the windfarm impact on adult mortality is 0.1, for example, then this means that mortality after impact will be 0.3 (30% of birds dying per year).

These metrics do not consider the rate at which displacement events occur so will, all else being equal, increase as the rate at which displacement occurs increases, as the results in WP3 clearly showed. The “windfarm effect on adult mortality” and “windfarm effect on chick survival” values defined above are population-level values, so relate to all individuals within the population, including those that never interact with the windfarm(s) or experience displacement. For the sake of illustration, consider a situation in which the population has a baseline adult mortality rate of 0.1, and involves two types of birds: 99% of birds suffer no (direct or indirect) consequences as a result of the windfarms, but 1% of birds experience a reduction in adult survival from 0.9 to 0.8 as a result of the windfarms. In this case the “windfarm effect on adult mortality” would be $((0.2 - 0.1) * (0.01)) = 0.001$. Within a population of size 10000, this would correspond to an additional $10000 \times 0.001 = 10$ annual adult deaths as a result of the windfarms.

SeabORD does not directly use a displacement mortality rate, because it simulates the fate of individual birds, and does this through modelling a series of mechanistic processes. The displacement mortality rate is also not an entirely straightforward concept within the context of SeabORD, in part because individuals may experience effects due to the operation of the windfarm(s) within SeabORD even if they are not themselves displaced – for example, due to the indirect effects of displacement leading to changes in competition, which in turn leads to changes in prey intake and thereby energetics and demography.

It is nonetheless possible to extract displacement mortality rates for both adults and chicks from the outputs that SeabORD produces. There are, broadly speaking, two possible ways to do this within SeabORD: either to focus only on the subset of individuals for which displacement occurs and to calculate the effects only for these individuals, or alternatively to continue to calculate the effects at a population

scale but then to adjust by these effects by calculating the ratio of these effects to the rate at which displacement occurs. Both approaches have advantages and disadvantages. The former approach focuses directly on displaced individuals, so has a neat biological interpretation, but it disregards the fact that birds that are not themselves displaced may nonetheless experience indirect consequences as a result of displacement (e.g., via increased competition) and may experience barrier as well as displacement effects. The latter approach is less easily interpretable in terms of biology, because it is defined across the entire population, but accounts for effects on all birds, not only birds that are directly displaced.

To ensure that we capture indirect as well as direct effects and consider metrics that could readily be extrapolated to new colonies or scenarios for which SeabORD has not yet been run, we focus here on the latter approach – i.e., on metrics that calculate the ratio of population-level displacement mortality effects to the average rate at which displacement occurs.

2.2 Quantifying levels of displacement

Mortality rates produced by SeabORD relate to chick-rearing period (for chicks) and to the entire year (for adults) – although note that the latter relate only to displacement during the chick rearing period. Translating these population-level impacts into displacement mortality rates depends upon specifying the time period over which displacement is being considered.

The most natural period to consider is the entire season (chick-rearing period), since SeabORD is quantifying mortality in relation to displacement effects across this period. Because SeabORD simulates foraging locations independently on each timestep, the mean proportion of birds displaced at any point during the season (“**psdisp**”) can be directly calculated from “totalpinords” (the proportion of the bird distribution that lies either within a footprint or within 2km of a footprint) via the equation:

$$\text{psdisp} = \text{Displacement susceptibility} * \{1 - (1 - \text{totalpinords})^{\text{Number of timesteps within season}}\}$$

The number of timepoints within the season in SeabORD is 30 days for kittiwake and 21 days for guillemot and razorbill. The displacement susceptibility rate is an input to SeabORD - it equates to the quantity that is more usually termed the “displacement rate”, although the term “susceptibility” is included in the SeabORD definition of it to capture the idea that this rate actually refers to a property of the individual, rather than to the rate at which displacement actually occurs, since the latter will depend on the level of baseline interaction between the population and the windfarm). The displacement susceptibility rate is assumed to be equal to 0.6 for all of the runs considered here (see WP3).

We also consider the impacts in relation to mean *proportion of population displaced from the footprint per timestep* (“**ptdisp**”), which was defined in WP3 by multiplying the total proportion of the bird distribution (according to the bird distribution map) that lies within any windfarm footprint (“totalpinords”), by the displacement susceptibility rate, so that:

$$\text{ptdisp} = \text{Displacement susceptibility} * \text{totalpinords}$$

2.3 Defining model-based displacement mortality rates

We define “model-based displacement mortality rates” for adults and chicks in relation to the levels of displacement per season (as quantified by “psdisp”) and per timestep (as quantified by “ptdisp”) by

dividing the population-level effect of the windfarm by the level of displacement. This leads us to define four metrics (Table 1).

Table 1, Definitions of “model-based displacement mortality rates” constructed from SeabORD outputs

Metric	Calculation
Model-based displacement mortality rate of adults per timestep	Windfarm effect on adult mortality/ptdisp
Model-based displacement mortality rate of chicks per timestep	Windfarm effect on chick mortality/ptdisp
Model-based displacement mortality rate of adults over season	Windfarm effect on adult mortality/psdisp
Model-based displacement mortality rate of chicks over season	Windfarm effect on chick mortality/psdisp

Note that the latter two metrics can be derived mathematically from the former two metrics, so that:

Model-based displacement mortality rate of adults over season = (ptdisp/psdisp) * Model-based displacement mortality rate of adults per timestep

Model-based displacement mortality rate of chicks over season = (ptdisp/psdisp) * Model-based displacement mortality rate of chicks per timestep

with the ratio between them (ptdisp/psdisp) depending only on the proportion of the bird distribution in or within 2km of a footprint (“totalpinords”), the displacement susceptibility rate and the number of timesteps within the chick rearing period (which is fixed at the species level within SeabORD).

2.4. Estimation of metrics

We consider two potential approaches to estimation of each of these four metrics.

2.4.1. Direct estimation via SeabORD outputs

The first approach is to calculate the value of the metric separately for each of the SeabORD model runs, and then to summarise these values across runs – for example by looking at the mean, standard deviation, median, range, and quartiles (25% and 75% quantiles, denoted Q1 and Q3 respectively). We do this for each of the four metrics, for each species, and calculate summaries both using all data for the species (i.e., pooling data across SPAs) and separately for each SPA.

One difficulty within this approach is that it may be sensitive to noise in the SeabORD runs, especially when the level of displacement is relatively low, and hence may not always be stable. That is because the impacts of windfarms within SeabORD include random variation, and the effects of this random variation can explode into very large values when there is a division by exposure variables that have small values. In particular, the approach is liable to become unstable, and to have very high levels of noise, in situations in which “totalpinords” is very small (i.e., there is very little overlap between the footprints and the bird distribution map). We focus on mean impacts per scenario, rather than outputs of individual model runs, to try to minimise this issue, but this does not completely overcome the problem.

2.4.2. Estimation via the emulator

The second approach, which attempts to address this issue and to provide a framework within which variations in rates can be quantified explicitly, is to derive the displacement mortality rates via the parameters of an emulation model. This approach overcomes the issue of instability due to noise by modelling the expected (i.e., predicted) rather than observed value of the response variable. The second approach is possible because the emulation models of WP3 were explicitly designed to be represented in terms of the model-based displacement mortality rates of adults and chicks per timestep. In particular, the simplest model considered in WP3, model R1, assumes that:

$$\text{Expected windfarm effect on mortality} = \text{Slope parameter} * \text{ptdisp} + \text{noise}$$

with separate emulators being constructed for adults and chicks for each species. Within this model, the slope parameter represents the ratio of the “expected windfarm effect on mortality” to the level of displacement per timestep (ptdisp). This ratio is the model-based displacement mortality rate per timestep (for adults or chicks, as appropriate), defined in terms of the expected population-level effects of the windfarm (i.e., the effects after removal of noise). The other models considered in WP3 have the same interpretation, but with the values of the slope parameter varying depending on scenario, varying between SPAs, and varying between in relation to a range of ORD and SPA characteristics. Because the slope parameter is equivalent to the model-based displacement mortality rate, the parameters in these models are quantifying variation in these rates. In particular, model R11, which was typically the best performing model empirically within WP3, assumed a separate slope parameter, and hence a separate model-based displacement mortality rate, for each SPA.

We focus here upon the estimates that are derived from the model which assumes a common displacement mortality rate in all circumstances (R1), and on the model whose empirical performance is typically best (R11). These models were constructed by using multiple regression to model mean impacts per scenario. We also consider equivalent models (M1 and M11) that model the raw SeabORD outputs via mixed models and use a random coefficient to allow for variations in rates between scenarios, in order to check for consistency between these two approaches. The random coefficients in models M1 and M11 represent the level of variability in rates between scenarios, expressed as a standard deviation.

These models, and the assumptions they correspond to regarding model-based displacement mortality rates, are summarised in Table 2.

Table 2. Emulation models used in inferring model-based displacement mortality rates

Model	Model type	Model assumption in relation to model-based displacement mortality rates per timestep
R1	Linear regression	Common rate in all situations
M1	Linear mixed model	Common mean rate, but with random variation between scenarios; random variations assumed to have a normal distribution
R11	Linear regression	Separate rate for each SPA, but common rate for different scenarios within each SPA
M11	Linear mixed model	Separate rate for each SPA and random variation between scenarios; random variations assumed to have a normal distribution

The corresponding effects on “model-based displacement mortality rates per season” are derived from the effects on “model-based displacement mortality rates per timestep” by multiplying the parameters of the former by the ratio of p_{tdisp} to p_{sdisp} (i.e., by the ratio of the proportion of birds displaced per timepoint to the proportion of birds ever displaced within the season).

3. Results

3.1. Displacement levels

In Figure 1 (top) we plot the relationship between the [expected] proportion of individuals displaced per timestep the proportion of individuals displaced at any point during the season.

This is a deterministic relationship that follows directly from the assumptions that the spatial movements of individuals within SeabORD are (a) derived from the same distribution for all timesteps and are (b) independent between timesteps. The relationship depends upon the number of timepoints within the season, which is why the relationship is different for kittiwakes than for the other species.

The relationship is non-linear, with the slope becoming smaller as the level of displacement per timestep increases. That is because increases in the level of displacement per timestep lead to increases in both the number of individuals ever displaced and in the frequency with which these individuals are displaced. As the number of individuals per timestep being displaced becomes larger, it becomes increasingly likely that each additional individual being added will already have been displaced at a different point in the season, so the rate at which the number of birds ever displaced increases will fall. The curve will asymptote towards the displacement susceptibility rate (often just called the “displacement rate”).

Figure 1 (bottom) shows the ratio of number of birds displaced per timestep to number of birds displaced per season. This ratio increases as the proportion of birds displaced per timestep increases, reflecting the declining gradient in Figure 1 (top). The ratio shown in Figure 1 provides the conversion needed to translate displacement mortality rates defined in relation to displacement per timestep into rates defined in relation to displacement over the entire season.

Figures 2 and 3 illustrate the consequences of these relationships. Figure 2 shows the number of occasions on which an individual is displaced, *given* that it has been displaced at least once – this is one when the proportion of birds displaced per timestep is equal to zero but increases steadily as that proportion increases. Figure 3 shows the histogram, within the actual SeabORD runs, of the proportion of individuals displaced per timestep, and over the entire season. The former is heavily skewed towards small values, and never exceeds 0.09, whereas the latter shows a broader distribution, and includes values that begin to get close to the rate of displacement susceptibility (0.6).

Figure 1. Top: Assumed mathematical relationship between the mean proportion of birds displaced per timepoint and the mean proportion of birds displaced over entire season for each species, under the assumptions of SeabORD, when the displacement susceptibility rate is 0.6 (lines). Values associated with the SeabORD runs used in the training set are shown as points, to show the span of points on the x-axis that are relevant to the SeabORD runs considered here. Bottom: Relationship between the mean proportion of birds displaced per timepoint and the ratio of birds displaced per timepoint to birds displaced per season, when the displacement susceptibility rate is 0.6.

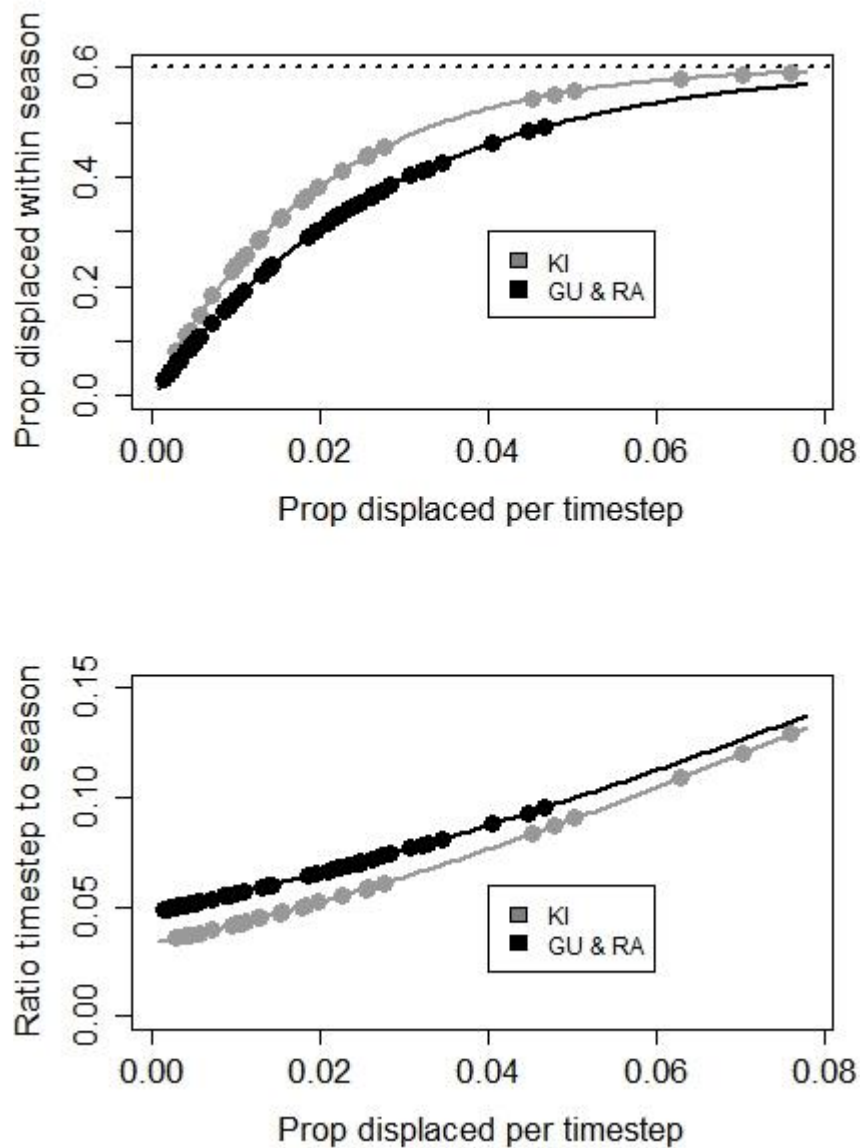


Figure 2. Assumed mathematical Relationship between the mean proportion of birds displaced per timepoint and the mean number of timepoints at which individuals that experience any displacement are displaced, for each species, under the assumptions of SeabORD, when the displacement susceptibility rate is 0.6 (lines).

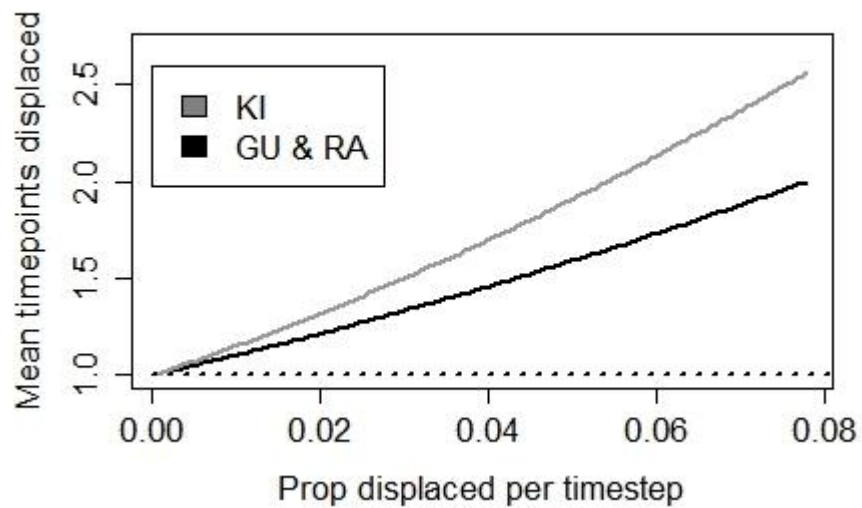
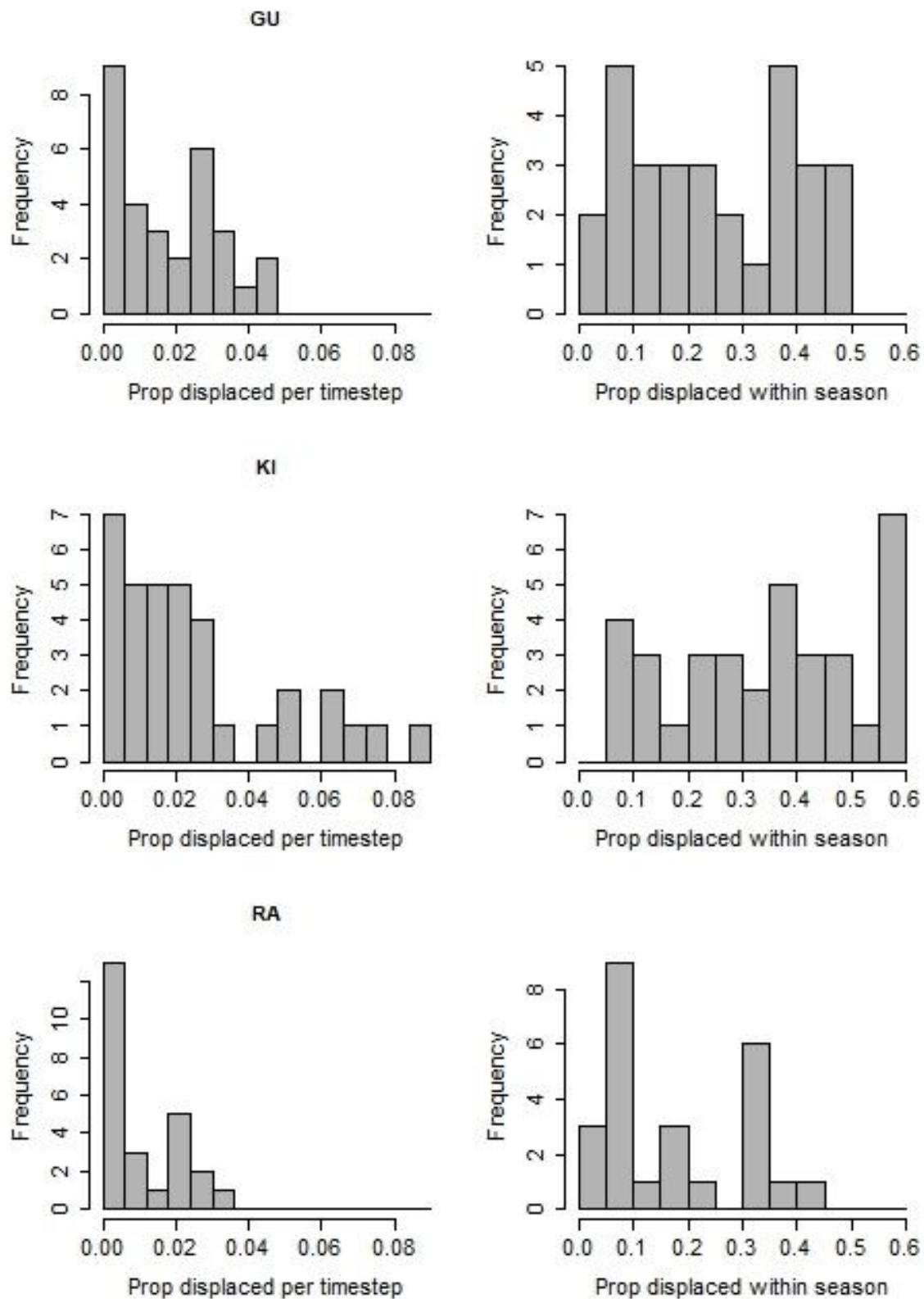


Figure 3. Histograms of the distribution of the proportion of individuals displaced per timestep (ptdisp) and the proportion of individuals displaced within the season (psdisp) for each species, within the SeabORD runs used to develop the emulator.



3.2. Model-based displacement mortality rates from SeabORD

Model-based displacement mortality rates per timestep can be calculated by dividing SeabORD impacts (mean per scenario) by the proportion of individuals displaced per timestep (“ptdisp”), and rates per season can be calculated by dividing SeabORD impacts by the proportion of individuals displaced per season (“psdisp”). It is important to note that “model-based displacement mortality rates per timestep” may be greater than one. This may appear implausible, given the displacement mortality rates are typically interpreted as a probability and so are assumed to be constrained to lie in the range 0 to 1. However, since the number of birds displaced per timestep is far lower than the number of birds displaced within the season (within SeabORD), and since individuals in SeabORD may experience impacts without experiencing displacement (e.g., as a result of barrier effects, or indirect effects resulting from changes to competition), there is no reason that the displacement mortality rate defined in relation to displacement per timestep must be less than one.

The contrast between results obtained in relation to displacement mortality rate per season and in displacement mortality rate per timestep is illustrated by Figure 1 (top). This graph shows the relationship between the mean proportion of birds displaced per day and the mean proportion of birds displaced over entire chick-rearing season for each species, under the assumptions of SeabORD when the displacement rate is set to a value of 0.6 (meaning 60% of individuals within the population are susceptible to displacement and barrier effects). As can be seen from the graph, the mean proportion of birds predicted to be affected by displacement over the course of the entire chick-rearing period is always greater than the mean proportion of birds predicted to be affected on a single day (Figure 1)

3.2.1. Impact on chick mortality

Table 3 shows estimates of the model-based displacement mortality rate for chicks per timestep, as derived directly from SeabORD training runs, whilst Table 4 shows the corresponding model-based displacement mortality rates for chicks over the entire season.

To assist in interpretation, consider the mean value from Table 3 for guillemots from all SPAs – 0.020. This value can be interpreted as predicting that for birds that experience displacement on a particular day, the individual-based model SeabORD predicts such birds will experience an additional 2% chick mortality when the windfarm is present than they do in the baseline without the windfarm present. Therefore, if we assume that a bird in the baseline with no windfarm present has a 20% probability of losing its chick(s) over the course of chick-rearing, SeabORD predicts that a bird suffering displacement due to the presence of the windfarm will have a $0.2 + 0.02 = 22\%$ probability of losing its chick(s). Note that this prediction relates *only* to birds observed to use the area affected by the windfarm on a single day, versus all of the birds ever affected by the windfarm over the whole of the chick-rearing season. In this context, the prediction implies that for all of the birds observed within the area affected by the windfarm on a single day, all of those birds are predicted to lose their offspring, as *well* as some other birds within the wider population. This is because the predicted windfarm impact from SeabORD on chick mortality is being assigned to only a small proportion of the birds (using the area on a single day) that are actually impacted by displacement over the whole of the chick-rearing season.

In contrast, if we consider the mean value from Table 4 for guillemots from all SPAs – 0.0023, SeabORD predicts that for birds that experience displacement *at any time* during the chick-rearing period they will suffer 0.23% higher chick mortality when the windfarm is present than they suffer in the baseline with no windfarm present. Therefore, for all birds affected by displacement at some point during the chick-rearing period, SeabORD predicts that if a bird has a baseline probability of 20% for losing its chick(s) over the

period when the windfarm is not present, then when the windfarm is present, they have a $0.2 + 0.0023 = 20.23\%$ of losing their chick(s).

3.2.2. Impact on adult mortality

Table 5 shows estimates of the model-based displacement mortality rate for adults per timestep, as derived directly from SeabORD training runs, whilst Table 6 shows the corresponding model-based displacement mortality rates for adults over the entire season. Adult mortality here refers to the probability of adults dying over the course of the whole year, i.e., from the end of the chick-rearing season in the current year to the start of the next chick-rearing season in the following year.

To assist in interpretation, consider the mean value from Table 5 for kittiwakes from all SPAs – 0.0384. This value can be interpreted as predicting that for birds that experience displacement on a particular day, the individual-based model SeabORD predicts such birds will experience an additional 3.84% mortality when the windfarm is present than they do in the baseline without the windfarm present. Therefore, if we assume that a bird in the baseline with no windfarm present has a 10% (0.1) probability of dying, SeabORD predicts that a bird suffering displacement due to the presence of the windfarm will have a $0.1 + 0.0384 = 13.84\%$ probability of dying. Again, this impact must be considered in the light of impacts being applied *only* to birds observed to use the area affected by the windfarm on a single day, versus all of the birds ever affected by the windfarm over the whole of the chick-rearing season. In this context, the prediction implies that for all of the birds observed within the area affected by the windfarm on a single day, all of those birds are predicted to die, *as well as* some other birds within the wider population. This is because the predicted windfarm impact from SeabORD on adult mortality is being assigned to only a small proportion of the birds (using the area on a single day) that are actually impacted by displacement over the whole of the chick-rearing season.

In contrast, if we consider the mean value from Table 6 for kittiwakes from all SPAs – 0.0027, SeabORD predicts that for birds that experience displacement *at any time* during the chick-rearing period they will suffer 0.27% higher mortality when the windfarm is present than they suffer in the baseline with no windfarm present. Therefore, for all birds affected by displacement at some point during the chick-rearing period, SeabORD predicts that if a bird has a baseline probability of dying of 10% when the windfarm is not present, then when the windfarm is present, they have a $0.1 + 0.0027 = 10.27\%$ probability of dying.

Table 3. Estimates of the model-based displacement mortality rate per timestep of chicks, based on calculating the rate directly from SeabORD outputs (mean per scenario) and summarising. Summaries shown are the minimum (Min), lower quartile (Q1), median, mean, upper quartile (Q3), maximum (max) and standard deviation (SD).

Species	SPA	Min	Q1	Median	Mean	Q3	Max	SD
GU	All	-0.803	-0.016	0.055	0.020	0.133	0.385	0.247
	UK9002271	-0.078	0.021	0.073	0.105	0.146	0.366	0.140
	UK9004171	-0.575	0.045	0.126	0.032	0.162	0.385	0.289
	UK9004271	-0.803	-0.131	-0.001	-0.097	0.015	0.132	0.280
KI	All	-0.326	0.203	0.335	0.592	0.842	2.685	0.671
	UK9002271	-0.326	0.205	0.223	0.234	0.306	0.630	0.260
	UK9004171	-0.028	0.152	0.703	0.672	1.133	1.458	0.609
	UK9004271	-0.015	0.348	0.773	0.601	0.890	1.086	0.371
	UK9006101	-0.020	0.215	0.330	0.851	1.598	2.685	1.031
RA	All	-0.518	-0.066	0.094	0.041	0.234	0.884	0.325
	UK9002271	-0.518	-0.400	-0.046	-0.098	0.100	0.432	0.326
	UK9004171	-0.191	0.118	0.224	0.225	0.268	0.884	0.284
	UK9004271	-0.476	-0.226	0.000	-0.063	0.118	0.250	0.287

Table 4. Estimates of the model-based displacement mortality rate over the entire season of chicks, based on calculating the rate directly from SeabORD outputs (mean per scenario) and summarising. Summaries shown are the minimum (Min), lower quartile (Q1), median, mean, upper quartile (Q3), maximum (max) and standard deviation (SD).

Species	SPA	Min	Q1	Median	Mean	Q3	Max	SD
GU	All	-0.0400	-0.0008	0.0041	0.0023	0.0106	0.0227	0.0132
	UK9002271	-0.0041	0.0019	0.0042	0.0067	0.0098	0.0202	0.0080
	UK9004171	-0.0284	0.0025	0.0100	0.0036	0.0115	0.0227	0.0156
	UK9004271	-0.0400	-0.0068	- 0.0001	-0.0045	0.0012	0.0079	0.0142
KI	All	-0.0117	0.0089	0.0181	0.0400	0.0774	0.1357	0.0452
	UK9002271	-0.0117	0.0086	0.0134	0.0115	0.0156	0.0265	0.0105
	UK9004171	-0.0013	0.0089	0.0314	0.0390	0.0636	0.0978	0.0373
	UK9004271	-0.0006	0.0181	0.0905	0.0625	0.0969	0.1335	0.0501
	UK9006101	-0.0012	0.0098	0.0168	0.0461	0.0949	0.1357	0.0557
RA	All	-0.0267	-0.0036	0.0060	0.0030	0.0161	0.0437	0.0173
	UK9002271	-0.0267	-0.0207	- 0.0027	-0.0050	0.0061	0.0218	0.0167
	UK9004171	-0.0096	0.0072	0.0160	0.0133	0.0176	0.0437	0.0143
	UK9004271	-0.0267	-0.0111	0.0000	-0.0024	0.0079	0.0166	0.0164

Table 5. Estimates of the model-based displacement mortality rate per timestep of adults, based on calculating the rate directly from SeabORD outputs (mean per scenario) and summarising. Summaries shown are the minimum (Min), lower quartile (Q1), median, mean, upper quartile (Q3), maximum (max) and standard deviation (SD).

Species	SPA	Min	Q1	Median	Mean	Q3	Max	SD
GU	All	-0.1803	-0.0358	-0.0019	-0.0017	0.0296	0.2937	0.0812
	UK9002271	-0.0297	0.0037	0.0214	0.0206	0.0348	0.0753	0.0299
	UK9004171	-0.1803	-0.0564	0.0080	-0.0215	0.0332	0.0830	0.0816
	UK9004271	-0.1077	-0.0540	-0.0202	-0.0071	-0.0122	0.2937	0.1188
KI	All	-0.2768	-0.0012	0.0247	0.0384	0.0728	0.2195	0.0896
	UK9002271	-0.2768	-0.0209	0.0011	-0.0178	0.0247	0.1191	0.1072
	UK9004171	-0.0269	0.0005	0.0367	0.0532	0.0989	0.1635	0.0705
	UK9004271	-0.0025	0.0479	0.0513	0.0475	0.0624	0.0898	0.0303
	UK9006101	-0.0647	0.0025	0.0187	0.0705	0.1687	0.2195	0.1068
RA	All	-0.1666	-0.0190	0.0762	0.0883	0.1873	0.4717	0.1591
	UK9002271	-0.0853	-0.0232	0.0568	0.0711	0.1890	0.2088	0.1147
	UK9004171	-0.1666	0.0538	0.0824	0.1074	0.1237	0.4380	0.1585
	UK9004271	-0.1502	-0.0800	0.0762	0.0808	0.1641	0.4717	0.2171

Table 6. Estimates of the model-based displacement mortality rate over the entire season of adults, based on calculating the rate directly from SeabORD outputs (mean per scenario) and summarising. Summaries shown are the minimum (Min), lower quartile (Q1), median, mean, upper quartile (Q3), maximum (max) and standard deviation (SD).

Species	SPA	Min	Q1	Median	Mean	Q3	Max	SD
GU	All	-0.00892	-0.00208	-0.00014	0.00009	0.00232	0.01461	0.00424
	UK9002271	-0.00155	0.00019	0.00137	0.00138	0.00259	0.00452	0.00176
	UK9004171	-0.00892	-0.00282	0.00059	-0.00067	0.00246	0.00489	0.00441
	UK9004271	-0.00536	-0.00307	-0.00142	-0.00062	-0.00099	0.01461	0.00598
KI	All	-0.00990	-0.00006	0.00164	0.00270	0.00610	0.01119	0.00447
	UK9002271	-0.00990	-0.00087	0.00007	-0.00047	0.00106	0.00502	0.00402
	UK9004171	-0.00128	0.00002	0.00214	0.00313	0.00641	0.00819	0.00383
	UK9004271	-0.00013	0.00220	0.00422	0.00434	0.00616	0.00931	0.00327
	UK9006101	-0.00239	0.00015	0.00139	0.00377	0.00882	0.01119	0.00527
RA	All	-0.00836	-0.00127	0.00427	0.00482	0.00937	0.02438	0.00813
	UK9002271	-0.00435	-0.00148	0.00326	0.00363	0.00947	0.01076	0.00585
	UK9004171	-0.00836	0.00319	0.00557	0.00603	0.00682	0.02243	0.00794
	UK9004271	-0.00771	-0.00407	0.00427	0.00446	0.00920	0.02438	0.01120

3.3. Emulation-based estimates

3.3.1. Chick mortality

The slope of “ptdisp” within the emulator models of chick mortality considered in WP3 can be interpreted as the model-based displacement mortality rate for chicks. We present these results, for both the null and best model, in Table 7, along (for comparison) with corresponding estimates derived from mixed models of the raw SeabORD outputs.

The results are broadly similar to those obtained in Table 4, although the emulation results generally show less variability than the raw metrics derived from SeabORD outputs, reflecting the fact that the emulation approach effectively “de-noises” the data before calculating the rate. The emulation approach also provides an estimate of uncertainty, via the standard error. In general, the levels of uncertainty are less high than we might expect based on the raw metrics, but the variations between SPAs within the models that allow for SPA-specific trends (R11 and M11) can be substantial.

Most, but not all, of the values shown are significant. However, p-values for the overall effect of “ptdisp” are not particularly relevant in this context, as the structure of SeabORD means that we would always, all else being equal, expect to see impacts increase as the level of displacement increases.

In Figure 4 we show the relationship between the proportion of individuals ever displaced over the season and the impact on chick mortality, along with the predictions from the model. The key thing to note is that the emulator implies a non-linear form for this relationship, even though the emulator itself assumes linearity, because of the non-linear relationship between the proportion of individuals displaced per timestep (ptdisp) and the proportion displaced ever within the season (psdisp). In all cases, the non-linearity takes the same form, with the gradient of the curve increasing as the level of displacement increases. This arises because the increase in the proportion of individuals ever displaced is also linked to an increase in the frequency of displacement for those individuals that are ever displaced, and hence a higher level of impact for those individuals (Figure 2).

This means that the model-based displacement mortality rate per season increases as the level of displacement increases (Figure 5). Note that this effect arises simply because the ratio of birds displaced per timestep to birds displaced over the season increases with the proportion of birds displaced per timestep. It reflects, biologically, the idea that increases in the number of individuals displaced ever within the season becomes a less and less informative measure of the overall level of displacement as the level of displacement rises, because as levels of displacement increase this displacement will tend to increasingly be seen as a rise in the frequency of displacement of birds that are already being displaced, rather than an increase in the number of birds being displaced.

3.3.2. Adult mortality

Corresponding estimates of the model-based displacement mortality rates per timestep for adult mortality are shown in Table 8. Figure 6 shows the relationship between the levels of displacement per season and the population-level impacts from SeabORD, with the fitted emulator models superimposed. Figure 7 shows the model-based displacement mortality rate per season based on the emulator models.

The key difference between the results for chick and adult mortality is that the absolute magnitude of impacts is consistently substantially higher for chick mortality than for adult mortality.

Table 7. Emulation-based estimates of the model-based displacement mortality rate per timestep of chicks, based on four different emulators of SeabORD: R1 (linear regression of mean per scenario, common rate), M1 (mixed model of raw SeabORD outputs, common rate), R11 (linear regression of mean per scenario, separate rate per SPA), M11 (mixed model of raw SeabORD outputs, separate rate per SPA). Estimates of the rate are given for each model, together with standard errors (SE) and t-statistics (t-val). For mixed models of raw SeabORD outputs, the standard deviation of the random slope per scenario is also shown, as is the residual standard deviation (per run). For regression models of means per scenario the residual standard deviation (per scenario) is shown. Values that are not relevant are shown in dark grey.

Species	Model	SPA	Estimated “ptdisp” slope			Random slope SD	Residual SD	
			Estimate	SE	t-value		Per scen	Per run
GU	R1	All	0.0847	0.0144	5.90		0.0018	
	M1	All	0.0702	0.0287	2.45	0.1394		0.0025
	R11	UK9002271	0.0878	0.0206	4.25		0.0015	
		UK9004171	0.1273	0.0212	6.01			
		UK9004271	0.0235	0.0245	0.96			
	M11	UK9002271	0.1138	0.0423	2.69	0.1292		0.0025
		UK9004171	0.1122	0.0491	2.29			
		UK9004271	-0.0216	0.0493	-0.44			
KI	R1	All	0.7596	0.0715	10.62		0.0145	
	M1	All	0.6088	0.1153	5.28	0.6674		0.0047
	R11	UK9002271	0.2398	0.2532	0.95		0.0140	
		UK9004171	0.7932	0.1890	4.20			
		UK9004271	0.8455	0.0876	9.65			
		UK9006101	0.6504	0.1648	3.95			
	M11	UK9002271	0.2482	0.2244	1.11	0.6516		0.0047

		UK9004171	0.6712	0.2477	2.71			
		UK9004271	0.6078	0.2189	2.78			
		UK9006101	0.8944	0.2144	4.17			
RA	R1	All	0.1466	0.0303	4.84		0.0022	
	M1	All	0.1417	0.0352	4.03	0.0513		0.0102
	R11	UK9002271	0.0036	0.0542	0.07		0.0019	
		UK9004171	0.2043	0.0353	5.78			
		UK9004271	0.1554	0.0583	2.67			
	M11	UK9002271	0.0036	0.0638	0.06	0.0000		0.0102
		UK9004171	0.2043	0.0416	4.91			
		UK9004271	0.1554	0.0687	2.26			

Figure 4. Scatterplots of proportion of birds displaced over season (psdisp) against simulated SeabORD impacts on chick mortality for each species, with different colours representing different SPAs, with fitted emulation models, transformed to use “psdisp”, shown. Left hand plots show raw SeabORD impacts (points) together with predicted values from the pooled mixed model M1 (thick lines) and SPA-specific mixed model M11 (dotted thick lines). Right hand plots show mean values per scenario with predicted values from the pooled regression model R1 (thick lines) and SPA-specific regression model R11 (dotted thick lines). The thick dashed black line represents an impact of zero.

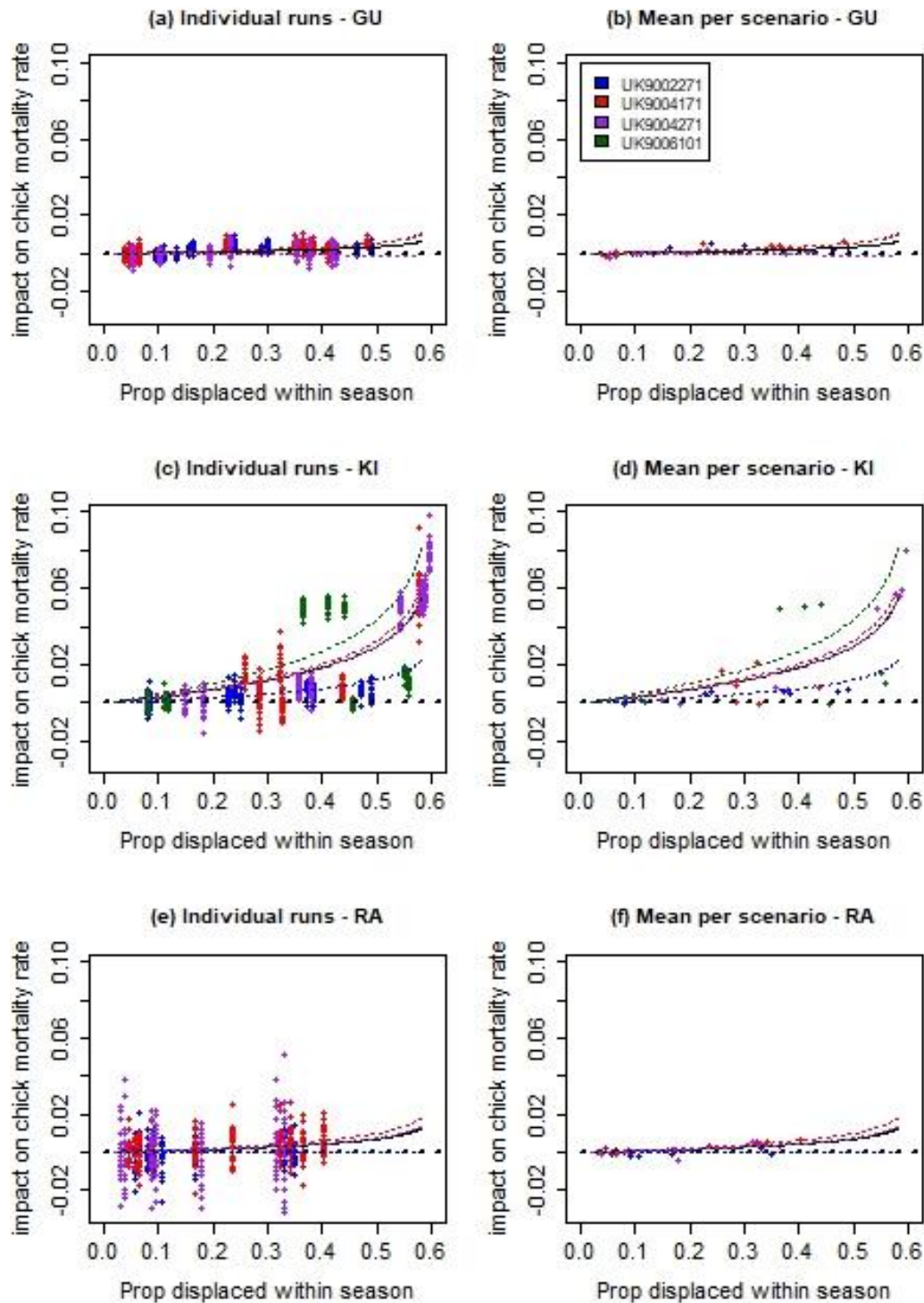


Figure 5. Plots of proportion of individuals displaced per timestep (ptstep) against the emulation-based estimated of the model-based displacement chick mortality rate per season, for each species, based on the null regression model (R1, solid line) and the SPA-specific regression model (R11, dotted coloured lines).

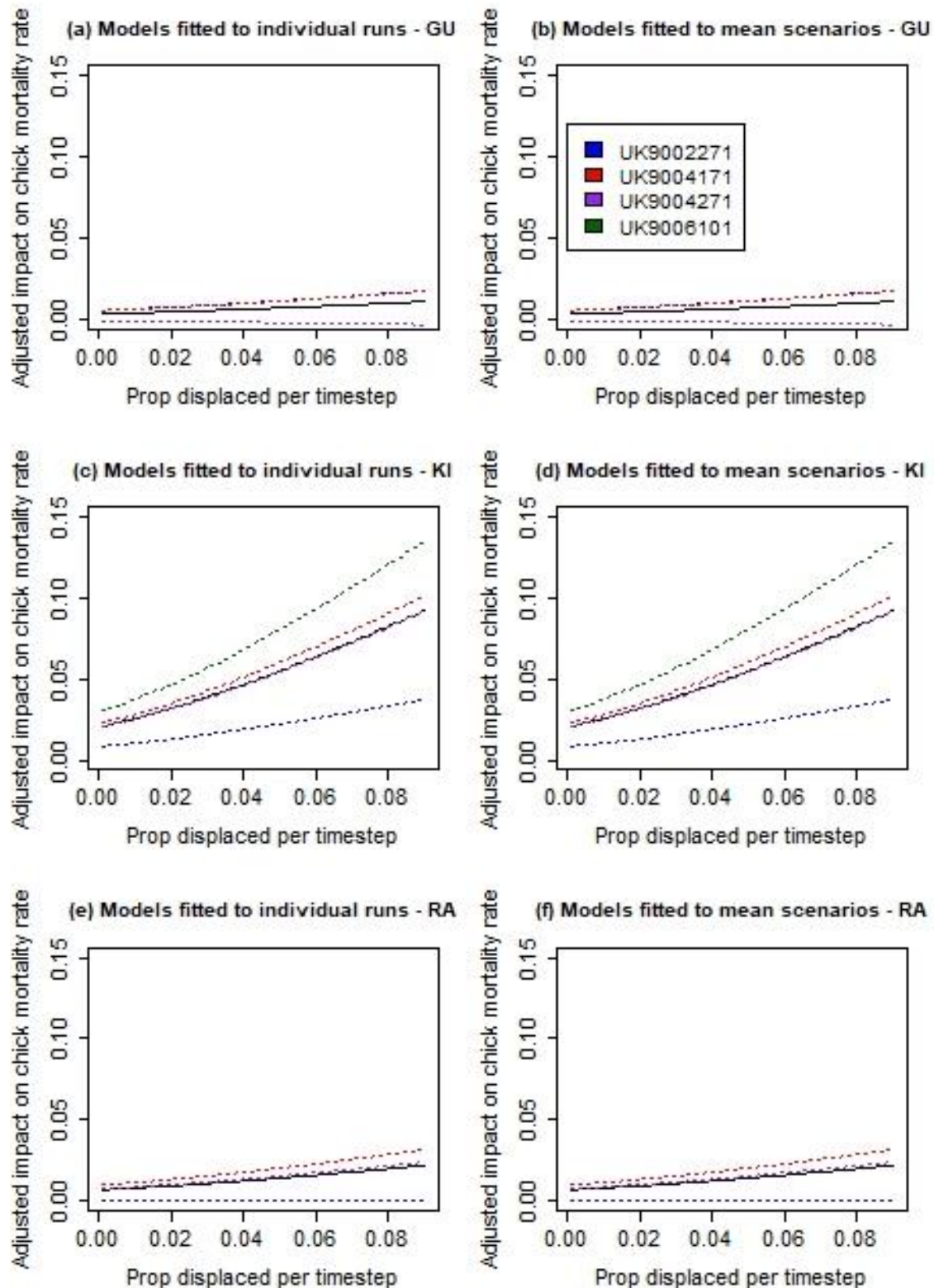


Table 8. Emulation-based estimates of the model-based displacement mortality rate per timestep of adults, based on four different emulators of SeabORD: R1 (linear regression of mean per scenario, common rate), M1 (mixed model of raw SeabORD outputs, common rate), R11 (linear regression of mean per scenario, separate rate per SPA), M11 (mixed model of raw SeabORD outputs, separate rate per SPA). Estimates of the rate are given for each model, together with standard errors (SE) and t-statistics (t-val). For mixed models of raw SeabORD outputs, the standard deviation of the random slope per scenario is also shown, as is the residual standard deviation (per run). For regression models of means per scenario the residual standard deviation (per scenario) is shown. Values that are not relevant are shown in dark grey.

Species	Model	SPA	Estimated "ptdisp" slope			Random slope SD	Residual SD	
			Estimate	SE	t-value		Per scen	Per run
GU	R1	All	0.0129	0.0046	2.78		0.0006	
	M1	All	0.0099	0.0071	1.40	0.0306		0.0011
	R11	UK9002271	0.0220	0.0056	3.93		0.0004	
		UK9004171	0.0248	0.0058	4.31			
		UK9004271	-0.0160	0.0067	-2.40			
	M11	UK9002271	0.0262	0.0070	3.74	0.0154		0.0011
		UK9004171	0.0254	0.0074	3.44			
		UK9004271	-0.0206	0.0078	-2.65			
KI	R1	All	0.0526	0.0065	8.11		0.0013	
	M1	All	0.0500	0.0122	4.11	0.0607		0.0022
	R11	UK9002271	0.0097	0.0235	0.41		0.0013	
		UK9004171	0.0662	0.0175	3.78			
		UK9004271	0.0554	0.0081	6.82			

		UK9006101	0.0506	0.0153	3.31			
	M11	UK9002271	0.0123	0.0246	0.50	0.0580		0.0022
		UK9004171	0.0523	0.0248	2.11			
		UK9004271	0.0453	0.0214	2.12			
		UK9006101	0.0886	0.0235	3.77			
RA	R1	All	0.0512	0.0129	3.97		0.0009	
	M1	All	0.0537	0.0151	3.56	0.0312		0.0038
	R11	UK9002271	0.0128	0.0260	0.49		0.0009	
		UK9004171	0.0631	0.0170	3.72			
		UK9004271	0.0635	0.0280	2.27			
	M11	UK9002271	0.0148	0.0300	0.49	0.0308		0.0038
		UK9004171	0.0673	0.0208	3.24			
		UK9004271	0.0653	0.0316	2.07			

Figure 6. Scatterplots of proportion of birds displaced over season (psdisp) against simulated SeabORD impacts on adult mortality for each species, with different colours representing different SPAs, with fitted emulation models, transformed to use “psdisp”, shown. Left hand plots show raw SeabORD impacts (points) together with predicted values from the pooled mixed model M1 (thick lines) and SPA-specific mixed model M11 (dotted thick lines). Right hand plots show mean values per scenario with predicted values from the pooled regression model R1 (thick lines) and SPA-specific regression model R11 (dotted thick lines). The thick dashed black line represents an impact of zero.

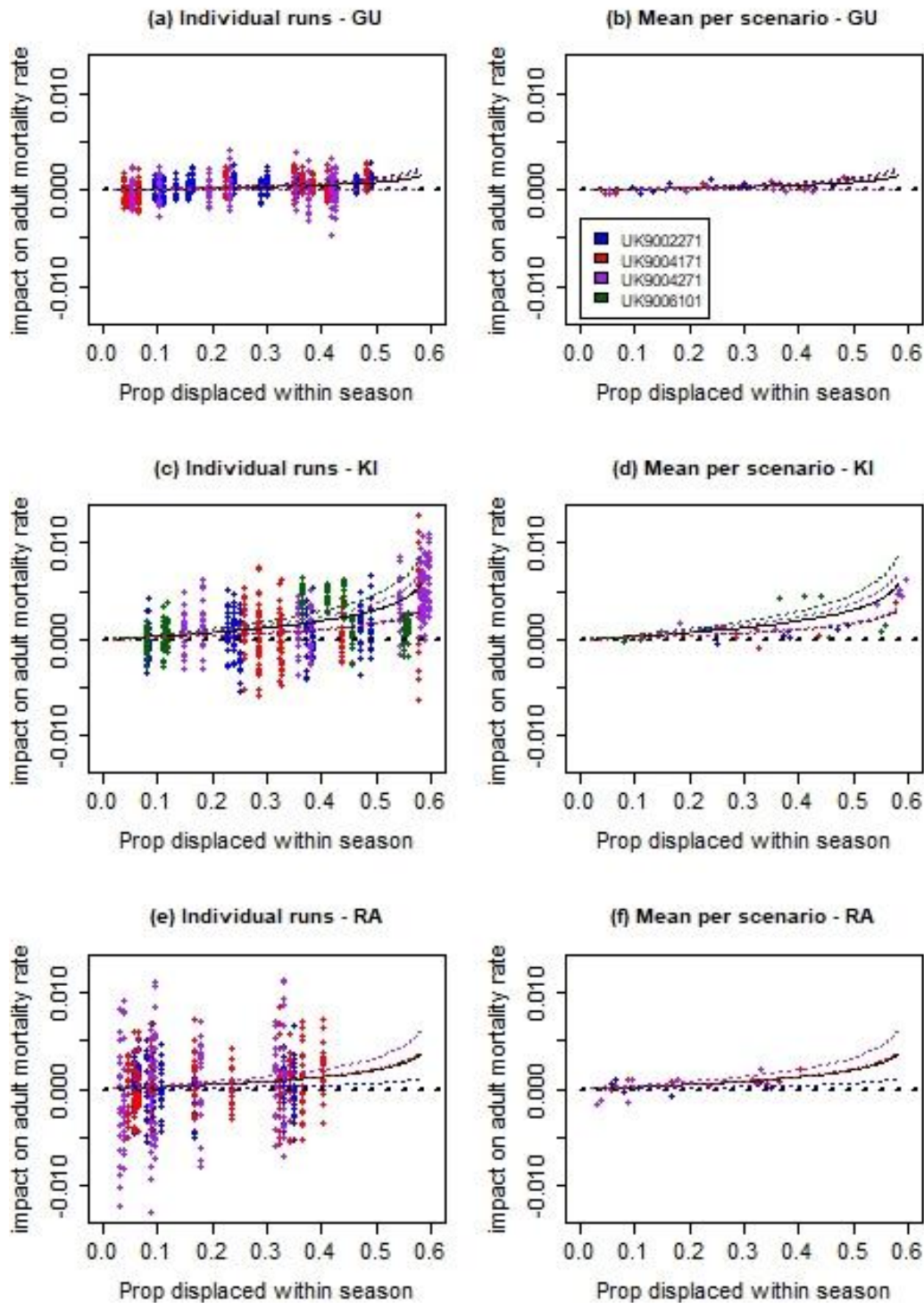
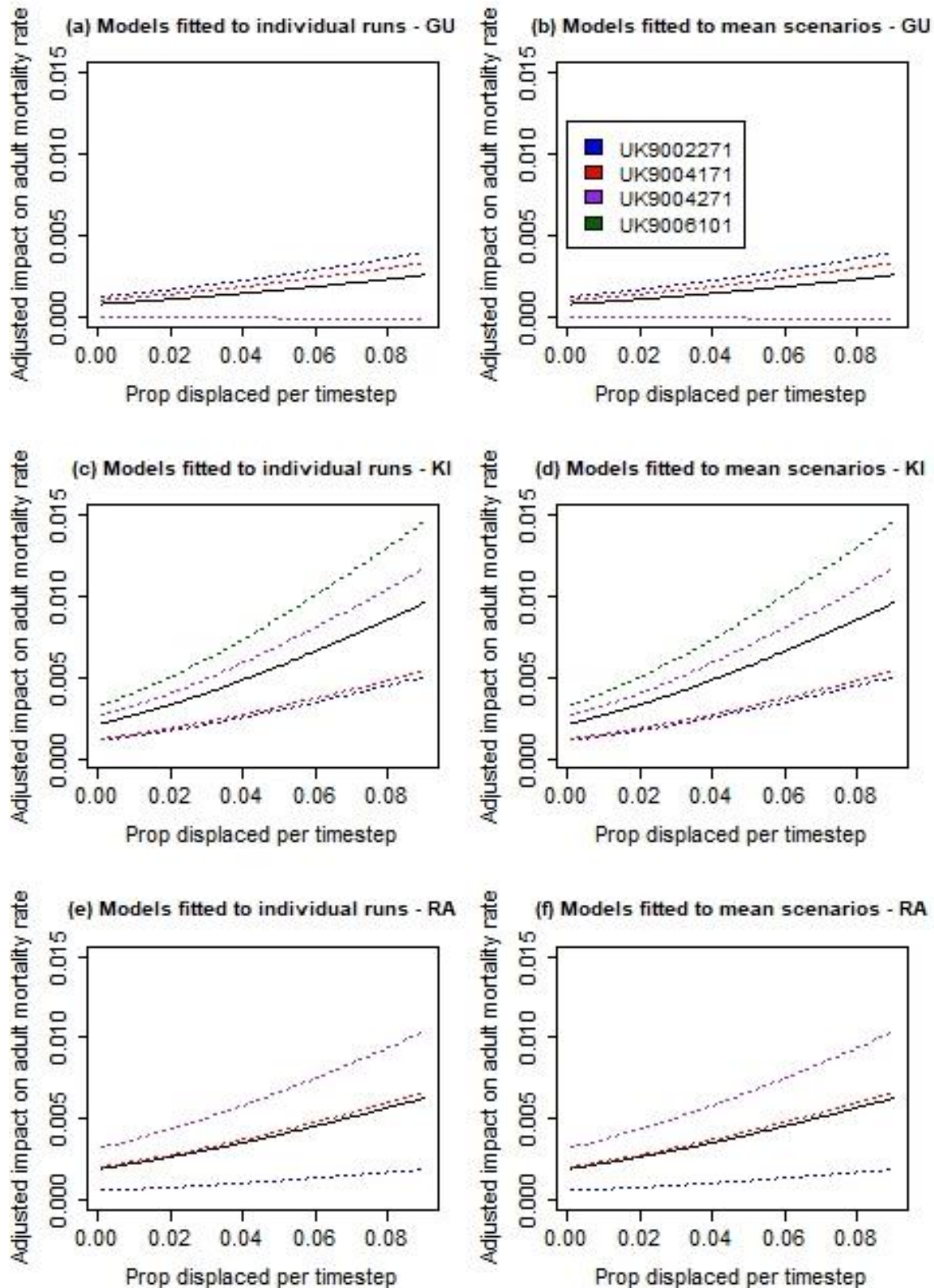


Figure 7. Plots of proportion of individuals displaced per timestep (ptstep) against the emulation-based estimated of the model-based displacement adult mortality rate per season, for each species, based on the null regression model (R1, solid line) and the SPA-specific regression model (R11, dotted coloured lines).



4. Conclusions

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 interpretation are dependent on the definition used. We have focused on the ratio of population-level windfarms impacts on adult or chick mortality, to either the mean proportion of birds using the windfarm footprint per timestep (day), or the mean proportion of birds that are ever in the windfarm over the whole of the chick-rearing season. 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 kittiwake, 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). The relationship is illustrated in Figure 1.

Estimates of this ratio based on SeabORD outputs typically show very high levels of variation, whilst the emulator-based ratios show lower levels of uncertainty/variation. This arises because the ratio derived directly from SeabORD 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 from SeabORD outputs (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 outlined here should be regarded as illustrative, rather than interpreted quantitatively, given that the training set of SeabORD runs is relatively small (especially in relation to the number of SPAs), that noise (unexplained run-to-run variation) is relatively high, and given that the scenarios considered were not able to span the full range of windfarm and SPA characteristics (in part because the Wakefield et al., 2017, maps were used to provide bird distributions for all scenarios, and in part because an upper limit of five was imposed on the number of windfarms considered). However, the results do provide a “proof of concept” of the approach, illustrating the potential for using SeabORD, in combination with emulation, to provide estimates of a “model-based displacement mortality rate” for adults and chicks, together with corresponding estimates of uncertainty.

The “model-based displacement mortality rates” defined here, for both chicks and adults, have similarities to the rates defined in the Displacement Matrix and Expert Elicitation, but there are also differences in the definitions used (hence the use of the terminology “model-based displacement mortality rate”) which make translation between the rates used in the different approaches challenging; we consider this further in WP5.

5. Future work

The future work outlined in Work Package 3 - to use a larger SeabORD training set, investigate alternative emulation methods, and improve elements of SeabORD itself - would all contribute to validating and improving the transferability of the rates presented here. They should also allow at least part of the unexplained variability between windfarm scenarios and SPAs to be explained in relation to windfarm and SPA characteristics.

The emulation methods used in this WP4 were sufficiently simple that it was possible to directly estimate parameters that relate directly to the ratios we are interested in estimating, but as the emulators become more sophisticated, this may no longer be possible. This may be because the concept of 'displacement mortality rate' involves a level of simplification that is difficult to reconcile with the structure of an individual-based model. SeabORD will effectively have different mortality rates for different subgroups of individuals, depending on the frequency at which they experience displacement, and will also have indirect impacts for individuals that never experience displacement via effects of competition. This makes it difficult to extract any single metric that fully captures all of these different mechanisms. It would be valuable to understand how the rates presented here compare to those using alternative metrics within SeabORD on the mortality of displaced birds.

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+44 (0) 20 7170 7000

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