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Final report to Marine Scotland Science

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This report presents the results of marine and freshwater scientific work carried out for Marine Scotland under external commission.

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Searle, K., Mobbs, D., Butler, A., Bogdanova, M., Freeman, S., Wanless, S. & Daunt, F.

May 2014

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Executive Summary

- The aim of this project was to develop a model to estimate the population consequences of displacement from proposed offshore wind energy developments for key species of seabirds breeding at SPAs in proximity to proposed Forth/Tay offshore wind farm developments.

- The steering group identified five seabird species for which displacement modelling was required in support of HRA/AA for Forth/Tay developments: black-legged kittiwakes *Rissa tridactyla;* common guillemot *Uria aalge;* razorbill *Alca torda;* Atlantic puffin *Fratercula arctica;* northern gannet *Morus bassanus*.

- The steering group agreed that the SPAs to be considered in this report were Buchan Ness to Collieston Coast SPA, Fowsheugh SPA, Forth Islands SPA and St Abb's Head to Fastcastle SPA.

- We considered impacts of displacement on population size operating via two main processes: reduced survival of offspring during the breeding season, and reduced body mass of adults leading to lower survival in the following winter.

- Displacement effects are of two main types: the effects of displacement of birds that intended to forage in the wind farm, and the effects of the wind farm acting as a barrier to movement of birds intending to forage beyond the wind farm.

- The principal requirement was to develop time and energy models of foraging to estimate consequences for demographic rates. A simulation model was developed that modelled the time/energy budgets of breeding seabirds during the chick-rearing period. The model was parameterised from information available in the literature or, where this was unavailable, from expert judgment. The model simulated foraging decisions of individual seabirds under the assumption that they were acting in accordance with optimal foraging theory. Each individual selected a suitable location for feeding during each foraging trip from the colony based on bird density maps derived from fitting a generalized additive model (GAM) to empirical location data (obtained from GPS tracking) for each species. Subsequent behaviour of birds was then simulated incorporating realistic assumptions and constraints derived from observed behaviour. Fundamentally, we assumed that the foraging behaviour of individual seabirds was driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of conspecifics.

- Choice of foraging location was dependent upon assumptions regarding the spatial distribution of prey, for which we had no direct empirical data. Therefore two scenarios were considered: an assumption that prey was distributed uniformly throughout the foraging range ("homogeneous" prey), and an assumption that prey was distributed proportional to the estimated distribution of birds after adjustment to account for the effects of availability due to proximity to colonies ("heterogeneous" prey).

- Baseline simulations from the model, in the absence of wind farms, were parameterised based on empirically estimated values for foraging time, flight time, adult body mass and chick survival from studies of these or closely related species from CEH's long term study of seabirds on the Isle of May or elsewhere.

- The impacts of the proposed wind farms were assessed by comparing simulated values of adult and chick survival in models that included the wind farms against the baseline simulations. Impacts were assessed separately for each of the proposed wind farms (Neart na Gaoithe, Inch Cape, Round 3 Alpha, Round 3 Bravo) and for the cumulative effect of all four wind farms.

- Models were initially run using relatively small numbers of simulated birds (1000 per species) for a relatively large number of different scenarios (66). The scenarios reflected possible assumptions regarding food availability (good, moderate or poor), the spatial distribution of prey (homogeneous or heterogeneous), the percentage of birds affected by barrier and displacement effects (assumed to be 100% when looking at individual wind farms, but scenarios of 50% displacement/50% barrier; 0% displacement/100% barrier; 100% displacement/0%barrier were considered when looking at cumulative effects) and the effect of the width of the buffer around the wind farm that is included within the wind farm footprint (values of 0km, 0.5km and 1km were considered for Neart na Gaoithe; values of 1km were used for all other wind farms).

- These exploratory simulations helped to identify those scenarios and SPA-by-species combinations that were of greatest interest. They also identified the fact that a substantial amount of uncertainty was introduced by running the models using relatively small numbers of birds. The final simulations therefore used much larger sets of simulated birds (20000 rather than 1000), but, in order to prevent the computational cost becoming prohibitive, focused on a smaller number of scenarios (ten). These scenarios involved looking at the effect of homogeneous and heterogeneous prey for each of the four individual wind farms (‘full’ and ‘fast’ models, see below) and for all four wind farms in combination (‘full’ model only). The final simulations assumed moderate food availability, a 1km buffer around each wind farm, and that 60% of birds experienced displacement and barrier effect (except for kittiwake, where the percentage was assumed to be 40%).

- The final simulations used both a “full” and “fast” version of the foraging model. The primary benefit of the “fast” model was the fact that the energetic consequences of barrier effects were included in a more realistic way. The fast model was also less computationally expensive, and was therefore used in performing a sensitivity analysis. Some aspects of the fast model are less biologically realistic than the full model, however, so the final estimates of wind farm effects were based on combining the “full” and “fast” model outputs in a way that captured the strengths of both models.

- The simulations indicated three species-by-SPA combinations for which declines in adult survival of more than 0.5% seemed to be possible - Forth Island kittiwakes, Fowlsheugh kittiwakes, and Forth Island puffins – with the largest declines corresponding to the two combinations involving the Forth Islands SPA. The results did not show evidence of declines in adult survival of more than 0.5% for gannets, razorbills or guillemots, or for kittiwakes at St. Abbs or Buchan Ness. The declines in kittiwakes at Forth Islands appeared to be driven by all four wind farms, but with the largest impact coming from Neart na Gaoithe. The declines in kittiwakes at Fowlsheugh appeared to be primarily driven by Alpha. The results for Forth Island puffins were sensitive to assumptions about the distribution of prey: if prey were assumed to be spatially homogeneous then the estimated declines were larger than for any other species-SPA combination, and driven primarily by Inch Cape and Alpha. If prey were assumed to be heterogeneous – and linked to the distribution of birds – then the estimated declines were much smaller and were primarily driven by Neart na Gaoithe. Estimates of cumulative effects were generally approximately equal to the sum of effects from individual wind farms.

- The results for breeding success were qualitatively similar, but were generally of lower magnitude (if we assume that a 1% decrease in adult survival is roughly equivalent, in demographic terms, to a 5% decrease in chick survival). Breeding success results were also harder to disentangle from the effects of stochastic noise, probably due to threshold effects in the model relating to the consequences of nest unattendance by adults on offspring survival. Only cumulative estimates for Forth Island puffins with homogeneous prey showed a decrease in chick survival of more than 2.5% and none showed an estimated decline of more than 5%.

- This study is, to our knowledge, the most comprehensive assessment of the population level consequences of displacement for seabirds to date. Displacement effects have been considered to potentially impact on chick survival. What has been less widely appreciated is that impacts on adult survival are also possible, mediated via changes in body condition. Declines in adult and chick survival were recorded for some species/wind farm/SPA combinations that matched expectations in terms of foraging range, foraging costs and wind farm location relative to SPAs. The model had to make a number of assumptions that would benefit from parameterisation with local data, in particular prey distribution, behaviour of seabirds in response to wind farms (including habituation) and effects of adult body mass change on subsequent survival.

1 Project scope

Offshore wind developments have the potential to impact on the daily energy and time budgets of seabirds by displacing birds from habitats that are essential for key life history behaviours such as foraging, maintenance and courtship (Larsen & Guillemette 2007). There is particular concern that wind farm developments which are located on favoured foraging habitats may force birds to forage at greater densities in suboptimal habitats. The impact of displacement is predicted to be particularly important for breeding seabirds that, as central place foragers, are constrained to obtain their food within a certain distance of the breeding colony (Daunt et al. 2002; Enstipp et al 2006). Changes in time and energy budgets resulting from displacement from renewable energy developments have the potential to impact on the body condition, and hence survival prospects, of breeding adults. Such changes may also reduce breeding success if provisioning rate declines result in offspring starvation, or if the extended time required for foraging results in temporary unattendance of eggs or young, which increases the likelihood of mortality from predation or exposure.

The best current evidence on displacement is for non-breeding individuals available from wind farm developments outside the UK, and results have been inconsistent with varying levels of displacement behaviour recorded among locations and species (Petersen et al. 2006, 2011; Fox et al 2006; Leopold et al. 2011; Vanerman et al. 2011, 2012; Leonhard et al. 2013). Furthermore, there is a paucity of information on the behaviour of breeding seabirds in response to wind farms, yet there is expected to be greater constraints on breeding individuals. In recognition of these substantial uncertainties and important knowledge gaps, Marine Scotland have commissioned this project with the aim of developing time and energy expenditure models to estimate population consequences of displacement from proposed offshore wind energy developments for key species of seabirds breeding at Scottish SPAs and to apply these models to the Forth/Tay offshore wind farm development area.

The steering group identified five seabird species for which displacement modelling was required in support of HRA/AA for Forth/Tay developments:

- black-legged kittiwakes *Rissa tridactyla*
- common guillemot *Uria aalge*
- razorbill *Alca torda*
- Atlantic puffin Fratercula arctica
- northern gannet *Morus bassanus*

The steering group agreed that the following SPAs close to the Forth/Tay region should be considered in this report:

- Buchan Ness to Collieston Coast SPA
- Fowsheugh SPA
- Forth Islands SPA
- St Abb’s Head to Fastcastle SPA

The group also agreed that four proposed wind farms should be considered:

- Neart na Goithe
- Inch Cape
- Round 3 Alpha
- Round 3 Bravo

and that cumulative effects of all four wind farms should also be estimated. A map of the study area can be found in Figure 1:1.

The project involved initially running a set of exploratory simulations on all species except gannet (because of time constraints and because this species was of least concern) in which a large number of scenarios were considered but a small sample of birds was used in order to prevent the computational cost becoming probative. These exploratory results were used to derive a smaller number of scenarios of greatest interest, and simulations from these scenarios using much larger samples of birds were then used to generate the final results.

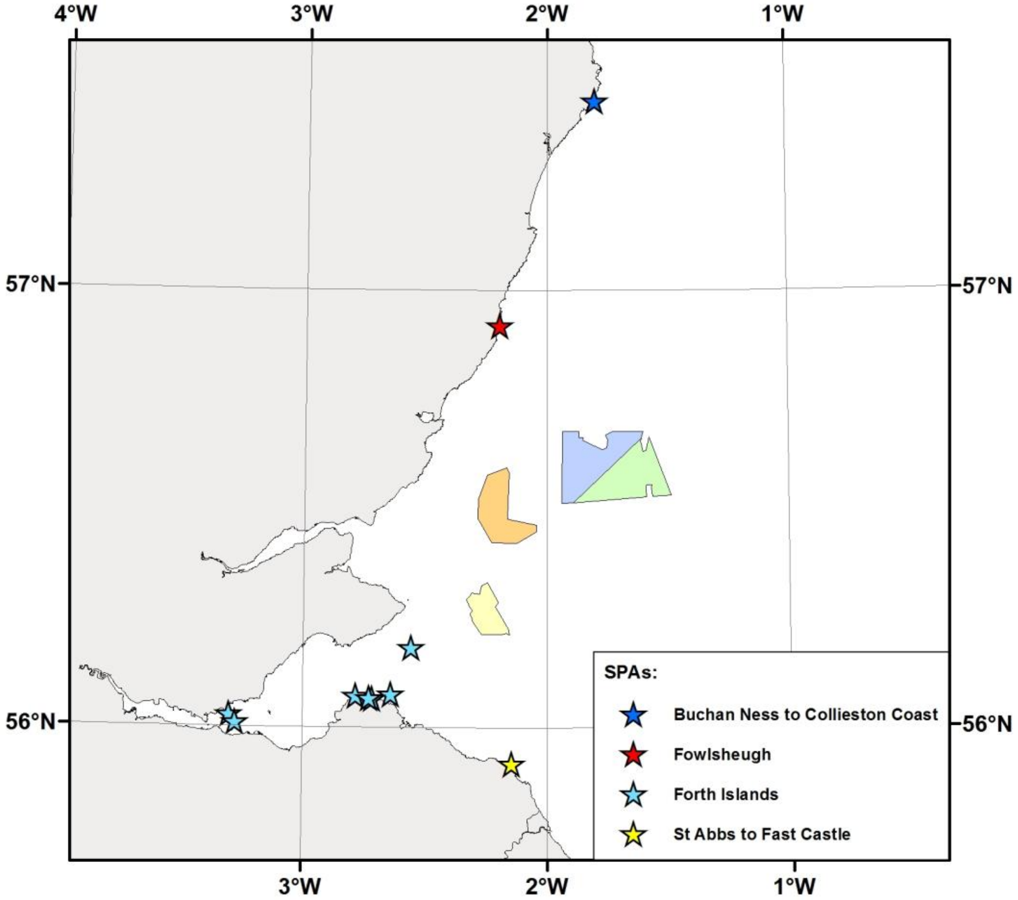

Figure 1:1: Map of study area showing SPAs and proposed wind farms.

2 Methodology

In this section we detail the development and validation of foraging model inputs (prey and bird density maps), the foraging model, and the subsequent translation of model output (adult body mass) into estimated population level adult survival.

2.1 Prey and bird density maps

A key aspect of the project involved the production of maps of expected bird and prey densities within the Forth/Tay area: bird density and prey density are key inputs to the foraging model, and it is therefore important that the spatial variations in these quantities represent, insofar as is practically possible, the actual characteristics of the Forth/Tay area.

2.1.1 Data on bird distributions

Data on bird distributions for the four species under initial consideration (kittiwake, guillemot, razorbill and puffin) were taken from GPS loggers that had been deployed on individual birds from the four SPAs of interest (Forth Islands, St. Abbs Head, Buchan Ness and Fowlsheugh) during the chick-rearing phases in 2010, 2011 and 2012. GPS tracking data enable us to estimate the relative spatial densities of birds that have come from a specific SPA; this would be difficult to do using at-sea or aerial transect data, because for transect data the origin of the bird is not known and non-breeding, as well as breeding, birds may be included in the counts. The initial intention had been to use at-sea, rather than GPS, data for puffins, because the GPS data for this species are limited. However, it was ultimately decided that GPS data would also be used for this species, since the at-sea data from outside the wind farm development areas but lying within the potential foraging range of the birds, available from the ESAS database, have poor coverage in recent years. Furthermore, the years for which coverage is good (the 1980s) represent periods when the population size and environmental conditions were very different to the present.

GPS data record the geographical location of each bird at specific points in time. The numbers of tracked birds for each species, SPA and year are shown in Table 2:1. Of the twelve species-by-SPA combinations that we consider, six have tracking data from more than 20 birds (all four SPAs for kittiwake, and Forth Islands for guillemot and razorbill), four have tracking data for less than 20 birds (guillemot for St. Abbs Head, Fowlsheugh and Buchan Ness, and puffin for Forth Islands), and two have no tracking data at all (razorbill for St. Abbs Head and Fowlsheugh).

Species	SPA	Total number of tracked birds in		
		2010	2011	2012
Kittiwake	Forth Islands	36	0	17
Kittiwake	St. Abbs Head	0	25	15
Kittiwake	Fowlsheugh	0	35	15
Kittiwake	Buchan Ness	0	0	25
Guillemot	Forth Islands	31	0	19
Guillemot	St. Abbs Head	0	8	1
Guillemot	Fowlsheugh	0	9	10
Guillemot	Buchan Ness	0	0	6
Razorbill	Forth Islands	18	0	15
Razorbill	St. Abbs Head	0	0	0
Razorbill	Fowlsheugh	0	0	0
Puffin	Forth Islands	0	0	7

Table 2:1: Availability of GPS tracking data for each species and SPA. Note that Buchan Ness is not an SPA for razorbill or puffin, and Fowlsheugh and St Abb's Head are not for puffin.

GPS tracking locations are nominally obtained once every 100 seconds, but in reality the gaps between consecutive records are often much longer than this (because during the intervening period the logger has not been able to obtain signals from sufficient satellites to compute an accurate estimate of current location).

The raw data obtained from GPS loggers were processed and filtered in four ways:

1/ Spurious duplicate records that occur when the signal to the satellite is lost were removed;

2/ Records with obvious location errors (where distance from the colony is implausibly large) were removed;

3/ Records within 1km of the colony were filtered out in order to retain only locations at sea;

4/ Records for which speed exceeds 14km/h were filtered out in order to retain only locations at sea associated with foraging or resting behaviours. This is the point that lies at the bottom of the trough of the bimodal distribution of speeds, one peak corresponding to the bird in flight and one to the bird not in flight. The exact threshold speed varies between species, but 14km/h is a reasonable compromise.

The overall number of GPS location records, after filtering, is shown in Table 2:2.

Species	SPA	Total number of GPS records	GPS records per bird, mean and (SD)
Kittiwake	Forth Islands	26325	497 (500)
Kittiwake	St. Abbs Head	19777	494 (265)
Kittiwake	Fowlsheugh	25253	505 (332)
Kittiwake	Buchan Ness	16352	654 (413)
Guillemot	Forth Islands	31899	638 (342)
Guillemot	St. Abbs Head	7411	823 (482)
Guillemot	Fowlsheugh	10280	541 (318)
Guillemot	Buchan Ness	3678	613 (136)
Razorbill	Forth Islands	16333	495 (390)
Razorbill	St. Abbs Head	0	-
Razorbill	Fowlsheugh	0	-
Puffin	Forth Islands	7465	1066 (681)

Table 2:2: Total number of GPS track locations and records, after filtering, for each species-by-SPA combination.

2.1.2 Estimation of bird densities

For each species, bird densities were estimated from the filtered GPS tracking data using a Binomial generalized additive model (GAM). This model compares the characteristics of the GPS tracking locations against the characteristics of a set of 'control' points that represent the set of positions that birds could potentially have visited. We take the control points to be on a regular 0.5 x 0.5km grid; the grid only includes points that are within a certain pre-specified distance of the SPA. This distance is taken to be either the maximum distance from colony that is observed in our GPS data, or the mean foraging trip length that is reported in the literature – we select whichever of these two values is greater in order to avoid excluding potential foraging areas from the analysis (

Table 2:3). For kittiwake, the maximum distance from colony observed in the GPS data is much larger than the mean foraging trip length reported in the literature; in order to avoid the computational cost of using a very large grid of points, we take the maximum distance for this species to be 170km on the grounds that only a very small number of

GPS records (28, or less than 0.04% of the entire dataset) occur beyond this distance (Figure 2:1).

The "foraging range" of the simulated birds was derived from the modelling of the GPS data, not from the specified 'maximum distance' value. The latter value is purely included for computational reasons, to ensure that we do not simulate birds in areas where they are very unlikely to occur (according to the GPS data) because (a) there is no point in doing so (birds wouldn't be sent there in practice because the probabilities associated with these areas are so low) and (b) it would substantially increase the computation to try to do so. This range is set to be sufficiently high that there would be a very low probability of birds travelling beyond it, according to the GPS data, but sufficiently low that computation is still feasible. The exact trade-off between the two things varies between species, but we have always tried to set the limit as high as we feasibly can – this is not conservative as such, because it simply ensures that the simulated distribution of foraging locations matches the observed distribution as closely as possible.

Species	Maximum distance from colony seen in GPS data	Mean maximum distance from colony (from literature)	Maximum distance used for our analysis
Kittiwake	246.1km	60km	170km
Guillemot	70.4km	84km	84km
Razorbill	70.0km	49km	71km
Puffin	66.1km	105km	105km

Table 2:3: Maximum distance to colony in GPS data, mean maximum distance from colony in literature (Thaxter et al. 2012) and maximum distance used in the analysis.

The GAMs are fitted simultaneously to data for all years and SPAs that have GPS tracking data. The models assume that the predicted density of birds can be decomposed into two parts: the first part captures the effects of distance to source SPA and distance to other nearest SPA (these are both assumed to have a linear relationship with log(density); the latter incorporates the potential effect of intraspecific competition) and a smooth term which represents spatial variations that cannot be attributed to distance to colony. These two components can be regarded as corresponding to "accessibility" and "suitability", respectively. The models are fitted in R using the bam function from the mgcv package. We had initially tried to fit models that described suitability in terms of environmental variables such as depth, sea surface temperature and sediment type ('habitat association models'), but this approach proved to be largely unsuccessful when it was applied to guillemots (see Appendix A) and was therefore abandoned. The GAM approach is somewhat similar to kernel density estimation, but it has the advantage that the smooth estimated density can be decomposed into components that relate to the characteristics of the location (suitability) and the availability of the location to birds from each SPA (accessibility).

The GAMs can be used to provide an estimate of the predicted bird density for each species-by-SPA combination. For species-by-SPA combinations without GPS tracking data (Razorbill at St. Abbs Head and Fowlsheugh) the model does not provide a meaningful estimate of suitability, and the predicted bird densities are therefore based solely on the estimated effects of distance to source SPA and distance to next nearest SPA.

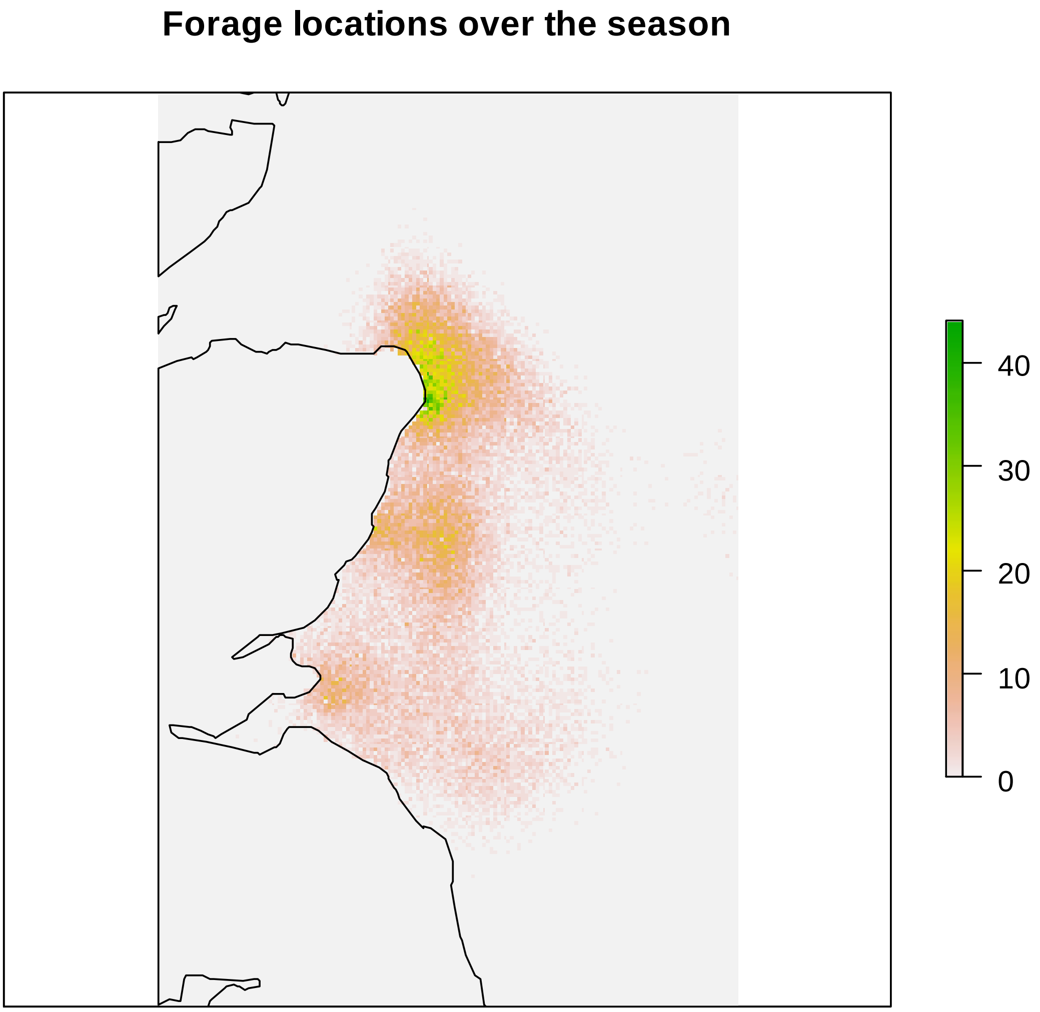

Figure 2:1. Bird density map for Kittiwakes. GPS data were available for birds at all four SPAs. The greater densities with increasing latitude reflect the larger colony sizes in the north of the study area.

GPS data on guillemots at Buchan Ness are more limited than those for any other species-by-SPA combination, and expert judgement suggests that they may not be representative (with most points occurring very close to the colony); these data are therefore excluded from our analyses, and predicted bird densities for guillemots at Buchan Ness are based on the distance to source SPA and distance to next nearest SPA effects that have been estimated using data for the remaining guillemot colonies.

2.1.3 Estimation of prey densities

We consider two scenarios for estimating the relative density of prey at different locations:

a) we assume that the density of prey is proportional to the suitability values that were estimated from the bird GPS tracking data (“heterogeneous prey”); and

b) we assume that the density of prey is uniform across the entire Forth/Tay area (“homogeneous prey”).

The heterogeneous prey scenario is based on the assumption that the distribution of foraging locations of birds across prey will, after accounting for the accessibility of locations to birds, be proportional to the distribution of prey across space. The homogeneous prey scenario assumes that prey densities are unrelated to the density of bird foraging locations. These represent two extreme scenarios, which form the ends of a continuum: it is likely, in reality, that bird foraging densities are related to prey densities but that they are not completely determined by prey densities. Comparing output from the two approaches therefore allows for a qualitative assessment of our uncertainty that is involved in accurately understanding the interaction between birds, wind farms and prey.

For the species-by-SPA combinations without adequate GPS tracking data (Razorbill at Fowlsheugh, Razorbill at St. Abbs, Guillemot at Buchan Ness) it is only possible to consider the uniform prey scenario. Therefore, prey density at colonies without GPS data was assumed to be uniform across the foraging range of the species. In areas of overlap between the foraging range of a colony without GPS data and a colony with GPS data, prey density was estimated from the GPS data.

2.2 The foraging model

We developed a model to simulate the feeding locations of multiple colonies over the chick-rearing period. The model simulated seabird foraging decisions assuming individuals were acting in concordance with optimal foraging theory. Each individual selected a suitable location for feeding during each foraging trip based on the spatial distribution of birds that was estimated from GPS tagging data using the approach of Section 2.1.2. Subsequent behaviour of birds was then simulated incorporating realistic assumptions and constraints derived from observed behaviour. The model simulated foraging behaviour for five species (note that exploratory analyses were carried out on four species excluding gannet, and final runs on all five species – see Section 2.6). The model was created and run using the statistical software R v 2.14.1(R Development Core Team 2012).

Fundamentally, we assumed that the foraging behaviour of individual seabirds was driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of con-specifics. Choice of foraging location was dependent upon prey density distribution maps produced using the GAM suitability models (Section 2.1.3). Flight cost was determined using linear distances from the central foraging location (SPA). We also obtained data on the bathymetry of the area from the British Geological Survey under licence (http://www.bgs.ac.uk/products/offshore.html) to determine the maximum possible dive depth for a bird foraging at each location.

The values for parameters are given in Table 2:4 and the sources for these values in Appendix D.

2.2.1 Selection of foraging location

Foraging location was selected by an individual bird based on the estimated distribution of foraging locations (that was calculated empirically using GPS tracking data; Section 2.1.2). Birds were apportioned to foraging locations in proportion to the estimated probability density from the bird distribution model for each cell in the simulated seascape (cell size 1.67km x 1.67km). The selection process was done stochastically using random numbers and cumulative density distributions of the predicted probability of foraging per cell. The density estimation is specific to each colony, such that colony level effects such as distance from colony and inter-colony density-dependent competition are included within the foraging location choice of all simulated birds.

Once all simulated birds had been assigned to a foraging location, the estimated prey density at each location (Section 2.1.3) was multiplied by total overall prey abundance to find the prey abundance associated with each grid cell in the simulation. No observational data were available on prey abundance; an overall prey abundance value for each species was therefore determined by running the foraging model using a range of possible values for total prey abundance (without any wind farms present) and choosing the value that gave the best match to empirical data on key bird traits (adult mass and survival, chick mass and survival, nest attendance rates, foraging hours and flight hours) during the breeding season (see Appendix F, section F1).

The daily energy requirement (DER) of each bird was then determined (see sections 2.2 & 2.3), and a calculation was made for each cell to determine if all birds that chose to forage there were able to meet their DER. This was done by comparing the total prey abundance within each cell to that required by summing the DER of all birds that have chosen to forage within that cell. Any resulting energy deficit was then averaged across all birds within the focal cell to determine the proportion of each bird’s DER that they were able to meet at that location. These deficits were recorded and used to update the bird’s body mass and that of its chick, and its subsequent behaviour at the next time step.

The total prey abundance per cell was then combined with the DER of each bird in the focal cell (via the functional response, see Section 2.2.2.1) and the total number of birds that chose to forage within the focal cell (via the interference competition equation, see Section 2.2.3) to determine the time each bird must spend foraging to meet its DER (or proportion thereof) in each cell. As a result, for each day and simulated bird, the model simulated the total time spent foraging, the total time spent in flight, and the proportion of the DER of the bird and chick that it was able to meet.

This process is summarised in Figure 2:2.

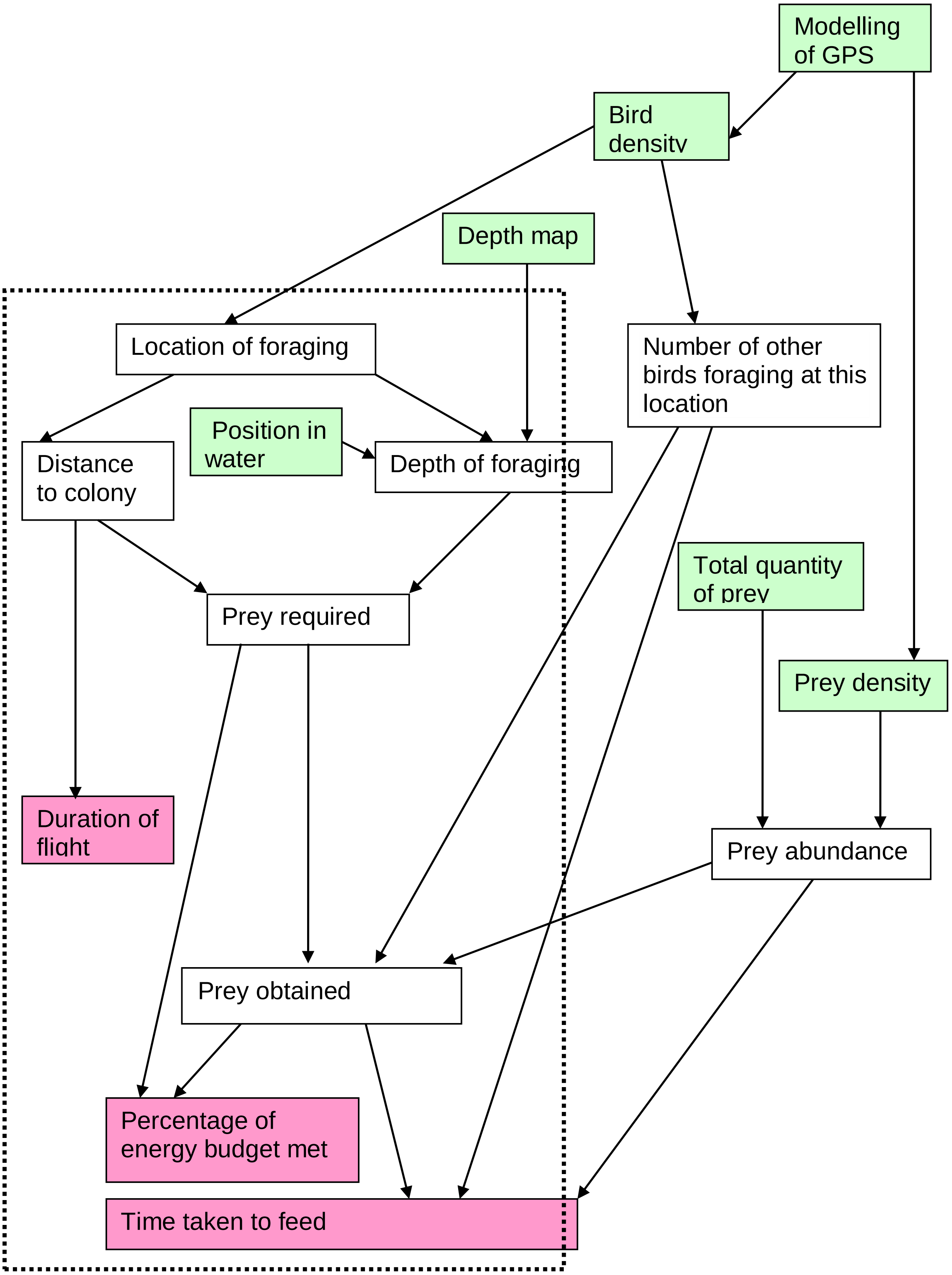

Figure 2:2: Diagram of foraging model structure and relationships between variables. Input data are in green boxes and model output used to estimate bird energy budgets are in pink boxes. All boxes contained within the dotted box represent the core of the foraging model functions, and are stochastic variables estimated for each simulated bird.

2.2.2 Intake rate and intra-specific interference competition

Two of the most important behavioural mechanisms governing the acquisition of energy in seabirds are the functional response (how intake rate varies with prey density) and intra-specific competition (how intake rate of an individual is affected by the density of other birds foraging in the same location). We created a set of rules determined from optimal foraging theory assuming that birds would employ behaviours to maximise daily energy gain up to an upper limit set from observational data on the DER of each species.

2.2.2.1 Functional response and achieved intake rate

Prey availability is the principal determinant of the amount of time an animal must spend foraging to meet its DER. Typically this relationship is modelled using a functional response equation that relates prey intake rate to the density of available prey at a particular foraging location. Empirical functional response estimates for seabirds are lacking, however using empirical data on the time spent foraging by 18 guillemots (Wanless *et al*. 2005) we estimated the key components of the functional response assuming a Type III response (Enstipp *et al.* 2007). We set a maximum prey intake rate per minute for each species based on available data (see Table 2:4). Our approach was to take the maximum mass of single prey and the mean prey capture rate to obtain an estimate of the maximum prey capture rate, based on empirical data (Birt-Friesen et al. 1989; Humphreys 2002; Lewis et al. 2003; Daunt et al. 2006; Harris & Wanless 2011; Thaxter et al. 2013, unpublished data). We obtained plausible values for all species except gannet. For this species, we set the maximum single prey recorded (559.4g, Lewis et al. 2003) as the maximum prey intake rate per minute, on the assumption that a second prey could not be obtained in that time period. We estimated that intake rate would not increase significantly until a certain prey density of prey per km^2 was exceeded. The parameters controlling the shape of the functional response (rate of increase in intake rate with increasing prey, and density of prey at which intake rate starts to increase) were set using expert opinion such that resulting intake rates achieved by simulated birds matched with knowledge regarding each species. Having defined the form of the functional response, we then calculated the prey capture rate for each individual foraging at its chosen location by multiplying the prey intake rate by the diving efficiency. The diving efficiency was included to account for the extra energy cost incurred with increasing dive depth (Daunt & Wanless 2008). Unlike razorbills, puffins and gannets, which are pelagic feeders, guillemots feed both benthically and pelagically, with a bimodal distribution of foraging depth (Daunt *et al*. 2006; Thaxter et al. 2010). To allow for this, 50% of guillemots were assumed to dive to the seafloor or the maximum dive depth recorded for the species, whilst the remaining 50% of guillemots selected a dive depth from a normal distribution with a mean of 11.71m and a standard deviation of 8.07m derived from empirical data (Daunt & Wanless 2008). Kittiwakes do not dive, therefore the diving efficiency adjustment was not used for this species. For all species, the resulting prey capture rate was used to determine the foraging time required by each bird to meet its DER for each time step.

Independent intake rate was defined using a sigmoidal function (Type III functional response) with three estimated parameters (IR.max, IR.mu and IR.lambda) and prey density (x):

Independent intake rate: IR.max * exp(-exp((IR.mu * exp(1) / IR.max) * (IR.lambda - x) + 1)) * diving efficiency

Intra-specific interference competition

Intra-specific interference competition was included in the foraging simulation model using the model of Hassell & Varley (1969):

$$a_i = Q^*P^{-m}$$

where a_i is the intake rate of an individual bird, Q is the intake rate achieved by a single bird foraging alone (derived from the equation above in section 2.2.2.1), P is the density of other individuals foraging at the location and m is the interference coefficient. The interference coefficient determines the strength of the density dependent reduction in intake rate due to conspecific foragers sharing the same location. The intake rate achieved by a single forager, Q, was determined by the prey availability and functional response curve for each species, P was the number of simulated seabirds choosing to forage at each location, and the level of interference, m, was set at a realistic value for each species based on previous observations and expert opinion (Ens and Goss-Custard 1984, Dolman et al. 1995, Goss-Custard et al. 1995), and by matching model output (adult intake rates, adult body mass change, foraging time) to observed values for each species.

2.2.3 Cost model

We developed a cost model to accrue the amount of time and energy birds expended in reaching and foraging within their chosen location. This model was an expanded version of that used in Daunt & Wanless (2008) and Wanless *et al*. (1997) and separated the flight cost and foraging cost for each seabird to derive total energy expenditure.

2.2.3.1 Activity costs

Foraging cost for each bird was defined as the amount of time an individual was required to spend foraging to meet both its own DER and 50% of the DER of its offspring. On the first time step of the simulation, adult Daily Energy Expenditure (DEE) was drawn from a normal distribution parameterised using the mean and standard deviation of adult DEE from empirical data. On all subsequent days adult DEE was set to match the energy expended by each bird in the previous time step. Chick DEE remained constant throughout the simulation. We chose not to model increases in chick DEE with growth in order to constrain model processing time to reasonable limits. The species-specific mean daily energy requirement of chicks was based on provisioning rates recorded at colonies for each species (see Table 2:4). This calculation implies both parents share the costs of provisioning equally. The resulting required daily energy expenditure (DEE) was divided by an assimilation efficiency (0.78, Hilton *et al.* 2000) to obtain the total DER of the birds.

Daily time budgets of birds during chick-rearing demonstrate that adults divide their activities into four categories of behaviour – foraging, flight, time spent at the colony, and time spent resting on the sea surface (Daunt et al. 2002). For each bird, the foraging model returns the simulated flight time for each bird spent travelling to its chosen foraging location, and the simulated foraging time required to meet its required DEE. The remaining time during each model time period was split into time spent at the colony and time spent resting at sea. A minimum of one hour spent resting at sea was required for each bird (Daunt et al. 2002), and each bird attempted to spend half of each time step at the colony thereby preventing unattendance of its chick at the nest.

Any remaining time was split evenly between time at the colony and time resting at sea. If a bird could not meet its DEE in the time available without unattending its nest, a set of decision rules were implemented based on the energy state of the adult. If an adult had a body mass that exceeded 90% of the mean body mass of an adult for that species at the start of the breeding season (based on empirical data; Appendix D) then it would return to its nest regardless of its achieved DEE for that day to prevent leaving its chick unattended. However, if its body mass was between 80-90% of mean initial mass then it would continue to forage to meet its required DEE for that time step, thereby leaving its chick unattended if its partner was not at the nest at that time.

We derived the flight cost incurred by each seabird by calculating the time taken to travel the distance both to and from the chosen foraging location assuming a mean flight speed for each species.

We then multiplied the time spent carrying out each of these activities by species- and activity-specific energy costs available from the literature (i.e. cost of flight, foraging, resting at and time at colony; Appendix D). In addition, we incorporated the energy cost of warming food to derive the total DER for each bird (Gremillet et al. 2003). These DER were converted into grams per day assuming a mean energy density of 6.1 kJg^{-1} (Harris *et al*. 2008).

2.2.4 Behavioural modes for adults and chicks and subsequent decisions

At the end of each time step each adult was assigned to a behavioural mode that determined its behaviour in relation to chick rearing in the following time step. Behavioural modes for adults were determined by a critical mass threshold below which the adult is assumed to defend its own survival above that of its chick. Therefore, when an adult's body mass was greater than 90% of the average initial pre-breeding season mass for the species (based on empirical data; Appendix D) it would not unattend its chick, even if it had not met its DEE. However, if its body mass was between 90% and 80% of the average pre-breeding season mass it would favour itself, and leave its chick unattended in order to achieve its required DEE. Adults with a bodymass of less than 80% of the average pre-breeding season mass switch to nest abandoned mode and give up the breeding attempt. This necessarily means that their partner also gives up the breeding attempt, resulting in chick death. Should an adult's body mass fall below that deemed critical for survival (60% of the average pre-breeding season adult body mass for each species), the adult is assumed to have died and is removed from the simulation. This causes its partner to switch to nest abandoned mode for the remainder of the simulation.

Behavioural modes for the chick are determined by the body mass of the chick at the start of each day. If the chick's body mass falls below a critical threshold ('chick_mort_f', Table 2:4) it is assumed to have died and is removed from the population, causing its parents to switch to 'nest abandonment' behaviour. Because the value of this parameter is not known for most of the species, it was fit within the model such that model output on chick survival rates in relation to observed data for each species (Table 2:4). If the time a chick's parents spent attending the nest fell below a critical threshold the chick was assumed to die through exposure and was removed from the population ('unnattendance_hrs', Table 2:4) – again causing its parents to switch to 'nest abandonment' mode. We also incorporated an increased risk of predation if a chick was left unattended by both parents for an amount of time less than that which would result in its death through exposure. This was modelled as a probability of death that increased linearly with time left unattended, up until the time threshold was reached at which point the chick was assumed to have died from exposure or predation ('unnattendance_hrs', Table 2:4). Again, because there are no data on which to set a value for the length of time a chick is unattended that is likely to result in death we estimated the value of this parameter by matching model output (chick survival) to observed values for each species (Table 2:4).

For burrow-nesting puffins, once the chick reached a certain energy deficit (80% of the body mass of a chick that have been provisioned with all its requirements at every previous time step) it was assumed the chick ventured to the entrance of the burrow and suffered a linearly increasing predation risk with its body mass deficit as a consequence (between 60% and 80%). Above the threshold body mass value of 80% there was no risk to the chick from unattendance by parents. Below the lower threshold of 60% the chick was assumed to have died.

2.2.5 Adult body mass change

All adult birds updated their body mass at the end of each day based on the energy they gained and expended in foraging and other activities

If the adult was able to successfully meet its estimated DER within the constraints of the time period its body mass was assumed to remain constant. However, if the adult was unable to meet its estimated DER within each time period its mass decayed according to the following equation:

Adult mass at time t = adult mass at time $t-1$ + (adult mass at time $t-1$ ^ (*adultmass.a*proportion*)) – (initial adult mass ^ *adultmass.a*)

where *adult_mass_a* (Table 2:4) was a parameter controlling the extent to which the daily energy deficit results in a reduction in adult body mass at the next time step, and 'proportion' was the percent of daily DEE achieved by the bird. This parameter was estimated from empirical data on the decline in body mass of adult birds during the breeding season (Appendix F, section F1).

2.2.6 Chick growth

Chick growth between days t-1 and t was a function of the mass on the previous day (t_{-1}) and the food it received on day t. The new mass at the end of each day was assumed to be related to the mass on the previous day using a sigmoidal function, such that chick growth increased with food provided but reached an asymptote at a maximum growth rate per day (whose value was fixed based on observed data; Appendix D). Similarly, chicks lost mass when adults failed to provide enough to satisfy the chick's DEE, but again mass loss was curtailed such that mass loss per day matched observed patterns. The assumed relationship was of the form

Chick mass at time t = chick mass at time $t-1$ + (*chickmass.a* * exp(-exp((*chickmass.mu* * exp(1) /*chickmass. a*) * (*chickmass.lambda* - x) + 1)))

Where *chickmass.a* was the maximum mass gain (g) per day, *chickmass.mu* was the rate at which growth rate increased with the increase in food provided by the adult, and *chickmass.lambda* was the mass of food (g) provided by the adult at which chick growth was positive, and '*x*' was the amount of food provided by the adult (g). The equation requires an estimate for the chick's assimilation efficiency (a.e, which was assumed to equal that of an adult).

Because life history theory demonstrates that long-lived species such as seabirds will prioritise their own survival over that of their offspring, we created a variable in the model ('adult_priority', Table 2:4) that determined the extent to which an adult bird favoured its own energy intake over that of providing for its chick. The value of this parameter can take on values from zero to one. A value of zero meant the adult favoured the chick above its own survival (i.e., all food acquired by the adult was supplied to meet the chick's DEE and any remainder was left for the adult); a value of one meant that the adult favoured itself over its chick (i.e., all food acquired by the adult was used to satisfy the adult's DEE and any remainder went to its chick). The values for this parameter for each species were set such that observed model output (adult mass change, chick mass change and survival) matched observed data (Appendix F, section F1).

2.2.7 Time steps and number of flights per day

Variable time steps were set for each species based on understanding of the behaviour of each species and the typical observed length of foraging trips (Appendix D). For Kittiwakes the model time step was 36 hours with 30 time steps (amounting to a 45 day chick-rearing period); for guillemot and razorbills the model time step was 24 hours with 21 time steps (amounting to a 21 day chick-rearing period); for puffins the model time step was 24 hours with 40 time steps (amounting to a 40 day chick-rearing period); and for gannets the model time step was 72 hours with 30 time steps (amounting to a 90 day chick-rearing period).

The number of flights per day was determined by the success of each bird's first simulated flight at the start of each time step. The number of flights for all species varied between one and three, with the exception of puffins where the number of flights varied between one and four per time step (in accordance with observed data; Appendix D). Given the lack of precise mechanistic understanding for the context- and state-dependence of foraging decisions in seabirds, such as the number and length of foraging trips to make per day, we formulated the foraging model such that the behaviour of birds matched empirical data on observed numbers of trips per day and the approximate duration of time spent foraging and time spent in flight. As such, at the start of each time step one foraging trip was simulated for each individual in the population. If an individual was able to meet one third of the combined DEE for itself and its chick in one third of the time step then the individual simply repeated the same foraging trip two more times to create the energy and time budget for that individual for the entire time step (resulting in three foraging trips to the same location per time step; note that no temporal depletion of prey occurred with the model timestep). If an individual could not meet the combined DEE in one third of the time step, we then calculated if it could meet half of its requirements in one half of the time step. If this were the case, that individual repeated the initial foraging trip one more time to create the final time-energy budget for that bird (resulting in two relatively longer foraging trips to the same location in the time step). Similarly, if an individual could not meet its combined DEE in one third or one half of the time step, we determined if it could meet its requirements within the entirety of the time step, and if so then the individual made just one, longer foraging trip to a single loaction per time step.

However, if the individual could not meet its combined DEE using any of the above possibilities, we assumed that bird would attempt to make two foraging trips within the time step, and randomly selected a second simulated foraging trip from another bird that had made two foraging trips. Therefore the bird would make two foraging trips, each to a different location. These birds would not meet their full requirement for the time step.

2.2.8 Sources and values for parameters in the foraging model.

Where available we set values for all parameters in the foraging model from published literature or CEH data from the long-term study on the Isle of May. When values were not available, parameters were fit such that they matched expert opinion and led to model output that matched empirical data on adult body mass change, chick growth and chick survival, foraging time and flight time. All parameters are listed in Table 2:4 below, and sources are given in Appendix D.

Parameter description	Parameter name	Species 1	Species 2	Species 3	Species 4
Short name	SID	Gu	Rz	Kw	Pu
Species name	Name	Guillemot	Razorbill	Kittiwake	Puffin
initial body mass mean, g	BM_adult_mn	920.34	600	361.64	392.8
initial body mass standard deviation, g	BM_adult_sd	57.44	87	36.14	21.95
Critical mass below which adult is dead, proportion of mean mass	BM_adult_mortf	0.6	0.6	0.6	0.6
Critical mass below which adult abandons chick, proportion of mean mass	BM_adult_abdn	0.8	0.8	0.8	0.8
Chick initial body mass mean, g	BM_chick_mn	75.8	64.9	36	42.2
Chick initial body mass standard deviation, g	BM_chick_sd	1	6.3	2.2	3.7
Critical mass below which chick is dead, proportion of initial mass	BM_Chick_mortf	0.725	0.8	0.6	0.6
Critical time threshold for unattendance at nest above which a chick is assumed to die through exposure or predation, hours	Unnattendance_hrs	96	96	18	NA
Mean adult DEE for initial DEE, kJ per day	adult_DEE_mn	1489.1	1231.89	802	871.5
Standard deviation for initial adult DEE,	adult_DEE_sd	169.9	95.3	196	80

kJ per day					
chick energy expenditure, kj per day	chick_DEE	221.71	195.67	525.71	325
maximum prey intake rate, g min-1	IR_max	23.17	28.47	22.98	19.71
slope of the functional response assuming a Type III response	IR_mu	0.0008	0.001	0.001	0.006
intake rate does not increase significantly until a prey density of IR_lambda individuals per km2 is exceeded	IR_lambda	9000	10000	8000	1500
forage interference coefficient	IR_m	0.15	0.6	0.3	0.6
Average speed in flight, metre per second	flight_msec	19.1	16	13.1	17.6
Number of trips carried out per day (from observed data)	Nforagetrips	2.02	2.35	1.9	3.34
fraction of dives assumed to be pelagic not to sea bed	pelagic	0.5	1	1	1
mean diving depth (set to 0 for non diving species)	forage_depth_mn	11.71	6.5	0	4.15
sd of diving depth (set to 0 for non diving species)	forage_depth_sd	8.07	5.2	0	2.1
assimilation efficiency	assim_eff	0.78	0.79	0.74	0.78
Diving efficiency parameter 1	diving_eff1	0.36	0.12	NA	0.12

Diving efficiency parameter 2	diving_eff2	-0.0021	0.0005	NA	0.0005
kj per gram from prey	energy_prey	6.1	6.1	6.1	6.1
kJ per day cost of nesting at colony	energy_nest	1168.91	932.17	427.75	665.41
kJ per day cost of flight	energy_flight	7361.72	3581.34	1400.74	3113.85
kJ per day cost of resting at sea	energy_searest	810.28	646.15	400.57	461.24
kj per day cost of foraging	energy_forage	1894.9	1421.45	1400.74	974.97
kJ per day cost of warming food	energy_warming	65.07	47.317	34.15	35.83812
observed mean time attending nest	time_nest_mn	11.86	11.73	11.23	NA
observed sd of time attending nest	time_nest_sd	3.48	4.96	3.9305	NA
adult mass gain parameter	adult_mass_a	0.44	0.4	0.4	0.45
chick mass gain parameter	chick_mass_a	20	7.25	12	12
chick mass gain parameter	chick_mass_mu	0.5	0.5	0.5	0.35
chick mass gain parameter	chick_mass_lambda	12	5	60	15
Division of food between parent and chick	Adult_priority	0.575	0.75	0.5	0.75

Table 2:4 Values for all parameters used in the foraging model runs with 1000 birds. Please note that parameter estimates for gannets are in Table 2:8, since they were not included in exploratory runs. See Appendix D for source references.

2.3 Effect of wind farms

2.3.1 Impact scenarios

Two main behavioural responses to wind farms were simulated in the model: displacement and barrier effects.

At the start of each simulation run, individuals were assigned as either birds that would chose to be displaced if their foraging location fell within the wind farm location (‘displacement-susceptible birds’), and/or as birds that would choose to fly around the wind farm (‘barrier-susceptible birds’) if their chosen foraging location lay on the far size of a wind farm. These values were fixed for the lifetime of each bird meaning that no habituation to wind farms occurred. The proportion of birds that were assigned to be displacement-susceptible and barrier-susceptible depended upon the scenario. In the exploratory scenarios, we considered scenarios in which (a) 100% of birds were both displacement-susceptible and barrier-susceptible, (b) 100% of birds were displacement-susceptible but none were barrier-susceptible, (c) 100% of birds were barrier-susceptible but none were displacement-susceptible and (d) 50% of birds were displacement susceptible and 50% of birds were barrier-susceptible.

Within the latter scenario (50% displaced / 50% barrier) the decision on allocating birds as barrier-susceptible was independent of the decision to allocate birds as displacement-susceptible – it follows that approximately 25% of individuals were displacement-susceptible but not barrier-susceptible (i.e., content to travel through a wind farm but not forage within it), approximately 25% of individuals were barrier-susceptible but not displacement (content to forage within the wind farm but would avoid flying through it), approximately 25% of individuals were neither barrier-susceptible nor displacement-susceptible (wind farm has no effect on behaviour), and approximately 25% of individuals would be susceptible to both displacement and barrier effects (not content to forage within or travel through a wind farm).

2.3.2 Spatial model for displacement and barrier effects

Displacement and barrier effects were determined using a set of zones created around the footprint of each wind farm (Figure 2:3).

If displacement-susceptible birds were simulated to choose a foraging location within the footprint of the wind farm, including a 1km exclusion area, as agreed by the steering group (Zone 4, Figure 2:3) then we assumed that they would instead chose a new foraging location within a 5km buffer zone of the wind farm (Zones 3&5, Figure 2:3). Under heterogeneous prey conditions the prey density at the new location may either be higher or lower than the density at the location that the bird had originally intended to visit. Displacement always incurred an additional outward travel cost, to represent the extra flight cost associated with travelling to the new foraging location (calculated as a direct line between the initial and final foraging locations). Displaced birds that selected a new foraging location in Zone 3 (Figure 2:3; the near-side of the wind farm) occurred no additional travel cost on the return journey, simply returning to the colony in a straight line. However, displaced birds that selected a new foraging location in Zone 5 (Figure 2:3; the far-side of the wind farm) incurred a second additional travel cost on the return journey to represent to consequences of having to travel around the wind farm on their return to the colony (sampled from a normal distribution with a mean of 20km and a standard deviation of 5km).

If barrier-susceptible birds were simulated to choose a foraging location in the far zone of the wind farm (Zone 6, Figure 2:3) then these birds continued to forage at the same location but they incurred additional outward and return travel costs (each being sampled from a normal distribution with a mean of 20km and a standard deviation of 5km in initial exploratory runs). More sophisticated estimates of barrier cost were incorporated into the model in later versions and runs (see Section 2.6.2).

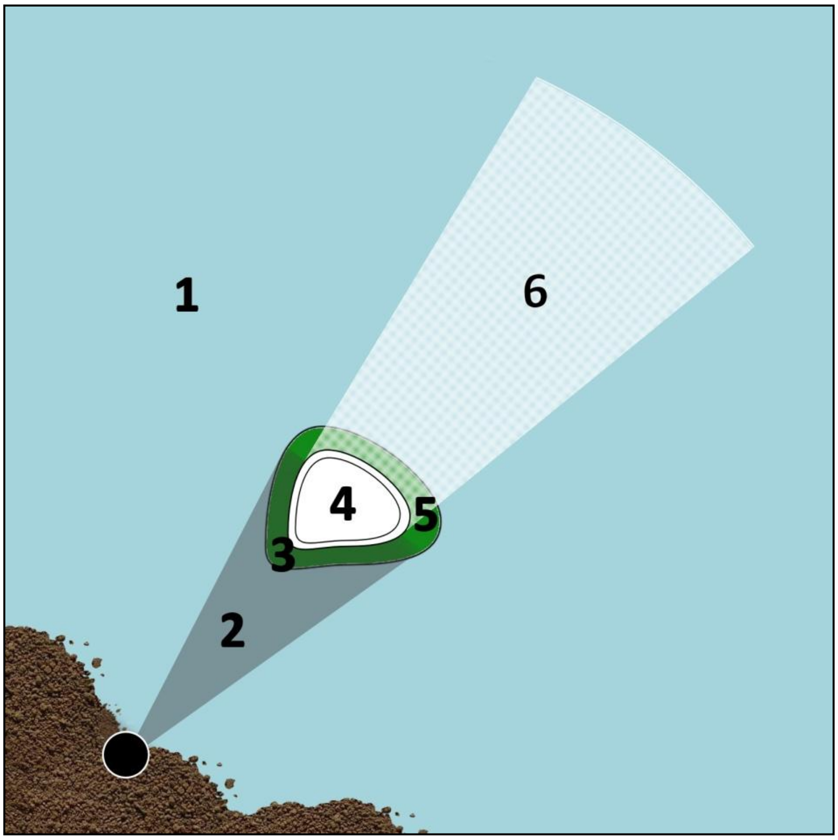

Figure 2:3: The zones used to determine the behavioural response of foraging seabirds to wind farms in relation to their colony. Zone 4 represents the wind farm footprint supplied by each developer, with the addition of a 1km exclusion buffer zone. The large black dot represents the colony location. Zones 3 to 6 define the behavioural response of foraging birds, as described in the text (Section 2.3.2).

2.4 Translating impacts on adult mass into impacts on adult survival

There are three key outputs from each run of the foraging model:

1. the status of each chick (alive / dead) at the end of the breeding season;
2. the status of each adult (alive / dead) at the end of the breeding season;

3. the mass of each living adult (in grams) at the end of the breeding season.

The first two of these quantify the chick and adult survival rates during the breeding season. The final quantity provides an indirect way of quantifying the adult survival rate during the subsequent winter period. We make use of published relationships between adult mass and annual survival rates in order to convert simulated adult mass values into survival rates. We do this in the same way for baseline simulations and for simulations that have been generated in the presence of wind farms, and we are thereby able to assess the impact of the wind farm upon the adult survival rate.

The procedure for converting individual adult mass values into an overall estimate of adult survival for each simulation run is summarised in Figure 2:4. Our approach is essentially based on the assumption 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 standardized mass of individual i in run j and p_{ij} denotes the 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 a wind farm). 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 and s_0. It is worth noting that the approach also makes one substantive assumption - that the relationship between mass and survival is linear, on a logit-transformed scale – but it would be impossible in practice to check the validity of this assumption using currently available information.

The value of the baseline survival, s_0, is assumed to vary between species and prey scenarios (poor, moderate or good) – the specific values are based upon the results of the population modelling performed by CEH for Marine Scotland (Freeman et al. 2014), and the specific values are given in Table 2:5.

The strength of the relationship between mass and survival, b, is determined using values given in the published literature. For kittiwakes the value of b is based on the value given in Oro *et al*. (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, guillemot or gannet, so we assume that they have the same value as that estimated for puffin in the Erikstad *et al*. (2009) paper. The fitted relationship in Oro *et al.* 2002 is shown in Figure 2**:4**. The actual estimated values for b are 1.03 (Erikstad *et al*., 2009) and 0.037 (Oro *et al*., 2002), but it is important to note that these values cannot be directly compared because they relate to mass values that are expressed on direct scales: for kittiwakes the mass is standardized solely by deducting the mean mass under the baseline scenario (because the paper by Oro *et al*. 2002 expresses *b* in grams), whereas for other species the standardization also involves dividing by the standard deviation under the baseline scenario (because Erikstad *et al*., 2009, expresses mass as a unit-free quantity).

	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

Table 2:5: Baseline survival probabilities that are used in the conversion between adult mass and overwintering survival (Freeman et al. 2014).

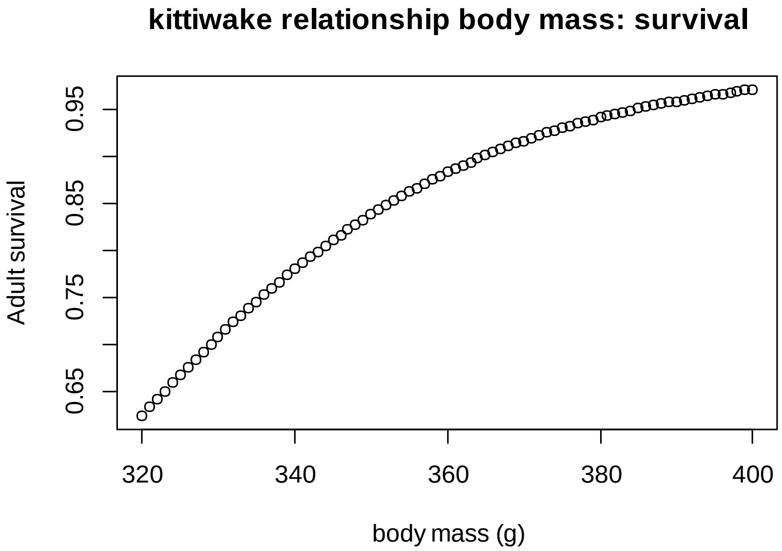

Figure 2:4: The published significant relationship for kittiwakes relating end of breeding season body mass to subsequent adult survival (Oro *et al.* 2002).

2.5 Exploratory model runs

This stage of the project involved running the model with 1000 birds for all scenarios.

The foraging model was used to generate five simulations of foraging for four species under each of 66 scenarios – the results that are presented (in Appendix F) are therefore based upon 1320 individual runs of the foraging model. Five simulation runs are used for each scenario in order to provide a quantitative indication of uncertainty – a full description of the way that we accounted for uncertainty in the exploratory runs is described in Appendix E.

The 66 scenarios represent all possible combinations of six scenarios regarding prey quantity and distribution (Table 2:6) and eleven scenarios regarding wind farm effects (Table 2:7).

Poor	Homogeneous
Poor	Heterogeneous
Moderate	Homogeneous
Moderate	Heterogeneous
Good	Homogeneous
Good	Heterogeneous

Table 2:6 Description of prey-related scenarios.

The wind-farm related scenarios primarily reflect the decision making process (which wind farms are being proposed: Neart na Gaoithe, Inch Cape, Round 3 Alpha, Round 3 Bravo, or all four combined), but also include scenarios that allow us to assess the impact of uncertainties related to the extent to which displacement and barrier-effects occur, and those related to the buffer distance around the wind farm (Table 2:7).

Wind farm(s)	% of displacement-susceptible birds	% of barrier-susceptible birds	Buffer around wind farm
None (baseline)	Not relevant	Not relevant	Not relevant
Neart na Gaoithe	100	100	1km
Neart na Gaoithe	100	100	0.5km
Neart na Gaoithe	100	100	0km
Inch Cape	100	100	1km
Round 3 Alpha	100	100	1km
Round 3 Bravo	100	100	1km
All four	100	100	1km
All four	100	0	1km
All four	0	100	1km
All four	50	50	1km

Table 2:7: Description of wind-farm related scenarios.

The full results of the exploratory model runs are given in Appendix F, together with the results of the uncertainty analysis.

2.6 Final model runs

2.6.1 Revisions to the full model

One of the key findings of the exploratory analysis was the result that there was a high degree of stochastic variation between different sets of 1000 birds: this suggested that it was possible to reduce uncertainty substantially by re-running the model with larger samples of birds. For computational reasons, however, it would not have been feasible to do this for all scenarios.

A set of ten key scenarios were therefore identified by MSS: these involved running each of the four wind farms, and the cumulative effects, under the two assumptions regarding the spatial distribution of prey (heterogeneous and homogeneous). For all scenarios the prey quantity was assumed to be moderate, the percentage of birds affected by barrier and displacement effects was assumed to be 60% (except for kittiwake, where it was assumed to be 40%; based on advice from JNCC/SNH), and the buffer around the wind farm was assumed to be 1km (as agreed by the steering group).

For the final simulations the ten short-listed scenarios were each run with 20,000 birds. Increasing the number of simulated birds necessitated changing the value of the foraging interference coefficient (m) to account for the increased density of birds within each foraging location. The new values for m were determined by matching model output for simulated intake rate with empirical data (Appendix F, section F1) or using expert opinion, and were as follows: guillemot 0.03; razorbill 0.14, kittiwake 0.08; puffin 0.2725.

In addition, we made a correction to the way the model accounted for cumulative effects of wind farms. This was incorrectly calculated in the exploratory model runs and as a result exploratory results were underestimating the cumulative effects of combined wind farms on each species.

The outputs from these simulations are in Section 3. Results are presented for those SPAs that were identified by MSS as being of interest, except those that we found did not interact with birds. Thus, Buchan Ness was excluded, as were the St. Abbs results for guillemot and the St. Abbs and Fowlsheugh results for razorbill - although the models have been run using all SPAs.

2.6.2 Use of a “fast model”

Computational time is a key limitation in using the foraging model that we outlined in Section 2.2. In order to explore wind farm impacts in more detail we developed a “fast” version of the model – the “fast model” runs much more quickly than the full model, but it does so by removing some of the biological realism within the full model.

The fast model is designed to be as identical as possible to the full model, but there are some substantive differences between the two models – some of these differences arise because there were mechanisms that we could not, for computational reasons, include within the fast model, and some arise because we chose to add some desirable features to the fast model that could not readily have been added to the full model. These methodological differences result in differences in the effect sizes recorded in the two models.

The differences between the fast and full models are:

1) the fast model is substantially faster than the full model to run, and can therefore be used to explore new scenarios, or to run sensitivity analyses, much more readily than the full model;

2) the full model allows birds to visit a different location if they will fail to meet their DER by visiting their original location; the fast model does not;

3) the fast model does not estimate cumulative effects;

4) the fast model matches birds between scenarios, so that the assessments of a wind farm quantify the impact of the wind farm on a particular set of birds (rather than comparing a set of birds that have been impacted by the wind farm against a different set of birds that have not).

5) the split in time between time on the nest and time resting at sea is slightly more realistic in the fast model than the full model (with birds favouring spending time at the nest over resting at sea to a greater degree than in previous model versions);

6) the fast model allows for variation in initial mass between adult birds.

7) the fast model has a smaller cell size (0.5x0.5km vs 1.67x1.67km)

8) the fast model includes barrier effects in a more realistic way than the full model

9) the fast model displaces birds into Zones 3 and 5 (the 5km buffer zone around each wind farm) in proportion to the estimated density of birds in those zones. This is in contrast to the full model, which displaces birds randomly into Zones 3 and 5 with no relation to the estimated bird density in those areas;

Points 1, 4, 7 and 8 can be regarded as the key advantages of the fast model, and points 5, 6 and 9 as minor advantages of it, whereas Points 2 and 3 can be regarded as the key advantages of the full model. These differences are explained in more detail in Appendix G.

We used the fast model to estimate the impact of the wind farms on gannets, based on a GIS tracking data set comprising 13 individuals in 2003 (CEH unpublished data; other GPS data collected at this colony were not available to the project). Earlier models were not run for this species due to time constraints and because this species was of lowest concern. Parameter values for gannets are listed below (Table 2:8). Baseline survival probability used in the conversion between adult mass and overwintering survival was 0.92 under moderate conditions (Wanless et al. 2006; WWT Consulting 2012).

Mass	G	BM.adult.mn	2998
Mass	G	BM.adult.sd	234
Mass	G	BM.chick.mn	79.3
Mass	G	BM.chick.sd	11.2
Time	Hours	time.rest.minimum	1
Time	Hours	Unattendance.hrs	96
Speed	m/s	flight.msec	14.9
Depth	m	forage.depth.mn	5.99
Depth	m	forage.depth.sd	5.03
Energy	kJ/day	energy.nest	2512.56
Energy	kJ/day	energy.flight	11316.9
Energy	kJ/day	energy.searest	3227.48
Energy	kJ/day	energy.forage	11316.9
Energy	kJ/day	energy.warming	170.29
Energy	kJ/day	adult.DEE.mn	4865
Energy	kJ/day	adult.DEE.sd	450
Energy	kJ/day	chick.DEE	1593.3
Energy	kJ/gram	energy.prey	6.1
Other	trips/day	Nforagetrips	0.38
Other		BM.adult.mortf	0.6
Other		BM.adult.abdn	0.8
Other		BM.chick.mortf	0.8
Other		adult.priority	0.5
Other		assim.eff	0.75
Other		diving.eff1	1
Other		diving.eff2	0
Other	g/min	IR.max	559.4
Other		IR.mu	0.01

Other	indiv/km2	IR.lambda	25000
Other		m	0.2
Other		adult.mass.a	0.5
Other		chick.mass.a	110
Other		chick.mass.mu	0.35
Other		chick.mass.lambda	10

Table 2:8 Parameter values used to simulated foraging gannets in the 'fast model'. See Appendix D for source references.

2.6.3 Adjustment

The full and fast models both had important features that could not be captured within the other model without substantial rewriting of the model code (which was not feasible within the timeframe of the project). We therefore draw inferences about the overall impacts of wind farms by synthesising the results obtained using the two analyses into a single assessment of impact.

2.6.3.1 Individual wind farms

The overall impact of individual wind farms on survival (either adult or chick) was assessed by calculating:

Estimated % change in survival = % change in survival from full model * adjustment factor

where

adjustment factor = % change in survival from fast model run using new barrier effects /

% change in survival from fast model run using old barrier effects

If the full model estimates a reduction of 4%, for example, and the fast model estimates reductions of 2% and 1% (respectively) under the old and new barrier effects, then this formula implies that the adjustment factor is 0.5 and the estimated reduction in survival is 4 * 0.5 = 2%.

It is important to note that the full model was always run using the old barrier effects (sampled from a normal distribution with a mean of 20km and a standard deviation of 5km). This approach assumed that the negative effect of the wind farm on survival would be reduced by moving from the old barrier effect calculations to the new barrier effect calculations, and assumed that the magnitude of this reduction would have been the same in the full model (if we had been able to run it using the new barrier effects). It assumed that the full model gave a more realistic estimate of the impact associated with the old barrier effects than the fast model, so the fast model output was used solely to account for the effect of improving the barrier effect calculations.

The adjustment factor will generally be close to one for scenario-by-wind farm-by-SPA combinations where the wind farm effects tend to be associated primarily with displacement rather than barrier effects, and will be relatively small for combinations that are dominated by barrier effects.

The adjustments may not be stable or robust if we are dealing with wind farm effects that are actually very small, because in these situations the estimated magnitude of wind farm effects (and even the estimated sign of these effects) will be heavily influenced by the effects of stochastic noise. The calculations may also be inappropriate if the models are genuinely behaving in unusual ways (e.g. if the shift from the old to new barrier effect calculations actually increases the magnitude of the barrier effect). It is therefore desirable to determine which of the adjustment factors have been estimated reliably and which have not. We achieved this by generating an additional 50 stochastic runs from the fast model for each scenario. These additional runs were used to quantify the degree of uncertainty associated with each adjustment factor, and thereby to assess the reliability of the values that were generated within our main simulations. We quantified the reliability of an adjustment factor by calculating:

d = Max(Abs(Main adjustment factor – 25% quantile of adjustment factors from additional runs),

Abs(Main adjustment factor – 75% quantile of adjustment factors from additional runs))

If the value of *d* is large then the additional simulations suggest that:

a) there is considerable uncertainty regarding the value of this adjustment factor; or

b) the adjustment factor used in the main assessment is well beyond the range of values that other stochastic runs of the model would typically have generated.

In both situations we classified the adjustment factor used in the main assessment as being “unreliable”. If the value of *d* was small then the adjustment factor was classified as “reliable”- in the sense that similar values of the adjustment factor were typically produced through additional stochastic runs from the model. The exact cut-off used in distinguishing between “unreliable” and “reliable” results was subjective, so we classified the results of our assessments into three groups:

1) low reliability (*d* greater than 0.2)

2) moderate reliability (*d* between 0.1 and 0.2)

3) high reliability (*d* below 0.1)

When presenting the results we coloured the adjustment factor values – and corresponding adjusted estimates – as light grey (low reliability), yellow (moderate reliability) or pink (high reliability).

2.6.3.2 Cumulative effects

The fast model cannot be used to generate cumulative effects, so the adjustment factor was, in this case, calculated based on the estimate of the sum of effects of individual wind farms as generated by the unmodified and modified versions of the full model. More specifically, it was equal to

Adjustment factor = SUM(Effect of wind farm *i* within full model) / SUM(Adjusted effect of wind farm *i*), and the estimate is then equal to

Estimated cumulative % change in survival = cumulative % change in survival from full model * Adjustment factor

We only used wind farms with moderate or high reliability in the calculation of cumulative effects (because the adjusted estimates for wind farms whose adjustment factors were classed as having low reliability were not likely to be meaningful), and we therefore did not produce estimates of cumulative effects for scenario-by-SPA combinations for which all wind farm effects were estimated to have low reliability. We also present the results that were obtained solely by using wind farms with high reliability.

2.6.4 Sensitivity analysis

We used the fast model to test the sensitivity of adult and chick survival to the following parameters:

- Unattendance duration at the breakpoint after which chick death is certain to occur (all species except puffins)
- Chick body mass below which chick leaves burrow (puffins only)
- Adult body mass below which adult dies
- Adult body mass below which adult leaves chick unattended
- Chick body mass below which chick dies
- Adult priority of resourcing between self and chick
- Intraspecific competition (m)

The sensitivity analysis involved running the same model but setting the parameter value of interest at, in turn, minimum plausible and maximum plausible values. The outputs from these two models can then be compared to the version using mean values (version 0) to assess the sensitivity of model outputs to variation in the parameter of interest. Minima and maxima were based where possible on empirical data or expert judgement, but in the absence of these the maxima and minima were assumed to be, respectively, 50% high and lower than the parameter values that were used for assessing wind farm impacts. The disadvantage of a fixed percentage change of 50% is that this may bear little relation to the biology: for some parameters a change of 50% may be large, in terms of the underlying biology, and for other parameters it may be small. Thus, the best estimate of the true biological range is more appropriate to use. See Table 2:9 for details.

	Parameter	Guillemot	Razorbill	Kittiwake	Puffin	Gannet	Method
1	Unattendance duration at breakpoint (hours)	48-144	48-144	9-27		48-144	Expert judgement
2	Chick body mass below which chick leaves burrow (proportion)				0.7-0.9		Expert judgement
3	Adult body mass below which adult dies (proportion)	0.56-0.64	0.56-0.64	0.56-0.64	0.56-0.64	0.56-0.64	Empirical data
4	Adult body mass below which adult leaves chick unattended (proportion)	0.7-0.9	0.7-0.9	0.7-0.9	0.7-0.9	0.7-0.9	Expert judgement
5	Chick body mass below which chick dies (proportion)	0.5-0.9	0.5-0.9	0.5-0.9	0.5-0.9	0.5-0.9	Expert judgement
6	Adult priority of resourcing between self and chick (unitless)	0.5-0.9	0.5-0.9	0.5-0.9	0.5-0.9	0.5-0.9	Expert judgement
7	Intraspecific competition (*m, unitless*)	0.0125-0.0375	0.07-0.21	0.04-0.12	0.13625-0.40875	0.125-0.375	Fixed % change

Table 2:9 Ranges used for each parameter and species in sensitivity analysis.

We assessed the extent to which adult and chick survival were modified by altering the parameter values. Within the outputs the parameter versions were assigned numeric codes, for convenience (Table 2:10). It was ultimately not possible to run versions 5 and 6, because of difficulties in tracking the occurrence of adult mortality during the breeding season within the fast model because of its extreme rarity (i.e. adults almost never die in the model). These estimates were therefore excluded from our results. Note that Versions 3 and 4 did not result in a change in effect size, so are not presented, and that Version 2 is not presented here because it was considered to provide little additional information in discussion with MSS.

Version no.	Version description
0	Scenario with all values at their mean and barrier effect based on new method [b]
1	Scenario with all values at their mean and barrier effect based on old method (worst case)
2	Scenario with all values at their mean and barrier effect based on new method [a]
3	As Scenario 0 but min values for Unattendance duration at breakpoint (non-puffins) / chick body mass below which chick leaves burrow (puffins)
4	As Scenario 0 but max values for Unattendance duration at breakpoint (non-puffins) / chick body mass below which chick leaves burrow (puffins)
5	As Scenario 0 but min values for Adult body mass below which adult dies
6	As Scenario 0 but max values for Adult body mass below which adult dies
7	As Scenario 0 but min values for Adult body mass below which adult leaves chick unattended
8	As Scenario 0 but max values for Adult body mass below which adult leaves chick unattended
9	As Scenario 0 but min values for Chick body mass below which chick dies
10	As Scenario 0 but max values for Chick body mass below which chick dies
11	As Scenario 0 but min values for Adult priority of resourcing between self and chick
12	As Scenario 0 but max values for Adult priority of resourcing between self and chick
13	As Scenario 0 but min values for Intraspecific competition (*m*)
14	As Scenario 0 but max values for Intraspecific competition (*m*)

Table 2:10 list of versions in output spreadsheets.

3 Results

3.1 Destinations of birds

Table 3:1 shows the percentage of initial simulated foraging locations that lie in Zone 4 (and are therefore potentially subject to displacement) and in Zones 5 or 6 (and are therefore potentially subject to barrier effects). Note that the actual percentage of displaced trips will be equal to

Percentage of initial simulated foraging locations that lie in Zone 4 *
Proportion of birds that are displacement-susceptible

and that the actual percentage of trips that are affected by barrier effects will be equal to

Percentage of initial simulated foraging locations that lie in Zones 5 or 6 *
Proportion of birds that are barrier-susceptible

Those species-SPA-wind farm combinations for which no simulated initial foraging locations lie in Zones 4, 5 or 6 (e.g. Guillemots at Buchan Ness, in relation to any of the wind farms) will therefore, by definition, show no effect of the wind farm on adult or chick survival – the simulated effect will be exactly equal to zero. For some other combinations there are trips that are associated with displacement effects but none associated with barrier effects (e.g. puffins from Forth Islands at R3 Alpha). In general, however, the percentage of foraging locations affected by barrier effects tends to be higher than the percentage affected by displacement effects. The percentage of locations that are potentially affected by displacement is never higher than 6%, whereas the percentage affected by barrier effects can be as high as 34% and is greater than 10% for five combinations. The relationship between the percentage of foraging locations that are associated with displacement and barrier effects and the subsequent effects on survival is not straightforward, but combinations for which birds rarely experience displacement or barrier effects are universally associated with low impacts of wind farms, as we might expect.

Table 3:1 also compares the simulated percentages spent in Zone 4 and Zones 5+6 against the proportion of foraging locations in the raw GPS data that lie within these zones. The modelled percentages are generally close to the observed percentages, although it is worth noting that some of the larger differences do relate to species-SPA-wind farm combinations which are of particular interest (e.g. Forth Island kittiwakes with Neart na Gaoithe, Fowlsheugh kittiwakes with Alpha, Forth Island puffins with Alpha). Larger differences between modelled and observed percentages do not necessarily indicate that the modelled percentages are incorrect, but they do suggest that the results may be sensitive to the assumptions of the model that is used to produce estimate foraging density.

Species	SPA	WindFarm	% raw observations in Zone 4				% simulated foraging locations in:		Mean additional distance (km):	
			2010	2011	2012	Overall	Zone4	Zones5+6	Displacement	Barrier
Guillemot	Buchan Ness	R3B	No data	No data	0	0	0.0000	0.0000		
Guillemot	Buchan Ness	R3A	No data	No data	0	0	0.0000	0.0000		
Guillemot	Buchan Ness	NnG	No data	No data	0	0	0.0000	0.0000		
Guillemot	Buchan Ness	IC	No data	No data	0	0	0.0000	0.0000		
Guillemot	ForthIslands	R3B	0	No data	0	0	0.0112	0.0000	19.37	
Guillemot	ForthIslands	R3A	0	No data	0	0	0.0099	0.0000	13.95	
Guillemot	**ForthIslands**	**NnG**	1.6814	No data	2.3336	1.8715	**2.3210**	**9.5837**	**10.27**	**6.55**
Guillemot	ForthIslands	IC	1.5221	No data	1.9249	1.6395	2.0949	0.2224	14.04	9.06
Guillemot	**Fowlsheugh**	**R3B**	No data	0	3.2232	0.0973	**0.3462**	**0.1022**	**14.89**	**8.39**
Guillemot	Fowlsheugh	R3A	No data	0	0.1604	1.9553	0.6873	0.4145	17.77	7.30
Guillemot	Fowlsheugh	NnG	No data	0	0	0	0.0000	0.0000		
Guillemot	Fowlsheugh	IC	No data	0	0	0	0.3039	0.0121	13.55	4.09
Guillemot	StAbbsHead	R3B	No data	0	0	0	0.0000	0.0000		
Guillemot	StAbbsHead	R3A	No data	0	0	0	0.0000	0.0000		
Guillemot	StAbbsHead	NnG	No data	0	0	0	0.0024	0.0000	8.16	
Guillemot	StAbbsHead	IC	No data	0	0	0	0.0008	0.0000	9.65	
Kittiwake	Buchan Ness	R3B	No data	No data	0	0	0.0036	0.0000	7.03	
Kittiwake	Buchan Ness	R3A	No data	No data	0	0	0.0044	0.0004	10.04	7.66
Kittiwake	Buchan Ness	NnG	No data	No data	0	0	0.0000	0.0000		
Kittiwake	Buchan Ness	IC	No data	No data	0	0	0.0000	0.0000		
Kittiwake	**ForthIslands**	**R3B**	1.8813	No data	4.8788	2.6515	**2.9058**	**1.7822**	**15.90**	**6.53**
Kittiwake	**ForthIslands**	**R3A**	3.5888	No data	1.7002	3.1035	**2.2497**	**2.1009**	**14.36**	**7.45**
Kittiwake	**ForthIslands**	**NnG**	0.7413	No data	6.5642	2.2374	**4.3001**	**26.6919**	**9.88**	**6.31**
Kittiwake	**ForthIslands**	**IC**	1.8864	No data	1.7593	1.8538	**2.3971**	**6.7317**	**13.46**	**7.39**
Kittiwake	**Fowlsheugh**	**R3B**		1.9752	0	1.447	**2.3117**	**2.0176**	**15.12**	**10.11**
Kittiwake	**Fowlsheugh**	**R3A**		6.2557	0	4.5828	**2.6138**	**4.0498**	**13.88**	**10.10**
Kittiwake	**Fowlsheugh**	**NnG**	No data	0	0	0	**0.0111**	**0.0016**	**13.02**	**6.82**
Kittiwake	**Fowlsheugh**	**IC**		0.8334	0	0.6105	**0.2562**	**0.1214**	**15.46**	**4.89**
Kittiwake	**StAbbsHead**	**R3B**	No data	0.0182	0	0.0101	**1.2042**	**1.2506**	**15.65**	**9.53**
Kittiwake	**StAbbsHead**	**R3A**	No data	0	0	0	**0.5714**	**0.4786**	**13.77**	**6.93**
Kittiwake	**StAbbsHead**	**NnG**	No data	0	0.3409	0.1517	**0.8368**	**1.1614**	**12.48**	**4.25**
Kittiwake	**StAbbsHead**	**IC**	No data	0	0.2841	0.1264	**0.2850**	**0.2353**	**13.52**	**6.21**
Puffin	**ForthIslands**	**R3B**	0.4554	No data	No data	0.4555	**0.2238**	**0.0000**	**7.65**	
Puffin	**ForthIslands**	**R3A**	1.996	No data	No data	1.996	**3.4838**	**0.0000**	**8.50**	
Puffin	**ForthIslands**	**NnG**	0.1206	No data	No data	0.1206	**0.4412**	**34.1124**	**6.87**	**5.02**
Puffin	**ForthIslands**	**IC**	8.8413	No data	No data	8.8413	**5.6704**	**17.2582**	**10.32**	**10.00**
Razorbill	**ForthIslands**	**R3B**	0	No data	0	0	**0.1635**	**0.0000**	**6.78**	
Razorbill	**ForthIslands**	**R3A**	2.9941	No data	0	2.4245	**1.9881**	**0.0927**	**13.36**	**0.64**
Razorbill	**ForthIslands**	**NnG**	0.1285	No data	0	0.1041	**0.7726**	**11.4550**	**10.67**	**5.93**
Razorbill	**ForthIslands**	**IC**	0.7636	No data	0	0.6184	**0.9909**	**3.6357**	**11.35**	**8.41**
Razorbill	Fowlsheugh	R3B	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	Fowlsheugh	R3A	No data	No data	No data	No data	0.0093	0.0000	11.02	
Razorbill	Fowlsheugh	NnG	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	Fowlsheugh	IC	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	StAbbsHead	R3B	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	StAbbsHead	R3A	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	StAbbsHead	NnG	No data	No data	No data	No data	0.0000	0.0000		
Razorbill	StAbbsHead	IC	No data	No data	No data	No data	0.0000	0.0000		
Gannet	**ForthIslands**	**R3B**	Not calculated				**0.0511**	**6.8145**	**14.76**	**6.10**
Gannet	**ForthIslands**	**R3A**	Not calculated				**0.0299**	**6.3438**	**17.28**	**7.28**
Gannet	**ForthIslands**	**NnG**	Not calculated				**0.3415**	**19.8710**	**11.23**	**5.93**
Gannet	**ForthIslands**	**IC**	Not calculated				**0.3323**	**5.8941**	**10.93**	**3.04**

Table 3:1 Destinations of birds. Purple: combinations that are presented in the final analysis; grey: incalculable values (mean additional distances cannot be calculated if no birds ever visit the wind farm). Zone 4 refers to the wind farm footprint plus 1km exclusion buffer zone (birds are displaced); Zones 5 & 6 refer to regions beyond the wind farm which incur barrier costs for birds choosing to feed in those locations.

3.2 Impact of wind farms on adult survival and breeding success

Table 3:2 shows the estimated impact of wind farms upon adult survival, for each species-by-SPA combination, with the exception of gannet which is shown in Table 3:4. In the former, raw estimates from the full and fast models are presented, along with the adjusted estimates that are derived by combining these. Tables H1 and H2 show the calculations that were used to assess the reliability of the results shown in Tables 3:2 and 3:3.

Guillemots, razorbills and gannets consistently yielded estimated wind farm effects on adult survival (both individual and cumulative) that either corresponded to declines of less than 0.5% or else could not be estimated reliably, as did kittiwakes from St. Abbs. The three species-by-SPA combinations that yielded estimated declines of more than 0.5% were therefore Forth Island kittiwakes, Fowlsheugh kittiwakes and Forth Island puffins. Estimated declines of more than 1% only occurred for Forth Island kittiwakes and Forth Island puffins, with the following specific combinations: Forth Island kittiwakes with Neart na Gaoithe (homogeneous or heterogeneous prey); Forth Island puffins with Alpha (homogeneous prey); and Forth Island puffins with Inch Cape (homogeneous prey). The combinations that led to declines of between 0.5% and 1% were Fowlsheugh kittiwakes with Alpha (heterogeneous or homogeneous prey) and Forth Island puffins with Neart na Gaoithe (heterogeneous prey). In most cases, there was close concordance between the results associated with homogeneous and heterogeneous prey. The main exception was puffins, where larger effects were generally apparent with homogeneous prey than with heterogeneous prey. Cumulative impacts were consistent with the individual wind farm scenarios, with estimated declines of more than 1% for Forth Island kittiwakes (homogeneous or heterogeneous prey) and Forth Island puffins (homogeneous prey only).

Table 3:3 shows corresponding values for breeding success (chick survival) for all species except gannet (shown in Table 3:4). The breeding success results were broadly consistent with adult survival, although appeared to contain a higher degree of stochastic noise (as had already been suggested by our exploratory simulation runs). Effects were greatest overall in puffins and in Fowlsheugh and Forth Islands kittiwakes, and were very low or unreliably estimated for gannets, guillemot and razorbills. There were no combinations for which the adjusted estimate of the decline in survival exceeded 5%, and only one (cumulative impact on Forth Island puffins with homogeneous prey) for which the decline exceeded 2.5%. The largest decline associated with an individual wind farm was, unsurprisingly, also related to Forth Island puffins with homogeneous prey – 1.73% for Inch Cape. Cumulative impacts on breeding success could only be calculated reliably for around half of the species-SPA-wind farm combinations. Cumulative impacts, where calculable, were generally consistent with the individual wind farm scenarios, and homogeneous and heterogeneous prey results were similar with the exception of puffins.

Tables H3 and H4 (see Appendix H) show the effect of changing the cut-off for reliability so that only 'high reliability', rather than both moderate and high reliability, results are used in calculating adjustment factors. The negative effect of wind farms on adult survival disappears for razorbills at Forth Islands with homogeneous prey when only ‘high reliability’ values are used, but has virtually no effect on the results for any other species-by-SPA-by-prey scenario combination.

Species	**SPA**	**Wind farm**	**Prey**	**ADULT SURVIVAL**				
			type	Big model	Fast model v1	Fast model v0	Adjustment	**Big model adjusted**
Guillemot	Forth Islands	NnG	Hom	-0.89	-0.73	-0.16	0.23	**-0.20**
			Het	-1.10	-0.23	-0.06	0.27	**-0.30**
Guillemot	Fowlsheugh	R3B	Hom	-0.15	-0.01	0.00	0.26	**-0.04**
			Het	0.14	0.00	0.00	0.73	**0.10**
Kittiwake	Forth Islands	R3B	Hom	-0.77	-0.11	-0.05	0.51	**-0.39**
			Het	-0.61	-0.10	-0.05	0.44	**-0.27**
		R3A	Hom	-0.32	-0.13	-0.06	0.45	**-0.14**
			Het	-0.87	-0.13	-0.06	0.47	**-0.41**
		NnG	Hom	-4.32	-0.96	-0.23	0.24	**-1.04**
			Het	-4.93	-1.02	-0.22	0.22	**-1.08**
		IC	Hom	-0.94	-0.28	-0.09	0.33	**-0.31**
			Het	-1.67	-0.29	-0.08	0.28	**-0.47**
		Cumulative	Hom	-6.62			0.30	**-1.97**
			Het	-6.58			0.28	**-1.82**
Kittiwake	Fowlsheugh	R3B	Hom	-0.49	-0.08	-0.04	0.50	**-0.24**
			Het	-0.49	-0.06	-0.03	0.47	**-0.23**
		R3A	Hom	-1.22	-0.15	-0.07	0.45	**-0.54**
			Het	-1.31	-0.10	-0.06	0.57	**-0.75**
		NnG	Hom	0.18	0.00	0.00	-0.66	**-0.12**
			Het	0.28	0.01	0.00	0.20	**0.06**
		IC	Hom	-0.34	-0.01	0.00	0.43	**-0.15**
			Het	0.26	0.00	0.00	-0.81	**-0.21**
		Cumulative	Hom	-1.04			0.46	**-0.48**
			Het	-0.81			0.55	**-0.44**
Kittiwake	St Abbs	R3B	Hom	-0.10	-0.05	-0.03	0.53	**-0.05**
			Het	0.22	-0.03	-0.02	0.55	**0.12**
		R3A	Hom	-0.04	-0.03	-0.02	0.84	**-0.03**
			Het	0.10	-0.01	0.00	0.05	**0.00**
		NnG	Hom	-0.14	-0.05	-0.02	0.33	**-0.05**
			Het	-0.48	-0.02	-0.01	0.30	**-0.14**
		IC	Hom	0.02	-0.02	0.00	0.18	**0.00**
			Het	0.28	-0.01	0.00	0.10	**0.03**
		Cumulative	Hom	-0.45			0.41	**-0.18**
			Het	-0.73			0.30	**-0.22**
Puffin	Forth Islands	R3B	Hom	-0.18	-0.05	-0.04	0.95	**-0.17**
			Het	0.36	0.02	0.02	1.00	**0.36**
		R3A	Hom	-1.16	-0.96	-0.96	0.99	**-1.15**
			Het	0.32	0.18	0.18	0.95	**0.31**
		NnG	Hom	-5.94	-1.38	-0.11	0.08	**-0.46**
			Het	-5.67	-1.34	-0.15	0.11	**-0.64**
		IC	Hom	-5.33	-1.29	-0.35	0.27	**-1.44**
			Het	-0.05	-0.07	-0.19	2.57	**-0.13**
		Cumulative	Hom	-13.00			0.26	**-3.32**
			Het	-7.22			-0.01	**0.04**
Razorbill	Forth Islands	R3B	Hom	-0.09	0.00	0.00	1.00	**-0.09**
			Het	-0.01	0.00	0.00	1.00	**-0.01**
		R3A	Hom	-0.07	-0.02	-0.01	0.77	**-0.05**
			Het	-0.07	-0.01	-0.01	0.76	**-0.05**
		NnG	Hom	-0.66	-0.35	-0.05	0.16	**-0.10**
			Het	-0.55	-0.32	-0.05	0.17	**-0.09**
		IC	Hom	-0.28	-0.14	-0.04	0.32	**-0.09**
			Het	-0.20	-0.05	-0.03	0.57	**-0.11**
		Cumulative	Hom	-0.82			1.00	**-0.82**
			Het	-0.75			0.32	**-0.24**

Table 3:2 Estimated change in annual adult survival (as a percentage point) as a result of including wind farms in the model. Colours denote the level of reliability associated with our estimates for adjusted impacts: high = pink, moderate = yellow, low = grey; these assessments are derived from the values of *d* presented in Table H1.

Species	**SPA**	**Wind farm**	**Prey**	**BREEDING SUCCESS**				
			type	Big model	Fast model v0	Fast model v1	Adjustment	**Big model adjusted**
Guillemot	Forth Islands	NnG	Hom	-0.37	-4.41	-0.42	0.10	**-0.03**
			Het	0.94	-1.15	-0.42	0.36	**0.34**
Guillemot	Fowlsheugh	R3B	Hom	-0.32	0.21	0.32	1.50	**-0.48**
			Het	-0.19	0.38	0.13	0.36	**-0.07**
Kittiwake	Forth Islands	R3B	Hom	-1.27	-0.88	0.64	-0.73	**0.93**
			Het	-1.43	-0.80	-0.40	0.50	**-0.72**
		R3A	Hom	0.00	-0.16	-0.08	0.50	**0.00**
			Het	-3.11	-0.80	-0.40	0.50	**-1.55**
		NnG	Hom	-7.32	-10.60	-1.91	0.18	**-1.32**
			Het	-6.45	-5.50	-0.80	0.14	**-0.93**
		IC	Hom	-1.04	-2.23	0.96	-0.43	**0.44**
			Het	-0.48	-0.80	0.24	-0.30	**0.14**
		Cumulative	Hom	-11.86			0.18	**-2.14**
			Het	-8.12			0.14	**-1.18**
Kittiwake	Fowlsheugh	R3B	Hom	-0.90	-1.73	-1.02	0.59	**-0.53**
			Het	-3.01	-2.17	-0.32	0.15	**-0.44**
		R3A	Hom	-2.21	-3.93	-1.85	0.47	**-1.04**
			Het	-2.18	-3.58	-0.45	0.13	**-0.27**
		NnG	Hom	0.00	-0.48	0.38	-0.80	**0.00**
			Het	-1.09	0.13	0.03	0.25	**-0.27**
		IC	Hom	0.06	0.13	0.13	1.00	**0.06**
			Het	-0.10	0.58	0.16	0.28	**-0.03**
		Cumulative	Hom	-3.29			**0.51**	**-1.67**
			Het	-2.02			**Not calculable**	
Kittiwake	St Abbs	R3B	Hom	0.07	-1.25	-1.11	0.89	**0.06**
			Het	-0.90	0.49	-0.14	-0.29	**0.26**
		R3A	Hom	0.49	-1.18	0.14	-0.12	**-0.06**
			Het	0.97	1.18	-0.07	-0.06	**-0.06**
		NnG	Hom	0.42	-0.70	-0.63	0.90	**0.38**
			Het	-1.04	-0.56	0.00	0.00	**0.00**
		IC	Hom	2.71	-0.21	-1.04	5.00	**13.57**
			Het	0.63	-0.14	-0.21	1.50	**0.94**
		Cumulative	Hom	0.84			**Not calculable**	
			Het	-0.14			**Not calculable**	
Puffin	Forth Islands	R3B	Hom	-0.15	-0.09	-0.06	0.67	**-0.10**
			Het	0.48	0.03	0.04	1.33	**0.64**
		R3A	Hom	-0.90	-1.42	-1.32	0.93	**-0.84**
			Het	0.41	0.41	0.30	0.73	**0.30**
		NnG	Hom	-8.12	-1.71	-0.20	0.12	**-0.94**
			Het	-7.87	-1.89	-0.26	0.14	**-1.08**
		IC	Hom	-7.09	-1.67	-0.41	0.24	**-1.73**
			Het	0.05	-0.06	-0.38	6.33	**0.31**
		Cumulative	Hom	-22.31			0.22	**-4.87**
			Het	-11.43			0.14	**-1.56**
Razorbill	Forth Islands	R3B	Hom	0.81	-0.03	-0.03	1.00	**0.81**
			Het	1.56	0.03	0.03	1.00	**1.56**
		R3A	Hom	1.70	0.03	0.06	2.00	**3.40**
			Het	1.67	0.12	0.12	1.00	**1.67**
		NnG	Hom	-1.73	-1.56	-0.12	0.07	**-0.13**
			Het	-0.69	-1.18	-0.20	0.17	**-0.12**
		IC	Hom	-0.20	-0.43	-0.14	0.33	**-0.07**
			Het	0.87	-0.29	-0.06	0.20	**0.17**
		Cumulative	Hom	-3.66			-0.54	**1.99**
			Het	-1.76			1.66	**-2.93**

Table 3:3 Estimated change in breeding success (chick survival, as a percentage point) as a result of including wind farms in the model. Colours denote the level of reliability associated with our estimates for adjusted impacts: high = pink, moderate = yellow, low = grey; these assessments are derived from the values of *d* presented in Table H2.

Species	**SPA**	**Wind farm**	**Prey type**	**Adult survival** Fast model v0	**Breeding success** Fast model v0
Gannet	Forth Islands	R3B	Hom	0.00	-0.03
			Het	-0.01	-0.05
		R3A	Hom	-0.01	0.00
			Het	-0.02	-0.01
		NnG	Hom	0.00	0.02
			Het	-0.01	-0.05
		IC	Hom	-0.01	0.03
			Het	-0.01	0.00

Table 3:4 Estimated change in annual adult and chick survival for gannets (as a percentage point) as a result of including wind farms in the model. Gannets are shown separately because they were only analysed using the fast model.

3.3 Sensitivity analysis

3.3.1 Baseline sensitivity

Table 3:5 illustrates the sensitivity of baseline estimates of adult survival to the choice of parameter value. There was no sensitivity at all to the value of unattendance duration (parameter versions 3 and 4) – the results are identical to those for Version 0 and so are not shown in the table. The remaining four parameters did have an impact on the level of adult survival, but in all cases the impact was fairly small. The largest changes in adult survival were generally those associated with Version 8 – increasing the adult body mass threshold for non-unattendance – and, unsurprisingly, were generally associated with an increase in adult survival.

Species	**SPA**	**Prey**	**V0**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**	**V13**	**V14**
Guillemot	ForthIslands	Hom	88.91	88.89	89.1	88.91	88.81	89.14	88.82	88.86	88.93
		Het	89.12	89.07	89.59	89.12	88.78	89.28	89.02	89.05	89.16
Guillemot	Fowlsheugh	Hom	89.1	89.08	89.27	89.1	89.01	89.34	89.01	89.02	89.16
		Het	89.11	89.09	89.46	89.11	88.9	89.15	89.1	89.04	89.14
Kittiwake	ForthIslands	Hom	74.12	74.05	74.99	74.12	74.06	74.4	73.94	74.04	74.23
		Het	74.07	74	74.88	74.07	73.99	74.35	73.91	73.99	74.16
Kittiwake	Fowlsheugh	Hom	74.3	74.19	75.11	74.3	74.25	74.51	74.01	74.14	74.45
		Het	74.34	74.19	75.11	74.34	74.29	74.49	73.94	74.17	74.42
Kittiwake	StAbbsHead	Hom	74.08	73.93	74.93	74.08	74.02	74.31	73.74	74	74.15
		Het	74	73.92	74.82	74	73.95	74.22	73.7	73.93	74.07
Puffin	ForthIslands	Hom	86.4	86.37	87.36	86.4	86.34	86.62	86.13	86.42	87.07
		Het	86.29	86.26	87.25	86.29	86.36	86.52	85.97	86.42	86.97
Razorbill	ForthIslands	Hom	86.77	86.7	86.8	86.77	86.71	86.92	86.69	86.65	86.92
		Het	86.7	86.61	86.75	86.7	86.63	86.85	86.63	86.58	86.83
Gannet	ForthIslands	Hom	88.82	88.79	89.05	88.82	88.81	88.83	88.81	88.83	88.86
		Het	88.79	88.77	89.02	88.79	88.79	88.81	88.79	88.81	88.86

Table 3:5 Baseline sensitivity analysis for adult survival. Please refer to Table 2.10 for explanation of the different sensitivity scenarios (V0-V14). Numbers in the table refer to adult survival (%).

Table 3:6 illustrates the corresponding results for breeding success (chick survival). The value of unattendance duration again has no effect (parameter versions 3 and 4, not shown), but the values of the remaining four parameters all have a very large impact on chick survival. Reducing the threshold for chick mass that is associated with death (parameter version 9) generally has only a modest impact, but all of the other changes in parameter values have – for at least some species-by-SPA combinations – a very substantial effect on chick survival. It is worth noting that many of the changes to chick survival are sufficiently large that the revised parameter values would have been rejected by the sense-checking procedure that we used, and that these values would therefore never have been considered as plausible when assessing the impacts of wind farms.

Species	SPA	Prey	V0	V7	V8	V9	V10	V11	V12	V13	V14
Guillemot	ForthIslands	Hom	91.24	96.12	38.25	94.23	3.04	87.15	45.07	95.07	87.46
		Het	88.88	95.44	26.29	90.4	1.15	85.05	74.45	93.07	86.67
Guillemot	Fowlsheugh	Hom	89.73	94.85	32.67	93.86	0.38	83.56	20.57	96.89	80.42
		Het	90.1	96.41	26.88	90.5	11.43	89.32	90.8	93.08	88.17
Kittiwake	ForthIslands	Hom	70.68	85.42	30.52	70.68	69.64	13.78	88.84	79.68	55.3
		Het	77.77	93.07	32.99	77.77	76.02	26.45	89.72	82.31	68.21
Kittiwake	Fowlsheugh	Hom	55.19	67.5	22.66	55.19	54.55	2.24	86.9	76.57	21.83
		Het	35.31	42.98	14.48	35.31	35.41	0.1	85.75	67.82	9.52
Kittiwake	StAbbsHead	Hom	55.91	67.8	23.09	55.91	54.87	1.81	87.34	67.66	42
		Het	53.76	65.3	23.44	53.76	53.27	1.6	88.18	66.27	42.14
Puffin	ForthIslands	Hom	92.91	99.97	24.16	92.93	0	86.32	97.13	99.96	37.92
		Het	91.78	99.93	22.51	91.73	0	85.82	94.94	99.94	46.43
Razorbill	ForthIslands	Hom	71.85	92.39	38.62	71.99	34.58	67.12	73.41	80.39	56.5
		Het	71.27	91.49	39.54	71.27	36.4	67.49	72.92	79.72	58.78
Gannet	ForthIslands	Hom	92.64	96.29	59.64	95.7	75.7	94.65	91.4	97.53	66.63
		Het	92.81	95.98	59.96	96.03	74.22	95.39	90.22	98.79	61.4

Table 3:6 Baseline sensitivity analysis for breeding success. Please refer to Table 2:10 for explanation of the different sensitivity scenarios (V0-V14). Numbers in the table refer to breeding success (%).

3.3.2 Sensitivity of wind farm effects

Table 3:7 illustrates the way in which the impact of the wind farm on adult survival is modified by using different parameter values. It can be seen that wind farm effects that are small almost always remain small when the parameters are modified – this is unsurprising, as these generally correspond to situations in which birds rarely foraging in areas that would be affected by displacement or barrier effects, and the wind farm effect is therefore likely to be estimated as consistently small, regardless of the structure or parameter values used.

Effects that are detected to be relatively large are generally also large when alternative parameter values are used. This is not always the case, however, and reduction of the intra-specific competition parameter (parameter version 13) often reduces relatively large effects down to being relatively small.

Table 3:8 presents the corresponding results for chick survival. The effects of wind farms on chick survival vary quite substantially when the parameter values are modified, with no obvious patterns apparent. This result is unsurprising given that the changes in parameter values have a very substantial effect on the baseline chick survival values.

Species	SPA	WindFarm	Prey	V0	V7	V8	V9	V10	V11	V12	V13	V14
Guillemot	ForthIslands	R3B	Hom	0	0	0	0	0	0	0	0	0.01
Guillemot	ForthIslands	R3B	Het	0.01	0.01	0	0	0	0	0.01	0	0
Guillemot	ForthIslands	R3A	Hom	0	0	0	0	-0.01	0	0	0	0.01
Guillemot	ForthIslands	R3A	Het	0	-0.01	0	0	0	0.01	0.01	0	0
Guillemot	ForthIslands	NnG	Hom	-0.16	-0.16	-0.18	-0.16	-0.2	-0.08	-0.18	-0.17	-0.15
Guillemot	ForthIslands	NnG	Het	-0.06	-0.06	-0.06	-0.06	-0.06	-0.02	-0.08	-0.07	-0.06
Guillemot	ForthIslands	IC	Flat	-0.05	-0.04	-0.04	-0.04	-0.06	-0.03	-0.05	-0.04	-0.04
Guillemot	ForthIslands	IC	GPS	-0.01	-0.02	-0.02	-0.01	-0.03	-0.01	-0.02	-0.01	-0.02
Guillemot	Fowlsheugh	R3B	Hom	0	-0.01	0	0	-0.01	-0.01	-0.01	-0.01	0.01
Guillemot	Fowlsheugh	R3B	Het	0	0	0	0	0	0	0	0	0
Guillemot	Fowlsheugh	R3A	Hom	-0.02	-0.02	-0.02	-0.01	-0.02	-0.01	-0.02	-0.02	-0.01
Guillemot	Fowlsheugh	R3A	Het	-0.01	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.02	-0.01
Guillemot	Fowlsheugh	NnG	Hom	0	0	0	0	0	0	0	0	0.01
Guillemot	Fowlsheugh	NnG	Het	0	0	0	0	0	0	-0.01	0	0
Guillemot	Fowlsheugh	IC	Flat	0	0	0	0	0	0	0	0.01	0.01
Guillemot	Fowlsheugh	IC	GPS	0	-0.01	0	0	0	0	0	0	0
Kittiwake	ForthIslands	R3B	Hom	-0.05	-0.05	-0.04	-0.05	-0.05	-0.01	-0.05	-0.05	-0.04
Kittiwake	ForthIslands	R3B	Het	-0.05	-0.05	-0.03	-0.05	-0.04	-0.04	-0.04	-0.05	-0.04
Kittiwake	ForthIslands	R3A	Hom	-0.06	-0.05	-0.05	-0.06	-0.05	-0.02	-0.06	-0.06	-0.03
Kittiwake	ForthIslands	R3A	Het	-0.06	-0.06	-0.04	-0.06	-0.06	-0.05	-0.06	-0.06	-0.05
Kittiwake	ForthIslands	NnG	Hom	-0.23	-0.26	-0.12	-0.23	-0.22	-0.09	-0.17	-0.25	-0.19
Kittiwake	ForthIslands	NnG	Het	-0.22	-0.26	-0.12	-0.22	-0.22	-0.13	-0.15	-0.22	-0.21
Kittiwake	ForthIslands	IC	Hom	-0.09	-0.09	-0.06	-0.09	-0.09	-0.03	-0.07	-0.09	-0.07
Kittiwake	ForthIslands	IC	Het	-0.08	-0.09	-0.05	-0.08	-0.08	-0.05	-0.06	-0.08	-0.08
Kittiwake	Fowlsheugh	R3B	Hom	-0.04	-0.05	-0.03	-0.04	-0.05	-0.01	-0.04	-0.05	-0.03
Kittiwake	Fowlsheugh	R3B	Het	-0.03	-0.03	-0.02	-0.03	-0.04	-0.04	-0.04	-0.05	-0.03
Kittiwake	Fowlsheugh	R3A	Hom	-0.07	-0.08	-0.05	-0.07	-0.08	-0.03	-0.07	-0.09	-0.06
Kittiwake	Fowlsheugh	R3A	Het	-0.06	-0.06	-0.03	-0.06	-0.06	-0.04	-0.06	-0.08	-0.04
Kittiwake	Fowlsheugh	NnG	Hom	0	0.01	0	0	0	0.02	0	0	-0.01
Kittiwake	Fowlsheugh	NnG	Het	0	0	0	0	0	-0.01	0	0	0
Kittiwake	Fowlsheugh	IC	Hom	0	0	0	0	0	0	0	0	0
Kittiwake	Fowlsheugh	IC	Het	0	-0.01	0	0	0	-0.01	0	0	0
Kittiwake	StAbbsHead	R3B	Hom	-0.03	-0.02	-0.02	-0.03	-0.03	-0.01	-0.04	-0.02	-0.03
Kittiwake	StAbbsHead	R3B	Het	-0.02	-0.02	-0.03	-0.02	-0.01	0.01	-0.04	-0.02	-0.03
Kittiwake	StAbbsHead	R3A	Hom	-0.02	-0.01	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02	-0.02
Kittiwake	StAbbsHead	R3A	Het	0	0	-0.01	0	-0.01	0.01	-0.02	0	-0.01
Kittiwake	StAbbsHead	NnG	Hom	-0.02	-0.01	-0.01	-0.02	-0.03	-0.01	-0.01	-0.02	-0.02
Kittiwake	StAbbsHead	NnG	Het	-0.01	-0.02	-0.01	-0.01	-0.01	0.02	-0.01	-0.01	-0.01
Kittiwake	StAbbsHead	IC	Hom	0	0	0	0	0	-0.03	0	-0.01	0
Kittiwake	StAbbsHead	IC	Het	0	-0.01	0	0	0	0.01	0	0	-0.01
Puffin	ForthIslands	R3B	Hom	-0.04	-0.04	-0.03	-0.04	0	-0.04	-0.04	0	-0.03
Puffin	ForthIslands	R3B	Het	0.02	0.03	0.02	0.02	0	0.02	0.03	0	0.01
Puffin	ForthIslands	R3A	Hom	-0.96	-0.98	-0.7	-0.97	-0.48	-0.76	-1.27	-0.03	-0.45
Puffin	ForthIslands	R3A	Het	0.18	0.19	0.11	0.18	0.01	0.13	0.28	0.02	-0.04
Puffin	ForthIslands	NnG	Hom	-0.11	-0.12	-0.08	-0.13	-0.03	-0.09	-0.11	0	-0.12
Puffin	ForthIslands	NnG	Het	-0.15	-0.14	-0.08	-0.14	-0.03	-0.13	-0.15	-0.03	-0.13
Puffin	ForthIslands	IC	Hom	-0.35	-0.37	-0.27	-0.36	-0.24	-0.3	-0.33	-0.02	-0.34
Puffin	ForthIslands	IC	Het	-0.19	-0.19	-0.11	-0.18	-0.02	-0.15	-0.17	0.03	-0.33
Razorbill	ForthIslands	R3B	Hom	0	0	0	0	0	0	0	0	0
Razorbill	ForthIslands	R3B	Het	0	0	0	0	0	0	0	0	0
Razorbill	ForthIslands	R3A	Hom	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0
Razorbill	ForthIslands	R3A	Het	-0.01	0.01	-0.02	-0.01	-0.02	-0.02	0	0.01	-0.01
Razorbill	ForthIslands	NnG	Hom	-0.05	-0.05	-0.06	-0.05	-0.05	-0.06	-0.05	-0.04	-0.03
Razorbill	ForthIslands	NnG	Het	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.04	-0.04
Razorbill	ForthIslands	IC	Hom	-0.04	-0.04	-0.05	-0.04	-0.04	-0.05	-0.05	-0.04	-0.03
Razorbill	ForthIslands	IC	Het	-0.03	-0.03	-0.03	-0.03	-0.02	-0.03	-0.03	-0.02	-0.03
Gannet	ForthIslands	R3B	Hom	0	0	0	0	0	0	0	0	0
Gannet	ForthIslands	R3B	Het	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0	-0.01
Gannet	ForthIslands	R3A	Hom	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
Gannet	ForthIslands	R3A	Het	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01
Gannet	ForthIslands	NnG	Hom	0	0	-0.01	0	0	-0.01	0	0	-0.02
Gannet	ForthIslands	NnG	Het	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0	-0.02
Gannet	ForthIslands	IC	Hom	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0	-0.01
Gannet	ForthIslands	IC	Het	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01

Table 3:7 Sensitivity of wind farm effects in relation to adult survival.

Species	**SPA**	**WindFarm**	**Prey**	**V0**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**	**V13**	**V14**
Guillemot	**ForthIslands**	R3B	Hom	0.21	-0.16	-0.31	-0.05	-0.05	-0.16	0	0	-0.05
			Het	0.31	-0.16	0.05	0.05	-0.05	-0.52	-0.47	-0.21	-0.05
		R3A	Hom	0.1	-0.1	-0.05	0.05	0.05	-0.1	-0.1	0	0.37
			Het	0.16	0.1	0.1	-0.31	-0.05	-1.1	-0.05	-0.37	-0.21
		NnG	Hom	-0.42	-0.73	-1.31	-0.1	-0.58	-1.36	-2.89	-0.47	-1.31
			Het	-0.42	-0.1	-0.58	-0.73	0.1	-1.31	0.31	-0.84	-0.42
		IC	Hom	0.1	-0.05	-0.42	0.16	-0.1	-1	-0.63	-0.05	-0.89
			Het	0.31	0.31	-0.26	-0.1	-0.1	-0.52	-0.21	-0.26	-1
Guillemot	**Fowlsheugh**	R3B	Hom	0.32	-0.03	-0.03	-0.05	-0.03	0.19	0	0	-0.64
			Het	0.13	0.16	0.05	0.19	0	0.19	-0.05	0.05	-0.03
		R3A	Hom	0.05	0	-0.38	-0.08	-0.08	0.56	-0.21	0	-0.89
			Het	-0.3	0.27	-0.03	-0.3	-0.03	-0.43	-0.7	-0.03	0.3
		NnG	Hom	0.11	0.19	0.03	0.16	-0.08	0.89	0.05	0.13	-0.48
			Het	0.16	-0.35	0.03	-0.03	0	-0.08	-0.35	0.03	0.24
		IC	Hom	0.05	0.05	0.08	0.03	-0.08	0.08	0.08	0.05	-0.54
			Het	0.3	0.38	0.08	0.08	0	-0.16	-0.11	0.24	-0.03
Kittiwake	**ForthIslands**	R3B	Hom	0.64	0.16	-0.24	0.64	-0.56	-1.67	-0.08	-0.4	-0.88
			Het	-0.4	0.08	-0.08	-0.4	-0.48	-2.95	-0.08	0	-0.72
		R3A	Hom	-0.08	-0.08	0.4	-0.08	-0.56	-1.91	-0.16	-0.24	-0.96
			Het	-0.4	0.24	-0.32	-0.4	-0.24	-3.03	0	-0.08	-0.24
		NnG	Hom	-1.91	-2.07	-0.72	-1.91	-1.43	-3.19	-0.24	-0.56	-2.39
			Het	-0.8	-0.96	-0.48	-0.8	-0.96	-3.59	-0.24	-0.32	-1.75
		IC	Hom	0.96	-0.16	-0.08	0.96	-1.2	-1.12	-0.16	-0.08	-1.04
			Het	0.24	0.24	-0.4	0.24	0.4	-3.9	-0.08	-0.16	-0.08
Kittiwake	**Fowlsheugh**	R3B	Hom	-1.02	-2.24	-0.13	-1.02	-1.28	-0.67	-0.22	-0.42	-0.77
			Het	-0.32	-1.21	-0.58	-0.32	-1.12	0.1	-0.13	-0.26	0.19
		R3A	Hom	-1.85	-2.72	-1.18	-1.85	-2.4	-0.7	-0.1	-0.96	-1.25
			Het	-0.45	-2.56	-0.74	-0.45	-1.73	0.13	-0.19	-0.42	-0.7
		NnG	Hom	0.38	-0.58	-0.1	0.38	-0.54	-0.26	0	-0.58	0.06
			Het	0.03	-0.29	0.16	0.03	-1.15	0.26	0	0.29	-0.42
		IC	Hom	0.13	-0.74	-0.13	0.13	-0.29	-0.29	0	-0.22	-0.89
			Het	0.16	-0.7	0.58	0.16	-1.12	0.06	0	0.42	-0.32
Kittiwake	**StAbbsHead**	R3B	Hom	-1.11	-0.7	-0.49	-1.11	0	0.07	-0.07	-1.39	-0.7
			Het	-0.14	-0.21	-0.7	-0.14	-0.9	0.14	-0.07	-1.6	-1.25
		R3A	Hom	0.14	-0.7	0	0.14	-0.28	-0.07	0.07	-0.49	0.35
			Het	-0.07	0	-0.83	-0.07	-0.21	-0.35	0	0.28	-1.11
		NnG	Hom	-0.63	-0.49	0.21	-0.63	0.07	-0.56	0	-0.7	-0.7
			Het	0	0.9	-0.83	0	-0.42	0.28	0	-0.49	-1.46
		IC	Hom	-1.04	-1.32	-0.56	-1.04	-0.21	0	-0.07	-0.49	-0.14
			Het	-0.21	-0.21	-0.56	-0.21	-0.28	0	-0.07	-0.76	-0.63
Puffin	**ForthIslands**	R3B	Hom	-0.06	0.01	-0.08	-0.03	0	-0.13	0.01	0	-0.08
			Het	0.04	0	-0.05	-0.02	0	0.06	0.1	0	0.09
		R3A	Hom	-1.32	-0.01	-3.08	-1.32	0	-1.86	-0.97	0	-2.94
			Het	0.3	0.01	0.99	0.26	0	0.47	0.21	0	-0.43
		NnG	Hom	-0.2	0	-0.24	-0.12	0	-0.03	-0.13	0	-0.89
			Het	-0.26	0	-0.27	-0.22	0	0.11	-0.1	-0.02	-0.79
		IC	Hom	-0.41	0	-1.26	-0.42	0	-0.47	-0.25	0	-2.25
			Het	-0.38	0	-0.45	-0.24	0	-0.06	-0.21	-0.02	-1.98
Razorbill	**ForthIslands**	R3B	Hom	-0.03	0	-0.03	-0.03	0	-0.03	-0.03	0	0.23
			Het	0.03	0	0	0.03	-0.03	0	0	0	-0.61
		R3A	Hom	0.06	0.12	-0.06	-0.12	-0.06	-0.12	0.14	-0.12	0.12
			Het	0.12	0	-0.06	0.12	-0.03	-0.09	0.06	-0.06	-0.26
		NnG	Hom	-0.12	-0.06	-0.32	-0.2	-1.18	-0.17	-0.4	-0.2	-0.58
			Het	-0.2	-0.09	-0.26	-0.2	-0.87	-0.32	-0.26	-0.17	-0.46
		IC	Hom	-0.14	-0.03	-0.23	-0.2	-1.01	-0.14	-0.26	-0.09	-0.14
			Het	-0.06	-0.06	-0.23	-0.06	-0.72	-0.14	-0.2	-0.09	-0.66
Gannet	**ForthIslands**	R3B	Hom	-0.03	-0.01	-0.05	-0.02	-0.04	-0.03	-0.05	0	-0.37
			Het	-0.05	-0.07	-0.05	-0.03	-0.1	-0.05	-0.04	-0.02	-0.41
		R3A	Hom	0	0	-0.12	-0.01	-0.13	-0.01	-0.06	0.01	-0.41
			Het	-0.01	-0.02	-0.13	0.04	-0.07	-0.08	-0.08	-0.02	-0.44
		NnG	Hom	0.02	-0.04	-0.05	0.01	0.02	0.04	0	0	-0.23
			Het	-0.05	-0.05	-0.11	0	-0.15	-0.09	-0.02	0	-0.68
		IC	Hom	0.03	0.01	-0.01	0.01	-0.08	-0.02	-0.02	0	-0.13
			Het	0	-0.04	-0.05	0.01	-0.06	-0.03	-0.08	-0.02	-0.49

Table 3:8**.** Sensitivity of wind farm effects in relation to breeding success.

4 Discussion

4.1 Summary of results

This study represents, to our knowledge, the most comprehensive assessment of the effects of displacement and barrier effects from wind farms on breeding seabirds yet undertaken. Using the best available empirical data and advanced modelling approaches across five species, we have demonstrated how these two factors may alter adult survival and breeding success mediated via changes in foraging energetics and body condition.

These results suggest the potential for declines in adult survival of more than 1% for Forth Island kittiwakes and Forth Island puffins, and for declines of more than 0.5% for Fowlsheugh kittiwakes and Forth Island razorbills. The results do not indicate any potential for declines of 0.5% or more for kittiwakes at St. Abbs, or for gannets or guillemots at any SPA.

Forth Island puffins show the largest estimated declines, but only if the distribution of prey is assumed to be homogeneous. Inch Cape and Alpha make the largest contributions to declines for this species-SPA combination (both have declines of more than 1% individually, but, again, only under an assumption of homogeneous prey distribution – if the prey is heterogeneous then the overall effect is much smaller and the main contribution is from Neart na Gaoithe). One possibility for this difference is due to the relative densities of birds in the wind farm footprint plus 1km buffer (Zone 4) compared to those in the surrounding 5km wide zone into which birds are displaced (Zones 3+5). Under heterogeneous prey, the 5km buffer area (Zones 3+5) may necessarily have quite different prey densities than the wind farm plus 1km exclusion area (Zone 4). For puffins at Alpha, the estimated density of birds within the wind farm footprint is much lower than that in the surrounding 5km area, and there is a large hotspot of predicted bird density (and therefore also of predicted prey in the heterogeneous prey simulations) just to the west of the wind farm. This means that under heterogeneous prey conditions displaced birds forage in a neighbouring location with a comparatively high density of prey and so little effect of the wind farm is felt. However, under homogeneous prey conditions displaced birds forage in an adjacent location with a comparatively lower prey level, which is unable to compensate for the increased density of birds and flight costs. Therefore, the effect of the wind farm in homogeneous prey conditions is much greater than that resulting from heterogeneous prey conditions where simulated prey much more closely matches the simulated bird distribution. The same is true for puffins at Inch Cape, although to a lesser extent because although the density of birds in the immediate vicinity of Inch Cape is relatively high compared to several other areas, the difference is not as great as that in the 5km buffer zone for Alpha. In summary, this means that birds displaced from wind farms under heterogeneous prey can move into areas with richer prey and so incur an advantage over their initial choice of foraging location that in part offsets the cost incurred. However, under homogeneous prey all areas are equivalent with respect to prey density, so this offset does not occur.

This result necessarily provokes the question as to which prey method, homogeneous or heterogeneous, is the most reliable. This is not a question that can easily be answered. Both methods rely on assumptions that are unlikely to be realistic in practice, but we do not know which of the two scenarios is likely to be closer to reality. Specifically,

1) the heterogeneous prey results assume that the density of prey can be directly inferred from the density of observed seabird foraging locations (within relatively small datasets), but in reality the GPS data may not give a complete picture of the density of foraging birds, and, further, the density of foraging birds is unlikely to be related solely to the density of prey.

2) the homogeneous prey results assume that prey is uniformly distributed across the Forth/Tay area, but this is clearly not true in reality.

We therefore recommend that the results from both methods should be considered, and that considerable caution should be applied to interpretation of all results. The greatest caution is needed in cases where bird distributions were inferred from GPS data for small numbers of birds, such as puffins, and in these situations the heterogeneous prey distributions are likely to be of particular concern.

Forth Island kittiwakes show cumulative declines of almost 2%, under both heterogeneous and homogeneous prey scenarios. Neart na Gaoithe appears to be the biggest contributor to this, with an estimated decline of more than 1%. Fowlsheugh kittiwakes show a cumulative decline of just under 0.5% (with either homogeneous or heterogeneous prey). This seems to be primarily driven by Alpha, which has an individual effect (under both homogeneous and heterogeneous prey scenarios) of between 0.5 and 1%. In all cases, the cumulative effect of all four wind farms is broadly similar to the sum of the effects of the individual wind farms.

Results for breeding success are qualitatively similar, but are of smaller magnitude (assuming that a 1% decline in adult survival decline corresponds to a 5% decline in breeding success; Freeman et al. 2014) and are more affected by stochastic noise (as shown by the assessment of reliability using additional runs; Tables H1 and H2). The only decline that is greater than 2.5% is for the cumulative impact on Forth Island puffins under homogeneous prey, and, although this decline is actually much closer to 5% than 2.5%, there are no declines of more than 5%. The effect of ~5% on Forth Island puffins appears to approximately decompose into a 2% effect of Inch Cape, a 1% effect of Neart na Gaoithe, a 1% effect of Alpha, and a 1% interaction effect.

The species-SPA-wind farm combinations with the largest declines in adult and chick survival generally correspond to those for which birds spend a substantial proportion of time in the zones (4, 5 and 6) that are affected by the wind farm. Forth Island puffins (for all wind farms except Bravo), Forth Island kittiwakes (for all four wind farms) and Fowlsheugh kittiwakes (for Alpha and Bravo) all have more than 2.5% of their foraging destinations in these zones. However, there are species-SPA-wind farm combinations with birds spending a substantial amount of time in these zones that do not have large estimated effects (Forth Island guillemots with Neart na Gaoithe; Forth Island razorbills with Neart na Gaoithe, and Forth Island gannets with all wind farms).

The interaction of Forth Island puffins with the Alpha wind farm entirely results from displacement effects, whereas the interaction with the Neart na Gaoithe wind farm is almost entirely in terms of barrier effects. Other important species-SPA-wind farm combinations involve a mix of barrier and displacement effects, but the percentage of time spent in barrier-related areas (zones 5 and 6) is often substantially larger than that spent in displacement-related areas (zone 4).

The relative effects on different study species result from variation in foraging ecology. Guillemots and razorbills typically have more restricted foraging ranges during chick-rearing than the other species (Daunt et al. 2011), resulting in limited interaction with wind farm footprints. The higher effects in kittiwakes and puffins are primarily because they have a greater foraging range than guillemots and razorbills, resulting in greater overlap with wind farms. Gannets from Bass Rock have foraging ranges that extend hundreds of kilometres beyond the wind farms (Hamer et al. 2007). For this species, the proportion of birds interacting with wind farms is comparatively high, but associated costs are small relative to the overall cost of foraging trips, so overall effects are negligible.

4.2 Uncertainty

4.2.1 Sources of uncertainty

There are a number of different sources of uncertainty associated within our results:

1) stochastic uncertainty associated with using a single run of the (full or fast) foraging model which involves a particular sample of birds ("sampling uncertainty");

2) uncertainty associated with the values of the parameters within the model ("parametric uncertainty");

3) uncertainty associated with the structure of the model that we use ("structural uncertainty").

Within the timescale of the project it has not been possible to perform a full quantification of uncertainty. Within the exploratory runs we were able to quantify sampling uncertainty and one particular component of parametric uncertainty. The results suggested that sampling uncertainty was substantial, and this motivated us to reduce this uncertainty by using a much larger sample of birds (20000 rather than 1000) when generating the final results. The additional computational effort required to run the larger samples uncertainty meant that it was not feasible to perform the additional model runs that would have been needed to properly quantify uncertainty within the final results, although we did use some additional runs to provide a rough quantification of sampling uncertainty. We can, nonetheless, make some general comments regarding the three different sources of uncertainty.

4.2.2 Sampling uncertainty

Additional simulations from the fast model (Section 2.6.3 and Appendix H) suggest the level of sampling uncertainty within the final results is low for adult survival: i.e. the results obtained by simulating one set of 20000 birds are similar to those obtained by simulating a different set of 20000 birds. The level of sampling uncertainty for chick survival is considerably higher. The higher level of sampling uncertainty for chick survival is likely to stem from certain threshold effects in the foraging model that determine chick survival based on the amount of time nests are unattended by adults.

These results suggest that it was valuable to run the final analysis using larger samples of birds than those which were used for the exploratory analysis (i.e. 20000 rather than 1000), but that uncertainty for adult survival would not be substantially reduced – and the results would not be qualitatively altered – if we were to re-run the analyses using more than 20000 birds. More precise results for chick survival could, however, be obtained through re-running the simulations with larger numbers of birds.

4.2.3 Parametric uncertainty

We used a sensitivity analysis to examine the effect of changing the values of specific parameters on the resulting estimates of chick and adult survival. The sensitivity analysis suggested that changes to the values of four of the parameters considered (adult body mass below which adult leaves chick unattended, chick body mass below which chick dies, adult priority of resourcing between self and chick, and intra-specific competition) have substantial – and in some cases very substantial – impacts upon chick survival. The impacts of changing parameter values on adult survival are generally much more modest, but the effects of wind farms on adult survival are highly sensitive to the values of the intra-specific competition parameter. Adult and chick survival both seem to be insensitive to the value of the fifth parameter that we considered (unattendance duration at the breakpoint).

The sensitivity analysis is of use in telling us which parameters are influential in the model, but should be interpreted cautiously. In some cases it will over-estimate uncertainty, because it will include parameter sets which would be associated with data characteristics (adult mass and chick survival in the baseline run) which would have led them to be rejected. In other cases it may under-estimate uncertainty, because a wider range than that considered would have led to data characteristics that would have been accepted.

The ideal way to avoid these problems would be through a full quantification of parametric uncertainty. Established methods for quantifying uncertainty within contexts such as this do exist (e.g. Approximate Bayesian Computation), but are computationally intensive because they require thousands, or tens of thousands, of simulations and so could not feasibly be used within the timescale of this project.

We know that model outputs are very sensitive to some parameters that were not explored within the sensitivity analysis - the total amount of prey is the most prominent of these, and we know that small changes in this value can have very substantial effects on the model output. The barrier and displacement rates, which were agreed by the Steering Committee, are also likely to be important parameters in determining the magnitude of the response to the wind farm (and our exploratory analyses, which used different scenarios for barrier and displacement rates, suggest that this is indeed the case). The parameters associated with the adult mass-survival relationship are also likely to be influential: the large standard errors given by Erikstad et al. (2009) suggest that there is considerable uncertainty regarding the magnitude of the mass-survival relationship, but for species other than kittiwake the standard deviation of adult masses is also likely to be a key parameter (because this determines the magnitude of change in standardized mass that results from a change in absolute mass).

4.2.4 Structural uncertainty

Inevitably, due to a lack of data for some of the key foraging behaviours and processes involved in determining seabird response to wind farms, there are a number of structural uncertainties in our model that will have had a bearing on model results and conclusions. One of the most important is the uncertainty about the form of the adult mass-survival relationships, and the lack of data on this relationship for three of the species, and for any species based on local data. We have attempted to quantify this uncertainty to the best of ability given the available published data, but we are only able to do so within the bounds of the two published studies that are currently available. The only way to better account for this would be to analyse local data (available for kittiwakes and guillemots) or collect new data (required for razorbills, puffins and gannets).

Some key behavioural responses are simply unknown: for example, how birds would balance the number of foraging trips taken against additional barrier flight costs imposed by wind farms. Our model has been structured to include behavioural processes that we believe are likely to result from the addition of a wind farm, but there is no way to assess the legitimacy of these processes without additional data. Various exploratory attempts to improve/amend the behavioural assumptions within the models did suggest that the magnitude of the wind farm effect was strongly related to the assumptions that we made about how birds determine the number of trips they will do in a day. However, we were unable to fully assess the consequences of alternative formulations of bird trip behaviour within the time constraints of this project.

We have made crude assumptions regarding the spatial distribution of prey: assuming that it is either uniform, or else proportional to the density of birds that were found within an area using the GPS data (after accounting for the effect of distance to colony). These scenarios are likely to correspond to two extreme cases (bird distributions do not reflect prey distributions at all, or bird distributions perfectly reflect prey distributions), and reality is likely to lie somewhere between these two extremes.

There is considerable uncertainty regarding the precise behaviours that birds will adopt during avoidance or displacement. In terms of barrier effects we have assumed that birds will fly right up to the edge of the 1km buffer zone around the wind farm before they begin to modify their flight path; this may be overly-conservative, because birds may in reality learn to avoid the wind farm by following a shorter route (e.g. flying directly from the colony to one edge of the wind farm footprint, and then flying directly from there to their destination). We have also assumed that birds do not habituate to the wind farm over the course of the breeding season, which is likely to be a conservative assumption.

The representativeness of the GPS tracking data is a key consideration when interpreting the results of the model. Confidence comes with larger sample sizes and consistent results across situations (e.g. among years within SPAs, or across SPAs). The most restricted sample sizes were apparent for guillemots away from Forth Islands and for puffins. For guillemots, we made an expert judgement on the representativeness of these data largely from our knowledge and experience of the at-sea range of Isle of May individuals estimated across many years (reviewed in Daunt et al. 2011). Whilst it is not possible to test the validity of this approach, it is probably reasonable that space use recorded at one SPA provides an indication of likely space use at adjacent SPAs, because of expected correlations in environmental conditions across the region (Frederiksen et al. 2007; Cook et al. 2011). On this basis, we discarded Buchan Ness data because sample sizes were very low and birds foraged in a very restricted area. In contrast, we considered that the data from Fowlsheugh and St Abbs Head guillemots were more representative because sample sizes were higher and foraging range and distribution were more in keeping with data from the Isle of May. Ultimately, the decision to exclude Buchan Ness on the basis of the quality of the data is unlikely to be a factor in assessments because of the distance of this colony from proposed wind farms. There is also increasing evidence that species from this colony preferentially forage to the north (RSPB unpublished data). For puffins, we considered the data from the 7 study individuals was plausible with respect to mean maximum foraging range and direction. However, there is a concern that shorter trips were under-represented (Harris et al. 2012). Thus, the true distribution may be concentrated closer inshore than we recorded, and overlap with the more distant proposed wind farm developments could be lower. However, without further data it is impossible to assess the extent of this potential under-representation. Further insights could be gained by combining tracking with at-sea survey data, although the latter would include non-breeding Puffins and those from other colonies, and much of it is comparatively old.

4.2.5 Reducing uncertainty: further work

This project has highlighted the need for more data regarding several crucial aspects of seabird behavioural response to wind farms, as well as more basic data on life history. In particular, data for displacement rates from wind farms by foraging birds, levels of barrier effects and width of buffer zones is required to better understand how individuals adjust their behaviour in response to wind farm development. Existing empirical data are primarily based on non-breeding birds that are not under the same spatial or physiological constraints. It is not known whether these estimates are relevant to breeding seabirds that have restricted foraging ranges and the requirement to repeatedly return to a central place; in other words, whether these behavioural responses are generic or state dependent. Furthermore, these data need to be collected over long timescales such that behavioural mechanisms such as habituation can be included in future modelling efforts.

One of the largest sources of uncertainty in this project has been the translation of adult body mass into subsequent survival over the remainder of the year. There is an urgent need for more local studies that attempt to determine the functional relationship between end of breeding season adult body mass and subsequent survival for these species. Furthermore, we have also not been able to include any effect of fledging mass of chicks on post-fledging survival; it is likely that chicks fledging at a lighter mass have lower over-winter survival prospects, but quantification of this relationship is currently lacking in the literature. In addition, this model did not consider other periods of the breeding cycle that could also be affected, including the probability of breeding and survival rates of eggs during incubation.

Finally, the addition of accurate data regarding prey distribution and density would greatly enhance the ability to better estimate impacts of wind farms. Moreover, collecting data on the prey response to wind farm development will also be crucial to better understand the impacts of wind farms on seabirds.

4.3 Conclusions

This analysis is the first, to our knowledge, to quantify consequences of displacement and barrier effects on seabird demographic rates. Displacement effects have been considered to potentially affect chick survival, but what has been less widely appreciated is that alterations to adult survival are also possible, mediated via changes in body condition. This model is readily adaptable to other locations, in particular in situations where GPS tracking data are available.

We have shown that there is considerable variation in the potential effects of SPA/species/wind farm combinations, with the greatest effects apparent with Forth Island kittiwakes, Fowlsheugh kittiwakes and Forth Island puffins. Within the scope of this project it has not been possible to conduct a full quantitative assessment of uncertainty; however, all of the qualitative indications are that the uncertainty in the magnitude of the wind farm effect is likely to be large. The outputs from this work should therefore be interpreted with considerable caution. Parameterisation with local data, in particular prey distribution, behaviour of seabirds in response to wind farms (including habituation) and influence of adult body mass change on subsequent survival, would be an important step for the future.

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Appendix A. Habitat association modelling

A.1. Environmental data

To explore links between guillemot foraging distributions and environmental conditions, we used data for four environmental variables (Table A. 1). Data on water depth were derived from the GEBCO dataset, and refer to a 0.5 x 0.5 minute grid. Depth gradient is derived from water depth using a standard algorithm (the Sobel filter) whilst quantifies the magnitude of the seabed gradient in the direction of greatest change. Sediment type is a categorical classification into five categories: sandy/fine, coarse, mud, mixed and rock. These correspond to aggregations of EUNIS categories:

Rock – “Circalittoral or infralittoral rock and other hard substrata” – A3.1, A3.2, A3.3, A4.1, A4.2, A4.27, A4.30, A4.33

Coarse – “Sublittoral coarse sediment” – A5.12, A5.13, A5.14

Fine/sandy – “Sublittoral fine or sandy sediment” – A5.23, A5.24, A5.25, A5.26, A5.27

Mud – “Sublittoral mud sediment” – A5.33, A5.34, A5.35, A5.36, A5.37

Mixed –“Sublittoral mixed sediment” – A5.43, A5.44, A5.45

Each square on the GEBCO grid (0.5 x 0.5 minute) was classified into exactly one of these categories.

Sea surface temperature (SST) data are derived from satellite data (the MODIS Aqua satellite), and are a monthly composite matching the time of logger deployment (which was in June in all cases). Data for this variable are available for shorter periods (daily/weekly), however these datasets frequently have missing data and were therefore not used.

Variable	Units	Source	Resolution
Water depth	Metres	GEBCO	0.5 min x 0.5 min
Seabed gradient	Slope (m/km)	Derived from GEBCO water depth using a Sobel filter	0.5 min x 0.5 min
Sediment type	Classification into five types	British Geological Survey	0.5 min x 0.5 min
Annual Sea Surface Temperature in June	Degrees Celcius	MODIS Aqua satellite	2.5 min x 2.5 min

Table A. 1. Details of environmental variables used in the analysis.

Figure A. 1 shows the spatial distribution of the four variables over the region of interest. Water depth generally increases with distance to coast, but there are extensive areas of shallow water around the coasts of the Firth of Forth and Firth of Tay and areas of deeper water in the NE and SE of the region of interest. Spatial variations in depth gradient are relatively complex, but there are areas of high gradient in both coastal and offshore areas. The majority of the region of interest is covered by two sediment type classifications – coarse and fine/sandy – but the Firth of Forth is predominantly classified as 'Mud'. The remaining two classifications ('rock' and 'mixed') have very limited spatial extent within this region. Spatial variations in SST vary substantially from year to year, with different overall spatial patterns occurring in 2010, 2011 and 2012.

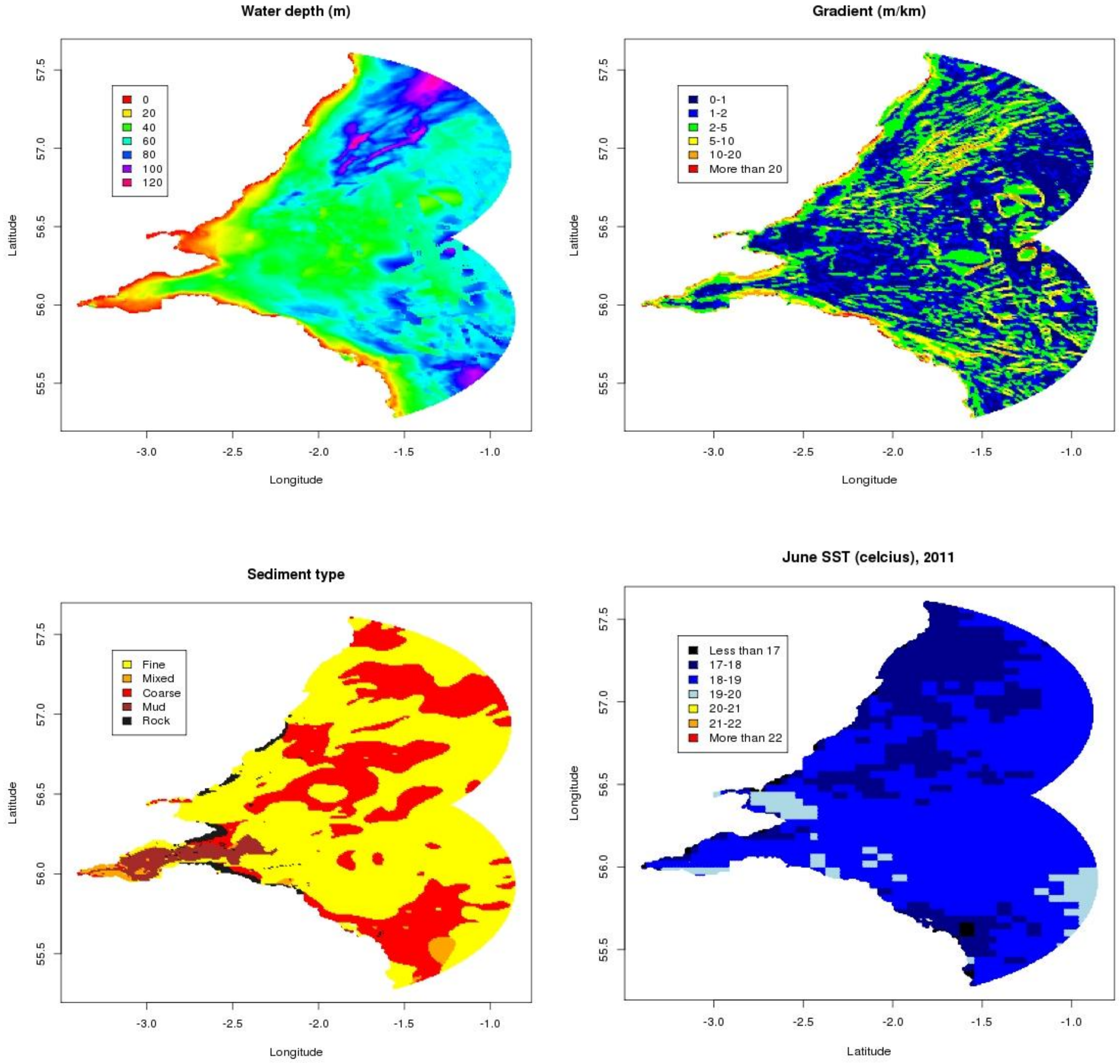

Figure A. 1. Variation in water depth (upper left), seabed gradient (upper right), seabed sediment (lower left) and sea surface temperature in June (lower right) within the study area; example is from 2011.

A.2. Habitat association model

We use a statistical model to describe the relationship between the amount of bird foraging activity and the spatial characteristics of each location within the region of interest. This relationship is assumed to depend on the colony from which birds originate, and the simplest model (our basic model) assumes that the density is determined solely be the distance to the colony:

foraging bird density = a * (Distance to colony)^b

The effect of distance from colony is expected to strong during the breeding season (the period for which we have data) because seabirds are central place foragers.

This basic model is then modified to account for the effects of environmental variables, by including an additional element in the model to represent spatial variation in the underlying suitability of different locations.

foraging bird density = a * (Distance to colony)^b * suitability

The basic model is equivalent to assuming that the value of suitability is equal to one for all locations. We assume that suitability does not depend on colony – this reflects that idea that suitability is a fundamental characteristic of the location, rather than a characteristic of the birds that feed at it.

The key assumption within this project is that ‘suitability’ is (approximately) proportional to prey abundance. The GPS data are used to estimate the unknown parameters within the model, which in turn allows us to produce estimate values of suitability for each site – finally, this allows us to produce indirect maps of prey abundance that are used as inputs to the model of seabird displacement.

We assume that suitability depends upon some or all of the four explanatory variables mentioned above. The most complicated model that we consider is of the form

log(suitability) = γ_1 * depth + γ_2 * gradient + γ_3 * sediment type + γ_4 * SST

Sixteen possible models were considered, based on all possible combinations of the four environmental variables:

1. Distance to colony (the basic model)
2. Distance to colony + depth
3. Distance to colony + gradient
4. Distance to colony + depth + gradient
5. Distance to colony + SST
6. Distance to colony + depth + SST
7. Distance to colony + gradient + SST
8. Distance to colony + depth + gradient + SST
9. Distance to colony + sediment type
10. Distance to colony + depth + sediment type

11. Distance to colony + gradient + sediment type#
12. Distance to colony + depth + gradient + sediment type
13. Distance to colony + SST+ sediment type
14. Distance to colony + depth + SST+ sediment type
15. Distance to colony + gradient + SST+ sediment type
16. Distance to colony + depth + gradient + SST + sediment type (the most complicated model)

The model is implemented in R using the ‘glm’ routine. The basic approach is to fit a logistic regression model (Binomial GLM) in which the data consist of observed foraging locations and control points (points on the regular 0.5 x 0.5 min grid that is used for the GEBCO bathymetry data) and the response variable is binary (1 = Case = actual foraging location; 0 = Control = point on the grid). The control data are repeated so as to cover all site-by-year combinations that are contained within the observed data. The basic model contains two explanatory variables: site-by-year combination (a categorical nuisance variable which accounts for differences in the number of GPS tags deployed for different years and sites), and distance to colony. The remaining models additional contain some or all of the environmental variables: water depth (numeric), depth gradient (numeric), June SST (numeric), sediment type (categorical).

A.3. Assessing model performance

To assess model performance we used a cross-validation approach whereby we applied each model to the entire dataset, and then to subsets of the data, omitting either one of the colonies or one of the years. We then compared the predicted and observed bird densities for each model using a statistical measure of similarity (called KL-divergence). We end up with three measures of performance for each model –

1) performance of the model in predicting foraging density for the entire dataset, given that the model was fitted to the entire dataset;

2) performance of the model in predicting foraging density for a year that was omitted from the modelling;

3) performance of the model in predicting foraging density for a site that was omitted from the modelling.

A.4. Results

A.4.1. Habitat suitability

The results of our initial modelling (Figure A. 2) suggest that models which contain sediment type exhibit substantial spatial variation in suitability, whilst those that exclude this variable contain only modest spatial variations. When sediment type is included in the model the areas with lowest suitability are found to be those associated with mud and mixed sediments, whilst the areas with highest suitability are those associated with coarse and fine/sandy sediments. This corresponds, geographical, to the areas of lowest suitability generally occurring in and around the Firth of Forth and the areas of highest suitability generally occurring offshore.

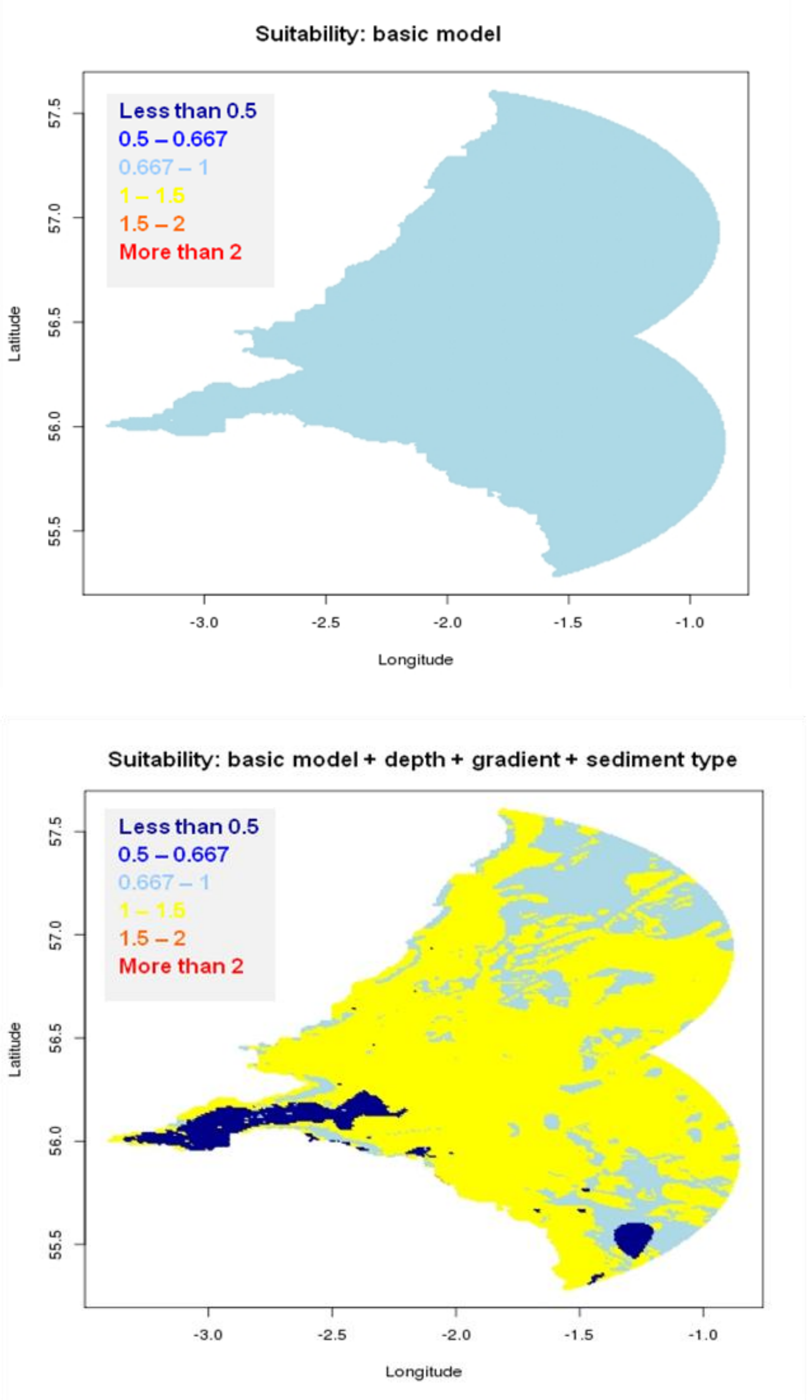

Figure A. 2 Habitat suitability maps of the study area derived from the basic model (upper) and derived from the model including all environmental variables (lower).

A.4.2. Predicted bird density

Suitability is the primary output from our analyses, since it assumed to provide a proxy measure for spatial variations in prey density, but we also use the models to produce predicted maps of bird density. These predictive maps are produced partly in order to summarize the outputs of our analyzes in such a way that they can be checked for biological plausibility.

The predicted bird densities for Fowlsheugh (Figure A. 3) are very similar for all of the models that we have considered. The predicted bird densities for the Isle of May (Figure A. 4) are very similar for all models that exclude sediment type, but models that include sediment type show much lower predicted bird densities in areas of mud and mixed sediment than in areas with more common sediment type classifications (sandy/fine and coarse). Both sets of results are derived from the same model, so the large differences in the results that are obtained for the two colonies seem somewhat contradictory. The apparent lack of effect at Fowlsheugh can be explained that mud and mixed sediment type classification are simply not present at all within the areas that are readily accessible from the colony. The results so far have not shown any strong effects of the other environmental variables (depth, gradient or SST).

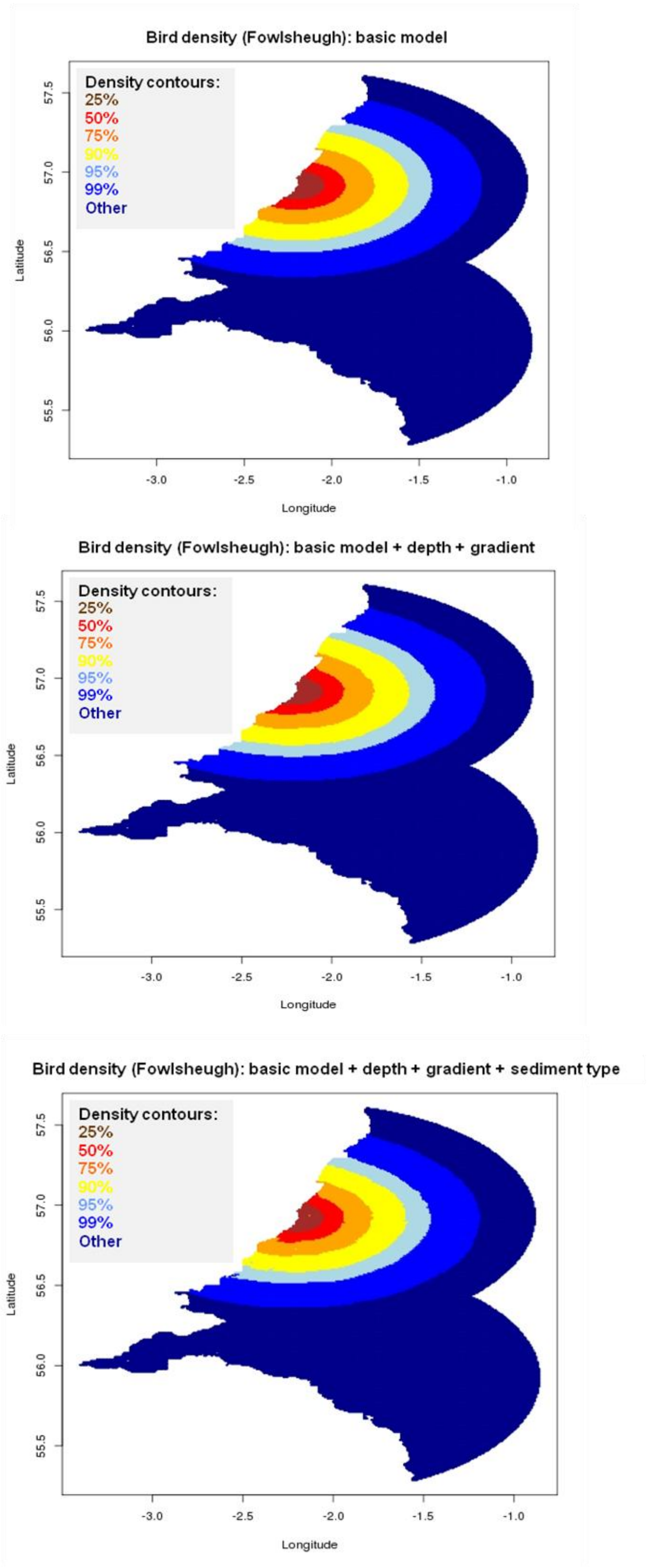

Figure A. 3. Predicted bird density map around the Fowlsheugh colony derived from the basic model (upper), the model with depth and seabed gradient (middle) and the model with depth, seabed gradient and sediment type (lower).

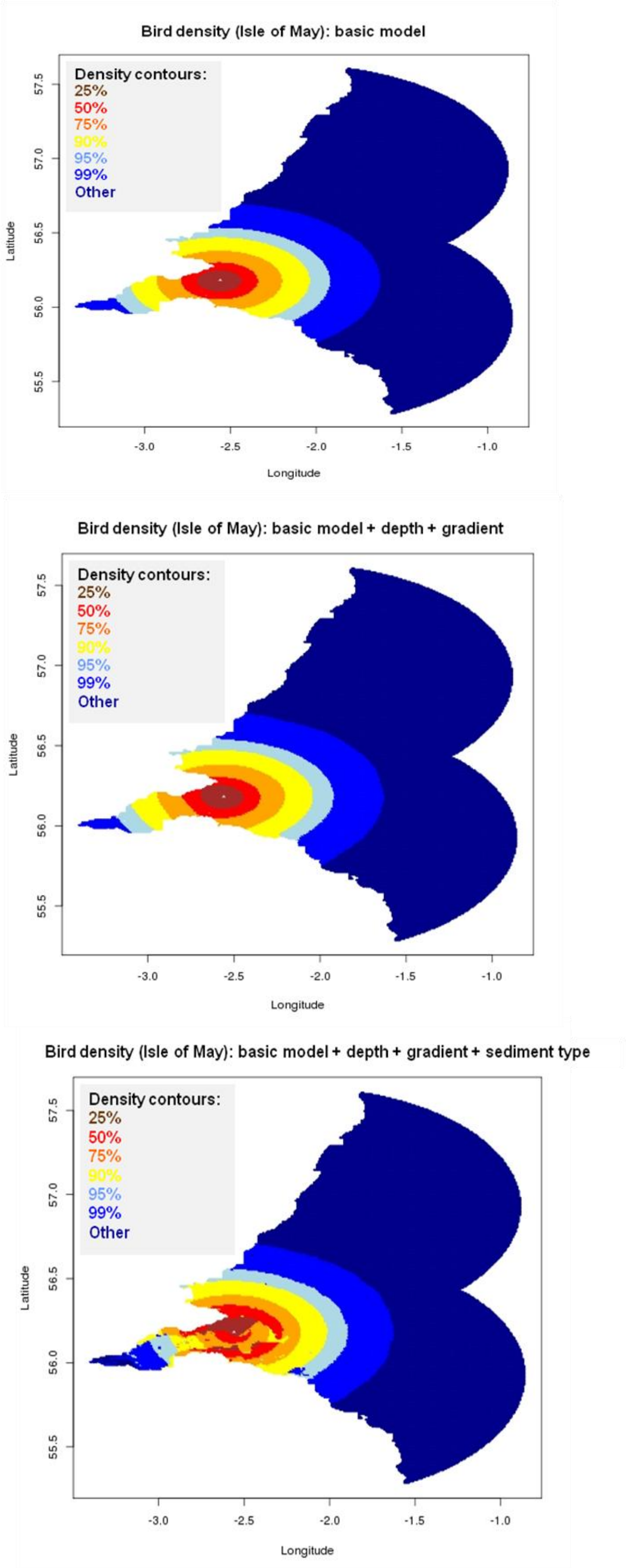

Figure A. 4. Predicted bird density map around the Isle of colony derived from the basic model (upper), the model with depth and seabed gradient (middle) and the model with depth, seabed gradient and sediment type (lower).

A.5. Interpretation

Sediment type is by the far the most important environmental variable in the models, and the best model contains just this one variable. The model with sediment type remains the best model if we assess performance against years that have been left out, suggesting there is no interannual variation in the importance of this variable (Table A. 2). However, models containing sediment type perform very poorly if performance is assessed against sites that have been left out (Table A. 2). Possible explanations for this are: 1/ the accessibility of sediment types differs widely between colonies, with all types of sediment only present around the Isle of May mainly fine and coarse sediments present in the areas surrounding the other two colonies; 2/ the 'sediment type' effect reflects a geographical effect of coastal features around the different colonies rather than a true effect of seabed sediment.

Model	All data	Omitting colonies	Omitting years
Dist	0	0	0
Dist + depth	-0.08	-0.82	-0.25
Dist + gradient	-0.08	-0.53	0.16
Dist + depth + gradient	-0.12	-1.54	0.05
Dist + sediment	0.67	-30.26	1.11
Dist + depth + sediment	0.57	-32.08	1.04
Dist + gradient + sediment	0.54	-30.48	0.89
Dist + depth + gradient + sediment	0.44	-31.98	0.90
Dist + SST	-0.05	-0.15	-0.13
Dist + depth + SST	-0.19	-1.19	-0.57
Dist + gradient + SST	-0.06	-0.71	0.12
Dist + depth + gradient + SST	-0.15	-1.98	-0.15
Dist + sediment +	0.56	-30.83	0.94

SST			
Dist + depth + sediment + SST	0.39	-32.94	0.71
Dist + gradient + sediment + SST	0.49	-31.03	0.80
Dist + depth + gradient + sediment + SST	0.34	-32.80	0.66

Table A. 2. Percentage change in model performance relative to the basic model.

Appendix B. Example prey density maps used in the foraging model

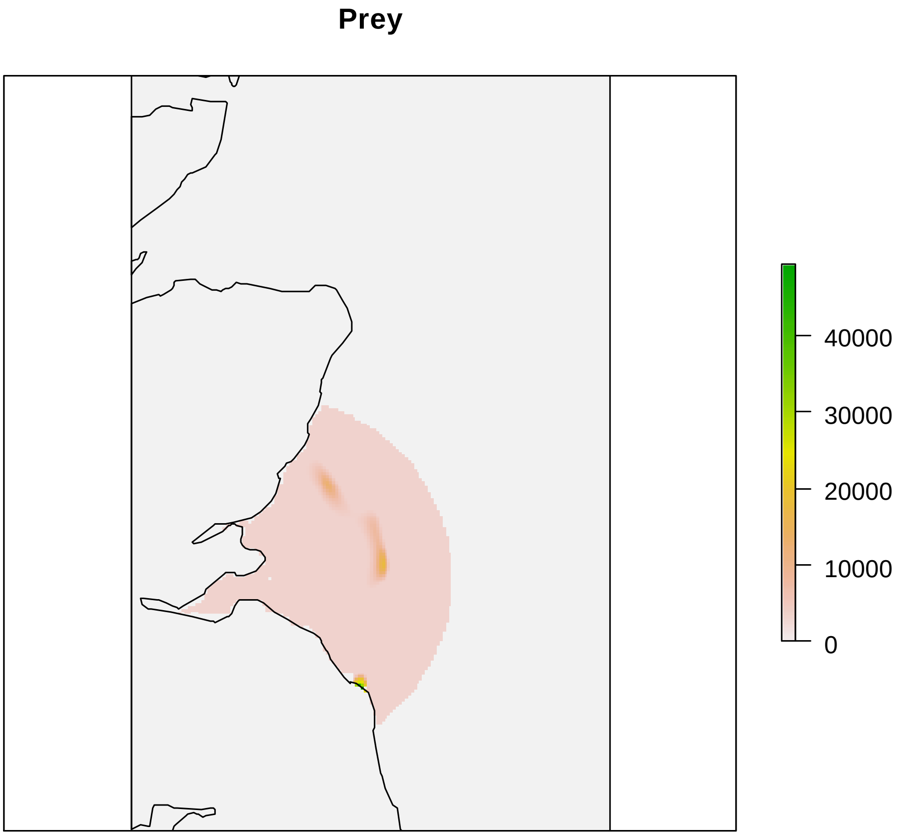

Figure B. 1. Puffin prey density in the moderate scenario for the Forth Islands.

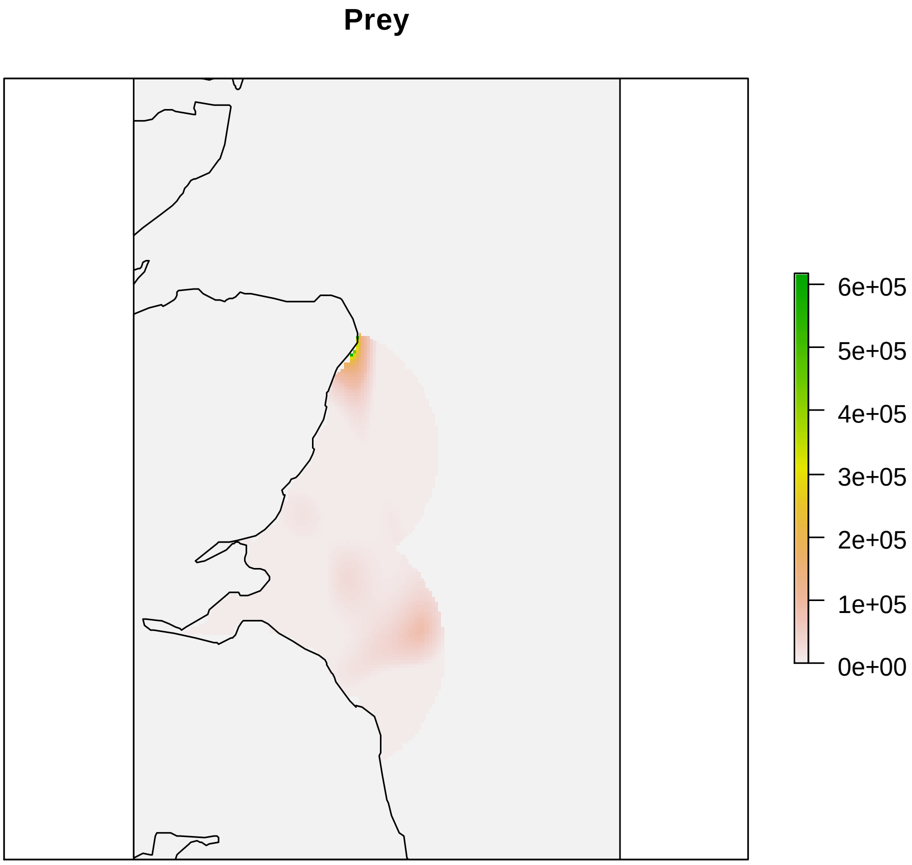

Figure B. 2. Guillemot prey density in the moderate scenario used for Forth Islands, St Abbs Head and Fowlsheugh. Guillemots at Buchan Ness were modelled using a homogeneous prey map only.

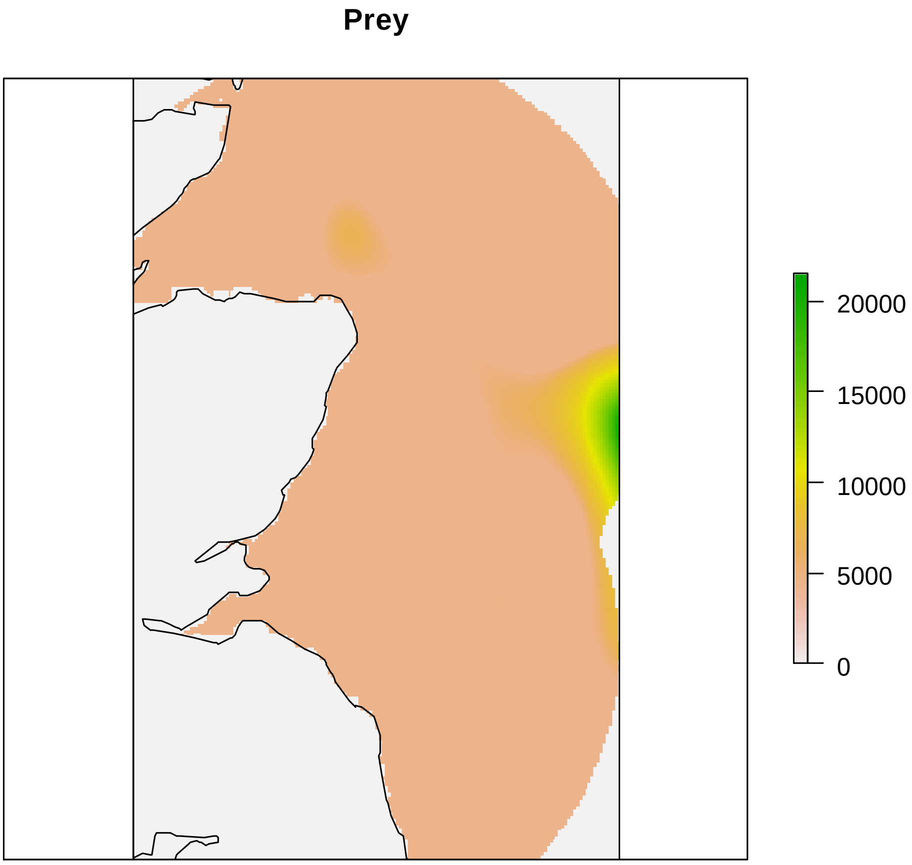

Figure B. 3. Kittiwake prey density in the moderate scenario used for all four SPAs.

Appendix C. Detailed foraging model structure

The foraging model has a modular structure, following a logical sequence of events, processes and behavioural decisions to shape model output. There are fourteen modules called upon by the main model file, each of which performs a specific section of the foraging model (Figure C. 1).

The most crucial modules are those that determine bird flights (S10), energy and time budgets (S12) and change in body mass for adults and chicks (S13). The logical flow of the processes and decisions within each of these modules is detailed in the flow charts below, Figure C. 1 to Figure C. 5.

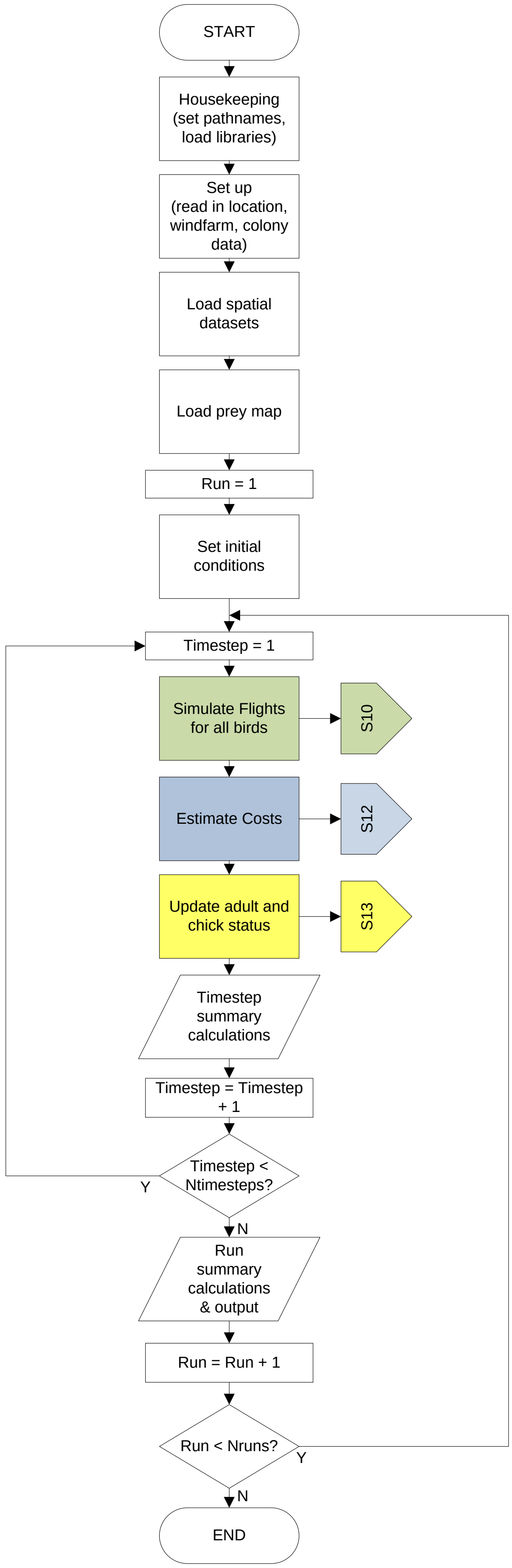

Figure C. 1. An outline of the logical flow for the model. Sections 10, 12 and 13 and expanded below.

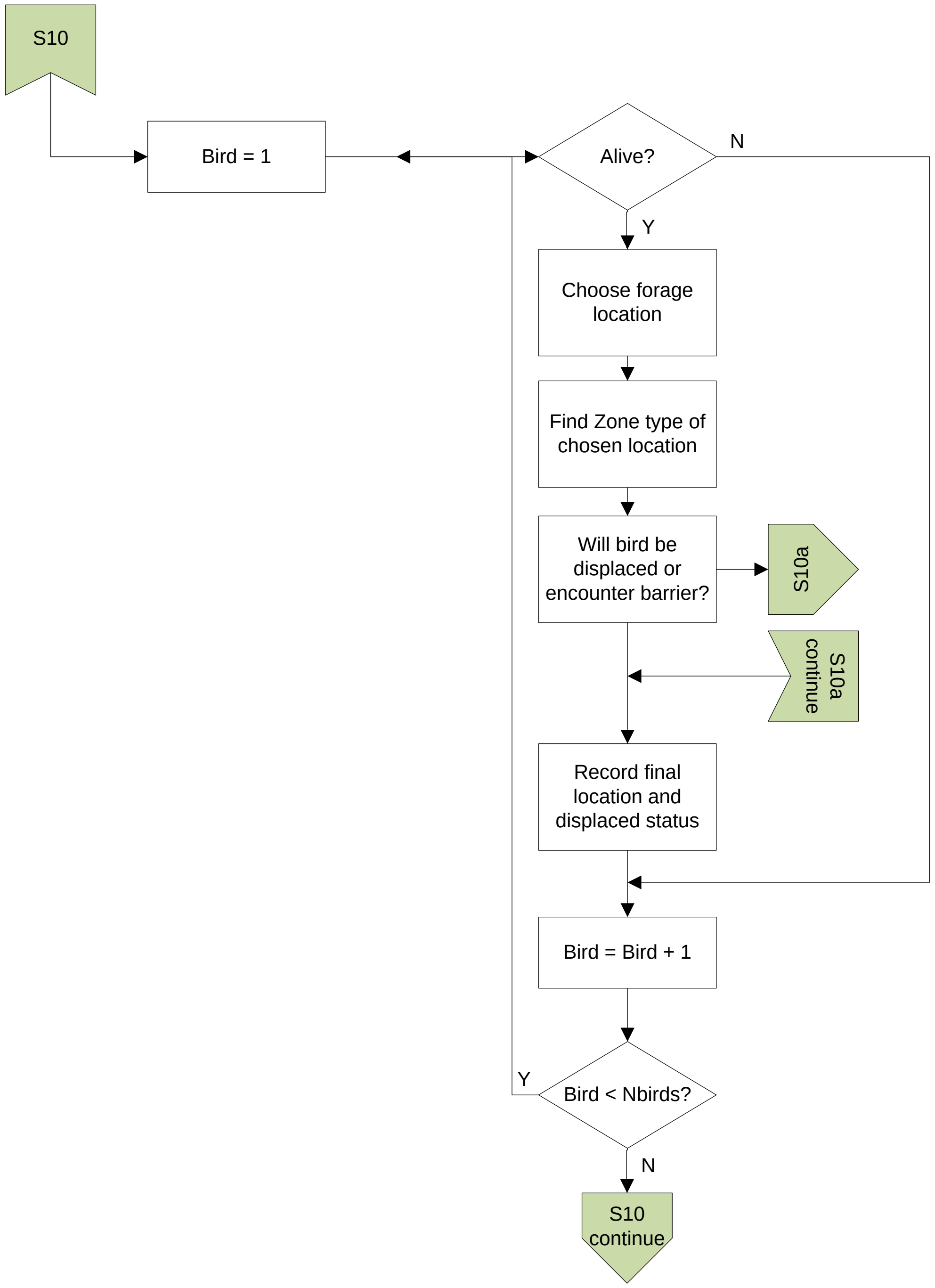

Figure C. 2 The logical flow for the selection of foraging sites for each bird in the simulation at the start of each time step

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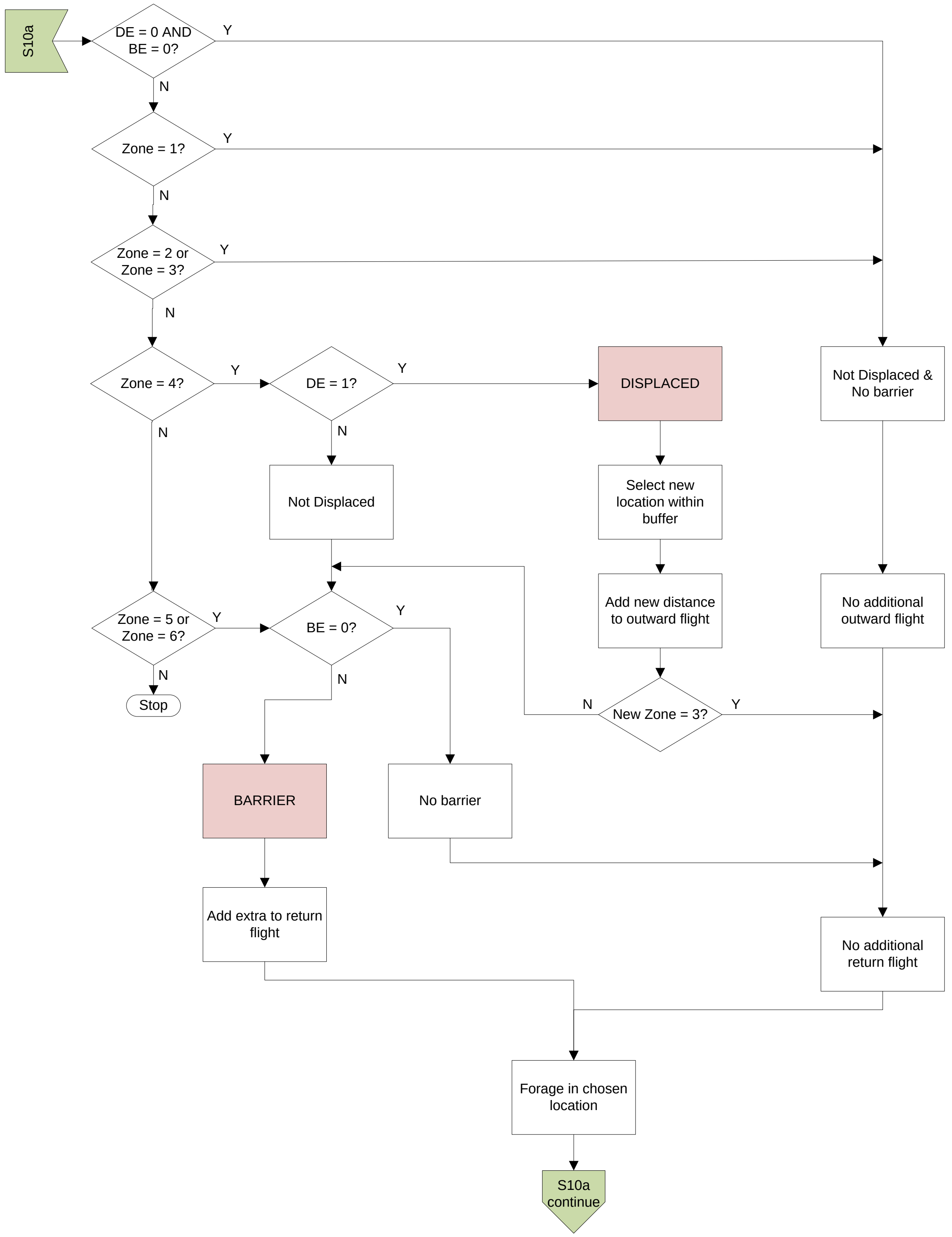

Figure C. 3. The logical flow for how displacement and barrier effects impact upon individual birds at within each time step of the foraging model.

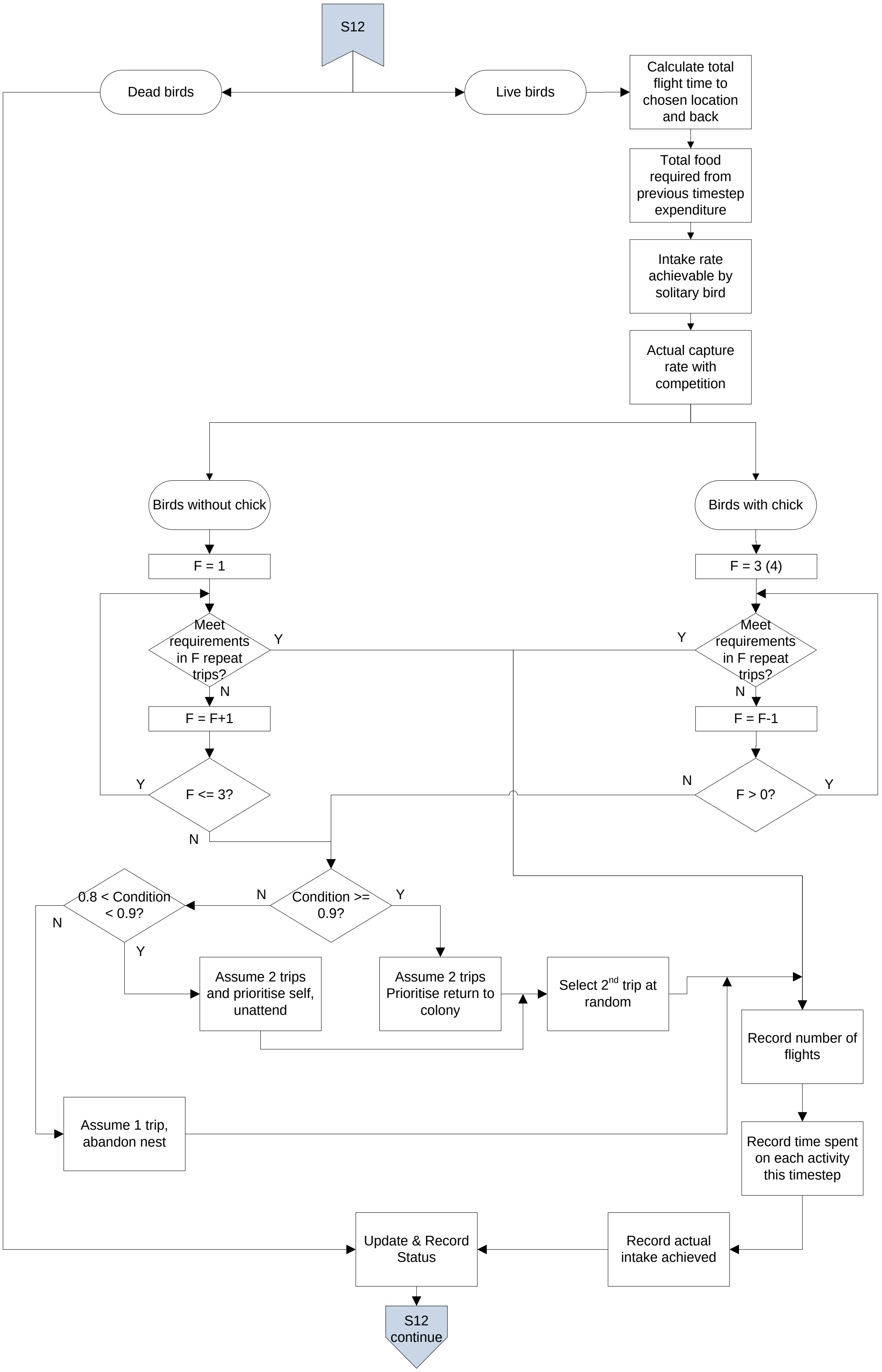

Figure C. 4 The logical flow for foraging behaviour by each individual bird each timestep

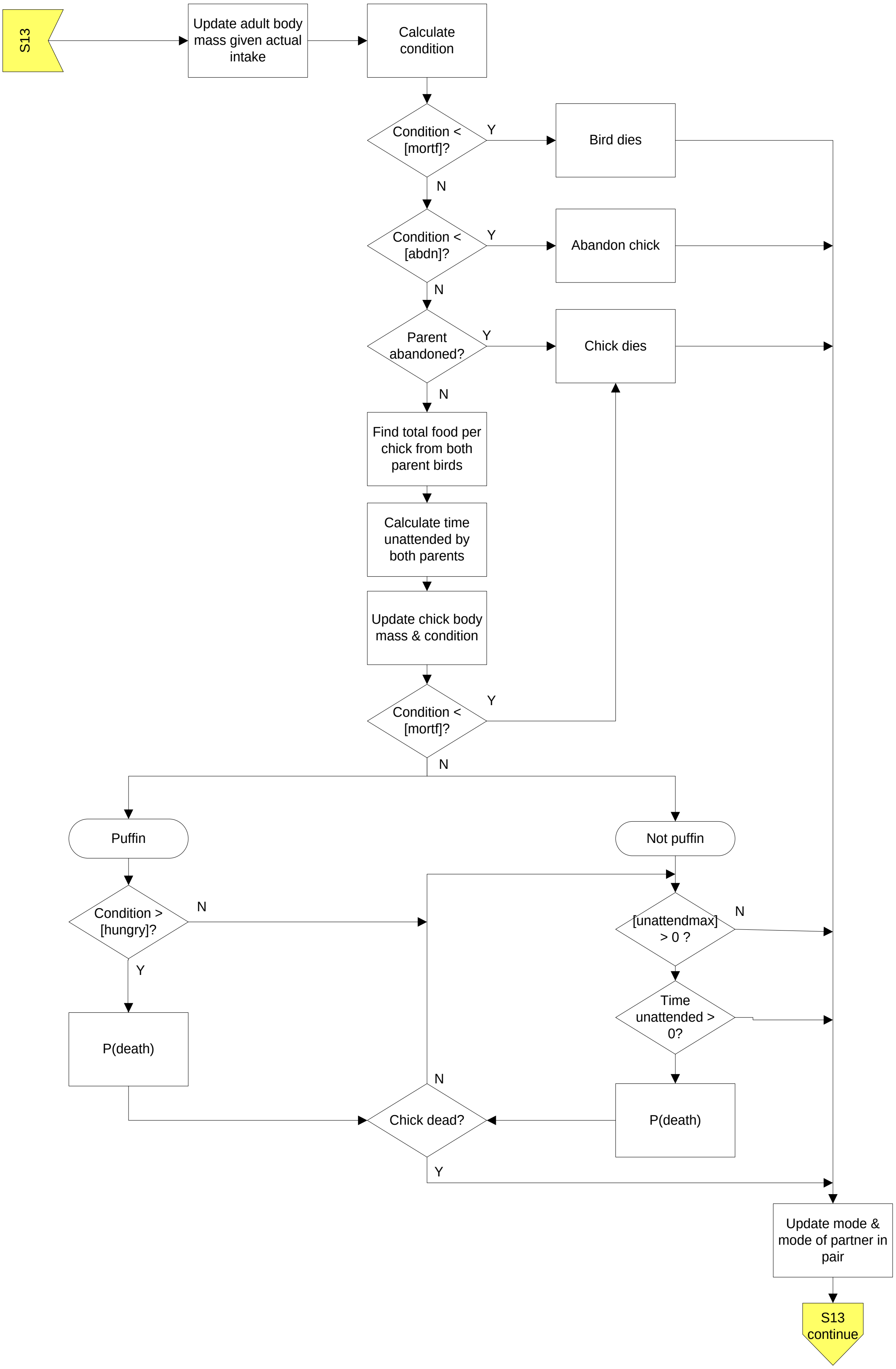

Figure C. 5 The logical flow within the model to determine the change of body condition of adults based on actual intake and the effect on the chick if unattended.

Appendix D. Source literature for model parameters.

Guillemot

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Thaxter, C.B., Wanless, S., Daunt, F., Harris, M.P., Benvenuti, S., Watanuki, Y., Grémillet, D & Hamer, K.C. (2010) Influence of wing loading on trade-off between pursuit-diving and flight in common guillemots and razorbills. Journal of Experimental Biology 213: 1018-1025

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Razorbill

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Appendix E. Quantification of uncertainty within exploratory runs

E.1. Quantifying uncertainty

The model was run five separate times for each species-by-scenario-by-SPA combinations, with each of the runs being generated using a common set of parameters. The variation between these runs tells us somewhat about the stochastic noise that is likely to be associated with the output from any single run. Note, however, that five runs are insufficient to provide a reliable estimate for the magnitude of the uncertainty that is associated within this noise.

When looking at chick survival, we summarise uncertainty by looking at the standard deviation in an overall summary (the proportion of chicks that survive for the duration of the breeding season) between the five model runs. Under an assumption of normality we also calculate crude estimates for the probabilities associated with exceeding particular thresholds. The key limitation of this approach is the number of runs: the very small number of runs (five) means that the mean and standard deviation of the wind farm effect may not be estimated reliably, and forces us to make a (potentially incorrect) assumption of normality in order to be able to estimate threshold probabilities.

When looking at adult survival, we focus on two sources of uncertainty: stochastic variation between model runs, and uncertainty associated with the magnitude of the published mass-survival relationship. Each run of the foraging model provides adult mass values for every individual within the simulated population at the end of the breeding season. These values can then be converted into adult survival values using the adult-survival relationships given in Section 2.4. The methodology within that section assumed that we used a value of *b* that was exactly equal to the value given in Oro *et al*. (2002) or Erikstad *et al*. (2009), but we actually go further – we account for the uncertainty in *b* by simulating 1000 values from a Normal distribution with a mean equal to the estimate of *b* given in the literature and a standard deviation equal to 0.359 times the mean. The ratio of the standard deviation to the mean (0.359) is based on the value obtained by Erikstad *et al*. (2009); this value is also applied to kittiwakes because the corresponding value within the Oro *et al*. (2002) paper (0.027) appeared to suggest an unrealistically low level of uncertainty. Each of these 1000 values is used to estimate an overall survival rate. For each species-by-scenario-by-SPA combination we therefore have 5000 simulated values for the overall adult survival rate (1000 for each of the 5 simulation runs). We assume that these values can be used to represent the uncertainty within the adult survival rate. We do not assume that these are normally distributed, but instead calculate probabilities and intervals directly from the simulated values (e.g. by estimating the probability of the impact exceeding 4% to be the proportion of simulated values for which the impact exceeds 4%). Note that the values of *b* are paired: the same value is used to calculate the uncertainty in the baseline and in the runs that include wind farms. This pairing reduces the uncertainty associated with the impact of the wind farm.

E.2. Presenting uncertainty

Assume that we are interested in a specific question: for example, what is the impact of all four wind farms upon guillemot adult survival in the Forth Islands SPA under a 'moderate' prey scenario, a 1km buffer, and 100-100% levels for displacement and barrier effects?

Our exploratory results provided the 'best estimate' for the magnitude of this impact (this is, in technical terms, the mean), but also provided information on the uncertainty associated with this. The raw results of uncertainty tell us, in effect, the probability that the actual impact would be greater than every possible threshold – the probability that the impact will be more than 0%, more than 0.1%,… etc. We summarise these raw results in two distinct, but closely related, ways:

1) we calculate the probabilities associated the impact exceeding a small number of fixed thresholds: 0%, 1%, 2%, 3%, 4%, 5%, 7.5% and 10%;

2) we calculate intervals that will contain the 'true' impact with a particular probability: e.g. the 50% interval (there is a 25% probability that the true impact will be lower than the bottom end of this interval and a 25% probability that the true impact will be higher than the upper end), the 33% interval, and the 95% interval.

Note that the two forms of summary come from the same underlying information, so they are, by definition, consistent with each other – they simply focus on summarizing the same information in two rather different ways.

In terms of the terminology for hypothesis testing, the impact of the wind farm would be classified as significant if the 95% interval contains only non-zero values and as non-significant if the 95% interval contains zero. Hypothesis testing is not necessarily a particularly useful concept in the context of decision making, however, and in this context the use of significance as a threshold for action would correspond to a highly anti-precautionary approach: it would imply that a negative impact should be considered to be problematic only if could be identified with virtual certainty.

The values that we produce may be related to the terminology produced by the IPCC (2010) working group. In particular, the probabilities of exceeding particular thresholds may be converted into textual descriptions using the following table (taken from Table 1 of the IPCC report):

"Very likely" (probability of greater than 90%)

"Likely" (probability of 67-90%)

"As likely as not" (probability of between 33% and 67%)

"Unlikely" (probability of between 10% and 33%)

"Very unlikely" (probability of less than 10%).

The original table also includes categories for 'exceptionally unlikely' and 'virtually certain', but we have not included these because we do not feel that our uncertainty assessment is sufficiently precise to be able to meaningfully assign very small probabilities to events.

E.3. Sources of uncertainty

It is important to understand that there are some sources of uncertainty that we explicitly quantified in the exploratory analyzes, and that these are the sources that are summarized using probabilities; however, there are also sources of uncertainty that we cannot explicitly quantify. For the exploratory analyzes we explicitly quantified two sources of uncertainty:

1) natural variations in behaviour between populations of birds; and

2) uncertainty about the magnitude of the relationship between mass and adult survival.

Our assessments of uncertainty – and the probabilities that they produce – include both of these sources. There are other sources of potential uncertainty that we are unable to quantify, because we either do not have any information on them or else do not have enough information to be able to meaningfully quantify uncertainty. These include the location of bird foraging areas, the extent to which adult birds prioritise their own survival over chick survival, and the magnitude of the reduction in chick mass that would lead to death. Finally, there are sources of uncertainty which we did not seek to quantify. These mainly include sources of uncertainty that are explicitly included with the scenarios that we consider – e.g. the size and locations of wind farms, the link between prey and seabird distribution, baseline survival rates, total amounts of prey, and the rates at which displacement and barrier effects occur. These sources are dealt with in a qualitative way, through the comparison of different scenarios. Another source of uncertainty that we do not wish to consider is variability between individual birds within a population: we are interested in the effects on the overall population, and inter-individual variability is averaged out in the process of estimating this.

E.4. Reducing uncertainty

The uncertainty associated with the strength of the mass-survival relationship reflects the current state of scientific knowledge in this area. This uncertainty could only be reduced if a new, relevant, study were to be published on this topic using a larger sample size.

The uncertainty regarding natural variation between populations is rather different. Ideally, each of our simulation runs from the foraging model would have contained a number of birds equal to the size of the actual population for the SPAs being considered. If that have been the case then our assessments of uncertainty would have related directly to the uncertainty associated with the impact of wind farms on the entire population of birds within the SPAs at risk – this uncertainty could not then have been reduced any further, since it would reflect genuine variation between populations of birds.

In reality, our exploratory models runs were based on a relatively small proportion of the overall population (between 1% and 5% of the population, depending on species). This was unavoidable, due to the time constraints of the project and the computationally intensive nature of the foraging model, and ensured that all of the relevant scenarios could be run through the model within a reasonable timeframe. It does mean, however, that these exploratory runs will tend to have substantially over-estimated uncertainty. We considered two options for further modelling:

a) including a larger proportion of the population in each simulation run; or

b) running more simulation runs.

The latter approach would improve the quality (accuracy) of our assessment of uncertainty, but would not actually systematically reduce uncertainty. The former approach would systematically reduce uncertainty – as the number of birds per run increased, the uncertainty would reduce. Naïve calculations suggest that variability (e.g. standard deviations) would be reduced by between 75% and 90% for chick survival if we were to run the simulations using the entire population rather than the subsamples that are currently used. The gain in precision would be less for adult survival, because in this case a proportion of the uncertainty represents the uncertainty associated with the mass-survival relationship (which would not be reduced by including more birds in each simulation run). These arguments led us to base the final set of model runs on a much larger proportion of the population than that use in the exploratory runs.

Appendix F. Full model results from exploratory runs with 1000 birds

Mean results are presented in the following pages. Because of the large sizes of tables, uncertainty results (see below for description) are available as Excel spreadsheets.

F.1. Prey availability in good, moderate and poor years

All estimated parameters in the model (not directly derived from data) were fitted assuming moderate prey availability. No direct data were available on prey availability, so we considered situations in which parameters in the birds estimated by the model that are sensitive to prey availability (adult mass change, chick mass growth, chick survival, adult foraging time, adult flight time) showed values that matched moderate values in the empirical data pertained to a moderate year. Similarly, to assess the impact of wind farms in poor and good years, prey availability was altered until model output matched empirical changes in adult body mass and chick survival observed during ‘poor’ and ‘good’ years (Table F. 1)

Kw	good	moderate	poor
mass change start vs end	0%	10%	20%
productivity	100%	50%	10%
Gu	good	moderate	poor
mass change start vs end	0%	7%	14%
productivity	90%	85%	40%
Rz	good	moderate	poor
mass change start vs end	0%	7%	14%
productivity	85%	80%	50%
Pu	good	moderate	poor
mass change start vs end	0%	7%	14%
productivity	95%	85%	75%

Ga	good	moderate	poor
mass change start vs end	0.0%	2.5%	5.0%
productivity	80%	75%	70%

Table F. 1. Observed changes to adult mass and population productivity in good, moderate and poor prey years for all species. These values were used to alter prey levels in good and poor scenarios such that model output matched as closely to observed values as possible. Sources. Freeman, S., Searle, K. Bogdanova, M., Wanless, S. & Daunt, F. (2013) Population dynamics of Forth & Tay breeding seabirds: review of available models and modelling of key breeding populations. Ref MSQ-0006. Draft final report to Marine Scotland Science; Gaston, A.J. & Hipfner, J.M. (2006) Body mass changes in Brunnich's guillemots Uria lomvia with age and breeding stage. Journal of Avian Biology 37: 101-109; Harris MP, Wanless S (1988) Measurement and seasonal changes in weight of guillemots Uria aalge at a breeding colony. Ring and Migr 9: 32-36; Jarvis, M. (1971) Ethology and ecology of the South African Gannet Sula capensis, Unpublished PhD thesis, University of Cape Town; Harris, M.P. (1979) Measurements and weights of British puffins. Bird Study 26: 179-186; Nelson, B. (2013) Early warnings of climate change on ecosystems: hormonally-mediated life-history decisions in seabirds. Unpublished PhD thesis, University of Glasgow; Newell, M., Harris, M., Wanless, S., Burthe, S., Bogdanova, M., Gunn, C., Daunt, F. (2012) The Isle of May Long-Term Study (IMLOTS) Seabird Annual Breeding Success 1982-2012. NERC-Environmental Information Data Centre. doi: 10.5285/d38b609b-7bc1-4204-86dd-022375208d4f; CEH unpublished data; Seabird Monitoring Programme online database (http://jncc.defra.gov.uk/smp/)

F.2. Black-legged kittiwake *Rissa tridactyla*

Four SPAs are designated for this species in the region (Buchan Ness to Collieston Coast, Fowlsheugh, Forth Islands and St Abb's Head to Fastcastle). For each SPA, and all SPAs combined, we carried out three sets of scenarios, presented in sections F.2.1, F.2.2 and F.2.3.

F.2.1. The effects of wind farms and prey availability

The following scenarios were explored:

- Effect of wind farm:
    - No wind farms (the baseline scenario)
    - each of the four individual wind farms separately
    - the combined impact of all four wind farms
- Overall prey availability
    - Good
    - Moderate
    - Poor

The above scenarios resulted in a total of 18 scenarios (six wind farms scenarios in three prey availabilities). For all scenarios, we assumed a 1km exclusion buffer, and that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Figure F. 1a shows the distribution of birds from all SPAs in the baseline scenario and Figure F. 1b the distribution of birds from all SPAs in the scenario with all four wind farms under moderate prey availability and homogeneous prey distribution. These two scenarios are shown again in Figure F. 2a and Figure F. 2b based on heterogeneous prey.

The number of birds displaced and for whom the wind farm(s) acted as a barrier is shown for all 18 scenarios in Table F. 2 under homogeneous prey distribution and Table F. 3 with heterogeneous prey.

Mean adult body mass is presented as a histogram plot showing the difference between the baseline and the four wind farm scenario for all SPAs combined under moderate prey availability with homogeneous Figure F. 3 and heterogeneous prey Figure F. 4. Mean adult mass at the end of the breeding season is given for all 18 scenarios is given in Table F. 4 (homogeneous prey) and Table F. 5 (heterogeneous prey). Adult survival change relative to the baseline can be found in Table F. 6 (homogeneous prey) and Table F. 7 (heterogeneous prey). Finally, chick survival change relative to the baseline can be found in Table F. 8 (homogeneous prey) and Table F. 9 (heterogeneous prey).

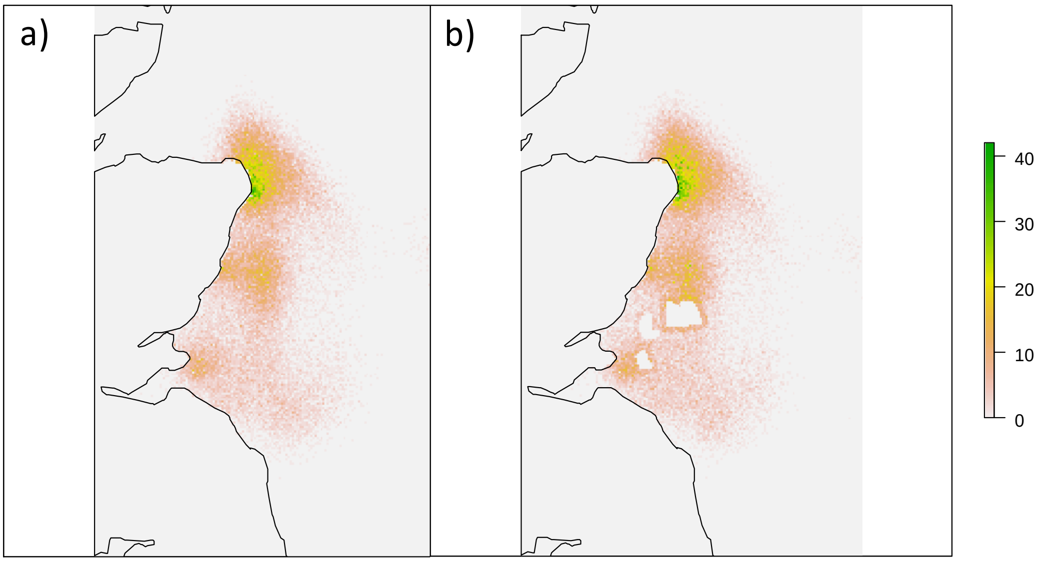

Figure F. 1: Kittiwake. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and homogeneous prey distribution.

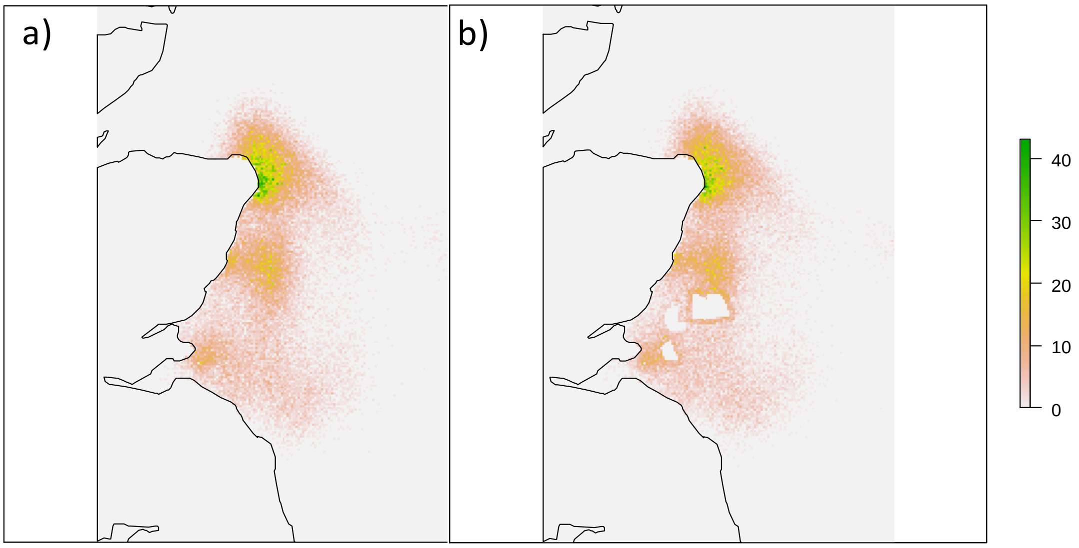

Figure F. 2. Kittiwake. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and heterogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	All	0.0	0.0	0.7	4.3	0.4	1.1	1.2	1.9	1.2	1.6	3.3	4.1
good	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
good	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.5	2.1	3.2	4.8	2.9
good	Forth	0.0	0.0	3.9	31.8	2.6	7.1	1.9	3.2	2.6	3.2	11.7	22.7
good	St Abbs	0.0	0.0	1.1	2.3	0.6	0.6	0.6	0.6	1.1	1.7	2.9	1.7
moderate	All	0.0	0.0	0.7	4.3	0.4	1.1	1.2	1.9	1.2	1.6	3.4	4.1
moderate	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
moderate	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.5	2.4	3.2	4.8	3.2
moderate	Forth	0.0	0.0	4.5	31.8	2.6	7.8	1.9	3.2	3.2	3.2	11.7	22.1
moderate	St Abbs	0.0	0.0	1.1	1.7	0.0	0.6	0.6	0.6	1.1	1.1	2.9	1.7
poor	All	0.0	0.0	0.7	4.3	0.5	1.0	1.2	1.9	1.2	1.7	3.4	4.0
poor	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poor	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.8	2.1	3.2	4.8	2.9
poor	Forth	0.0	0.0	4.5	31.2	2.6	7.1	1.9	3.2	2.6	3.2	11.7	22.1
poor	St Abbs	0.0	0.0	0.6	2.3	0.6	0.6	0.6	0.6	1.1	1.1	2.9	1.7

Table F. 2 Kittiwake. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for each SPA and all four SPAs combined, based on homogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	All	0.0	0.0	0.7	4.3	0.5	1.1	1.2	2.0	1.2	1.7	3.4	4.1
good	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
good	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.8	2.1	3.5	5.1	2.9
good	Forth	0.0	0.0	3.9	31.8	2.6	7.1	1.9	3.2	3.2	3.2	11.0	22.1
good	St Abbs	0.0	0.0	1.1	2.3	0.0	0.6	0.6	0.6	1.1	1.7	2.9	1.7
moderate	All	0.0	0.0	0.7	4.2	0.4	1.1	1.2	1.9	1.2	1.6	3.4	4.1
moderate	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
moderate	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.5	2.1	2.9	5.1	2.9
moderate	Forth	0.0	0.0	3.9	31.2	2.6	7.8	1.9	3.2	2.6	3.2	11.0	22.7
moderate	St Abbs	0.0	0.0	1.1	1.7	0.0	0.6	0.6	0.6	1.1	1.7	2.9	1.7
poor	All	0.0	0.0	0.7	4.3	0.4	1.1	1.2	1.9	1.2	1.6	3.4	4.1
poor	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poor	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.3	2.7	4.8	2.1	3.2	5.1	2.9
poor	Forth	0.0	0.0	4.5	31.2	2.6	7.1	1.9	3.2	2.6	3.2	11.7	22.7
poor	St Abbs	0.0	0.0	0.6	2.3	0.6	0.6	0.6	0.6	1.1	1.7	2.9	1.7

Table F. 3 Kittiwake. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for each SPA and all four SPAs combined, based on heterogeneous prey distribution.

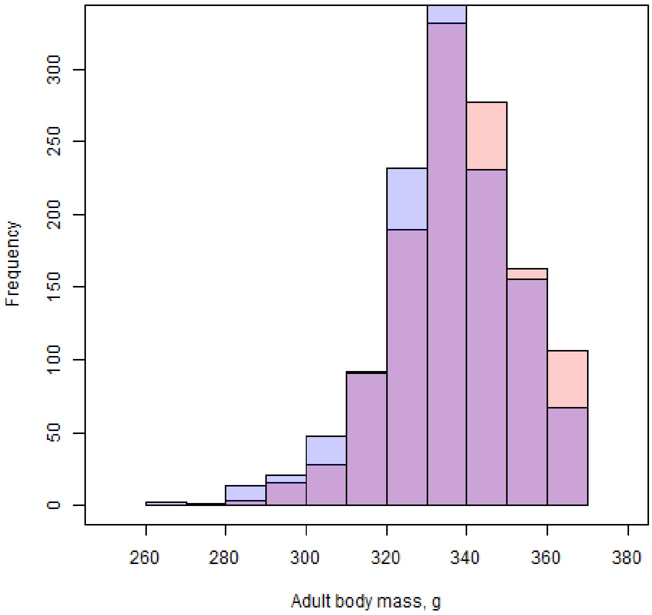

Figure F. 3 Kittiwake. Histogram of distribution of adult body mass at all four SPAs at the end of the chick-rearing period under moderate conditions with homogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

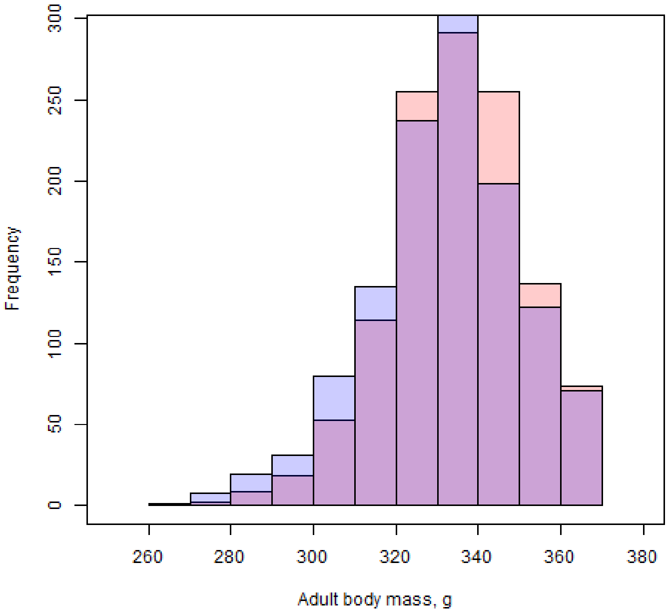

Figure F. 4. Kittiwake. Histogram of distribution of adult body mass at all four SPAs at the end of the chick-rearing period under moderate conditions with heterogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	354.4	353.8	354.3	353.5	353.5	352.7
good	Buchan Ness	354.4	354.3	354.3	353.9	354.2	354.1
good	Fowlsheugh	352.2	351.6	352.2	350.9	350.6	349.8
good	Forth	354.9	351.8	353.8	352.9	353.0	349.7
good	St Abbs	358.5	358.8	359.0	358.7	358.2	357.6
moderate	All	338.3	337.5	337.7	337.5	337.1	335.8
moderate	Buchan Ness	336.7	336.7	336.1	336.5	336.0	336.8
moderate	Fowlsheugh	334.8	336.3	334.7	333.6	334.2	332.9
moderate	Forth	343.8	333.2	339.9	340.1	338.3	331.2
moderate	St Abbs	346.1	346.0	346.5	346.5	345.5	343.5
poor	All	316.7	314.8	316.2	315.3	315.1	314.3
poor	Buchan Ness	313.0	313.0	313.0	313.8	313.7	313.9
poor	Fowlsheugh	312.8	313.1	313.4	310.1	310.6	310.9
poor	Forth	324.6	311.7	321.0	320.1	318.9	309.2
poor	St Abbs	328.4	326.1	327.2	326.6	325.9	327.0

Table F. 4. Kittiwake. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for each SPA and all combined for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	353.1	352.3	352.9	352.2	352.5	351.3
good	Buchan Ness	353.3	353.1	353.4	353.1	353.5	353.1
good	Fowlsheugh	351.5	351.0	350.9	349.8	349.9	348.9
good	Forth	352.0	348.2	351.0	350.2	350.4	346.1
good	St Abbs	357.0	356.6	357.2	356.9	356.8	355.7
moderate	All	334.9	333.8	334.5	333.7	333.7	331.9
moderate	Buchan Ness	335.0	336.1	335.4	335.1	335.4	335.5
moderate	Fowlsheugh	331.1	331.5	330.9	328.4	329.5	328.1
moderate	Forth	337.1	326.0	334.1	335.6	332.2	322.8
moderate	St Abbs	341.0	339.3	340.3	339.4	338.8	337.8
poor	All	318.7	317.6	317.9	317.9	317.5	315.5
poor	Buchan Ness	317.3	318.7	316.9	318.8	318.2	317.6
poor	Fowlsheugh	314.5	315.7	315.1	311.4	312.7	312.2
poor	Forth	323.3	309.4	318.4	320.8	317.9	307.9
poor	St Abbs	328.0	325.6	326.4	326.7	325.3	323.4

Table F. 5. Kittiwake. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for each SPA and all combined for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.2	0.0	-0.4	-0.4	-0.7
good	Buchan Ness	-0.1	0.0	-0.2	-0.1	-0.1
good	Fowlsheugh	-0.2	0.1	-0.5	-0.7	-0.9
good	Forth	-1.3	-0.5	-0.9	-0.8	-2.3
good	St Abbs	0.1	0.2	0.1	-0.2	-0.4
moderate	All	-0.6	-0.5	-0.5	-0.8	-1.7
moderate	Buchan Ness	-0.1	-0.3	-0.1	-0.5	0.1
moderate	Fowlsheugh	0.8	-0.3	-0.9	-0.5	-1.4
moderate	Forth	-7.5	-2.6	-2.4	-3.7	-9.1
moderate	St Abbs	0.0	0.3	0.3	-0.4	-1.8
poor	All	-1.5	-0.4	-1.1	-1.2	-2.0
poor	Buchan Ness	0.0	0.1	0.7	0.5	0.7
poor	Fowlsheugh	0.2	0.3	-2.3	-1.9	-1.7
poor	Forth	-10.4	-3.0	-3.7	-4.6	-12.5
poor	St Abbs	-1.8	-1.1	-1.4	-2.1	-1.2

Table F. 6. Kittiwake. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.3	-0.1	-0.4	-0.3	-0.8
good	Buchan Ness	0.0	0.1	-0.1	0.1	-0.1
good	Fowlsheugh	-0.3	-0.2	-0.8	-0.7	-1.1
good	Forth	-1.7	-0.5	-0.8	-0.7	-2.7
good	St Abbs	-0.1	0.1	0.0	-0.1	-0.5
moderate	All	-0.7	-0.2	-0.8	-0.8	-2.1
moderate	Buchan Ness	0.7	0.3	0.1	0.3	0.4
moderate	Fowlsheugh	0.3	-0.1	-1.8	-1.1	-2.1
moderate	Forth	-7.8	-2.0	-1.2	-3.4	-10.3
moderate	St Abbs	-1.1	-0.6	-1.2	-1.5	-2.2
poor	All	-1.0	-0.7	-0.7	-1.0	-2.7
poor	Buchan Ness	1.0	-0.3	1.1	0.7	0.2
poor	Fowlsheugh	0.8	0.4	-2.5	-1.6	-2.1
poor	Forth	-11.4	-4.2	-2.2	-4.4	-12.4
poor	St Abbs	-2.0	-1.3	-1.1	-2.2	-3.8

Table F. 7. Kittiwake. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-2.0	-1.8	-1.4	-1.9	-3.6
good	Buchan Ness	-2.6	-1.9	-1.1	-2.1	-2.6
good	Fowlsheugh	-0.9	-1.1	-1.6	-2.1	-3.5
good	Forth	-2.3	-2.3	-1.6	-1.8	-5.5
good	St Abbs	-2.3	-2.3	-1.6	-1.2	-4.8
moderate	All	-3.3	-2.7	-0.9	-5.3	-6.3
moderate	Buchan Ness	-0.6	-1.3	0.1	-1.2	-1.8
moderate	Fowlsheugh	-1.6	-0.1	-2.1	-6.4	-4.9
moderate	Forth	-15.6	-8.1	-3.6	-14.0	-19.7
moderate	St Abbs	-3.5	-7.4	1.2	-7.1	-10.3
poor	All	-2.3	-0.9	-1.5	-0.8	-3.1
poor	Buchan Ness	-0.3	-0.1	-0.6	-0.5	-1.8
poor	Fowlsheugh	-1.5	-0.2	-1.7	-0.6	-2.2
poor	Forth	-9.9	-3.9	-3.1	-1.0	-8.1
poor	St Abbs	-3.0	-2.1	-2.5	-1.8	-4.4

Table F. 8. Kittiwake. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.1	0.0	0.4	-1.9	-2.0
good	Buchan Ness	0.6	-0.2	0.3	-1.7	-2.0
good	Fowlsheugh	1.0	1.1	0.9	-2.5	-1.6
good	Forth	-2.9	0.5	0.3	-2.3	-1.6
good	St Abbs	-2.1	-2.1	-0.2	-0.9	-3.5
moderate	All	-3.8	0.2	-2.0	-1.8	-7.1
moderate	Buchan Ness	-3.6	2.9	1.0	0.8	-2.9
moderate	Fowlsheugh	-2.7	-1.9	-6.1	-4.4	-9.9
moderate	Forth	-10.7	-2.1	-3.6	-3.6	-15.8
moderate	St Abbs	-0.7	-0.9	0.0	-1.8	-5.5
poor	All	-3.2	-1.9	-2.1	-2.2	-4.0
poor	Buchan Ness	0.6	-0.3	1.4	1.7	-0.9
poor	Fowlsheugh	-2.0	-0.7	-3.8	-3.5	-3.1
poor	Forth	-13.5	-7.5	-9.6	-5.2	-14.0
poor	St Abbs	-7.6	-3.7	-1.8	-7.8	-5.8

Table F. 9. Kittiwake. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.2.2. The effects of buffer width

The following scenarios were explored:

- 0km buffer around wind farm
- 0.5km buffer around wind farm
- 1km buffer around wind farm

The three scenarios were carried out on all SPAs in three prey availability levels for Neart na Gaoithe wind farm only. The third scenario is a repeat scenario from section F.2.1. For all scenarios, we assumed that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Adult survival change relative to the baseline can be found in Table F. 10 and Table F. 11 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 12 and Table F 13 or homogeneous and GPS-derived prey, respectively.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.2	-0.2	-0.2
good	Buchan Ness	0.0	0.1	-0.1
good	Fowlsheugh	-0.2	-0.2	-0.2
good	Forth	-1.3	-1.5	-1.3
good	St Abbs	0.1	0.1	0.1
moderate	All	-0.7	-0.8	-0.6
moderate	Buchan Ness	-0.5	-0.1	-0.1
moderate	Fowlsheugh	0.5	0.2	0.8
moderate	Forth	-5.9	-7.4	-7.5
moderate	St Abbs	0.5	0.7	0.0
poor	All	-1.2	-1.7	-1.5
poor	Buchan Ness	0.5	0.0	0.0
poor	Fowlsheugh	0.3	-0.6	0.2
poor	Forth	-10.1	-10.4	-10.4
poor	St Abbs	-1.4	-1.4	-1.8

Table F. 10. Kittiwake. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.2	-0.3	-0.3
good	Buchan Ness	0.2	0.0	0.0
good	Fowlsheugh	0.0	0.0	-0.3
good	Forth	-1.7	-1.5	-1.7
good	St Abbs	-0.1	-0.4	-0.1
moderate	All	-0.6	-0.7	-0.7
moderate	Buchan Ness	0.5	0.9	0.7
moderate	Fowlsheugh	-0.1	-0.2	0.3
moderate	Forth	-6.8	-7.6	-7.8
moderate	St Abbs	0.3	-0.4	-1.1
poor	All	-1.1	-1.2	-1.0
poor	Buchan Ness	0.6	0.6	1.0
poor	Fowlsheugh	0.3	-0.2	0.8
poor	Forth	-9.5	-10.2	-11.4
poor	St Abbs	-1.6	-0.9	-2.0

Table F. 11. Kittiwake. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-2.2	-1.8	-2.0
good	Buchan Ness	-3.1	-2.3	-2.6
good	Fowlsheugh	-0.7	-1.2	-0.9
good	Forth	-2.6	-1.8	-2.3
good	St Abbs	-2.1	-1.8	-2.3
moderate	All	0.6	-3.2	-3.3
moderate	Buchan Ness	2.6	-1.6	-0.6
moderate	Fowlsheugh	3.0	-1.8	-1.6
moderate	Forth	-10.7	-14.6	-15.6
moderate	St Abbs	-0.2	-0.5	-3.5
poor	All	-2.0	-1.4	-2.3
poor	Buchan Ness	-0.9	-0.2	-0.3
poor	Fowlsheugh	-1.0	-0.6	-1.5
poor	Forth	-9.4	-8.1	-9.9
poor	St Abbs	-0.7	-0.2	-3.0

Table F. 12 Kittiwake. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.1	-0.4	-0.1
good	Buchan Ness	-0.2	-0.4	0.6
good	Fowlsheugh	1.5	0.2	1.0
good	Forth	-3.4	-2.1	-2.9
good	St Abbs	0.0	0.0	-2.1
moderate	All	-3.5	-4.5	-3.8
moderate	Buchan Ness	-0.6	-1.9	-3.6
moderate	Fowlsheugh	-6.1	-4.3	-2.7
moderate	Forth	-11.7	-14.0	-10.7
moderate	St Abbs	0.7	-3.9	-0.7
poor	All	-3.1	-3.2	-3.2
poor	Buchan Ness	-0.2	-0.1	0.6
poor	Fowlsheugh	-1.9	-3.8	-2.0
poor	Forth	-14.3	-13.3	-13.5
poor	St Abbs	-4.1	-1.6	-7.6

Table F. 13. Kittiwake. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.2.3. The effects of percentage of birds displaced

The following scenarios were explored:

- 50% of birds displaced and 50% for whom the wind farm acted as a barrier
- 0% of birds displaced and 100% for whom the wind farm acted as a barrier
- 100% of birds displaced and 0% for whom the wind farm acted as a barrier

The three scenarios were carried out on all SPAs in three prey availability levels for all wind farms combined. The results were compared with equivalent scenarios where level for displacement and barrier effect were both 100% (repeat of scenario presented in Section F.2.1). For all scenarios, we assumed a buffer with of 1km.

Adult survival change relative to the baseline can be found Table F. 14 and Table F. 15 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 16 and Table F. 17 for homogeneous and GPS-derived prey, respectively.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.7	-0.3	-0.3	-0.3
good	Buchan Ness	-0.1	-0.1	0.0	0.0
good	Fowlsheugh	-0.9	-0.3	-0.4	-0.4
good	Forth	-2.3	-1.1	-1.5	-0.7
good	St Abbs	-0.4	-0.1	0.2	-0.5
moderate	All	-1.7	-0.7	-1.3	-1.0
moderate	Buchan Ness	0.1	0.0	-0.3	-0.5
moderate	Fowlsheugh	-1.4	-0.5	-1.2	-1.0
moderate	Forth	-9.1	-3.6	-6.9	-3.0
moderate	St Abbs	-1.8	-0.6	-0.1	-0.9
poor	All	-2.0	-1.0	-1.6	-1.0
poor	Buchan Ness	0.7	0.0	-0.1	0.1
poor	Fowlsheugh	-1.7	-0.3	-0.4	-1.2
poor	Forth	-12.5	-5.6	-10.5	-3.6
poor	St Abbs	-1.2	-1.6	-1.4	-1.3

Table F. 14. Kittiwake. Mean change in adult survival (as a percentage point) between scenario of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.8	-0.3	-0.5	-0.4
good	Buchan Ness	-0.1	0.1	-0.2	-0.1
good	Fowlsheugh	-1.1	-0.5	-0.5	-0.5
good	Forth	-2.7	-1.4	-1.6	-1.2
good	St Abbs	-0.5	-0.2	-0.1	-0.4
moderate	All	-2.1	-0.8	-1.1	-0.5
moderate	Buchan Ness	0.4	0.2	0.8	0.5
moderate	Fowlsheugh	-2.1	-0.5	-1.1	-0.9
moderate	Forth	-10.3	-4.3	-7.0	-2.9
moderate	St Abbs	-2.2	-1.0	-1.8	-0.8
poor	All	-2.7	-0.8	-1.7	-1.1
poor	Buchan Ness	0.2	0.9	0.6	0.2
poor	Fowlsheugh	-2.1	-0.3	-1.0	-1.1
poor	Forth	-12.4	-5.9	-9.7	-4.3
poor	St Abbs	-3.8	-2.1	-2.8	-2.2

Table F. 15. Kittiwake. Mean change in adult survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-3.6	-1.6	-2.0	-1.8
good	Buchan Ness	-2.6	-1.7	-1.7	-1.5
good	Fowlsheugh	-3.5	-2.0	-1.5	-1.5
good	Forth	-5.5	-1.0	-3.1	-3.1
good	St Abbs	-4.8	-1.2	-2.8	-2.1
moderate	All	-6.3	-3.3	-4.4	-1.3
moderate	Buchan Ness	-1.8	-2.5	-0.4	0.0
moderate	Fowlsheugh	-4.9	-1.4	-4.4	-2.3
moderate	Forth	-19.7	-12.0	-14.3	-1.6
moderate	St Abbs	-10.3	-2.1	-7.1	-2.8
poor	All	-3.1	-2.0	-2.0	-2.1
poor	Buchan Ness	-1.8	-0.5	-0.9	-0.9
poor	Fowlsheugh	-2.2	-1.3	-1.5	-2.6
poor	Forth	-8.1	-4.2	-8.3	-2.6
poor	St Abbs	-4.4	-6.2	-0.5	-4.4

Table F. 16. Kittiwake. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-2.0	-1.3	-1.9	-1.4
good	Buchan Ness	-2.0	-2.4	-1.4	-1.4
good	Fowlsheugh	-1.6	1.5	-0.7	-0.9
good	Forth	-1.6	-1.6	-2.9	-3.1
good	St Abbs	-3.5	-4.1	-5.1	-1.4
moderate	All	-7.1	-1.3	-3.2	0.0
moderate	Buchan Ness	-2.9	0.3	-0.6	2.2
moderate	Fowlsheugh	-9.9	-4.9	-5.6	-3.5
moderate	Forth	-15.8	-4.7	-11.7	-1.8
moderate	St Abbs	-5.5	4.6	2.1	3.0
poor	All	-4.0	-2.0	-4.2	-2.5
poor	Buchan Ness	-0.9	0.6	0.1	-0.2
poor	Fowlsheugh	-3.1	-1.7	-4.3	-2.1
poor	Forth	-14.0	-10.9	-14.8	-8.6
poor	St Abbs	-5.8	-2.5	-6.9	-4.6

Table F. 17. Kittiwake. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.3. Common guillemot *Uria aalge*

Four SPAs are designated for this species in the region (Buchan Ness to Collieston Coast, Fowlsheugh, Forth Islands and St Abb's Head to Fastcastle). For each SPA, and all SPAs combined, we carried out three sets of scenarios, presented in sections F.3.1, F.3.2 and F.3.3. Models based on heterogeneous prey included birds from all SPAs, but outputs were only recorded for Fowlsheugh, Forth Islands and St Abb's Head to Fastcastle, because of the lack of sufficient GPS data available from Buchan Ness to Collieston Coast.

F.3.1. The effects of wind farms and prey availability

The following scenarios were explored:

- Effect of wind farm:
    - No wind farms (the baseline scenario)
    - each of the four individual wind farms separately
    - the combined impact of all four wind farms
- Overall prey availability
    - Good
    - Moderate
    - Poor

The above scenarios resulted in a total of 18 scenarios (six wind farms scenarios in three prey availabilities). For all scenarios, we assumed a 1km exclusion buffer, and that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Figure F. 5a shows the distribution of birds from all SPAs in the baseline scenario and Figure F. 5b the distribution of birds from all SPAs in the scenario with all four wind farms under moderate prey availability and homogeneous prey distribution. These two scenarios are shown again in Figure F. 6a and Figure F. 6b based on heterogeneous prey.

The number of birds displaced and for whom the wind farm(s) acted as a barrier is shown for all 18 scenarios in Table F. 18 under homogeneous prey distribution and Table F. 19 with heterogeneous prey.

Mean adult body mass is presented as a histogram plot showing the difference between the baseline and the four wind farm scenario for all SPAs combined under moderate prey availability with homogeneous Figure F. 7 and heterogeneous prey Figure F. 8. Mean adult mass at the end of the breeding season is given for all 18 scenarios is given in Table F. 20 (homogeneous prey) and Table F.21 (heterogeneous prey). Adult survival change relative to the baseline can be found in Table F. 22 (homogeneous prey) and Table F. 23 (heterogeneous prey). Finally, chick survival change relative to the baseline can be found in Table F. 24 (homogeneous prey) and Table F25.

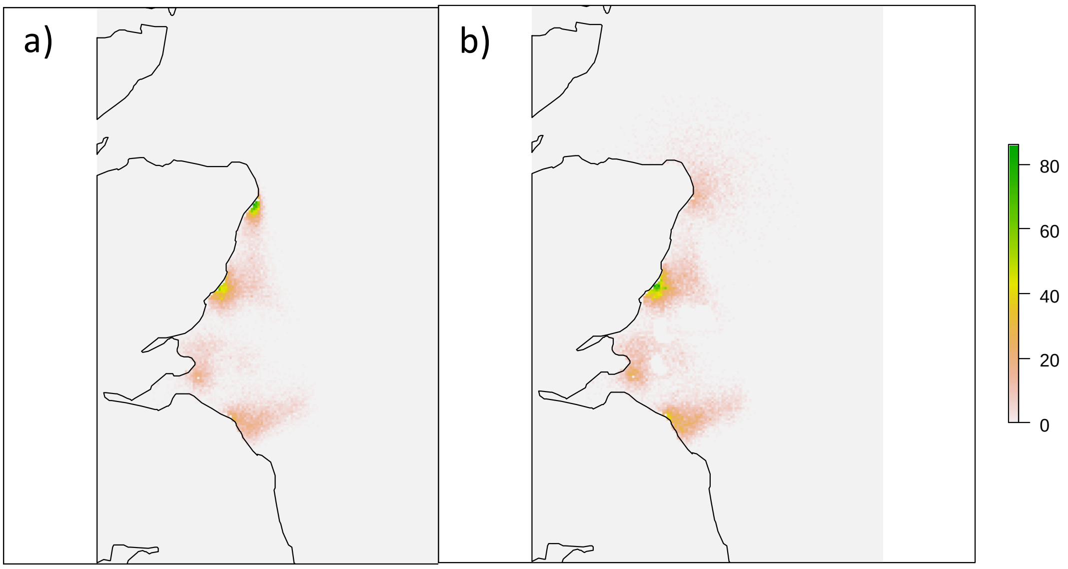

Figure F. 5. Guillemot. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and homogeneous prey distribution.

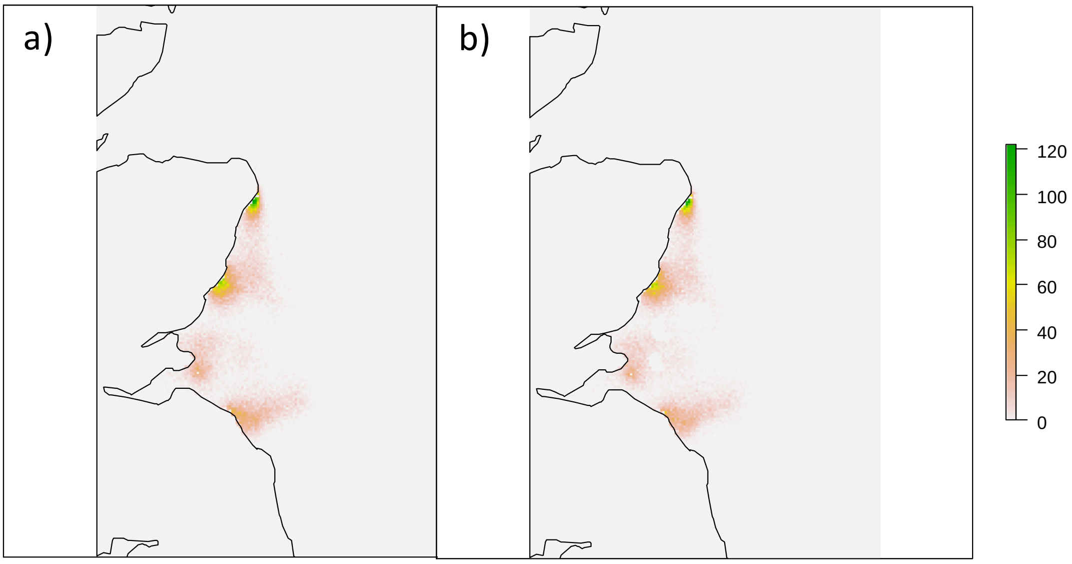

Figure F. 6. Guillemot. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and prey distribution derived from seabird GPS data.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	All	0.0	0.0	0.5	2.8	0.4	0.1	0.3	0.3	0.1	0.2	1.3	1.9
good	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
good	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.1	0.5
good	Forth	0.0	0.0	2.6	14.9	1.5	0.5	0.0	0.0	0.0	0.0	4.1	9.3
good	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
moderate	All	0.0	0.0	0.5	2.7	0.4	0.1	0.3	0.3	0.1	0.2	1.3	2.0
moderate	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
moderate	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.3	0.5
moderate	Forth	0.0	0.0	2.6	14.4	1.5	0.5	0.0	0.0	0.0	0.0	4.1	9.8
moderate	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poor	All	0.0	0.0	0.5	2.8	0.4	0.1	0.3	0.3	0.1	0.2	1.2	2.0
poor	Buchan Ness	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poor	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.3	0.5
poor	Forth	0.0	0.0	2.6	14.9	1.5	0.5	0.0	0.0	0.0	0.0	4.1	9.3
poor	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table F. 18. Guillemot. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for each SPA and all four SPAs combined, based on homogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	All	0.0	0.0	0.6	3.3	0.5	0.1	0.3	0.3	0.1	0.2	1.5	2.3
good	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.3	0.5
good	Forth	0.0	0.0	2.6	14.4	1.5	0.5	0.0	0.0	0.0	0.0	4.1	9.3
good	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
moderate	All	0.0	0.0	0.6	3.3	0.5	0.1	0.3	0.3	0.1	0.2	1.5	2.2
moderate	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.3	0.5
moderate	Forth	0.0	0.0	2.6	14.4	1.5	0.5	0.0	0.0	0.0	0.0	4.1	8.8
moderate	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
poor	All	0.0	0.0	0.6	3.3	0.5	0.1	0.3	0.3	0.1	0.2	1.5	2.3
poor	Fowlsheugh	0.0	0.0	0.0	0.0	0.3	0.0	0.8	0.8	0.3	0.5	1.3	0.5
poor	Forth	0.0	0.0	2.6	14.4	1.5	0.5	0.0	0.0	0.0	0.0	4.1	9.3
poor	St Abbs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table F. 19. Guillemot. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for each SPA and all three SPAs combined, based on heterogeneous prey distribution.

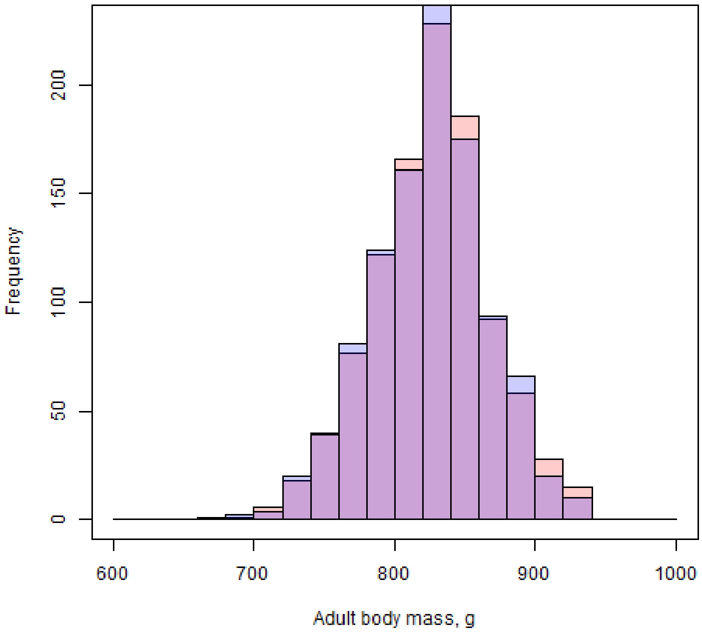

Figure F. 7. Guillemot. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with homogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

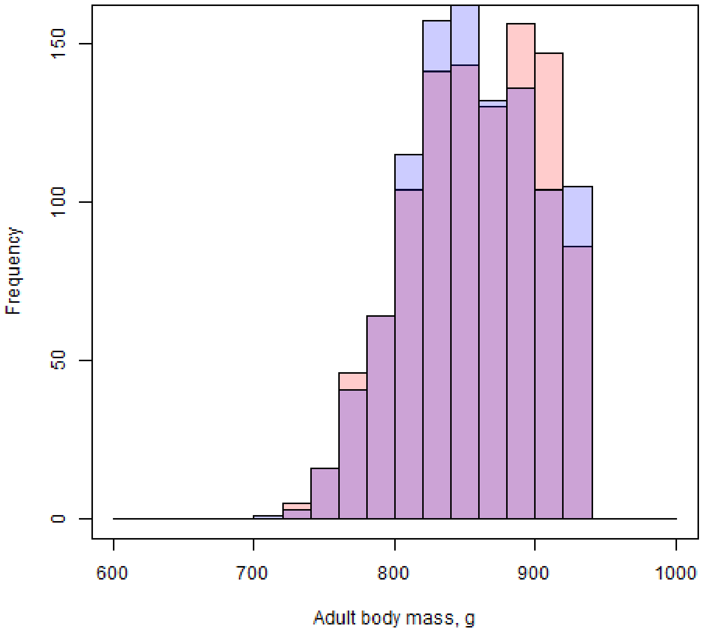

Figure F. 8. Guillemot. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with heterogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	885.0	883.7	885.2	885.5	885.8	884.2
good	Buchan Ness	895.3	894.4	895.2	894.8	894.8	895.2
good	Fowlsheugh	881.8	881.6	881.2	881.3	882.2	880.3
good	Forth	901.5	893.6	901.3	902.4	902.5	896.2
good	St Abbs	871.8	873.4	873.4	873.8	873.8	874.4
moderate	All	849.9	847.4	849.8	849.2	849.3	847.9
moderate	Buchan Ness	851.2	850.0	850.7	849.7	850.6	849.8
moderate	Fowlsheugh	853.4	853.2	853.4	853.4	851.2	852.2
moderate	Forth	862.7	849.9	861.0	860.9	862.9	852.6
moderate	St Abbs	836.0	836.8	837.2	835.9	836.9	837.9
poor	All	792.9	790.6	792.3	792.7	793.2	791.0
poor	Buchan Ness	813.2	813.6	813.9	811.9	813.1	814.5
poor	Fowlsheugh	797.8	796.5	795.1	795.7	796.8	795.0
poor	Forth	786.6	773.1	785.0	787.8	787.9	776.8
poor	St Abbs	778.4	780.6	780.5	780.4	780.1	780.9

Table F. 20. Guillemot. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for each SPA and all combined for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	891.9	889.0	890.8	891.6	891.6	889.6
good	Fowlsheugh	880.6	880.2	879.4	880.1	880.7	880.4
good	Forth	899.7	888.2	896.8	900.2	899.3	889.2
good	St Abbs	901.0	900.8	901.3	900.6	900.5	901.6
moderate	All	860.7	858.3	861.2	860.1	860.4	859.2
moderate	Fowlsheugh	859.2	859.3	860.6	858.2	859.4	859.3
moderate	Forth	854.7	842.9	854.4	854.5	854.1	847.0
moderate	St Abbs	866.7	867.3	866.4	866.2	865.9	867.2
poor	All	786.2	784.2	786.5	785.6	786.8	785.2
poor	Fowlsheugh	782.0	782.8	783.0	781.2	782.9	782.8
poor	Forth	769.4	760.4	769.8	769.3	770.5	764.8
poor	St Abbs	802.7	802.0	802.2	801.9	802.7	801.8

Table F. 21. Guillemot. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for each SPA and all combined for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.3	0.0	0.2	0.4	-0.2
good	Buchan Ness	-0.3	0.2	-0.1	0.2	0.1
good	Fowlsheugh	-0.4	-0.6	-0.5	0.0	-0.7
good	Forth	-4.8	-0.3	0.4	0.4	-3.1
good	St Abbs	0.5	0.5	0.6	0.8	0.8
moderate	All	-0.6	0.1	-0.2	-0.1	-0.5
moderate	Buchan Ness	-0.5	-0.4	-0.8	-0.3	-0.7
moderate	Fowlsheugh	0.1	0.1	0.0	-0.8	-0.4
moderate	Forth	-4.2	-0.4	-0.5	0.2	-3.4
moderate	St Abbs	0.2	0.4	0.0	0.2	0.6
poor	All	-0.9	-0.1	0.0	0.2	-0.8
poor	Buchan Ness	0.1	0.2	-0.7	-0.3	0.5
poor	Fowlsheugh	-0.4	-1.1	-0.9	-0.3	-1.3
poor	Forth	-6.0	-1.0	0.1	0.0	-4.4
poor	St Abbs	1.1	1.1	0.9	1.1	1.2

Table F. 22. Guillemot. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-1.0	-0.4	-0.1	-0.1	-0.8
good	Fowlsheugh	-0.2	-0.3	-0.3	0.0	-0.1
good	Forth	-6.1	-1.5	0.4	-0.1	-5.3
good	St Abbs	-0.1	0.3	-0.2	-0.3	0.3
moderate	All	-1.1	0.1	-0.3	0.0	-0.7
moderate	Fowlsheugh	-0.3	0.3	-0.7	-0.1	-0.2
moderate	Forth	-3.3	0.0	0.1	0.1	-2.3
moderate	St Abbs	0.3	0.0	0.0	0.0	0.3
poor	All	-0.9	0.3	-0.2	0.3	-0.4
poor	Fowlsheugh	0.4	0.4	-0.2	0.5	0.5
poor	Forth	-3.8	0.2	0.0	0.4	-2.1
poor	St Abbs	-0.4	0.1	-0.4	0.0	-0.3

Table F. 23. Guillemot. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.7	-0.7	0.4	-0.3	0.3
good	Buchan Ness	0.7	0.2	0.2	0.0	0.2
good	Fowlsheugh	-1.6	-1.4	1.5	-0.1	0.5
good	Forth	-0.4	0.2	-1.7	0.2	-0.8
good	St Abbs	-0.6	-1.0	0.3	-1.1	0.7
moderate	All	-1.2	0.8	-0.5	-0.5	0.2
moderate	Buchan Ness	-1.8	1.4	-0.9	-2.5	2.3
moderate	Fowlsheugh	-1.1	-0.1	-1.5	0.4	-0.1
moderate	Forth	-3.5	-0.8	-0.2	1.0	-0.8
moderate	St Abbs	0.7	2.6	0.7	-1.6	-0.1
poor	All	-2.7	-0.7	-1.9	-0.2	-4.0
poor	Buchan Ness	-2.7	-1.6	-1.1	-3.2	-1.8
poor	Fowlsheugh	-1.9	-0.9	-4.1	-1.6	-6.7
poor	Forth	-8.3	-1.0	-1.9	2.3	-8.9
poor	St Abbs	0.1	0.4	0.4	1.8	1.4

Table F. 24. Guillemot. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.1	0.7	0.4	0.1	-0.1
good	Fowlsheugh	-0.2	0.0	-1.2	0.4	-0.9
good	Forth	-2.7	-0.6	0.8	-0.8	-2.1
good	St Abbs	1.8	2.6	2.2	0.1	2.1
moderate	All	-0.3	-0.4	0.2	0.1	-2.4
moderate	Fowlsheugh	0.2	0.3	1.7	-0.8	-3.2
moderate	Forth	-0.2	0.4	0.0	0.0	-0.4
moderate	St Abbs	-1.1	-1.8	-1.5	1.4	-2.6
poor	All	-3.8	-0.2	-0.8	-1.1	-2.1
poor	Fowlsheugh	-1.1	0.0	-1.8	-0.6	-3.4
poor	Forth	-12.0	-0.4	0.6	-2.5	-5.4
poor	St Abbs	-1.8	-0.4	-0.6	-0.8	1.6

Table F. 25. Guillemot. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.3.2. The effects of buffer width

The following scenarios were explored:

- 0km buffer around wind farm
- 0.5km buffer around wind farm
- 1km buffer around wind farm

The three scenarios were carried out on all SPAs in three prey availability levels for Neart na Gaoithe wind farm only. The third scenario is a repeat scenario from section F.3.1. For all scenarios, we assumed that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Adult survival change relative to the baseline can be found in Table F. 26 and Table F. 27 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 28 and Table F 29 or homogeneous and GPS-derived prey, respectively.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.2	-0.2	-0.3
good	Buchan Ness	-0.6	0.5	-0.3
good	Fowlsheugh	-0.3	-0.3	-0.4
good	Forth	-4.0	-4.5	-4.8
good	St Abbs	0.6	0.6	0.5
moderate	All	-0.6	-0.6	-0.6
moderate	Buchan Ness	-0.9	-1.0	-0.5
moderate	Fowlsheugh	-0.4	0.3	0.1
moderate	Forth	-3.2	-3.9	-4.2
moderate	St Abbs	0.3	0.1	0.2
poor	All	-0.9	-0.9	-0.9
poor	Buchan Ness	0.4	-0.6	0.1
poor	Fowlsheugh	-0.2	0.0	-0.4
poor	Forth	-5.9	-5.5	-6.0
poor	St Abbs	0.9	0.7	1.1

Table F. 26. Guillemot. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.7	-0.9	-1.0
good	Fowlsheugh	0.1	0.1	-0.2
good	Forth	-4.9	-6.3	-6.1
good	St Abbs	-0.2	-0.1	-0.1
moderate	All	-0.7	-0.8	-1.1
moderate	Fowlsheugh	-0.2	-0.4	-0.3
moderate	Forth	-2.4	-2.3	-3.3
moderate	St Abbs	0.2	0.3	0.3
poor	All	-0.5	-0.7	-0.9
poor	Fowlsheugh	0.3	0.6	0.4
poor	Forth	-3.2	-3.3	-3.8
poor	St Abbs	0.9	-0.4	-0.4

Table F. 27. Guillemot. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.1	-0.9	-0.7
good	Buchan Ness	0.9	0.9	0.7
good	Fowlsheugh	0.4	0.0	-1.6
good	Forth	-0.6	-1.2	-0.4
good	St Abbs	-1.0	-2.7	-0.6
moderate	All	0.3	-1.2	-1.2
moderate	Buchan Ness	1.6	-0.7	-1.8
moderate	Fowlsheugh	-0.3	-1.4	-1.1
moderate	Forth	-1.4	-3.1	-3.5
moderate	St Abbs	1.5	0.0	0.7
poor	All	-4.1	-3.2	-2.7
poor	Buchan Ness	-1.8	-4.0	-2.7
poor	Fowlsheugh	-4.7	-3.3	-1.9
poor	Forth	-8.7	-6.4	-8.3
poor	St Abbs	-1.8	-0.6	0.1

Table F. 28. Guillemot. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.8	-0.1	-0.1
good	Fowlsheugh	-1.4	-0.3	-0.2
good	Forth	-2.5	-1.2	-2.7
good	St Abbs	1.0	1.0	1.8
moderate	All	-1.8	-1.4	-0.3
moderate	Fowlsheugh	-0.2	-2.8	0.2
moderate	Forth	-2.3	0.0	-0.2
moderate	St Abbs	-3.4	-0.6	-1.1
poor	All	-3.7	-2.6	-3.8
poor	Fowlsheugh	-3.5	-0.9	-1.1
poor	Forth	-9.1	-7.6	-12.0
poor	St Abbs	-0.4	-1.5	-1.8

Table F. 29 Guillemot. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.3.3. The effects of percentage of birds displaced

The following scenarios were explored:

- 50% of birds displaced and 50% for whom the wind farm acted as a barrier
- 0% of birds displaced and 100% for whom the wind farm acted as a barrier
- 100% of birds displaced and 0% for whom the wind farm acted as a barrier

The three scenarios were carried out on all SPAs in three prey availability levels for all wind farms combined. The results were compared with equivalent scenarios where level for displacement and barrier effect were both 100% (repeat of scenario presented in Section F.3.1). For all scenarios, we assumed a buffer with of 1km.

Adult survival change relative to the baseline can be found Table F. 30 and Table F. 31 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 32 and Table F. 33 for homogeneous and GPS-derived prey, respectively.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.2	0.1	-0.2	0.2
good	Buchan Ness	0.1	0.2	-0.2	0.1
good	Fowlsheugh	-0.7	-0.3	-0.4	-0.1
good	Forth	-3.1	-1.0	-3.3	-0.1
good	St Abbs	0.8	0.6	0.4	0.6
moderate	All	-0.5	-0.2	-0.7	0.1
moderate	Buchan Ness	-0.7	-0.6	-0.3	-0.6
moderate	Fowlsheugh	-0.4	0.0	-0.6	-0.3
moderate	Forth	-3.4	-1.3	-3.0	-0.4
moderate	St Abbs	0.6	0.1	-0.2	0.9
poor	All	-0.8	-0.7	-0.8	0.2
poor	Buchan Ness	0.5	0.1	1.1	0.6
poor	Fowlsheugh	-1.3	-1.2	-0.8	-0.6
poor	Forth	-4.4	-2.1	-5.6	-0.8
poor	St Abbs	1.2	0.0	1.1	1.3

Table F. 30. Guillemot. Mean change in adult survival (as a percentage point) between scenario of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.8	-0.7	-1.0	-0.1
good	Fowlsheugh	-0.1	-0.3	-0.4	0.1
good	Forth	-5.3	-3.3	-5.8	-0.6
good	St Abbs	0.3	-0.2	-0.1	-0.2
moderate	All	-0.7	-0.3	-0.8	0.0
moderate	Fowlsheugh	-0.2	-0.4	-0.2	-0.2
moderate	Forth	-2.3	-0.8	-2.4	-0.1
moderate	St Abbs	0.3	0.4	0.2	0.2
poor	All	-0.4	-0.3	-0.6	0.6
poor	Fowlsheugh	0.5	0.1	-0.2	1.0
poor	Forth	-2.1	-0.7	-2.7	0.4
poor	St Abbs	-0.3	-0.6	0.5	0.1

Table F. 31 Guillemot. Mean change in adult survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	0.3	-0.8	-0.7	-0.2
good	Buchan Ness	0.2	-0.9	0.2	0.9
good	Fowlsheugh	0.5	-0.1	-1.3	-1.2
good	Forth	-0.8	-1.2	-1.4	-1.2
good	St Abbs	0.7	-1.4	0.0	1.2
moderate	All	0.2	-0.7	-1.8	0.9
moderate	Buchan Ness	2.3	-2.9	-0.2	2.3
moderate	Fowlsheugh	-0.1	-0.6	-1.2	-0.5
moderate	Forth	-0.8	-2.7	-3.7	1.2
moderate	St Abbs	-0.1	2.1	-2.3	1.5
poor	All	-4.0	-1.7	-2.4	-1.1
poor	Buchan Ness	-1.8	-0.7	-0.9	2.3
poor	Fowlsheugh	-6.7	-2.0	-1.6	-3.2
poor	Forth	-8.9	-5.2	-10.5	-3.1
poor	St Abbs	1.4	0.3	1.2	0.8

Table F. 32. Guillemot. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.1	-0.2	-0.5	0.5
good	Fowlsheugh	-0.9	-0.4	-0.1	0.5
good	Forth	-2.1	-1.7	-0.8	-1.4
good	St Abbs	2.1	1.0	-0.7	1.6
moderate	All	-2.4	-1.3	-2.5	-0.1
moderate	Fowlsheugh	-3.2	-0.4	-1.3	-0.1
moderate	Forth	-0.4	0.2	-4.3	1.0
moderate	St Abbs	-2.6	-3.3	-2.7	-1.0
poor	All	-2.1	-1.6	-1.3	-0.2
poor	Fowlsheugh	-3.4	-0.4	-3.3	-1.8
poor	Forth	-5.4	-2.5	-4.5	-0.6
poor	St Abbs	1.6	-2.6	3.4	2.2

Table F. 33. Guillemot. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on heterogeneous prey distribution.

F.4. Razorbill *Alca torda*

Three SPAs are designated for this species in the region (Fowlsheugh, Forth Islands and St Abb's Head to Fastcastle). For each SPA, and all SPAs combined, we carried out three sets of scenarios, presented in sections F.4.1, F.4.2 and F.4.3. Models based on heterogeneous prey included birds from all SPAs, but outputs were only recorded for Forth Islands, because of the lack of GPS data available from Fowlsheugh at St Abb's Head to Fastcastle.

F.4.1. The effects of wind farms and prey availability

The following scenarios were explored:

- Effect of wind farm:
    - No wind farms (the baseline scenario)
    - each of the four individual wind farms separately
    - the combined impact of all four wind farms
- Overall prey availability
    - Good
    - Moderate
    - Poor

The above scenarios resulted in a total of 18 scenarios (six wind farms scenarios in three prey availabilities). For all scenarios, we assumed a 1km exclusion buffer, and that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Figure F. 9a shows the distribution of birds from all SPAs in the baseline scenario and Figure F. 9b the distribution of birds from all SPAs in the scenario with all four wind farms under moderate prey availability and homogeneous prey distribution. These two scenarios are shown again in Figure F. 10a and Figure F. 10b based on heterogeneous prey.

The number of birds displaced and for whom the wind farm(s) acted as a barrier is shown for all 18 scenarios in Table F. 34 under homogeneous prey distribution and Table F. 35 with heterogeneous prey.

Mean adult body mass is presented as a histogram plot showing the difference between the baseline and the four wind farm scenario for all SPAs combined under moderate prey availability with homogeneous Figure F. 11 and heterogeneous prey Figure F.12. Mean adult mass at the end of the breeding season is given for all 18 scenarios is given in Table F. 36 (homogeneous prey) and Table F.37 (heterogeneous prey). Adult survival change relative to the baseline can be found in Table F. 38 (homogeneous prey) and Table F. 39 (heterogeneous prey). Finally, chick survival change relative to the baseline can be found in Table F. 40 (homogeneous prey) and Table F41.

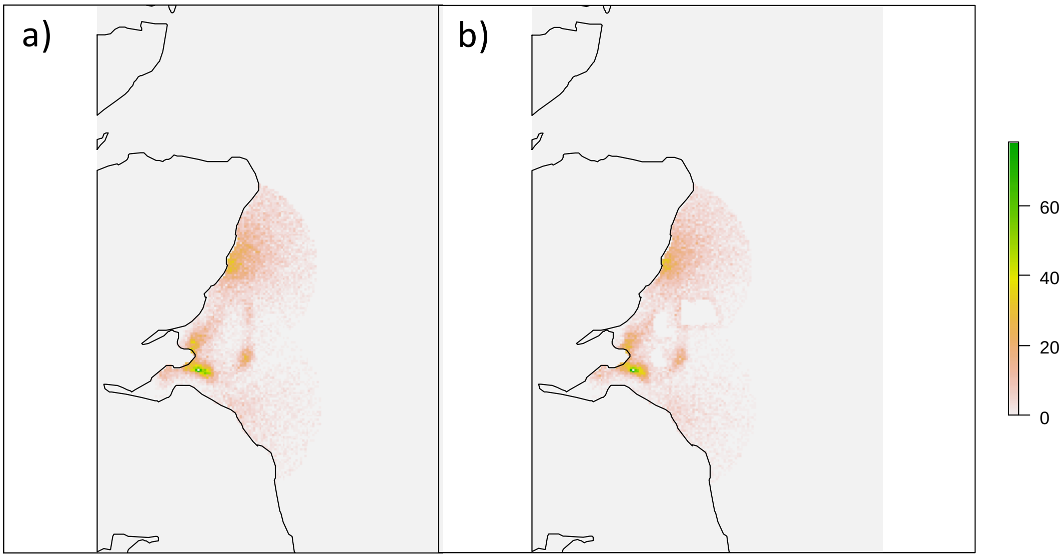

Figure F. 9. Razorbill. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and homogeneous prey distribution.

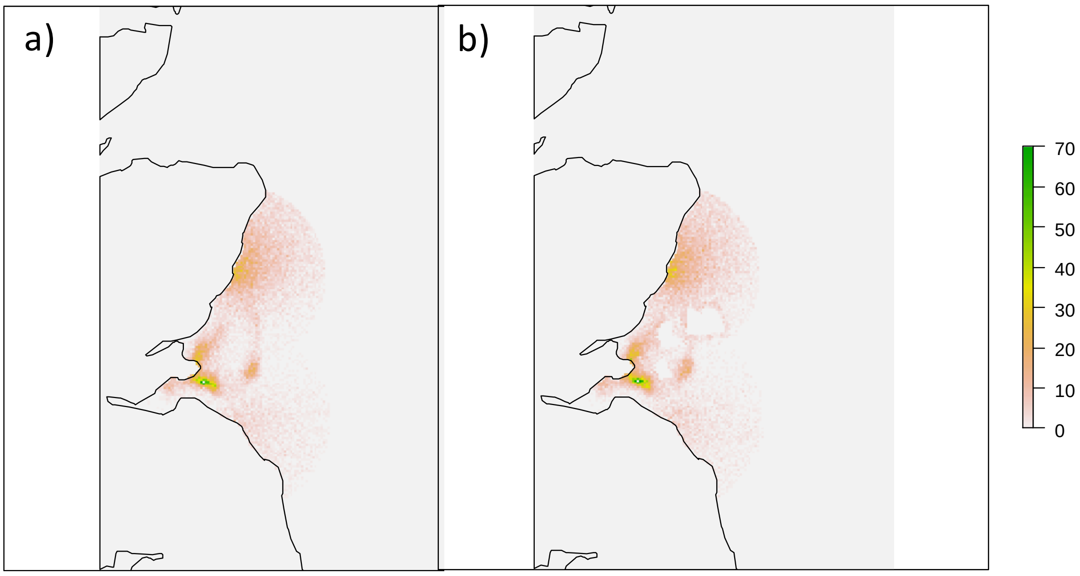

Figure F. 10 Razorbill. Distribution of birds from each SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and heterogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	All	0.0	0.0	0.3	5.1	0.6	2.0	1.2	0.8	0.4	0.7	2.4	5.4
good	Fowlsheugh	0.0	0.0	0.0	0.0	0.4	0.2	1.2	1.4	0.6	1.0	2.0	1.0
good	Forth	0.0	0.0	0.6	13.4	1.1	4.8	2.0	0.3	0.3	0.6	3.4	13.1
good	St Abbs	0.0	0.0	0.8	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.8
moderate	All	0.0	0.0	0.3	5.1	0.5	2.0	1.2	0.9	0.4	0.7	2.3	5.6
moderate	Fowlsheugh	0.0	0.0	0.0	0.0	0.4	0.2	1.2	1.4	0.6	1.0	1.8	1.2
moderate	Forth	0.0	0.0	0.9	13.6	0.9	4.8	1.7	0.3	0.3	0.6	3.4	13.6
moderate	St Abbs	0.0	0.0	0.8	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0
poor	All	0.0	0.0	0.3	5.1	0.6	2.0	1.2	0.9	0.5	0.7	2.5	5.6
poor	Fowlsheugh	0.0	0.0	0.0	0.0	0.4	0.4	1.0	1.6	0.8	1.0	2.0	1.0
poor	Forth	0.0	0.0	0.9	13.4	1.1	4.8	2.0	0.3	0.3	0.6	3.7	13.6
poor	St Abbs	0.0	0.0	0.8	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.8

Table F. 34. Razorbill. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for each SPA and all four SPAs combined, based on homogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	Forth	0.0	0.0	0.6	13.4	1.1	4.8	1.7	0.3	0.3	0.6	3.4	13.4
moderate	Forth	0.0	0.0	0.9	13.9	1.1	4.8	2.0	0.3	0.3	0.6	3.7	13.6
poor	Forth	0.0	0.0	0.9	13.4	1.1	4.8	1.7	0.3	0.3	0.6	3.7	13.9

Table F. 35. Razorbill. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for Forth Islands SPA, based on heterogeneous prey distribution.

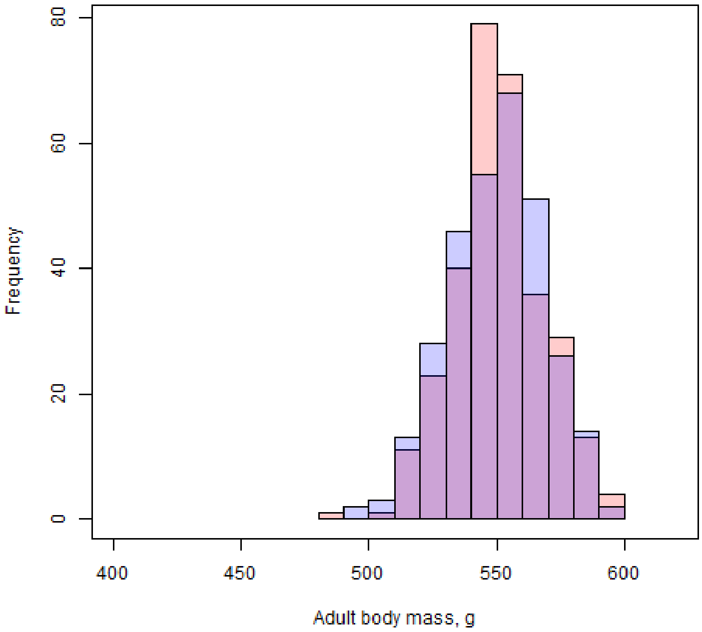

Figure F. 11. Razorbill. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with homogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

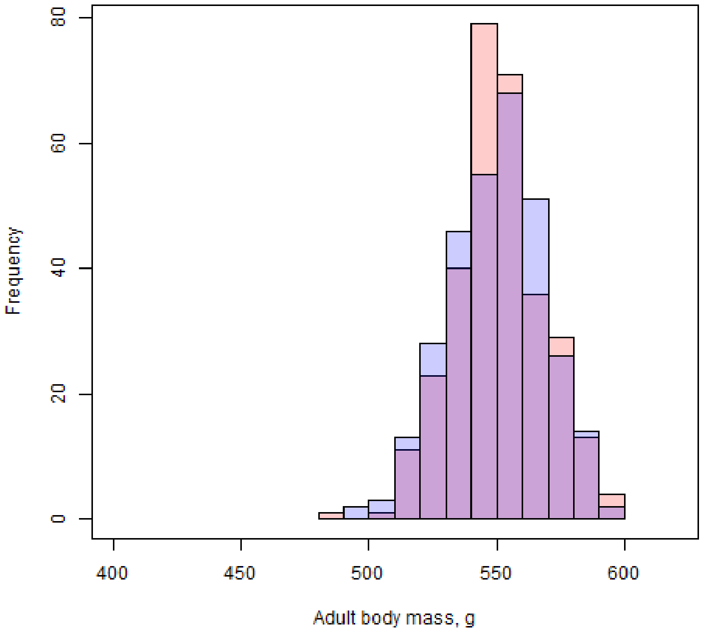

Figure F. 12. Razorbill. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with heterogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	577.2	577.0	577.6	577.3	577.3	575.6
good	Fowlsheugh	575.8	576.4	576.7	576.4	575.7	574.6
good	Forth	573.8	572.8	573.7	573.6	574.4	571.6
good	St Abbs	591.7	591.2	592.0	591.3	591.1	591.0
moderate	All	553.9	552.7	553.3	553.4	553.5	552.6
moderate	Fowlsheugh	558.4	558.3	559.0	558.7	558.4	558.5
moderate	Forth	543.8	541.4	542.0	542.3	542.6	540.2
moderate	St Abbs	564.6	562.5	562.8	564.0	564.6	564.3
poor	All	535.4	534.4	534.4	533.8	534.9	533.5
poor	Fowlsheugh	543.6	542.4	542.8	540.9	542.5	540.9
poor	Forth	525.5	524.7	524.3	524.8	525.7	524.2
poor	St Abbs	531.2	530.2	529.8	531.6	531.0	530.5

Table F. 36. Razorbill. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for each SPA and all combined for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	595.5	595.7	595.6	595.8	595.8	595.9
moderate	Forth	551.5	548.3	551.4	551.0	552.1	549.0
poor	Forth	525.4	524.7	525.9	526.0	526.2	524.1

Table F. 37 Razorbill. Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario, for Forth Islands SPA and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	-0.2	0.3	0.2	0.1	-0.9
good	Fowlsheugh	0.4	0.6	0.5	0.1	-0.6
good	Forth	-0.9	0.0	-0.1	0.4	-1.5
good	St Abbs	-0.5	0.4	-0.3	-0.9	-0.4
moderate	All	-0.7	-0.3	-0.3	-0.3	-0.8
moderate	Fowlsheugh	0.1	0.6	0.3	0.0	0.2
moderate	Forth	-1.5	-0.8	-0.9	-0.8	-2.0
moderate	St Abbs	-1.4	-1.5	-0.8	0.0	-0.5
poor	All	-0.8	-0.8	-1.0	-0.3	-1.4
poor	Fowlsheugh	-1.0	-0.6	-2.4	-0.9	-2.2
poor	Forth	-0.9	-1.1	-0.6	0.0	-1.5
poor	St Abbs	-0.8	-1.2	0.5	0.1	-0.5

Table F. 38. Razorbill. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	0.2	-0.1	0.4	0.5	0.5
moderate	Forth	-2.1	-0.4	-0.6	0.3	-1.9
poor	Forth	-0.9	0.2	0.4	0.4	-1.4

Table F. 39. Razorbill. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	All	0.3	0.3	-0.8	0.6	-2.4
good	Fowlsheugh	-0.2	-0.3	-2.5	0.4	-3.9
good	Forth	0.3	0.5	0.8	0.0	-2.7
good	St Abbs	1.9	2.5	1.6	2.9	4.1
moderate	All	-3.2	-1.3	-1.0	-2.5	-4.1
moderate	Fowlsheugh	-1.6	0.7	0.2	-1.1	-2.1
moderate	Forth	-5.7	-4.1	-3.3	-4.6	-7.5
moderate	St Abbs	-1.9	-1.3	1.0	-2.2	-1.9
poor	All	-1.2	-0.4	-0.6	-1.8	-0.8
poor	Fowlsheugh	0.2	0.6	-0.6	-2.4	0.7
poor	Forth	-3.3	-1.4	-1.9	-1.6	-3.8
poor	St Abbs	-1.0	-1.3	3.2	0.0	1.3

Table F. 40. Razorbill. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	-0.1	-0.2	0.6	-0.1	0.0
moderate	Forth	-1.6	0.9	-0.2	2.4	-3.0
poor	Forth	-2.3	2.6	1.7	0.2	-0.6

Table F. 41. Razorbill. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and all combined, for each prey availability, based on heterogeneous prey distribution.

F.4.2. The effects of buffer width

The following scenarios were explored:

- 0km buffer around wind farm
- 0.5km buffer around wind farm
- 1km buffer around wind farm

The three scenarios were carried out on all SPAs in three prey availability levels for Neart na Gaoithe wind farm only. The third scenario is a repeat scenario from section F.4.1. For all scenarios, we assumed that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Adult survival change relative to the baseline can be found in Table F. 42 and Table F. 43 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 44 and Table F 45 or homogeneous and GPS-derived prey, respectively.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	-0.1	-0.3	-0.2
good	Fowlsheugh	0.5	0.3	0.4
good	Forth	-0.8	-0.9	-0.9
good	St Abbs	-0.5	-1.2	-0.5
moderate	All	-0.5	-0.6	-0.7
moderate	Fowlsheugh	-0.2	0.4	0.1
moderate	Forth	-0.8	-1.3	-1.5
moderate	St Abbs	-0.9	-1.7	-1.4
poor	All	-0.9	-0.3	-0.8
poor	Fowlsheugh	-0.9	0.3	-1.0
poor	Forth	-1.2	-0.5	-0.9
poor	St Abbs	-1.2	-1.3	-0.8

Table F. 42. Razorbill. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	0.2	0.2	0.2
moderate	Forth	-1.5	-1.3	-2.1
poor	Forth	-1.3	-0.5	-0.9

Table F. 43. Razorbill. Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	All	1.1	0.0	0.3
good	Fowlsheugh	0.5	-0.8	-0.2
good	Forth	1.7	0.0	0.3
good	St Abbs	1.6	3.5	1.9
moderate	All	-0.6	-0.7	-3.2
moderate	Fowlsheugh	-0.7	1.3	-1.6
moderate	Forth	-1.4	-3.2	-5.7
moderate	St Abbs	1.6	-1.6	-1.9
poor	All	1.8	3.1	-1.2
poor	Fowlsheugh	3.7	7.2	0.2
poor	Forth	-0.8	-1.0	-3.3
poor	St Abbs	1.9	-1.3	-1.0

Table F. 44 . Razorbill. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	-0.1	0.1	-0.1
moderate	Forth	-1.6	0.7	-1.6
poor	Forth	-1.7	0.0	-2.3

Table F. 45. Razorbill. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

F.4.3. The effects of percentage of birds displaced

The following scenarios were explored:

- 50% of birds displaced and 50% for whom the wind farm acted as a barrier
- 0% of birds displaced and 100% for whom the wind farm acted as a barrier
- 100% of birds displaced and 0% for whom the wind farm acted as a barrier

The three scenarios were carried out on all SPAs in three prey availability levels for all wind farms combined. The results were compared with equivalent scenarios where level for displacement and barrier effect were both 100% (repeat of scenario presented in Section F.4.1). For all scenarios, we assumed a buffer with of 1km.

Adult survival change relative to the baseline can be found Table F. 46 and Table F. 47 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 48 and Table F. 49 for homogeneous and GPS-derived prey, respectively.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-0.9	0.1	-0.3	0.2
good	Fowlsheugh	-0.6	0.1	0.7	0.1
good	Forth	-1.5	0.3	-1.6	0.6
good	St Abbs	-0.4	-1.3	-0.5	-0.9
moderate	All	-0.8	-0.1	-0.5	-0.2
moderate	Fowlsheugh	0.2	0.4	0.0	-0.2
moderate	Forth	-2.0	-0.8	-1.0	-0.3
moderate	St Abbs	-0.5	0.4	0.0	-0.7
poor	All	-1.4	-0.7	-1.4	-0.3
poor	Fowlsheugh	-2.2	-0.8	-2.0	-0.8
poor	Forth	-1.5	-0.2	-1.6	-0.6
poor	St Abbs	-0.5	-2.5	-0.1	1.0

Table F. 46. Razorbill. Mean change in adult survival (as a percentage point) between scenario of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	0.5	-0.2	-0.1	0.9
moderate	Forth	-1.9	-0.3	-2.1	0.1
poor	Forth	-1.4	0.5	-0.2	-0.2

Table F. 47. Razorbill. Mean change in adult survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	All	-2.4	-1.3	-1.3	-0.1
good	Fowlsheugh	-3.9	-3.4	-3.4	-1.1
good	Forth	-2.7	0.5	1.0	0.5
good	St Abbs	4.1	1.9	0.0	1.9
moderate	All	-4.1	-1.2	-1.1	-1.6
moderate	Fowlsheugh	-2.1	0.2	1.4	-2.1
moderate	Forth	-7.5	-4.7	-4.6	-2.3
moderate	St Abbs	-1.9	3.5	-1.3	2.2
poor	All	-0.8	-2.4	-0.7	1.4
poor	Fowlsheugh	0.7	0.0	-0.8	1.9
poor	Forth	-3.8	-3.5	-0.6	0.8
poor	St Abbs	1.3	-8.6	-0.6	1.0

Table F. 48. Razorbill. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for each SPA and all combined, and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	0.0	-0.5	-0.2	-0.2
moderate	Forth	-3.0	0.9	-1.9	0.5
poor	Forth	-0.6	0.0	2.4	-0.1

Table F. 49. Razorbill. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

F.5. Atlantic puffin Fratercula arctica

One SPA is designated for this species in the region (Forth Islands). We carried out three sets of scenarios, presented in sections F.5.1, F.5.2 and F.5.3.

F.5.1. The effects of wind farms and prey availability

The following scenarios were explored:

- Effect of wind farm:
    - No wind farms (the baseline scenario)
    - each of the four individual wind farms separately
    - the combined impact of all four wind farms
- Overall prey availability
    - Good
    - Moderate
    - Poor

The above scenarios resulted in a total of 18 scenarios (six wind farms scenarios in three prey availabilities). For all scenarios, we assumed a 1km exclusion buffer, and that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Figure F. 13a shows the distribution of birds from all SPAs in the baseline scenario and Figure F. 13b the distribution of birds from all SPAs in the scenario with all four wind farms under moderate prey availability and homogeneous prey distribution. These two scenarios are shown again in Figure F. 14a and Figure F. 14b based on heterogeneous prey.

The number of birds displaced and for whom the wind farm(s) acted as a barrier is shown for all 18 scenarios in Table F. 50 under homogeneous prey distribution and Table F. 51 with heterogeneous prey.

Mean adult body mass is presented as a histogram plot showing the difference between the baseline and the four wind farm scenario for all SPAs combined under moderate prey availability with homogeneous Figure F. 15 and heterogeneous prey Figure F.16. Mean adult mass at the end of the breeding season is given for all 18 scenarios is given in Table F. 52 (homogeneous prey) and Table F.53 (heterogeneous prey). Adult survival change relative to the baseline can be found in Table F. 54 (homogeneous prey) and Table F. 55 (heterogeneous prey). Finally, chick survival change relative to the baseline can be found in Table F. 56 (homogeneous prey) and Table F57.

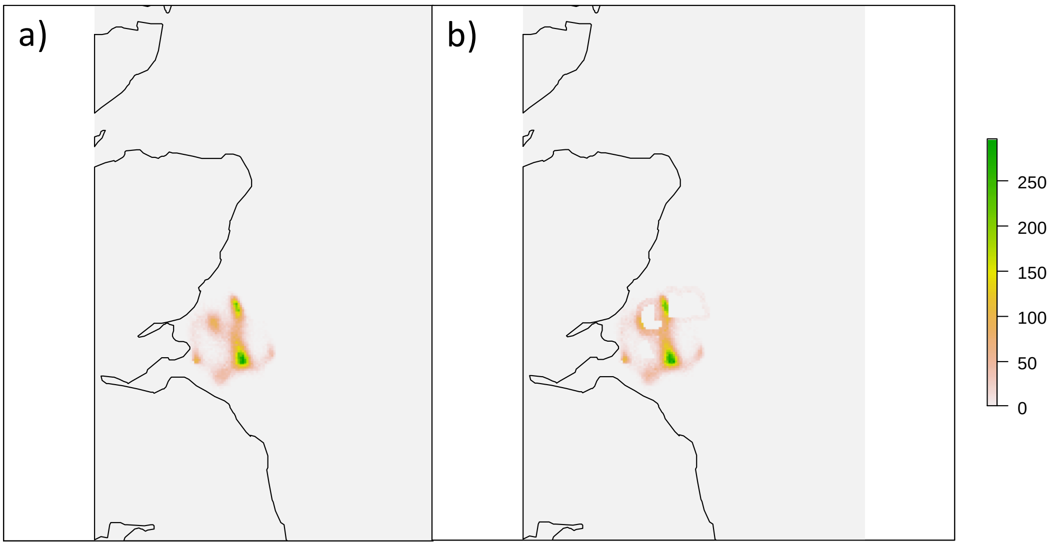

Figure F. 13 Puffin. Distribution of birds from Forth Islands SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and homogeneous prey distribution.

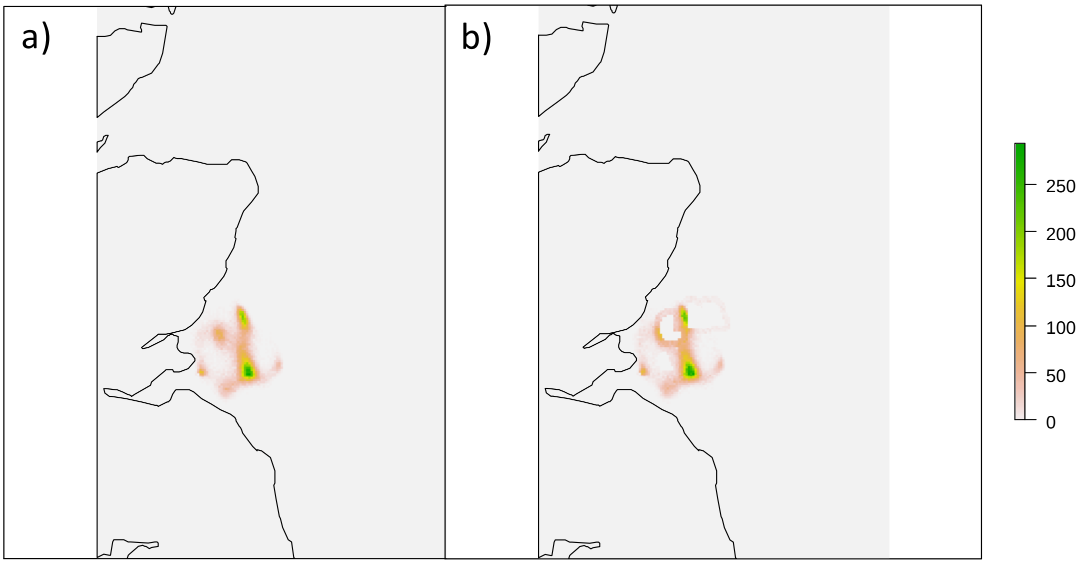

Figure F. 14. Puffin.Distribution of birds from Forth Islands SPA a) in the absence of wind farms and b) with all four wind farms present, under moderate prey availability and heterogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	Forth	0.0	0.0	0.5	38.8	5.8	19.3	2.4	0.2	0.3	0.6	8.7	32.6
moderate	Forth	0.0	0.0	0.4	38.8	5.8	19.3	2.5	0.2	0.3	0.7	8.7	32.6
poor	Forth	0.0	0.0	0.5	38.9	5.9	19.3	2.5	0.2	0.3	0.6	8.6	32.6

Table F. 50. Puffin. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for Forth Islands SPA, based on homogeneous prey distribution.

		Baseline		*NnG*		*Inch*		*Alpha*		*Bravo*		*All 4*	
Prey	*SPA*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*	*Disp*	*Barr*
good	Forth	0.0	0.0	0.4	38.9	5.8	19.3	2.5	0.2	0.3	0.6	8.7	32.6
moderate	Forth	0.0	0.0	0.5	38.9	5.8	19.3	2.4	0.2	0.3	0.6	8.6	32.6
poor	Forth	0.0	0.0	0.5	38.9	5.8	19.3	2.5	0.2	0.3	0.6	8.6	32.6

Table F. 51. Puffin. Mean across time steps percentage of the population displaced and for whom the wind farm(s) were a barrier for each wind farm scenario under three prey availabilities for Forth Islands SPA, based on heterogeneous prey distribution.

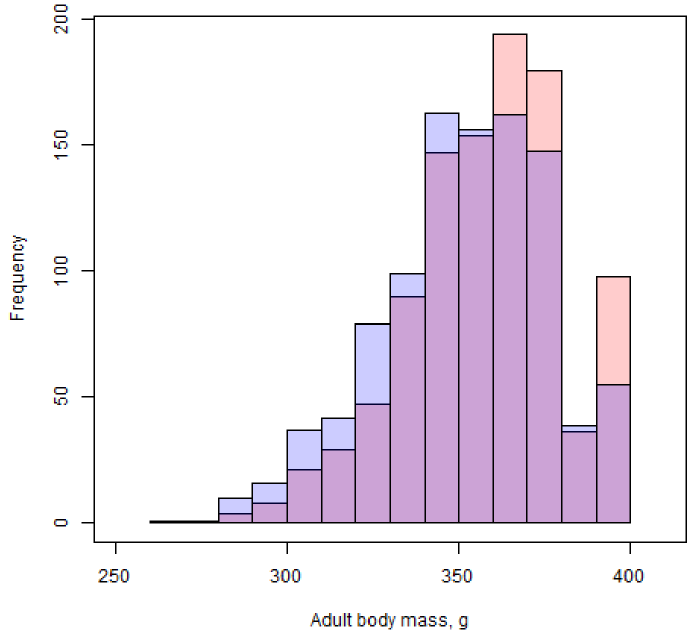

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Figure F. 15. Puffin. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with homogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

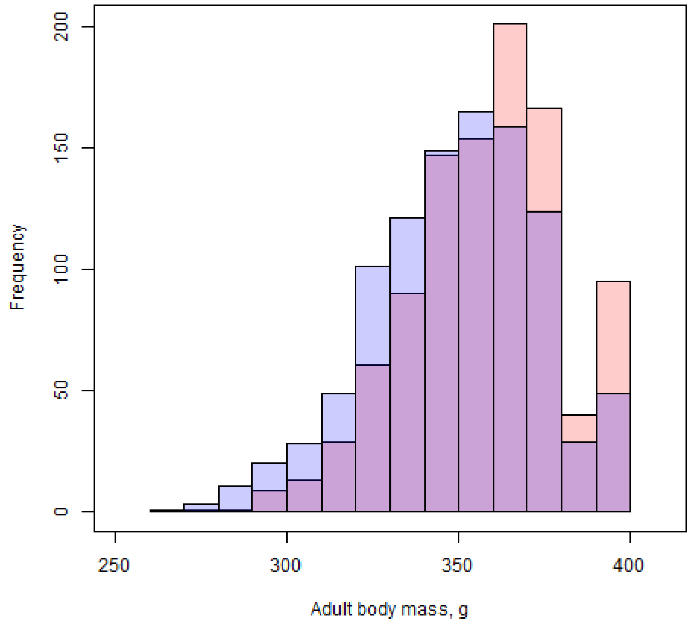


Figure F. 16. Puffin. Histogram of distribution of adult body mass at Forth Islands SPA at the end of the chick-rearing period under moderate conditions with heterogeneous prey distribution, with purple bars denoting the distribution of masses shared between baseline scenario and scenario with all four wind farms, blue denoting the distribution in the scenario with all four wind farms not the baseline, and pink denoting the distribution in the baseline and not the scenario with all four wind farms.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	370.6	365.1	368.3	370.4	371.7	364.6
moderate	Forth	359.7	351.4	355.1	357.3	360.3	350.5
poor	Forth	341.9	332.3	336.5	340.7	341.8	331.7

Table F. 52: Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario for Forth Islands SPA and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*Baseline*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	390.7	390.2	390.2	390.5	390.8	390.1
moderate	Forth	357.6	348.4	355.2	355.9	357.2	348.3
poor	Forth	348.1	339.2	344.5	346.7	349.0	338.4

Table F. 53: Mean adult body mass at the end of chick-rearing in the baseline and each wind farm scenario, for Forth Islands SPA and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	-3.1	-1.3	-0.2	0.4	-3.4
moderate	Forth	-5.2	-2.8	-1.3	0.5	-5.8
poor	Forth	-6.4	-3.5	-1.0	-0.3	-6.8

Table F. 54. Puffin. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	-2.9	-2.7	-1.4	0.0	-3.4
moderate	Forth	-5.8	-1.4	-0.8	-0.2	-6.0
poor	Forth	-6.2	-2.5	-0.9	0.5	-6.9

Table F. 55. Puffin. Mean change in adult survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and for each prey availability, based on heterogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	-1.9	-0.5	0.3	0.1	-1.5
moderate	Forth	-9.4	-4.2	-1.3	1.9	-10.0
poor	Forth	-22.5	-11.4	-5.0	-1.5	-24.7

Table F. 56. Puffin. Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and for each prey availability, based on homogeneous prey distribution.

Prey	*SPA*	*NnG*	*Inch*	*Alpha*	*Bravo*	*All 4*
good	Forth	-0.4	-0.4	-0.1	-0.2	-0.2
moderate	Forth	-11.7	-1.2	-1.0	-0.8	-12.3
poor	Forth	-16.9	-5.6	-2.0	1.6	-19.3

Table F. 57. Puffin.: Mean change in chick survival (as a percentage point) between each wind farm scenario and the baseline for Forth Islands SPA and for each prey availability, based on heterogeneous prey distribution.

F.5.2. The effects of buffer width

The following scenarios were explored:

- 0km buffer around wind farm
- 0.5km buffer around wind farm
- 1km buffer around wind farm

The three scenarios were carried out on all SPAs in three prey availability levels for Neart na Gaoithe wind farm only. The third scenario is a repeat scenario from section F.5.1. For all scenarios, we assumed that 100% of birds that were intending to forage in the wind farm were displaced and for 100% of birds that were intending to forage beyond the wind farm, it acted as a barrier such that they flew around it, not through it.

Adult survival change relative to the baseline can be found in Table F. 58 and Table F. 59 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 60 and Table F 61 or homogeneous and GPS-derived prey, respectively.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	-2.5	-2.2	-3.1
moderate	Forth	-4.1	-3.5	-5.2
poor	Forth	-4.2	-4.8	-6.4

Table F. 58. Puffin.: Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	-2.0	-1.1	-2.9
moderate	Forth	-4.7	-4.1	-5.8
poor	Forth	-4.0	-5.0	-6.2

Table F. 59. Puffin.: Mean change in adult survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	-1.8	-1.4	-1.9
moderate	Forth	-6.8	-5.5	-9.4
poor	Forth	-16.2	-18.2	-22.5

Table F. 60. Puffin. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on homogeneous prey distribution.

		Buffer width		
Prey	*SPA*	*0 km*	*0.5 km*	*1 km*
good	Forth	-0.2	-0.4	-0.4
moderate	Forth	-8.9	-7.7	-11.7
poor	Forth	-10.9	-13.4	-16.9

Table F. 61. Puffin. Mean change in chick survival (as a percentage point) between Neart na Gaoithe scenario and the baseline at three alternative buffer widths, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

F.5.3. The effects of percentage of birds displaced

The following scenarios were explored:

- 50% of birds displaced and 50% for whom the wind farm acted as a barrier
- 0% of birds displaced and 100% for whom the wind farm acted as a barrier
- 100% of birds displaced and 0% for whom the wind farm acted as a barrier

The three scenarios were carried out on all SPAs in three prey availability levels for all wind farms combined. The results were compared with equivalent scenarios where level for displacement and barrier effect were both 100% (repeat of scenario presented in Section F.5.1). For all scenarios, we assumed a buffer with of 1km.

Adult survival change relative to the baseline can be found Table F. 62 and Table F. 63 for homogeneous and GPS-derived prey, respectively. Chick survival change relative to the baseline can be found in Table F. 64 and Table F. 65 for homogeneous and GPS-derived prey, respectively.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	-3.4	-2.1	-3.7	0.3
moderate	Forth	-5.8	-3.5	-5.9	-0.6
poor	Forth	-6.8	-3.5	-6.5	-0.9

Table F. 62. Puffin. Mean change in adult survival (as a percentage point) between scenario of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for Forth Islands SPA for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	-3.4	-2.3	-4.0	-0.6
moderate	Forth	-6.0	-3.6	-5.3	-0.3
poor	Forth	-6.9	-4.1	-6.8	-0.5

Table F. 63. Puffin. Mean change in adult survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	-1.5	-0.2	-2.7	0.4
moderate	Forth	-10.0	-4.4	-9.6	0.6
poor	Forth	-24.7	-12.4	-23.2	-5.0

Table F. 64. Puffin. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages, for Forth Islands SPA and for each prey availability, based on homogeneous prey distribution.

		Displacement/Barrier %			
Prey	*SPA*	*100/100*	*50/50*	*0/100*	*100/0*
good	Forth	-0.2	0.3	-0.3	-0.2
moderate	Forth	-12.3	-7.4	-9.8	-0.9
poor	Forth	-19.3	-12.0	-20.2	-2.1

Table F. 65. Puffin. Mean change in chick survival (as a percentage point) between of all four wind farms combined and the baseline in relation to alternative displacement and barrier percentages for Forth Islands SPA for each prey availability, based on heterogeneous prey distribution.

Appendix G. Differences between the full and fast models

1) the fast model is substantially faster than the full model to run, and can therefore be used to explore new scenarios, or to run sensitivity analyzes, much more readily than the full model

The fast model is written so that all calculations are performed simultaneously on all birds by applying formulae to vectors or arrays; this is substantially faster than using for and if loops to model the fate of each individual, but is more restrictive and less flexible in terms of the forms of behaviour that can be captured by the model.

2) the full model allows birds to visit a different location if they will fail to meet their daily energy requirements (DER) by visiting their original location; the fast model does not

In the full model, birds favour more trips over less trips, attempting to make first 3, then 2 and then 1 trip per time step. If a bird cannot meet its daily energy expenditure (DEE) in 3, 2 or 1 trips, it then completes 2 trips for that day. The first trip is conducted at the chosen foraging location for that bird and will result in the bird not meeting its DEE for approximately half of the time step. The second trip is taken randomly from another bird that did meet its DEE successfully in 2 trips at an alternative location - so the second half of the time step results in the bird doing somewhat better in terms of meeting its DEE than if it had stayed at the same, original location. This is done to represent how birds move to new foraging locations if they find they are not able to meet their DEE at one location, perhaps using public information from other successful birds to direct the outward foraging trip from the colony.

In the fast model, birds favour more trips over less trips as described above, attempting to make first 3, then 2 and then 1 trip per time step. However, if a bird cannot meet its DEE in 1 trip it then does not complete a second trip for that time step, but merely remains at the original foraging location and forages for as long as it chooses before returning to the colony (subject to various foraging rules explained in Section 2.2). The reason for this difference is the large penalty in terms of computing time that is associated with selecting randomly from a different bird that did complete two trips successfully. Overall, we felt this was the best compromise between maintaining computing speed in the simpler model whilst trying to most faithfully represent the mechanisms in the full model.

3) the fast model does not include any mechanism for estimating cumulative effects

It would be possible in principle to incorporate such effects into the model, in the same way that they enter into the full model, and this is not likely to add substantially to the computational power required to run the model. The time required to add this to the code would be substantive, however, and it was not possible to do this within the timescale of this project.

4) the fast model matches birds between scenarios, so that the assessments of a wind farm quantify the impact of the wind farm on a particular set of birds (rather than

comparing a set of birds that have been impacted by the wind farm against a different set of birds that have not)

Matching increases the precision for estimates of the impact of the wind farm, without incurring any substantive computational cost. It is achieved by ensuring that stochastic decisions which are not affected by the wind farm are identical in those model runs which include a wind farm and those model runs that do not. This is done within the fast model by setting the seed to be the same in both runs. This cannot be done in the full model because the model is coded in such a way that decisions related to the wind farm are not easily separated from other decisions.

5) the split in time between time on the nest and time resting at sea is slightly more realistic in the fast model than the full model;

The time adults would choose to spend unattending the nest differs subtly in each model. In the full model, if a bird has met its DEE and spent 50% of the time step at the colony, any remaining time is split 50:50 between attending the nest and resting at sea. However, in the fast model, a bird in this state will spend all remaining time at the nest, with only one hour spent resting at sea. This means the fast model allows for partnered birds to compensate slightly more for one another in terms of nest attendance than in the full model. This is a model refinement we chose to enact in the later, fast model because we felt it was more biologically realistic than the way in which this behaviour was coded in the original full model.

6) the fast model allows for variation in initial mass between adult birds;

Adult birds in the full model all start off each simulation at the same mass – this mass is the average mass recorded for the species from local empirical data. However, in the fast model, the starting masses for all adults are drawn from a distribution characterised by the mean and standard deviation of local empirical data for each species. The reason for this difference is simply that we felt drawing masses from a distribution would more realistically capture the reality of bird masses for each population, however, this change was difficult to enact in the full model because of processing time required to match up starting and end masses of individual birds. This problem was not an issue in the fast model because of the array structure of the model code.

7) the fast model uses a higher spatial resolution than the full model (0.5 x 0.5km rather than 1.67 x 1.67km);

Computational constraints restricted us to using a relatively coarse spatial resolution within the full model, but the reduced computational cost of the fast model allowed us to adopt a higher spatial resolution. The key advantage of the higher spatial resolution should be a more accurate description of the boundaries of the wind farms.

8) the fast model includes barrier effects in a more realistic way than the full model;

The full model assumes that the additional distance incurred as a result of barrier effects could be simulated from a normal distribution with a mean of 20km and a standard deviation of 5km. This can justified as being a “worst case scenario”, but there are a number of limitations to this approach:

1) 20km is overly conservative in most situations;
2) it does not allow for the different sizes of different wind farms;

3) it does not allow for heterogeneity in the extent to which birds have to cross wind farms in order to reach their destination;
4) it does not allow for the variation in shapes of wind farms;
5) it does not allow for uncertainty about how birds actually respond to wind farms.

The fast model incorporates a revised approach that attempts to deal with the first three of these limitations. The fourth limitation is difficult to deal with from a technical perspective, and we did not have sufficient information to be able to deal with the final limitation.

The revised approach calculates the additional distance that a bird incurs in avoiding a wind farm using geometric calculations. It is based on two assumptions:

1) wind farms can be approximated by a circle;

2) in the absence of a wind farm birds will fly in a straight line; if their route passes through a wind farm they will adjust to this by flying around the perimeter of the wind farm using the shortest possible route.

In Figure G. 1 the bird would originally have taken the purple line from the colony to the foraging location, but the wind farm forces it to abandon part of this route (shown with red dots) and to fly around the perimeter of the wind farm (the route shown in red) instead.

The radius of the circle is defined by calculating (maximum bearing from colony that would hit a location in the wind farm – minimum bearing from colony that would hit a location in the wind farm).

The magnitude of the barrier effect depends on three quantities:

a) the distance from the colony to the centre of the wind farm (*D*)

b) difference between the bearing from the colony to the centre of the wind farm and the edge of the wind farm (ϕ)

c) the relative angle at which the line from the colony to the foraging location hits the wind farm (*p*)

The additional distance incurred as a result of the barrier effect is equal to

$$D\sin(\phi)\{\theta - 2*\sin(\theta/2)\},$$

where

$$\theta = 2\sin^{-1}\left[\frac{\sin(\phi p)}{\sin(\phi)}\right] - \pi$$

p represents the relative angle from the colony to the foraging destination, in relation to the wind farm. If *p* = 0 the line from the colony to the foraging destination passes straight through the middle of the wind farm (and the maximum barrier cost is incurred). If *p* = 1 the line from the colony to the foraging destination just grazes the edge of the wind farm (and the barrier cost is zero).

We have estimated the distribution of additional flight costs in relation to *p* for each wind farm, shown in Figure G. 2. This figure shows that 20km is an appropriate maximum to represent the worst case at the larges wind farm, but the average barrier distances are considerably lower. Since the main effect on adult and chick survival has resulted from barrier effects (in particular with puffins), this new method of calculating barrier effects will reduce the effect sizes.

Figure G. 1. Illustration of method of calculating barrier effects. See main text for full details.

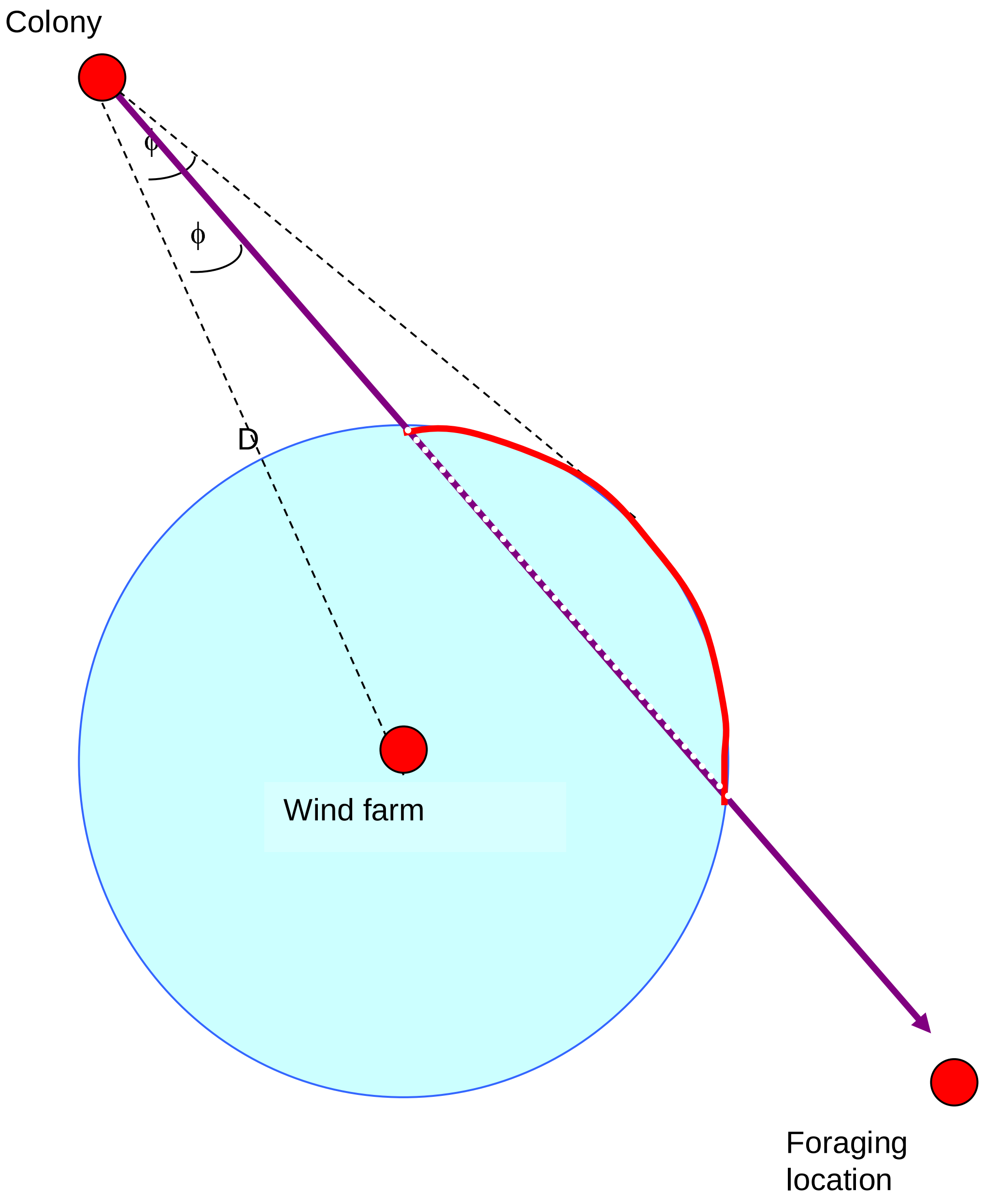
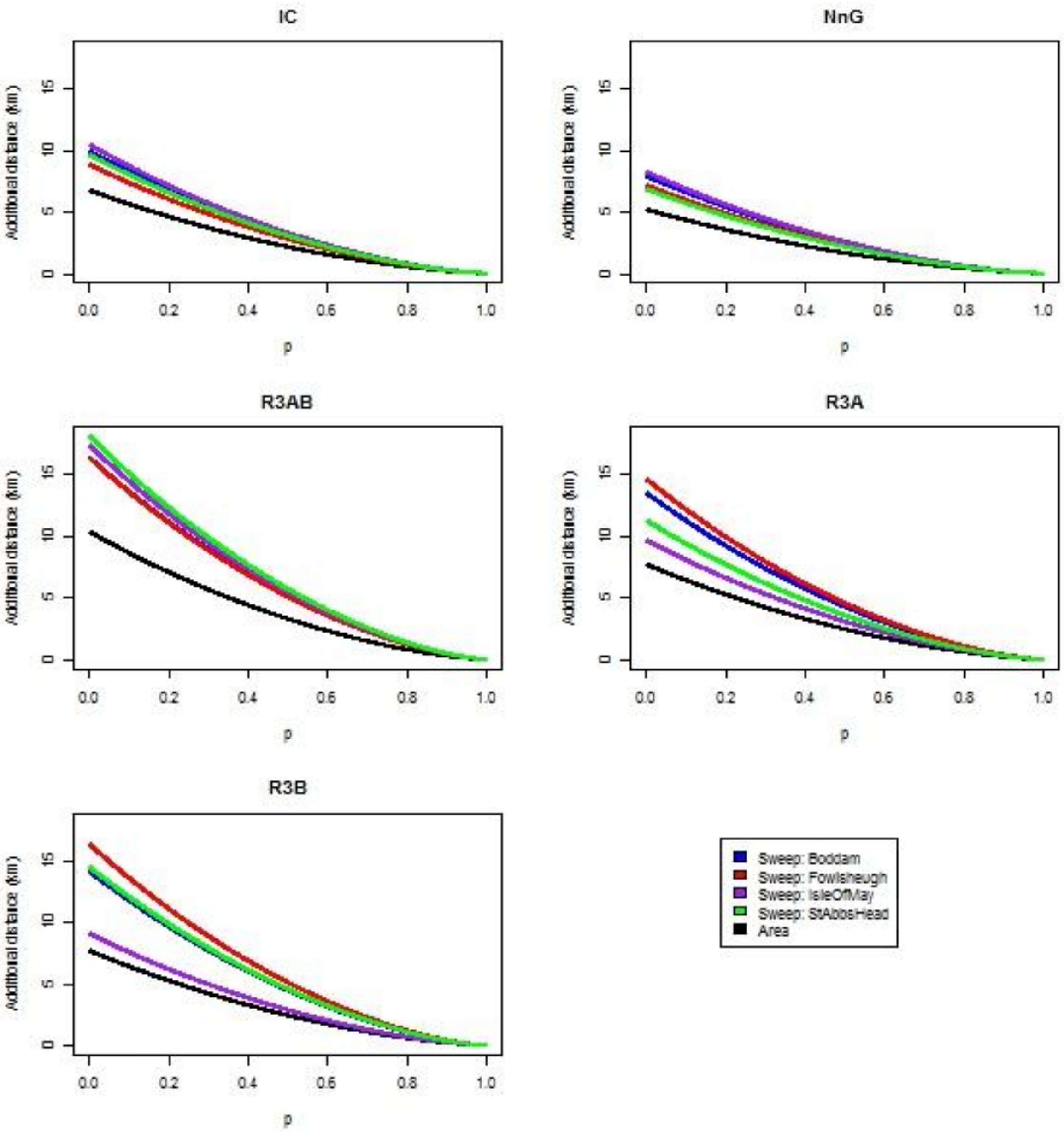


Figure G. 2. Distribution of additional flight costs in relation to angle swept (relative to total angle swept by wind farm). See main text for details.



9) the fast model displaces birds into Zones 3 and 5 (the 5km buffer zone around each wind farm) in proportion to the estimated density of birds in those zones. This is in contrast to the full model, which displaces birds randomly into Zones 3 and 5 with no relation to the estimated bird density in those areas;

The reason for this difference is simply that we felt it more ecologically viable that birds would choose a new foraging location in relation to the suitability of available foraging locations within the 5km buffer around each wind farm. The consequence of this change is that under homogeneous prey the fast model will tend to estimate larger wind farm effects than the full model because it will tend to concentrate displaced birds into regions within the 5km buffer with high predicted bird density.

Under homogeneous prey conditions these regions will not contain correspondingly high levels of prey, and so displaced birds may suffer greater interference competition that they would if they were more evenly distributed across the 5km buffer as occurs in the full model. However, given the lack of data on the displacement behaviour of birds and subsequent choices of foraging location it is impossible to assess which model incorporates the more realistic method for redistributing displaced birds to new foraging locations.

Appendix H. Appendix H. Reliability of adjustment factors

Species	SPA	Wind farm	Prey type	ADULT SURVIVAL				
				Main	MC Q25	MC Q75	d	Reliability
Guillemot	Forth Islands	NnG	Hom	0.23	0.21	0.23	**0.01**	**High**
			Het	0.27	0.22	0.25	**0.05**	**High**
Guillemot	Fowlsheugh	R3B	Hom	0.26	0.36	0.79	**0.53**	**Low**
			Het	0.73	0.30	1.10	**0.43**	**Low**
Kittiwake	Forth Islands	R3B	Hom	0.51	0.42	0.48	**0.09**	**High**
			Het	0.44	0.43	0.51	**0.07**	**High**
		R3A	Hom	0.45	0.40	0.47	**0.05**	**High**
			Het	0.47	0.40	0.47	**0.06**	**High**
		NnG	Hom	0.24	0.22	0.23	**0.03**	**High**
			Het	0.22	0.22	0.23	**0.01**	**High**
		IC	Hom	0.33	0.29	0.32	**0.04**	**High**
			Het	0.28	0.29	0.32	**0.04**	**High**
Kittiwake	Fowlsheugh	R3B	Hom	0.50	0.52	0.59	**0.09**	**High**
			Het	0.47	0.47	0.57	**0.09**	**High**
		R3A	Hom	0.45	0.47	0.51	**0.06**	**High**
			Het	0.57	0.46	0.53	**0.11**	**Moderate**
		NnG	Hom	-0.66	-0.25	1.37	**2.03**	**Low**
			Het	0.20	-0.13	1.95	**1.74**	**Low**
		IC	Hom	0.43	0.19	0.86	**0.43**	**Low**
			Het	-0.81	-0.05	1.41	**2.22**	**Low**
Kittiwake	St Abbs	R3B	Hom	0.53	0.37	0.49	**0.16**	**Moderate**
			Het	0.55	0.32	0.51	**0.23**	**Low**
		R3A	Hom	0.84	0.34	0.56	**0.51**	**Low**
			Het	0.05	0.30	0.61	**0.56**	**Low**
		NnG	Hom	0.33	0.27	0.40	**0.07**	**Low**
			Het	0.30	0.31	0.41	**0.11**	**Moderate**
		IC	Hom	0.18	0.16	0.67	**0.48**	**Low**
			Het	0.10	0.17	0.63	**0.54**	**Low**
Puffin	Forth Islands	R3B	Hom	0.95	0.95	1.06	**0.11**	**Moderate**
			Het	1.00	0.96	1.10	**0.10**	**High**
		R3A	Hom	0.99	0.99	1.02	**0.03**	**High**
			Het	0.95	0.96	1.02	**0.07**	**High**
		NnG	Hom	0.08	0.08	0.08	**0.01**	**High**
			Het	0.11	0.10	0.11	**0.01**	**High**
		IC	Hom	0.27	0.26	0.28	**0.01**	**High**
			Het	2.57	2.53	3.05	**0.48**	**Low**
Razorbill	Forth Islands	R3B	Hom	1.00	1.00	1.00	**0.00**	**High**
			Het	1.00	1.00	1.00	**0.00**	**High**
		R3A	Hom	0.77	0.74	0.86	**0.09**	**High**
			Het	0.76	0.65	0.95	**0.19**	**Moderate**
		NnG	Hom	0.16	0.15	0.16	**0.00**	**High**
			Het	0.17	0.16	0.16	**0.01**	**High**
		IC	Hom	0.32	0.31	0.33	**0.01**	**High**
			Het	0.57	0.55	0.58	**0.02**	**High**

Table H1. Reliability of adjustment factors associated with adult survival. The column ‘Main’ refers to the adjustment factors used in the main assessment (Table 3:2). The columns MC Q25 and MC Q75 contain 25% and 75% quantiles for this adjustment factor, as derived from 50 additional simulation runs of the model. *d* is derived from these three quantities (see Section 2.6.3), and the value of *d* is used to classify the level of reliability (high: $d < 0.1$, moderate: $0.1 < d < 0.2$, low $d > 0.4$).

Species	SPA	Wind farm	Prey type	BREEDING SUCCESS				
				Main	MC Q25	MC Q75	d	Reliability
Guillemot	Forth Islands	NnG	Hom	0.10	0.18	0.30	0.20	Moderate
			Het	0.36	0.01	0.29	0.36	Low
Guillemot	Fowlsheugh	R3B	Hom	1.50	-0.69	1.19	2.19	Low
			Het	0.36	-0.20	1.86	1.50	Low
							0.00	
Kittiwake	Forth Islands	R3B	Hom	-0.73	0.12	0.67	1.39	Low
			Het	0.50	-0.33	0.83	0.83	Low
		R3A	Hom	0.50	0.02	0.63	0.48	Low
			Het	0.50	0.12	0.96	0.46	Low
		NnG	Hom	0.18	0.14	0.23	0.05	High
			Het	0.14	0.13	0.20	0.06	High
		IC	Hom	-0.43	0.17	0.48	0.91	Low
			Het	-0.30	0.11	0.44	0.74	Low
Kittiwake	Fowlsheugh	R3B	Hom	0.59	0.42	0.74	0.17	Moderate
			Het	0.15	0.25	0.76	0.61	Low
		R3A	Hom	0.47	0.36	0.61	0.13	Moderate
			Het	0.13	0.39	0.62	0.49	Low
		NnG	Hom	-0.80	-0.65	1.53	2.32	Low
			Het	0.25	-0.31	1.50	1.25	Low
		IC	Hom	1.00	-0.05	0.73	1.05	Low
			Het	0.28	-0.11	1.24	0.96	Low
Kittiwake	St Abbs	R3B	Hom	0.89	-0.79	0.80	1.68	Low
			Het	-0.29	-0.06	1.39	1.67	Low
		R3A	Hom	-0.12	-0.11	1.25	1.36	Low
			Het	-0.06	-0.61	1.11	1.17	Low
		NnG	Hom	0.90	-0.38	0.95	1.28	Low
			Het	0.00	-0.13	0.65	0.65	Low
		IC	Hom	5.00	-0.21	1.20	5.21	Low
			Het	1.50	-0.53	1.38	2.03	Low
Puffin	Forth Islands	R3B	Hom	0.67	0.39	1.34	0.67	Low
			Het	1.33	0.00	1.46	1.33	Low
		R3A	Hom	0.93	0.94	1.08	0.15	Moderate
			Het	0.73	0.80	1.23	0.49	Low
		NnG	Hom	0.12	0.04	0.10	0.08	High
			Het	0.14	0.06	0.13	0.07	High
		IC	Hom	0.24	0.21	0.28	0.04	High
			Het	6.33	0.25	3.44	6.08	Low
Razorbill	Forth Islands	R3B	Hom	1.00	1.00	1.00	0.00	High
			Het	1.00	1.00	1.00	0.00	High
		R3A	Hom	2.00	-0.20	1.00	2.20	Low
			Het	1.00	0.37	2.00	1.00	Low
		NnG	Hom	0.07	0.12	0.19	0.12	Moderate
			Het	0.17	0.11	0.20	0.06	High
		IC	Hom	0.33	0.23	0.46	0.13	Moderate
			Het	0.20	0.38	0.89	0.69	Low

Table H2. Reliability of adjustment factors associated with breeding success. The column 'Main' refers to the adjustment factors used in the main assessment (Table 3:3). The columns MC Q25 and MC Q75 contain 25% and 75% quantiles for this adjustment factor, as derived from 50 additional simulation runs of the model. *d* is derived from these three quantities (see Section 2.6.3), and the value of *d* is used to classify the level of reliability (high: *d* < 0.1, moderate: 0.1 < *d* < 0.2, low *d* > 0.4).

Species	**SPA**	**Prey** type	**ADULT SURVIVAL** Big model	Adjustment factor		**Big model adjusted**	
				Good	Mod+Good	Good	Mod+Good
Kittiwake	Forth Islands	Hom	-6.62	0.30	0.30	**-1.99**	**-1.99**
		Het	-6.58	0.28	0.28	**-1.84**	**-1.84**
Kittiwake	Fowlsheugh	Hom	-1.04	0.46	0.46	**-0.48**	**-0.48**
		Het	-0.81	0.47	0.55	**-0.38**	**-0.45**
Kittiwake	St Abbs	Hom	-0.45	0.33	0.41	**-0.15**	**-0.18**
		Het	-0.73	**Not calculated**	0.30	**Not calculated**	**-0.22**
Puffin	Forth Islands	Hom	-13.00	0.25	0.26	**-3.25**	**-3.38**
		Het	-7.22	-0.01	-0.01	**0.07**	**0.07**
Razorbill	Forth Islands	Hom	-0.82	1.00	1.00	**-0.82**	**-0.82**
		Het	-0.75	0.28	0.32	**-0.21**	**-0.24**

Table H3. Cumulative effects on adult survival: comparison of results obtained by using only wind farms whose effects are estimated with high reliability when estimating adjustment factors against those obtained by using wind farms with either high or moderate reliability.

Species	**SPA**	**Prey** type	**BREEDING SUCCESS** Big model	Adjustment factor		**Big model adjusted**	
				Good	Mod+Good	Good	Mod+Good
Kittiwake	Forth Islands	Hom	-11.86	0.18	0.18	-2.14	**-2.14**
		Het	-8.12	0.14	0.14	-1.14	**-1.14**
Kittiwake	Fowlsheugh	Hom	-3.29	Not calculated	0.51	Not calculated	**-1.68**
		Het	-2.02	Not calculated	Not calculated	Not calculated	Not calculated
Kittiwake	St Abbs	Hom	0.84	Not calculated	Not calculated	Not calculated	Not calculated
		Het	-0.14	Not calculated	Not calculated	Not calculated	Not calculated
Puffin	Forth Islands	Hom	-22.31	0.18	0.22	-4.02	**-4.91**
		Het	-11.43	0.14	0.14	-1.60	**-1.60**
Razorbill	Forth Islands	Hom	-3.66	1.00	-0.54	-3.66	**1.98**
		Het	-1.76	1.66	1.66	-2.92	**-2.92**

Table H4. Cumulative effects on breeding success: comparison of results obtained by using only wind farms whose effects are estimated with high reliability when estimating adjustment factors against those obtained by using wind farms with either high or moderate reliability.

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