

Effects of Displacement from Marine Renewable Development on Seabirds Breeding at SPAs:

A Proof of Concept Model of Common Guillemots Breeding on the Isle of May

Final report to MSS

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**Centre for
Ecology & Hydrology**

NATURAL ENVIRONMENT RESEARCH COUNCIL

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Executive Summary

- Offshore renewable developments have the potential to impact on seabirds by displacing individuals from foraging habitats. The impact of displacement is particularly important for breeding seabirds that, as central place foragers, are constrained to obtain food within a certain distance from the breeding colony. The current worst case scenario is that displacement causes 100% mortality, so there is a need to model more realistic consequences of displacement.
- Displacement is likely to result in changes to daily energy and time budgets. Such changes may impact on the body condition of adult breeders which, in turn, can affect breeding success, adult survival and, ultimately, population size. Additionally, breeding success may be affected directly if provisioning rates alter significantly.
- The Forth and Tay Offshore Wind Developers Group (FTOWDG) have exclusivity licences for proposed wind farm developments in the outer Forth and Tay which are offshore from a suite of SPAs for seabird species that will potentially interact with these developments. As part of the environmental evaluation of these developments there is a need to assess the potential impacts of displacement on breeding birds.
- This report presents a displacement model for adult common guillemots *Uria aalge* rearing chicks on the Isle of May (part of Forth Islands SPA) in relation to the proposed offshore wind farm at Neart na Gaoithe. The model estimates the consequences of displacement and barrier effects on the time/energy budget of breeding birds.
- Our model incorporates several novel features resulting in a step change in the degree of realism captured in terms of incorporating how guillemots use their foraging landscape and in how their fish prey are distributed within it.
- The model compares the time/energy budget of 1,000 breeding guillemots over a 24 hour period in the absence or presence of a wind farm. The model is based on assumptions regarding behavioural change in response to a wind farm and explores scenarios simulating different prey distributions (dispersed or patchy) and different levels of interference competition among guillemots feeding in the same patch.

Under all scenarios, the presence of the Neart na Gaoithe wind farm resulted in an increase in the average costs of foraging. For example, where prey were randomly distributed, mean flight and foraging costs in the absence of the wind farm were 1.18 h (± 0.60 h) and 2.19 h (± 0.96 h) respectively; equivalent values in the presence of the wind farm were 1.60 (± 0.67) and 2.58 (± 1.57) respectively. Under this scenario, the mean number of birds displaced was 101, and the wind farm was a barrier to movement for 44 birds.

- The impact of displacement is driven by two main processes: 1) the increased travelling costs to the subset of the population that is displaced or for which the wind farm forms a barrier to movement, and 2) the reduction in average prey densities in the remaining habitat due to intensified intra-specific competition, affecting not just displaced birds but the population as a whole.
- These results indicate that displacement effects on seabird populations could be important and therefore merit further consideration. The most appropriate method of estimating the population consequences of displacement is to link time-energy budget models of foraging with population models under a range of plausible scenarios of displacement. The report describes a framework for undertaking this linked modelling based on three components:
 - A time-energy budget model in the absence of a wind farm which extends the model presented here to produce a cumulative profitability surface over the course of the breeding season from which consequences on adult survival and breeding success are estimated.
 - A time-energy budget model in the presence of a wind farm in which the consequences of displacement and barrier effects on demographic rates are quantified.
 - A stochastic time-specific matrix model which quantifies the population consequences of displacement in three steps: a) a retrospective analysis of population change in relation to environmental conditions; b) a forecasting analysis of predicted population change under scenarios of future environmental change which provides a baseline for c) the predicted
- In conclusion, our model demonstrates that displacement of foraging seabirds from an offshore wind farm could result in changes to their time/energy budgets with potential consequences for breeding performance and/or survival. It also lays the foundation for estimating population consequences of displacement by linking time-energy budget models of foraging with population models.

1. Introduction

1.1. Background

Offshore renewable developments may have an effect on the daily energy and time budgets of seabirds by displacing birds from favoured foraging habitats, potentially forcing them to forage at greater densities in sub-optimal habitats (Larsen & Guillemette 2007). The current worst case scenario is that displacement causes 100% mortality, so there is a need to model more realistic consequences of displacement.

The impact of displacement is predicted to be particularly important for breeding seabirds that, as central place foragers, are constrained to obtain food within a certain distance from the breeding colony (Daunt *et al.* 2002; Enstipp *et al.* 2006). Changes in time and energy budgets resulting from displacement from a renewable development have the potential to impact on the body condition, and hence survival prospects, of breeding adults and also reduce breeding success because of changes in provisioning rates. Both these outcomes could have population consequences and thus need to be quantified, particularly where renewable developments are proposed within the foraging range of breeding individuals from SPAs.

1.2. Aims & Objectives

The aim of this project is to develop a displacement model for adult common guillemots *Uria aalge* rearing chicks on the Isle of May (part of Forth Islands SPA) in relation to the proposed offshore wind farm at Neart na Gaoithe. This site is one of a suite proposed in the Forth/Tay region that currently also include Inch Cape and Firth of Forth Zone 2. The model compares the time/energy budgets of breeding guillemots in the absence of a wind farm, utilising available data on distribution and activity budgets, with time/energy budgets in the presence of the wind farm, based on plausible behavioural responses to the development.

Our novel approach represents a significant advancement in our understanding of the potential effects of displacement based on a step change in the degree of realism captured by the model in terms of incorporating both:

- how guillemots use their foraging landscape, both in the absence and presence of a wind farm, and
- how their fish prey are distributed within it.

Thus, our model compares the effects of displacement when prey is dispersed or patchy, and under elevated levels of interference competition among guillemots feeding in the same patch (individuals may interfere with one another at higher densities, resulting in lower prey capture rates, Hassell & Varley 1969).

In addition to presenting outputs from the model, this report discusses how the model can be adapted to other species or locations and expanded in complexity to parameterise population models that estimate the population consequences of displacement.

2. Methods

2.1. Study Area and Species

The Isle of May NNR, south-east Scotland (56°11'N, 02°33'W) is part of the Forth Islands SPA (<http://www.jncc.gov.uk/pdf/SPA/UK9004171.pdf>). This SPA is designated for its numbers of common guillemot (hereafter 'guillemot'), razorbill *Alca torda*, Atlantic puffin

Fratercula arctica, lesser black-backed gull *Larus fuscus*, northern gannet *Morus bassanus*, European shag *Phalacrocorax aristotelis*, great cormorant *P. carbo*, roseate tern *Sterna dougallii*, common tern *S. hirundo* and sandwich tern *S. sandvicensis*.

This pilot study focused on one species for which a large body of empirical data exist from the Isle of May, the guillemot. The guillemot is the third most numerous breeding species in the Forth Islands SPA, after northern gannet and Atlantic puffin. The population has been in sharp decline in the last decade from a peak in 2001 of

c. 30,000 pairs to the current population of ca. 18,000 pairs (Pickett & Squire 2011; Bruce 2011). The guillemot is a pursuit-diving seabird that preys primarily on small, shoaling fish such as lesser sandeels *Ammodytes marinus* and sprat *Sprattus sprattus* (Harris & Wanless 1985; Wilson *et al.* 2004). It breeds in dense colonies on cliff ledges, and both parents share the duty of incubation and rearing the single offspring. Typically, one parent attends the young whilst the other is at sea.

There is a paucity of published data on the behaviour of breeding guillemots in response to wind farms. The best current evidence on displacement is for non-breeding individuals available from wind farm developments outside the UK. Studies at Horns Rev wind farm, Denmark, suggest that guillemots did not forage in or travel through wind farms (Petersen 2005). However, patterns were less clear cut at the Egmond wind farm, off of the Dutch coast, with displacement recorded in some situations but not others (Leopold *et al* 2011), and there was no evidence of displacement of guillemots from Belgian developments (Vanermen *et al.* 2011). The development of offshore wind farm sensitivity scores for seabirds (Garthe & Hüppop 2004) ranked guillemot 20th out of 26, although this low relative vulnerability score was primarily due to the low collision risk for this species. Guillemots were scored as moderate to high vulnerability for two of the factors most pertinent to displacement ('habitat use flexibility' and 'adult survival rate'). In accordance with this, the guillemot was ranked 11th out of 38 in the list of species of concern due to disturbance and/or displacement from habitat due to offshore wind farms by Furness & Wade (2012). The inconsistent results obtained from empirical studies, paucity of published information on displacement of breeding individuals, and moderate to high vulnerability to displacement compared to other seabird species in the two reviews on seabirds, highlight the importance of a displacement model for this species for the outer Forth and Tay region.

2.2. Simulation Model

A model was created to simulate the feeding location of 1000 guillemots (ca. 6% of the SPA population) over a 24 hour period during chick-rearing (see Appendix 1 for details of model input parameters including sources). The simulation model allowed guillemots to choose the most suitable location for feeding during one foraging trip

from the colony. The model incorporated realistic assumptions based on the known behaviour of guillemots (Section 2.2.2.) to deduce what the best location would be. The location of the 1000 guillemots and information on their chosen location are stored for each simulation. The model incorporated the Isle of May and the surrounding sea and land (OS Grid reference of bounding box of the model: xmin 332451 ymin 676319, xmax 423657, ymax 747098, area: 6532km²). The resolution of the model was defined by the resolution of the input datasets (1 km²). The model was run using the statistical software R v 2.14.1 (R Development Core Team 2012).

2.2.1. Input layers

For the model to run successfully, three input layers were required (Figure 1): a prey density distribution across the area, the bathymetry of the area (maximum possible dive depth for the bird) and the distance of each location from the Isle of May (OS Grid Reference 365679, 699182). The bathymetry of the area was obtained from the British Geological Survey under licence (<http://www.bgs.ac.uk/products/offshore.html>) and the distance of each location was calculated using the *raster* package in R (Hijmans & van Etten 2012). The prey density distribution was simulated using the *rMatClust* function in the R package *spatstat* (Baddeley & Turner 2005). This function generates a random number of points representing prey individuals, such as lesser sandeels or sprat, inside the bounding box of the model. The function also generates a Matérn's cluster process which entails, for each point, adding more points to create groupings of points. As the level of clustering increases, more points occur within groups and distances increase between groups. Unfortunately, no empirical data on fish shoal size and distribution were available for use in the model, so it is uncertain how realistic is the clustering level selected for examination here. However, it is likely that a clustered distribution is more realistic than the random distribution. A grid is placed onto the surface of points and the points summarised to create a prey density value for each 1km² location. We used linear distances, but note that this would underestimate distances for some areas, notably in the Firth of Tay, which birds can not travel to directly.

The input layers were used to create a set of rules to enable the simulated guillemots to choose the best location to forage. The most suitable location was defined as being less than 50km and greater than 0km from the Isle of May based on empirically determined distributions of chick-rearing adults from animal-borne instrumentation spanning several years (Wanless *et al.* 1990; 2000; 2005a; Thaxter *et al.* 2009; 2010; Daunt *et al.* 2011a; b), the depth at the location had to be greater than 0m (guillemots are entirely marine, Cramp 1985) and there had to be one or more prey individuals at the location (for example, one or more lesser sandeels). If more than one location met these criteria then the cells were ranked so that the location that had the lowest dive depth, the smallest distance and highest prey density was the one chosen (based on optimal foraging theory that individuals would maximise gain and minimise cost, Stephens & Krebs 1986). The prey density layer was updated after each guillemot had chosen a location to account for prey being consumed and/or dispersed after feeding (Ashmole 1963; Lewis *et al.* 2001). The update was applied through the interference competition model of Hassell & Varley 1969:

$$a^i = Q * P^{-m}$$

Where a^i is the intake rate of an individual, Q is the intake rate achieved by a single forager, P is the density of individuals at the site and m is interference coefficient. The interference coefficient determined the strength of the density dependent reduction in intake rate. For example, by increasing the interference coefficient, the maximum intake rate achieved by an individual will be decreased. For the simulation, Q was set at 0.4, P was taken from the number of guillemots at a location in the simulation and m was set at 0.6. The values of Q and m were obtained from both expert opinion and other interference competition studies on birds (Ens and Goss-Custard 1984, Dolman *et al.* 1995, Goss-Custard *et al.* 1995).

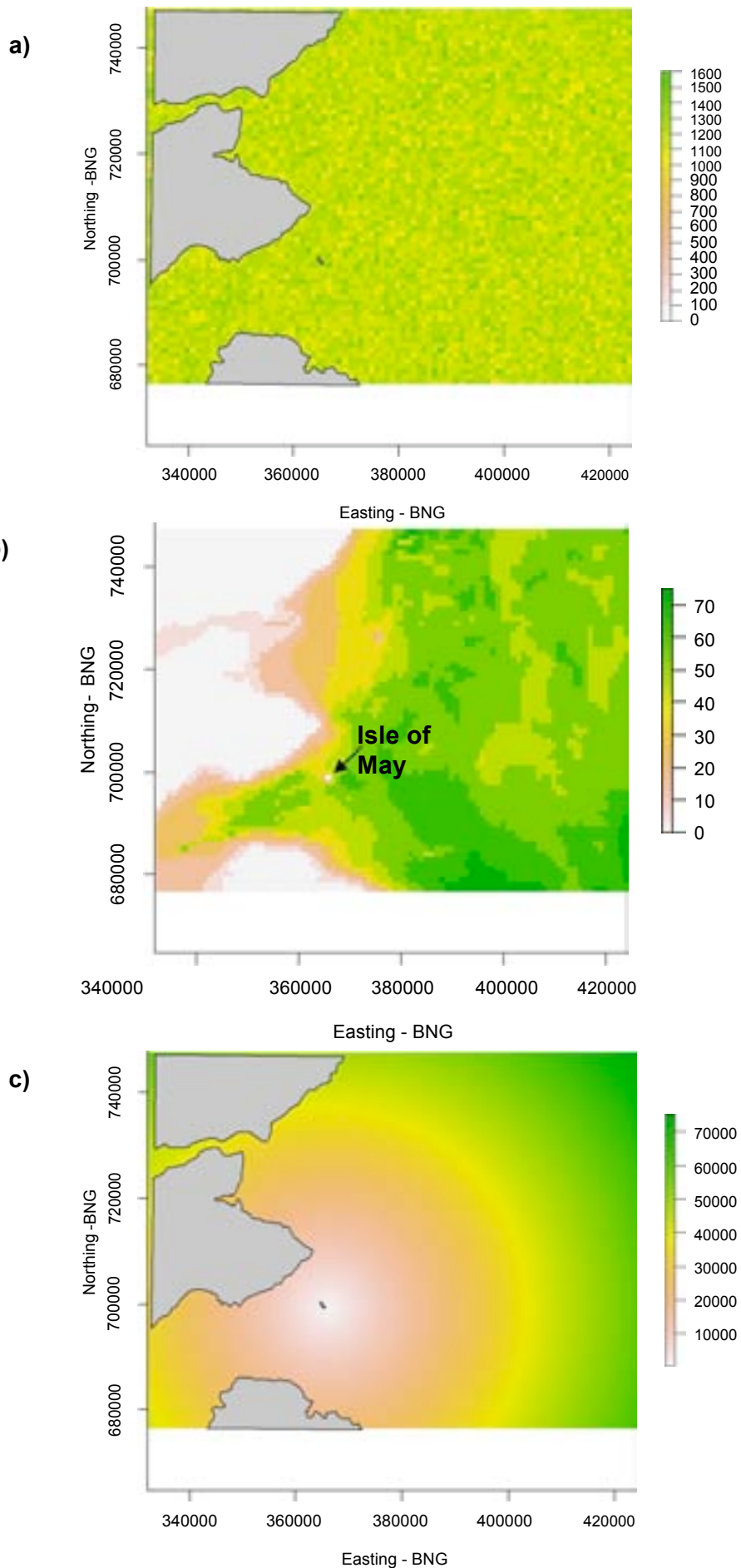


Figure 1. The three simulation model input layers required each at 1km² resolution and land is shown in grey. a) Prey density distribution – scale bar is number of prey individuals. b) Bathymetry data – scale bar is in depth (m), c) distance map layer – scale bar is the distance (m). Northings and Eastings are in the British National Grid (BNG) reference system.

2.2.2. Guillemot behaviour

When guillemots fly away from the colony they typically do so on a bearing which they continue to fly on until they reach their first foraging destination (Daunt *et al.* 2011a,b). This behaviour was incorporated into the model using the distribution of empirical data on directions of guillemot flight for 159 trips from 54 individuals recorded in 1999, 2002, 2003, 2005 and 2010 (Thaxter *et al.* 2009; 2010; Daunt *et al.* 2011a; b). We considered it preferable to use empirical data on flight directions than assume that flight direction was random. For each guillemot in the simulation, a direction was sampled with replacement from the data. The summary statistics of the flight direction distribution were then used to estimate a number of sectors to restrict the flight path of guillemots in the simulation and, therefore, the feeding locations potentially available to them on that foraging trip. A total of 11 sectors were created in ArcMap v10 using the Sectors Tool (downloaded from the ESRI Mapping Centre). This required the bearing, sector angle, radius and centre coordinates in latitude and longitude for each sector. The sectors were different sizes to distribute the number of different bearings evenly (Figure 2).

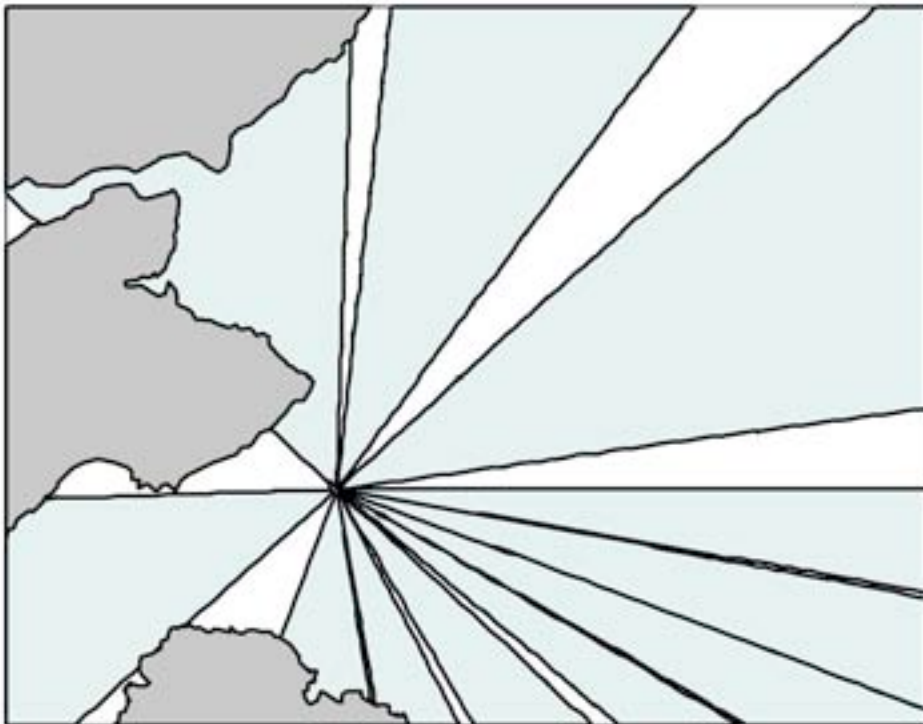


Figure 2. The 11 sectors (blue polygons) used in the simulation model to represent the distribution of guillemot flight directions from the Isle of May. The grey polygons represent the land.

Guillemots depart the colony either singly or in flocks. Therefore, the simulation code was adjusted to account for variation in the number of birds departing the colony simultaneously. The estimates of flock size were based on data from 535 birds from colonies at Fowlsheugh and St. Abbs (Daunt *et al.* 2011c). The flock size ranged from 1 to 50 birds and a negative binomial distribution was fitted to the data. In the simulation, a flock size was sampled from this distribution and coupled to the direction of flight. For example, if a guillemot left the colony on a bearing of 45° with a flock size of 5, then the next 4 guillemots in the simulation would also need to find a suitable location within the sector that incorporates 45° . After the five simulated guillemots had chosen a location, the 6th bird would fly in a different direction.

It was assumed that when shoals were disturbed by the foraging activity of guillemots, prey availability will be adversely affected, for example because shoal size is reduced and/or the shoaling behaviour of the fish breaks down (Lewis *et al.* 2001). To incorporate this in the simulation model, an exponential decay function on the effect of prey availability was added:

$$\text{prey} = \exp(-\lambda d_{ij})$$

Where λ controls the level of the decay (decay constant) and d_{ij} is the distance between points i and j . After exploring a range of decay rates using simulated data to find the most appropriate effect distance (expert opinion), a decay rate of 0.001 was used with the distance layer calculated previously to obtain a decay rate distribution surface for the simulation. The decay rate distribution and the prey density layer are multiplied together to obtain a halo (*sensu* Lewis *et al.* 2001) of reduced prey availability around the Isle of May (Figure 3). For the set of input parameters used here the halo effect was detectable up to a maximum distance of approximately 8km from the Isle of May.

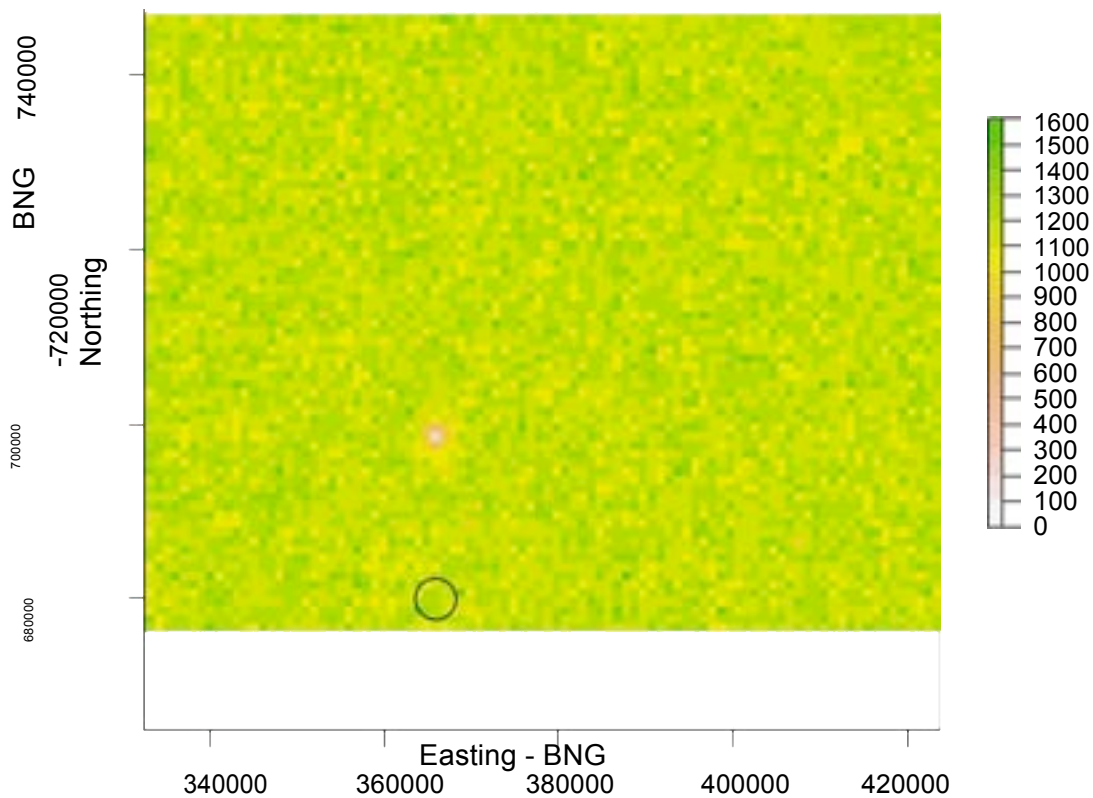


Figure 3. The prey density map used in the simulation model with a halo of reduced prey density shown in the circled area. Scale bar is the number of individual prey within a cell. Easting and Northing are in the British National Grid (BNG) reference system.

2.2.3. Wind farm presence

The simulation was modified to incorporate the presence of Neart na Gaoithe wind farm within the model area (Figure 4). When a suitable foraging location was chosen by a guillemot, then if that location was in the area of the wind farm as defined by the red polygon (Figure 4), then the bird had to move to a new suitable location within a 5km buffer zone of the wind farm (Figure 4). The assumption of the model was that guillemots had no prior knowledge of the wind farm location and therefore may fly out in the direction of the wind farm and will then need to feed in a suitable location close by.

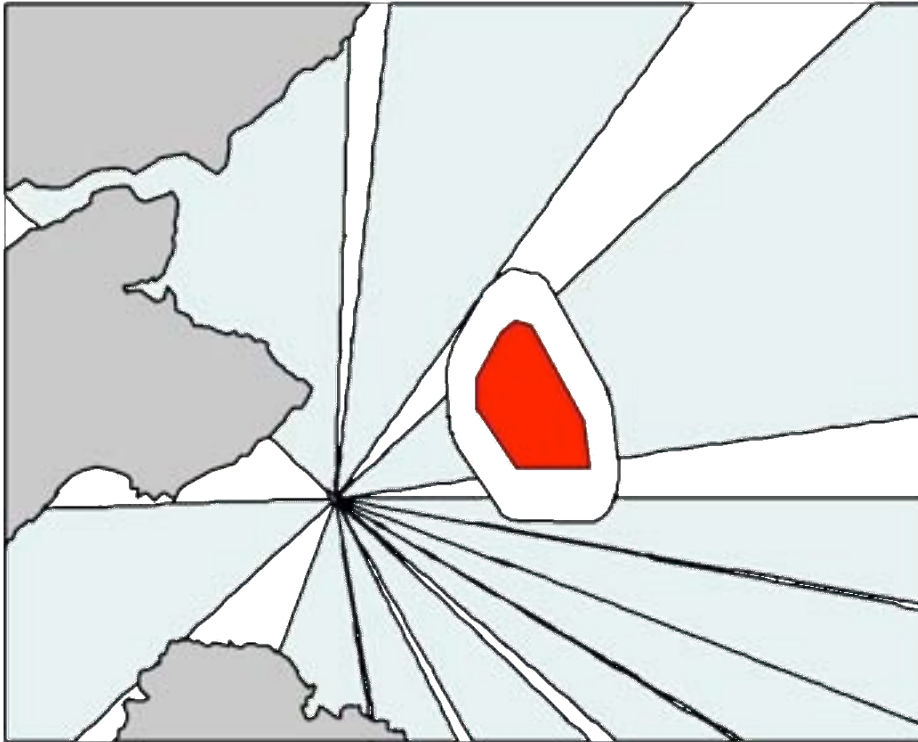


Figure 4. The location of the Neart na Gaoithe wind farm (red polygon) and the 5km buffer zone (white polygon) used in the simulation model. The grey polygons represent land and the blue polygons mark out the sectors of bird flight direction.

2.2.4. Model Output

The simulation model produced a foraging location map of 1000 birds, the depth at that location, the prey density at the location and the distance of the location from the Isle of May. This information was used to calculate the flight and foraging cost incurred by the guillemots (see Section 2.3). The simulation was repeated 50 times to obtain a mean and standard deviation of guillemot locations. When the wind farm was present within the model the number of birds that were displaced to a new location was counted. In addition, the number of birds for which the wind farm acted as a barrier to movement, either on their outward journey, return journey or both by the wind farm, were recorded. It was assumed that birds would have to fly around the wind farm, hence increasing the distance travelled and associated flight costs.

2.3. Cost Model

The output of the simulation model was used to calculate the time cost incurred by the guillemots at their chosen feeding location. The cost model was an expanded version of that used in Daunt & Wanless (2008) and Wanless *et al.* (1997). The cost was separated into flight cost and foraging cost for each guillemot. The simulation model generated information about one foraging trip per guillemot and the cost incurred on this trip was multiplied by the average number of trips a guillemot makes per day during chick-rearing (2.02 trips) to obtain a valid cost for a period of 24 hours. This estimate is based on empirical data from 2002-03 (Enstipp *et al.* 2006), supported by a very similar value recorded in 1981-84 (Harris & Wanless 1985).

2.3.1. Flight Cost

The flight cost incurred by the guillemots was the time taken to travel the distance both to and from the chosen location. This was calculated as the distance travelled multiplied by 2 (assuming the same return path from the location) and divided by the mean flight speed for a guillemot (19.1 ms^{-1} ; Pennycuick 1997).

2.3.2. Foraging Cost

The foraging cost calculated from the simulation was defined as the amount of time the guillemots spend foraging to meet both the daily energy requirements of the adult and 50% of the daily energy requirement of the offspring (assuming that two parents share the costs of provisioning equally). Daily energy expenditure is multiplied by the assimilation efficiency (0.78, Hilton *et al.* 2000b) to obtain the total daily energy requirement of the guillemot.

The adult daily energy requirement is the total energy needed by the guillemot to fly to the suitable location in the simulation plus the energy required carrying out other activities such as resting on the sea surface and the length of time spent at the colony. The time spent carrying out these activities was multiplied by activity-specific energy costs taken from the literature (Flight energy cost: $7361.72 \text{ kJ day}^{-1}$, Pennycuick 1987, 1989; resting at sea energy cost: $810.28 \text{ kJ day}^{-1}$, Croll & McLaren 1993; time at colony energy costs: $1168.91 \text{ kJ day}^{-1}$ Hilton *et al.* 2000a). The energy costs are then added to the cost of warming food (51.92 kJ , Grémillet *et al.* 2003). The mean daily energy requirement of a guillemot chick was based on provisioning rates recorded at this colony ($221.71 \text{ kJ day}^{-1}$, Harris & Wanless

1985). The daily energy requirement was converted into grams per day assuming a mean energy density of 6.1 kJg^{-1} (Harris *et al.* 2008). Only total flight time could be calculated from the output of the simulation model to estimate the daily energy requirement. Therefore, the time spent resting at sea and at the colony was estimated from the distribution of empirical data on activity budgets of 18 birds (Wanless *et al.* 2005a). There are a number of sources of potential error when calculating daily energy budgets. Activity specific costs are typically estimated in captive studies, and it is possible that wild individuals are not equivalent. Assimilation efficiency has also been estimated in captivity. The mean flight speeds used in the calculation of flight costs may not be entirely accurate, and are likely to vary among individuals dependent on environmental conditions (in particular wind speed and direction). The mean energy density of prey is also expected to vary, as demonstrated from analyses of interannual variation (Wanless *et al.* 2005b).

The amount of time guillemots spent foraging to meet their daily energy requirements was assumed to depend on the prey availability at the chosen location. This relationship was defined in the cost model by incorporating a functional response between prey intake rate and prey density (Figure 5; Enstipp *et al.* 2007). This relationship assumed a maximum prey intake rate of 5 g min^{-1} and that the intake rate does not start to increase significantly until there is a prey density of 200 individuals per km^2 . A prey capture rate is obtained by multiplying the prey intake rate by the diving efficiency. The diving efficiency was included to account for the extra cost incurred with increased dive depth and it is obtained using the following equation: (Daunt & Wanless 2008):

$$\text{Dive efficiency} = 0.36 - (0.0021 * \text{dive depth (m)})$$

The depth at the feeding location was obtained from the simulation and used in the equation to calculate the diving efficiency. Using water depth at the location would assume all dives were benthic. However, guillemots are known to forage throughout the water column with a bimodal distribution of foraging depth (Daunt *et al.* 2006). To allow for this, depth at the location for 50% of the birds was sampled from a normal distribution with a mean of 11.71 m and a standard deviation of 8.07m (the distribution was obtained using empirical data, Daunt & Wanless 2008). The prey capture rate was then used to calculate the foraging time required by the bird to meet half of the daily energy requirement (foraging for one trip). If the total foraging time was greater than 12 hours for one trip then the birds would not be able to fulfil their daily energy requirements.

2.3.3. Wind farm specific costs

The flight and foraging costs calculated for the simulation results with a wind farm were the same as above, but with additional costs due to increased distance travelled. The additional distance travelled between the first chosen suitable location and the new location the guillemot was displaced to was included, as well as the distance from the Isle of May to the first location on the outward journey and the distance from the final location back to the Isle of May on the return journey. The presence of the wind farm may not only displace birds to a new location, but may also be a barrier to movement such that birds fly around it, therefore incurring increased flight time. Guillemots with a final location beyond the wind farm, but which were not displaced directly by the wind farm, had an additional outward distance to travel. The additional outward cost was sampled from a normal distribution with a mean of 20km and standard deviation of 5km due to the size of the wind farm (birds would need to fly around the wind farm which would be approximately half of the 40km perimeter). Guillemots with a final location also beyond the wind farm, whether they were displaced or not by the wind farm, would also incur an additional return cost to fly around the wind farm. The return cost was also sampled from the same distribution as the outward cost.

2.4. Scenarios

The simulation and cost models were run both with and without the presence of the wind farm using the following scenarios:

1. The prey density layer was assumed to have a random distribution across the model area (Figure 1a).
2. The prey density layer was changed to give a more clustered distribution across the model area (Figure 5). The number of prey individuals across the surface was the same as the random distribution, but the degree of clustering was increased to give a more realistic representation of fish shoals within the individual locations.
3. The interference coefficient in the simulation model was increased to 0.9 to simulate more intense interference competition between foraging guillemots that might occur if prey availability decreased.

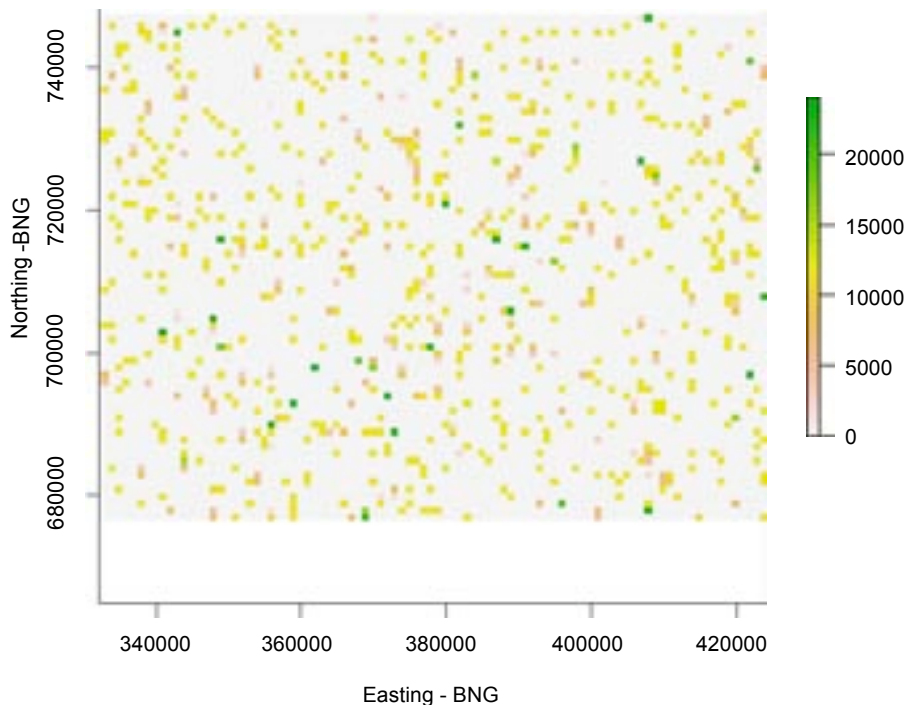


Figure 5. The clustered prey distribution used in Scenario 2 to represent prey items as a shoal. Scale bar is the number of individuals in each cell. Northings and Eastings are in the British National Grid (BNG) reference system.

3. Results

3.1. Random prey density

Using a random prey density distribution as an input layer in the simulation model produced a mean distribution of birds per cell across the model space as shown in Figures 6 and 7. In all results, the mean number given is from 50 simulations of 1000 birds in each run. The presence of the wind farm results in a higher density of birds per cell with a particular increase in density of birds on the colony side of the wind farm due to the birds being displaced. The flight and foraging costs increase with increasing distance away from the Isle of May in simulation models both with and without the wind farm (Figures 8 and 9 respectively). The guillemots incur increased average flight costs (Figure 8) and foraging costs (Figure 9) when the wind farm is present. The foraging costs for birds are higher on the colony side of the wind farm, while the flight and foraging costs are higher on the far side. The higher flight costs in Figure 8 are due to birds having to travel a longer distance. The higher foraging costs in Figure 9 are due to an increase in the number of birds in one location which leads to increased disturbance of prey, increased competition and hence, an increase in foraging time to meet energy requirements. Mean flight and foraging costs with and without the wind farm are presented in Table 1 and Figures 10 and 11 respectively.

Table 1. The mean flight and foraging costs for guillemots from the simulations under the three scenarios tested. The summary results are from 50 simulations of 1000 birds.

		Wind farm absent	Wind farm present
Type of Cost	Scenario	Mean cost /hours (\pm S.D.)	Mean cost /hours (\pm S.D.)
Flight	Random prey	1.18 (\pm 0.60)	1.60 (\pm 0.67)
	Clustered prey	1.15 (\pm 0.67)	1.54 (\pm 0.66)
	Increased interference coefficient	1.18 (\pm 0.61)	1.57 (\pm 0.66)
Foraging	Random prey	2.19 (\pm 0.96)	2.58 (\pm 1.57)
	Clustered prey	2.05 (\pm 0.85)	2.37 (\pm 1.16)
	Increased interference coefficient	2.21 (\pm 1.15)	2.55 (\pm 1.81)

When the wind farm was not present, the number of birds which do not meet their energy requirements was 1.82 (± 3.86) individuals (0.18%). When the wind farm was present, 4.46 (± 7.19) guillemots could not meet their energy requirements (0.46%). The mean number of birds that were displaced by the wind farm was 100.66 (± 28.00) individuals (10.07%). The mean number of birds which incurred additional costs on their outward journey was 43.22 (± 10.68) individuals and 45.18 (± 11.18) individuals incurred additional costs on their return journey (4.32% and 4.52% respectively).

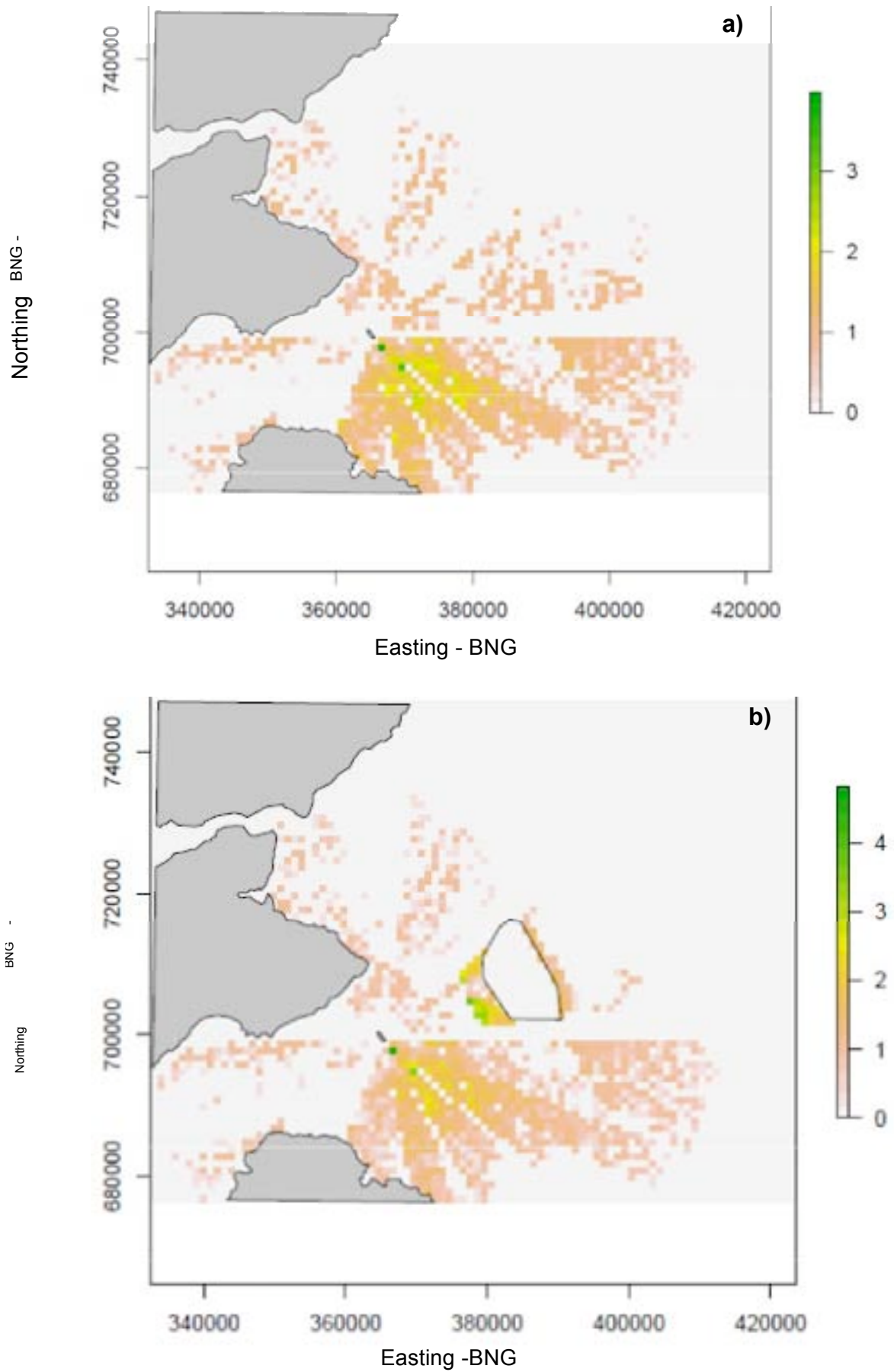


Figure 6. The mean number of guillemots within each cell of the simulation model using a random prey density distribution from 50 simulations with a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in British National Grid reference system.

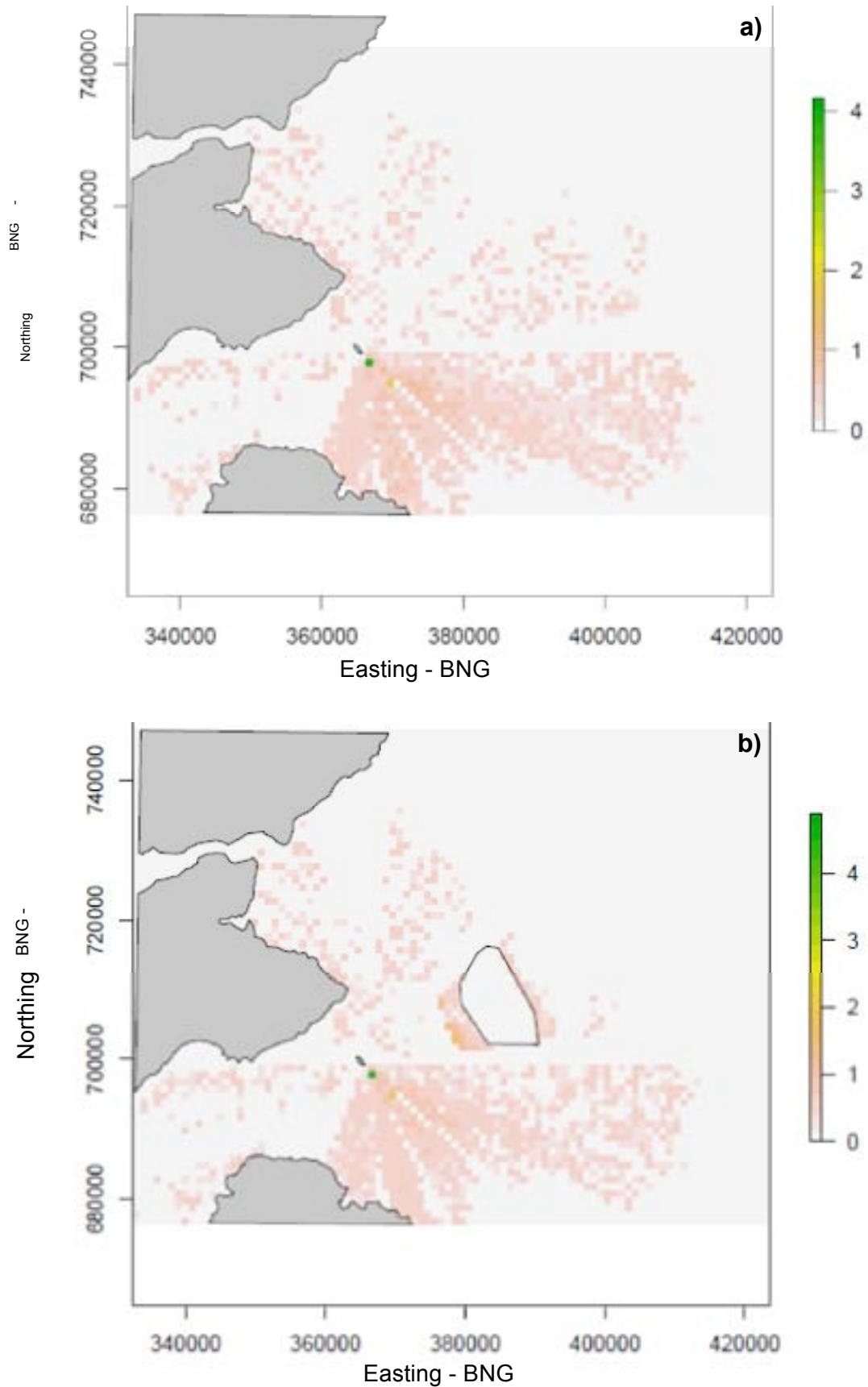


Figure 7. The standard deviation of the mean number of guillemots within each cell from 50 simulations with a random prey density distribution: a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The white polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

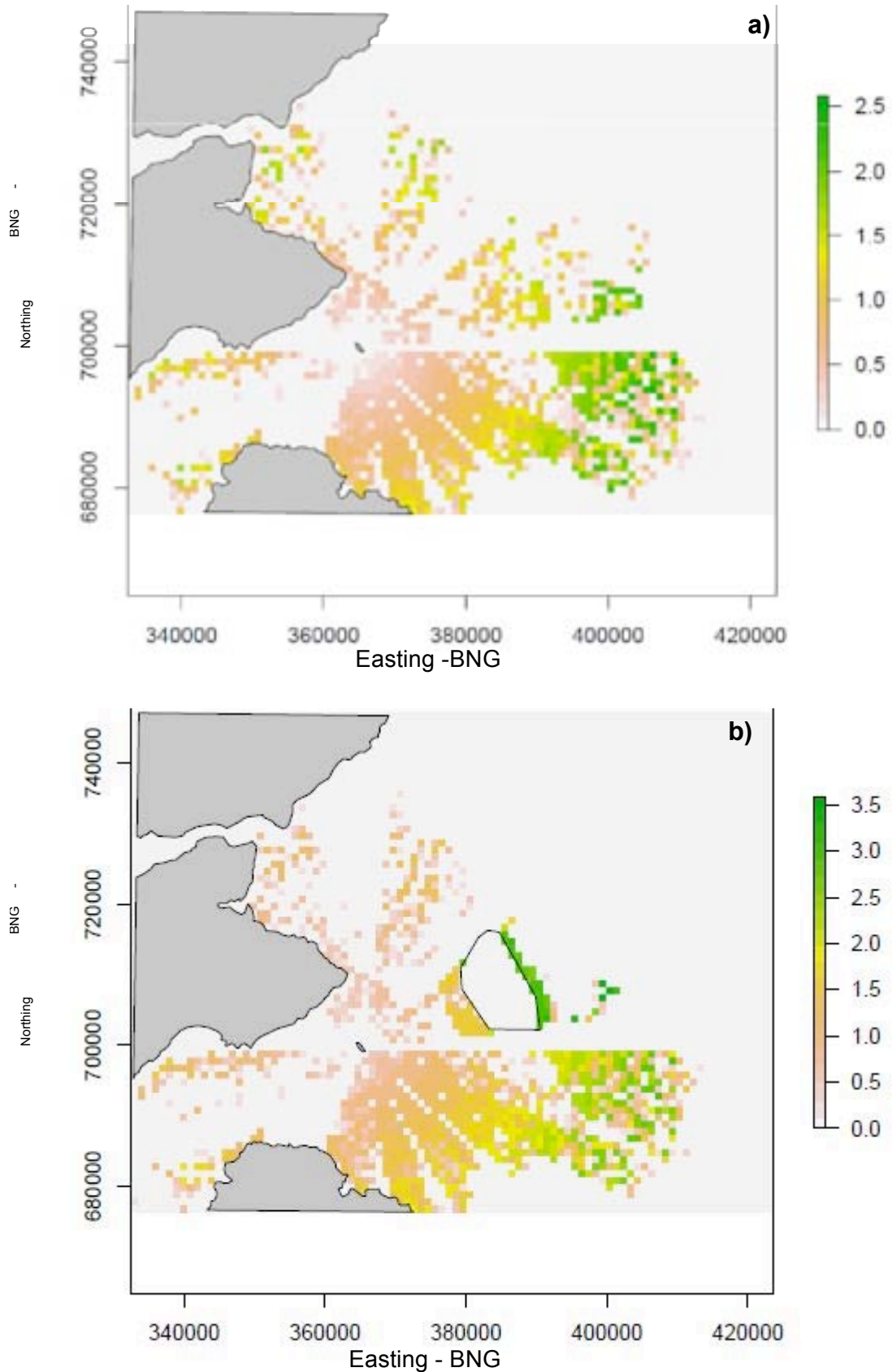


Figure 8. The mean flight cost incurred at each cell after 50 simulations of the model with a random prey density distribution layer and with a) no wind farm and b) with a wind farm present. The scale bars are the number of hours spent in flight and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

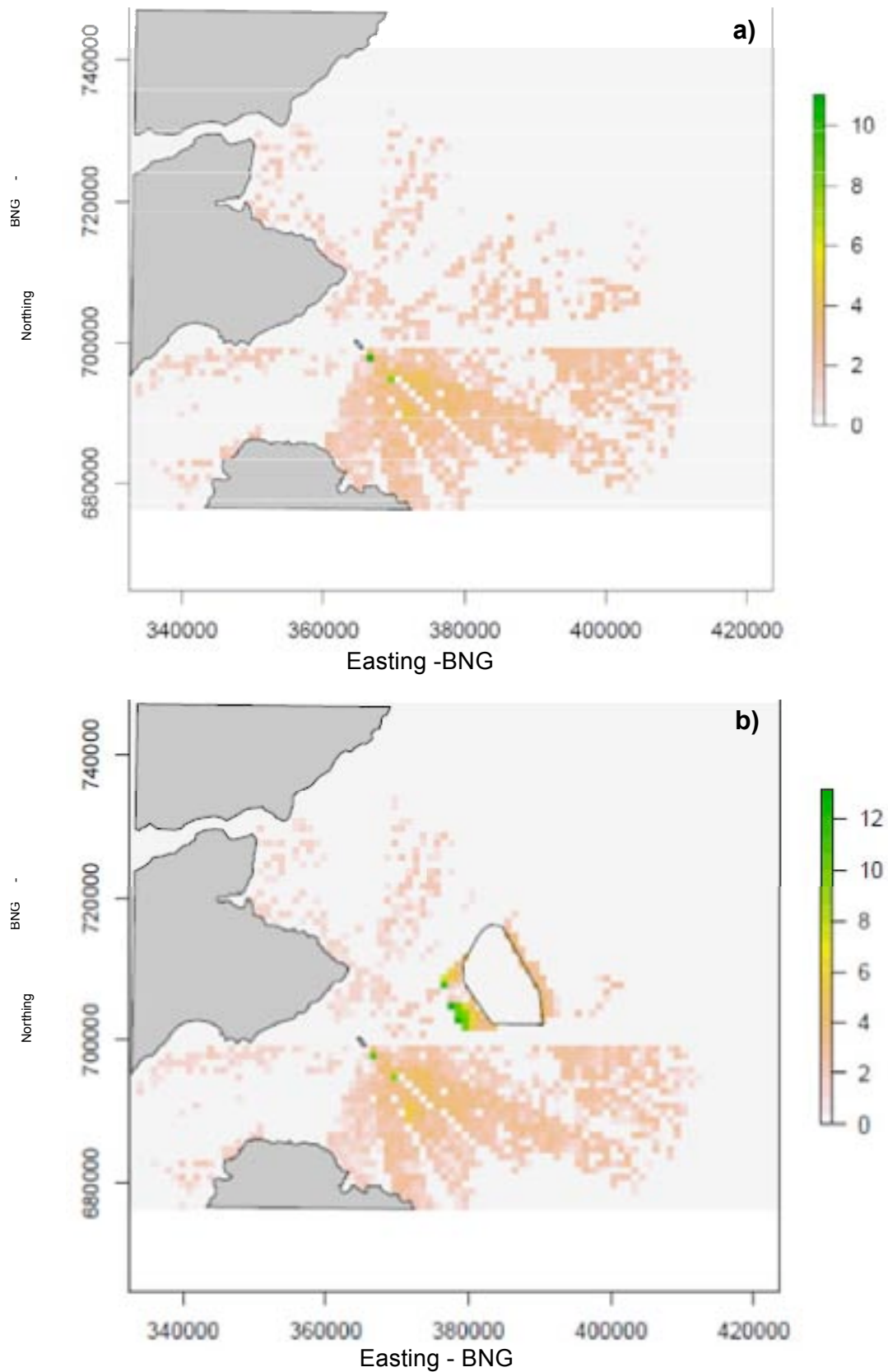
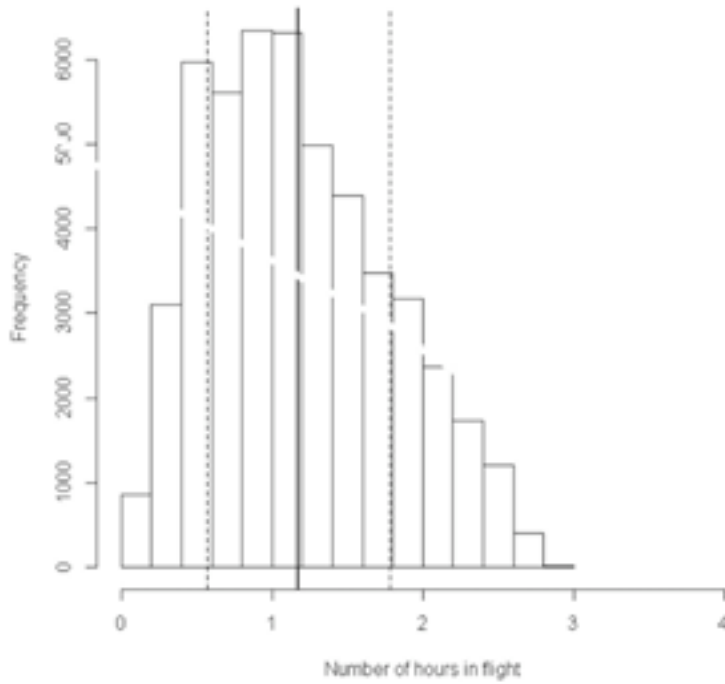


Figure 9. The mean foraging cost incurred at each cell after 50 simulations of the model with a random prey distribution layer and with a) no wind farm and b) with a wind farm present. The scale bars are the number of hours spent foraging and the grey areas indicate land. The white polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

a) Without a wind farm



b) With a wind farm

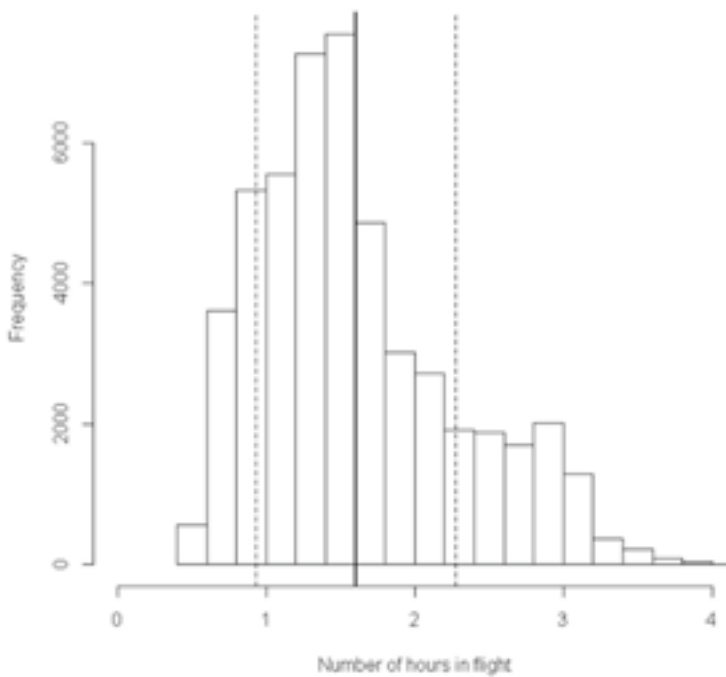
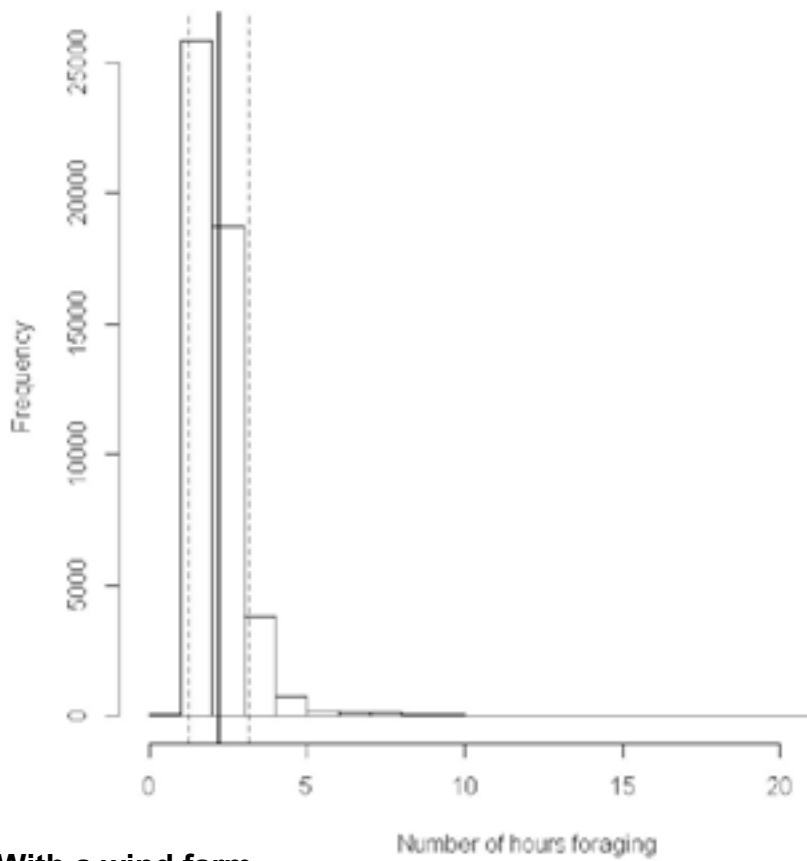


Figure 10. The distribution of flight costs incurred for 50 simulations of 1000 birds with a random prey density layer: a) without a wind farm present and b) with a wind farm present. The bold line indicates the mean flight cost in hours and the dashed lines are the \pm standard deviations.

a) Without a wind farm



b) With a wind farm

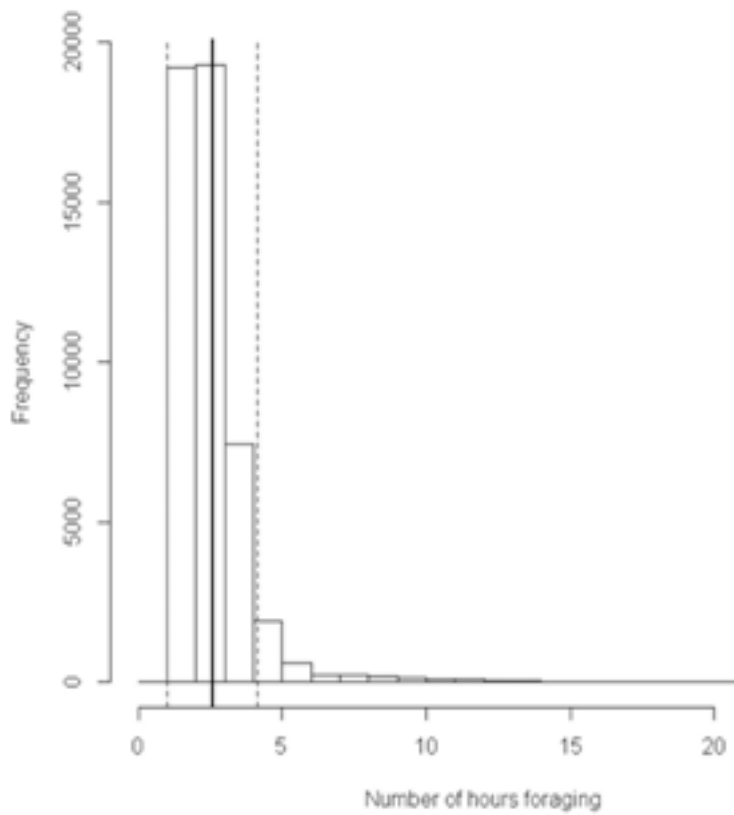


Figure 11. The distribution of foraging costs incurred for 50 simulations of 1000 guillemots with a random prey density layer: a) without a wind farm present and b) with a wind farm present.

3.2. Clustered prey

Using a more clustered prey density distribution that mimics the shoaling behaviour of forage fish targeted by guillemots as an input layer in the simulation model, produced a mean distribution of birds across the model space as shown in Figures 12 and 13. In all results, the mean number given is from 50 simulations of 1000 birds in each run. Compared to the random prey density distribution model output, there is an increase in the number of birds sharing each location (Figures 12 and 13). The presence of the wind farm results in a higher density of birds per cell with particular increase in density on the colony side of the wind farm due to the birds being displaced. The flight and foraging costs increase with increasing distance away from the Isle of May in simulation models both with and without the wind farm (Figure 14 and Figure 15 respectively). The higher flight costs in Figure 14 are due to birds having to travel a longer distance. The higher foraging costs in Figure 15 are due to an increase in the number of birds in one location which leads to increased disturbance of prey, increased competition and hence, an increase in foraging time to meet energy requirements. The frequency distribution of flight costs and foraging costs for the guillemots are in Figures 16 and 17 and the flight and foraging costs are summarised in Table 1.

When no wind farm is present, the mean number of birds which do not meet their energy requirements was 6.76 (± 3.93) individuals (0.68%). When the wind farm was present, 7.66 (± 3.93) guillemots could not meet their energy requirements (0.77%). The mean number of birds that were displaced by the wind farm was 103.34 (± 29.65) individuals (10.33%). The mean number of birds which incurred additional costs on their outward journey and return journey were both 15.10 (± 5.72) individuals (1.51%).

Compared to the cost results for the random prey density distribution, the mean flight costs and mean foraging costs were marginally lower when a clustered prey density distribution was used. The presence of the wind farm caused an increase in the mean flight and foraging cost for the clustered prey distribution scenario.

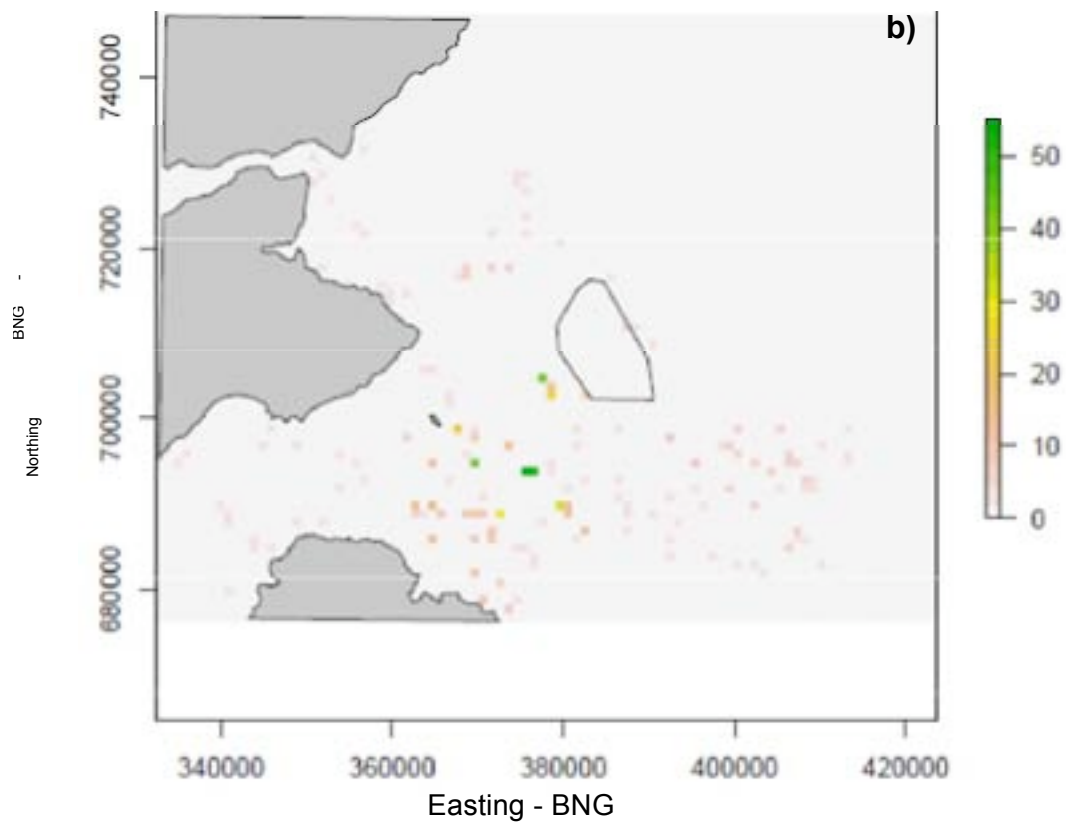
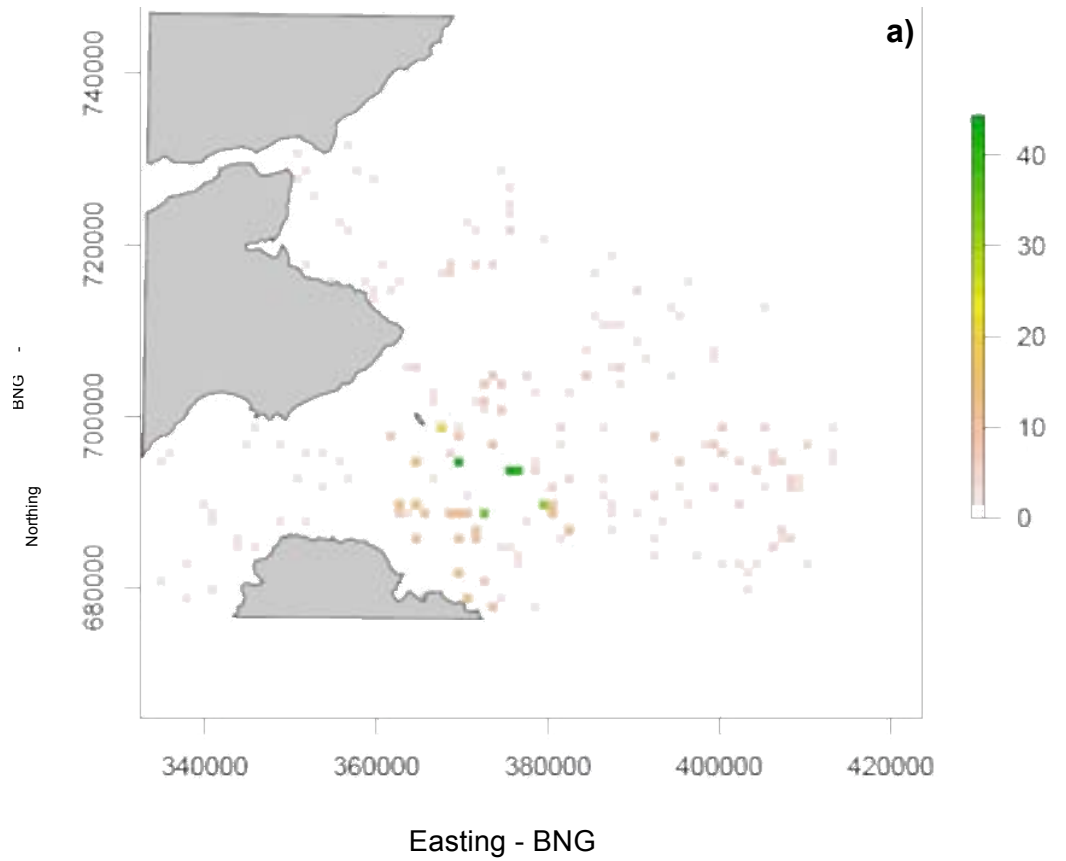


Figure 12. The mean number of guillemots within each cell of the simulation model using a clustered prey density map from 50 simulations with a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

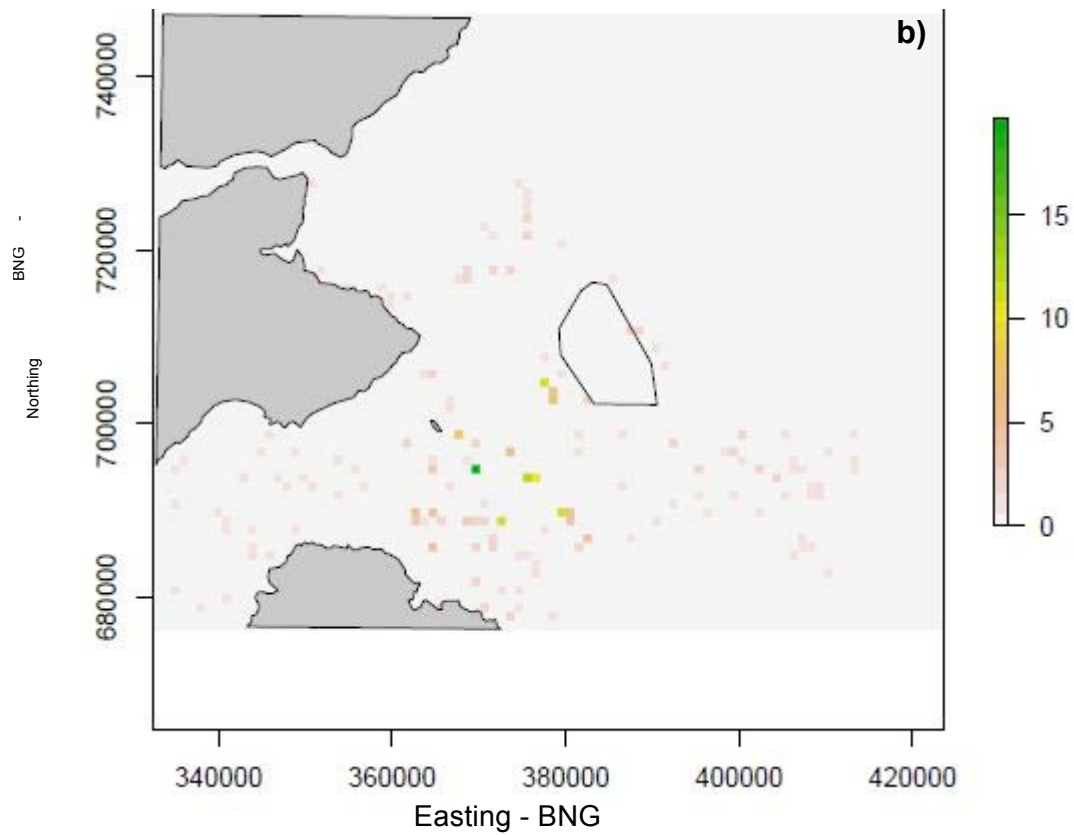
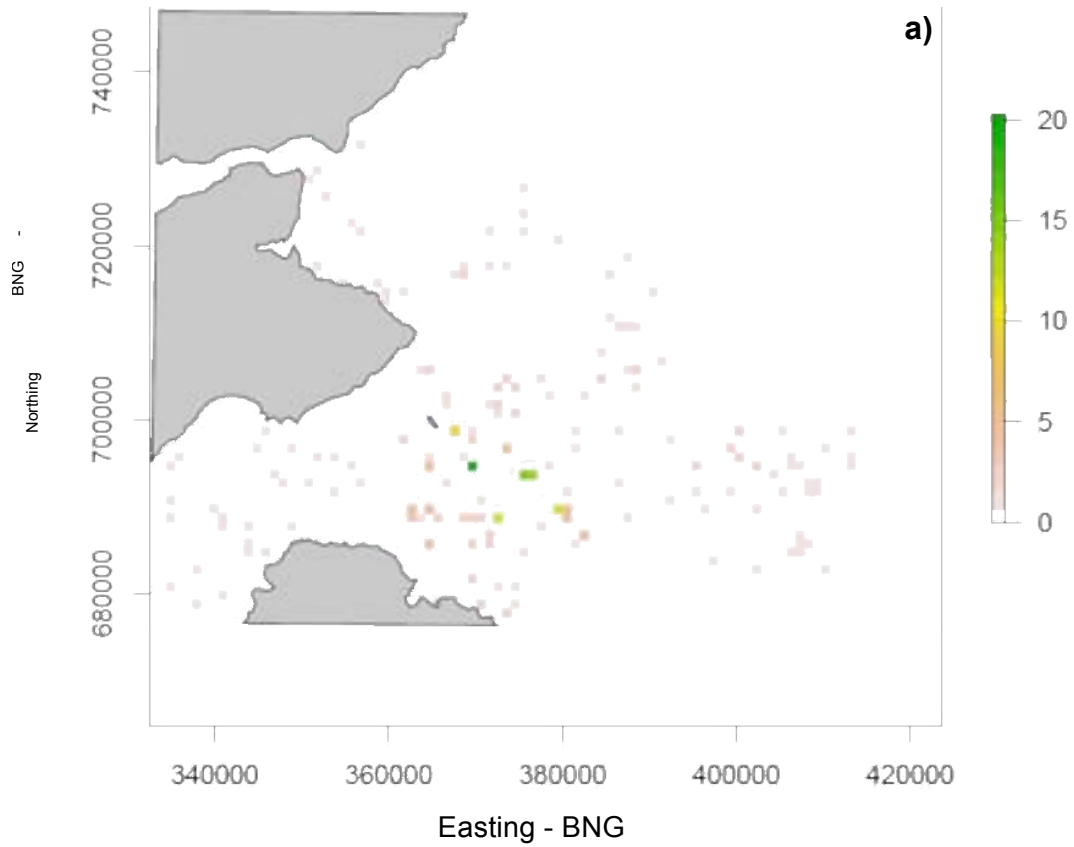


Figure 13. The standard deviation of the mean number of guillemots within each cell from 50 simulations with a clustered prey density distribution: a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) system.

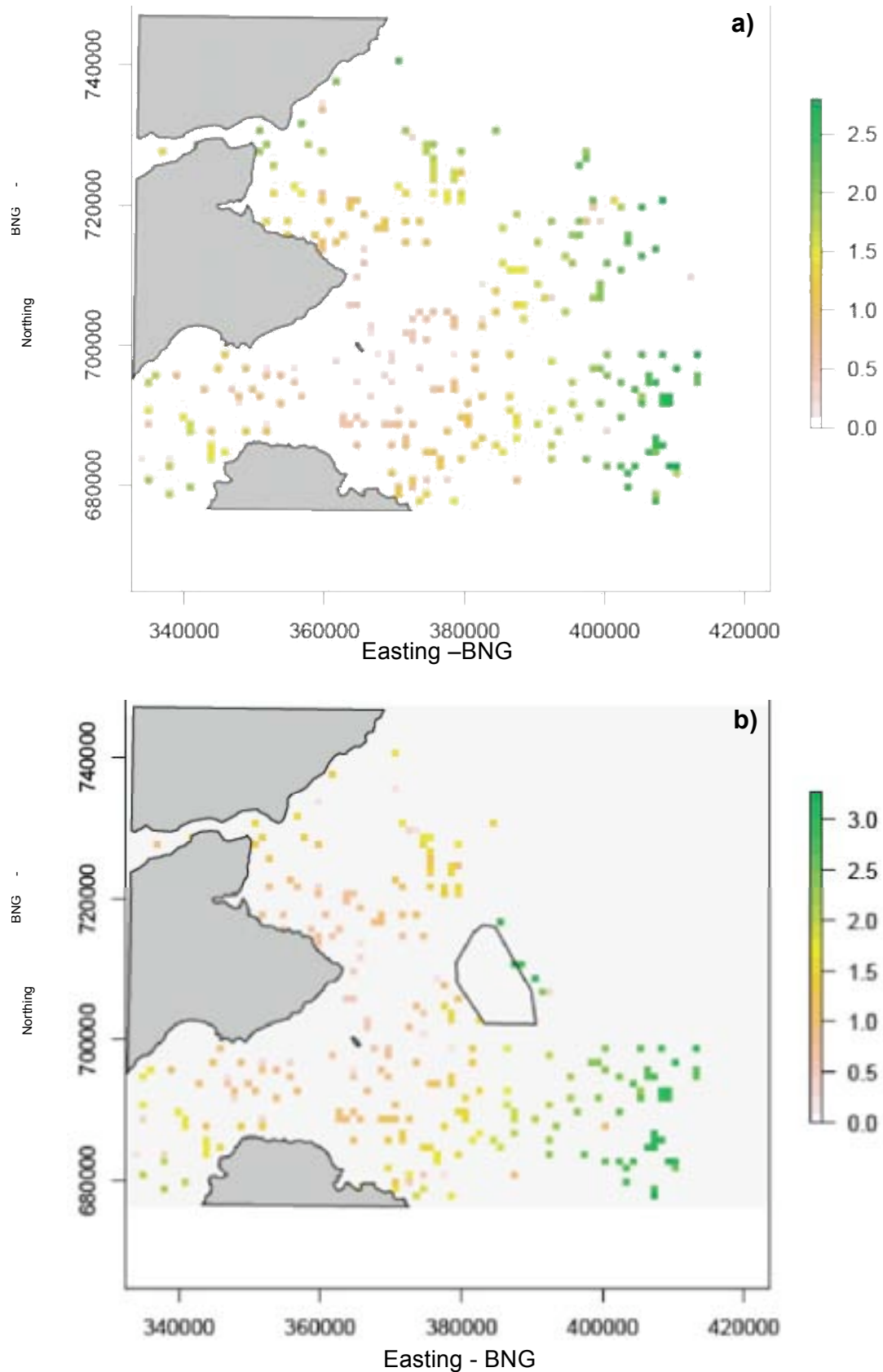


Figure 14. The mean flight cost incurred at each cell after 50 simulations of the model with a clustered prey density distribution layer and with a) no wind farm and b) with a wind farm present. The scale bars are the number of hours in flight and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

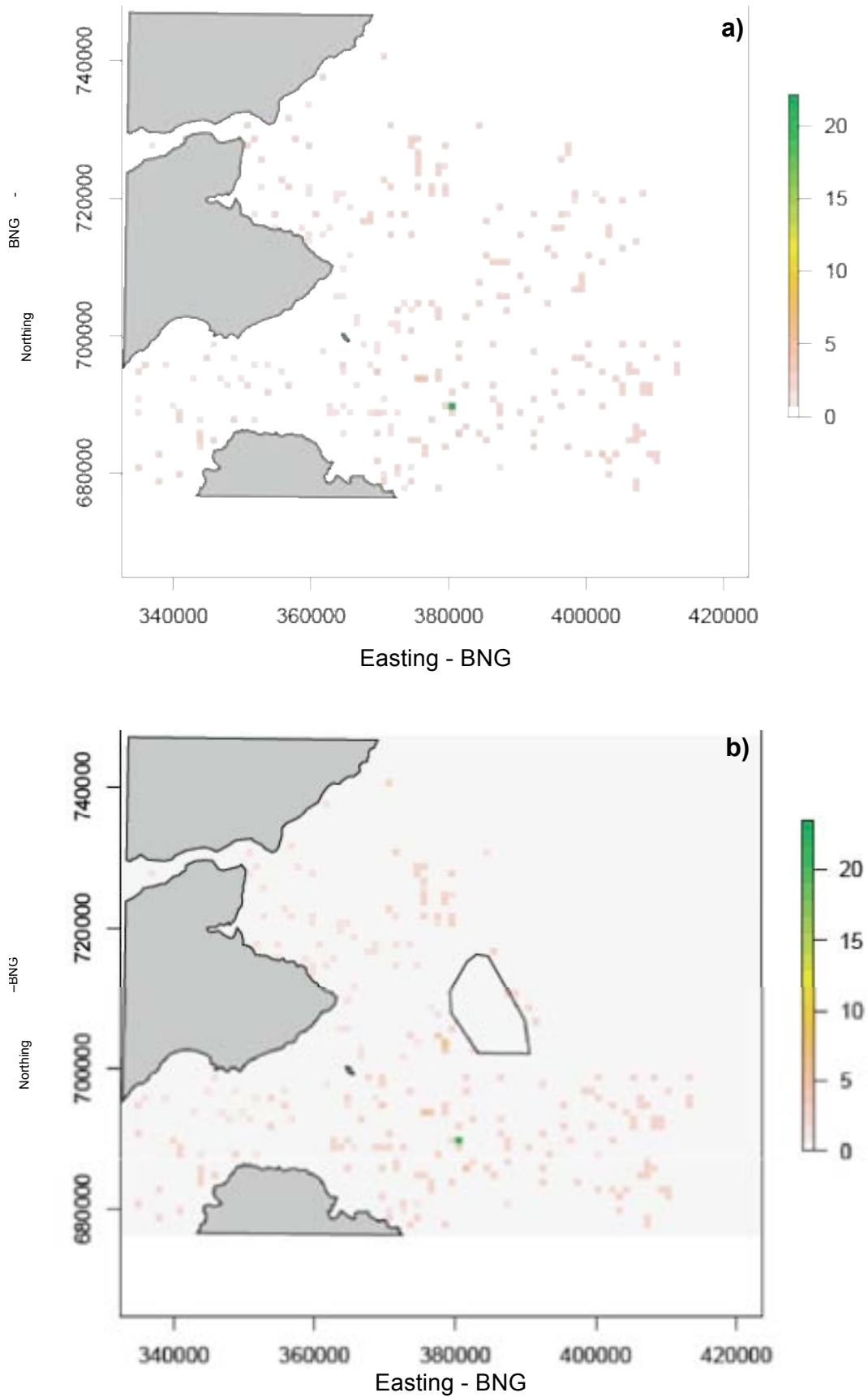
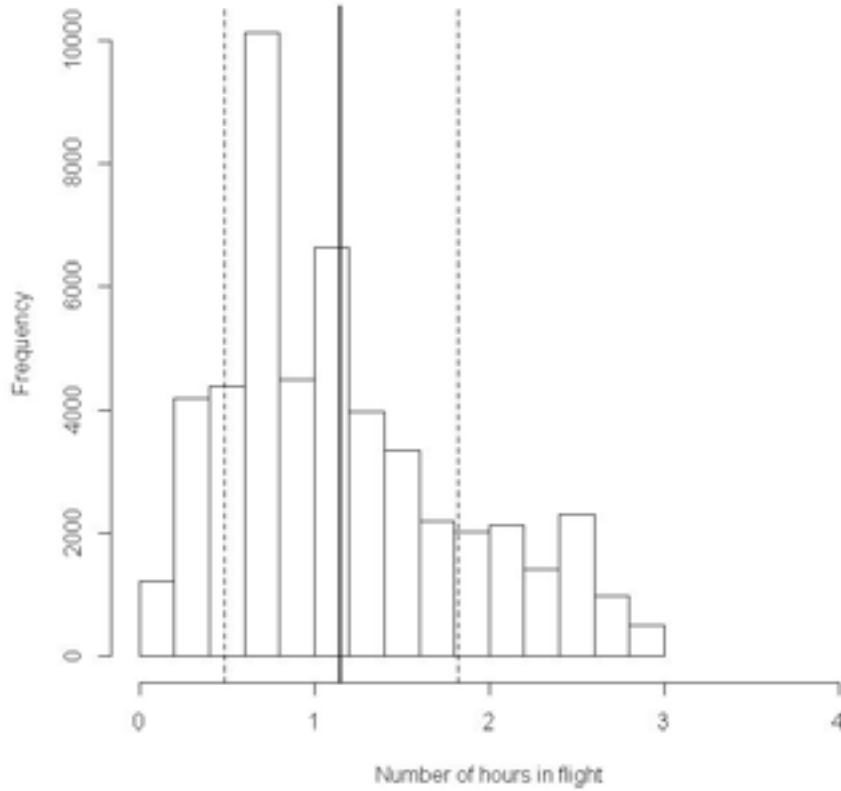


Figure 15. The mean foraging cost incurred at each cell after 50 simulations of the model with a clustered prey distribution layer and with a) no wind farm and b) with a wind farm present. The scale bars are the number of hours spent foraging and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

a) No wind farm present



b) With a wind farm present

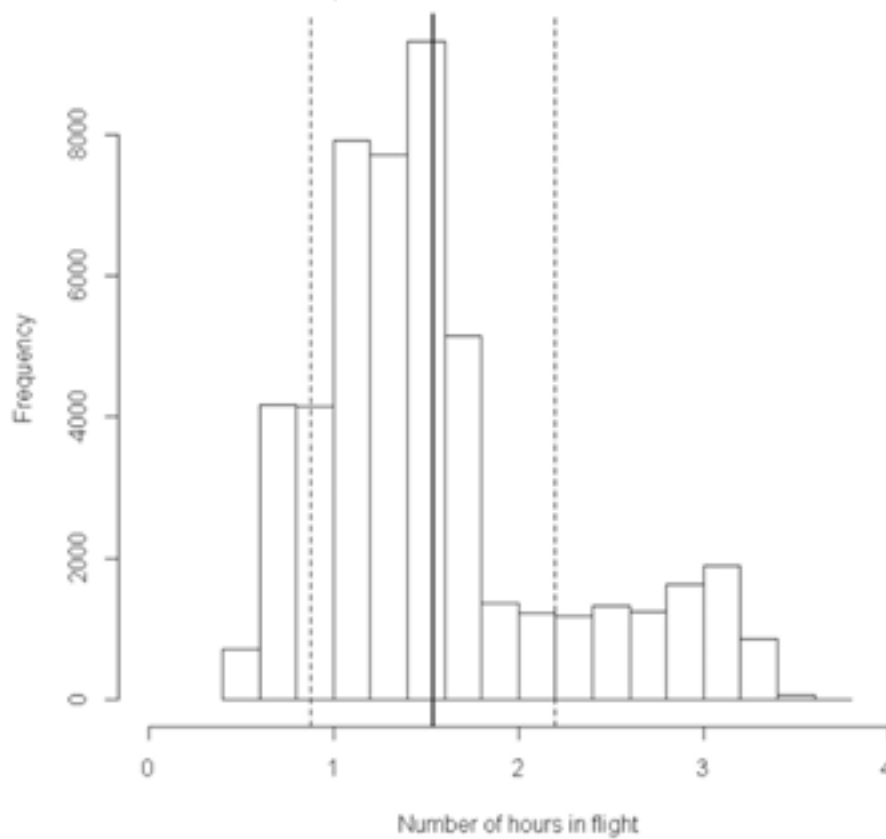
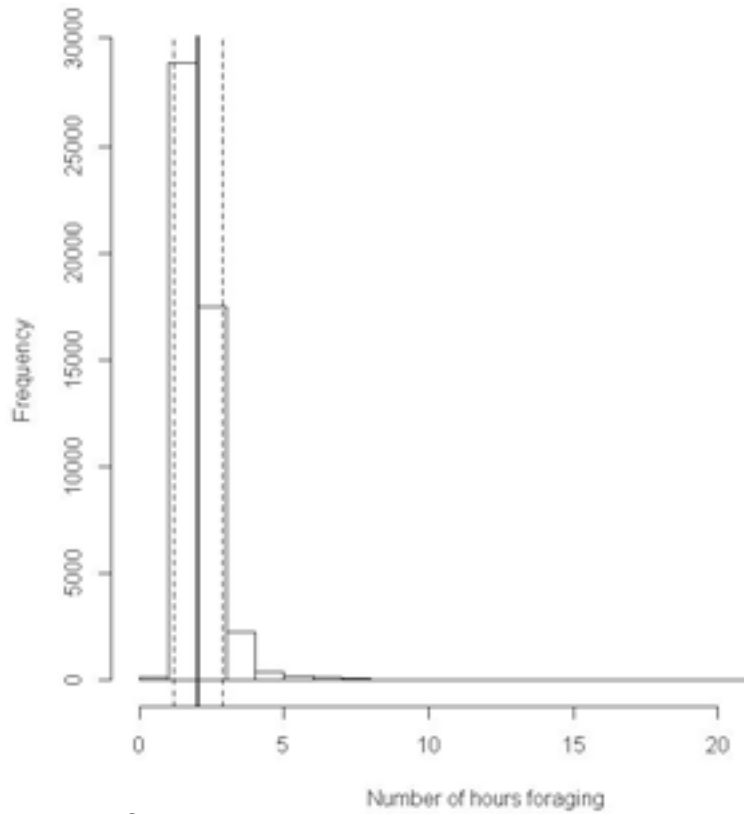


Figure 16. The distribution of flight costs incurred for 50 simulations of 1000 birds with a clustered prey density layer: a) without a wind farm present and b) with a wind farm present.

a) No wind farm present



b) With a wind farm present

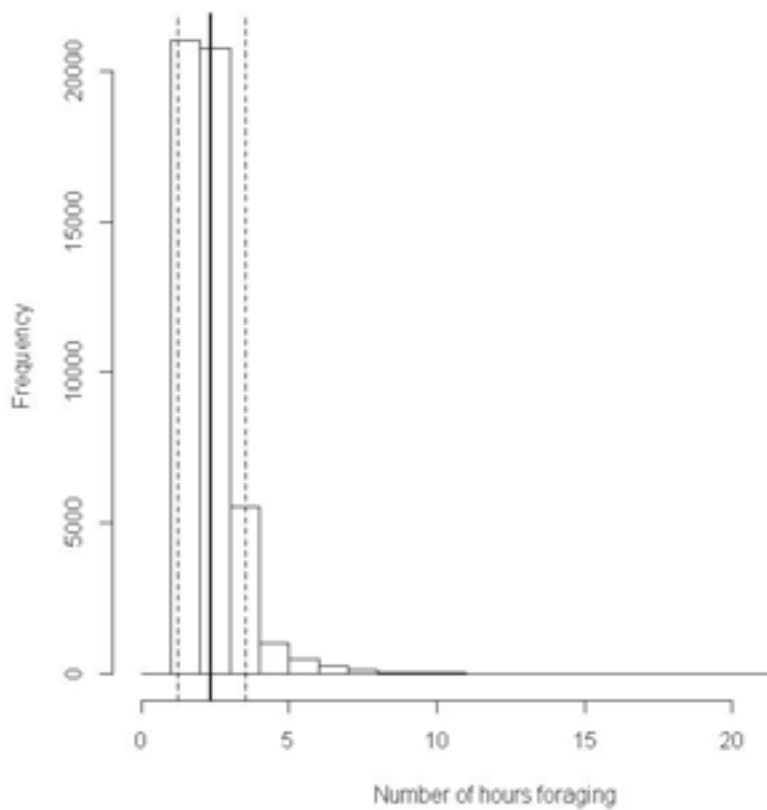


Figure 17. The distribution of foraging costs incurred for 50 simulations of 1000 guillemots with a clustered prey density layer: a) without a wind farm present and b) with a wind farm present. The bold line indicates the mean foraging cost in hours and the dashed lines are the \pm standard deviations.

3.3. Increased Interference Coefficient

The simulation using an increased interference coefficient in the simulation model produced a mean distribution of birds per cell across the model space as shown in Figures 18 and 19. In all results, the mean number given is from 50 simulations of 1000 birds in each run. Compared to the random prey density distribution model output, there is an increase in the number of birds sharing each location (Figures 18 and 19). The presence of the wind farm results in a higher density of birds per cell particularly on the colony side of the wind farm due to the birds being displaced. Flight and foraging costs increase with increasing distance away from the Isle of May in simulation models both with and without the wind farm (Figure 20 and 21 respectively). The foraging cost for guillemots are higher on the colony side of the wind farm, but the flight and foraging costs are higher on the far side of the wind farm. The higher flight costs in Figure 20 are due to birds having to travel a longer distance. The higher foraging costs in Figure 21 are due to an increase in the number of birds in one location which leads to increased disturbance of prey, increased competition and hence, an increase in foraging time to meet energy requirements. The frequency distribution of flight costs and foraging costs for the guillemots in the simulation with and without the wind farm are shown in Figures 22 and 23. The flight and foraging costs for simulations both with and without a wind farm are summarized in Table 1.

With no wind farm, the mean number of birds which do not meet their energy requirements was 2.40 (± 5.15) individuals (0.24%). When the wind farm was present, 5.86 (± 7.07) individuals could not meet their energy requirements (0.59%). The mean number of birds displaced by the wind farm was 83.84 (± 27.84) individuals (8.38%). The mean number of birds incurring additional costs was 38.02 (± 9.69) individuals on the outward journey and 39.40 (± 10.16) individuals on their return journey (3.80% and 3.94% respectively).

The increased interference coefficient scenario produced similar flight costs to the scenario with a lower interference coefficient. With no wind farm, the mean number of hours spent foraging is greater with an increased interference coefficient, but when the wind farm is present there is no difference in the mean number of hours spent foraging.

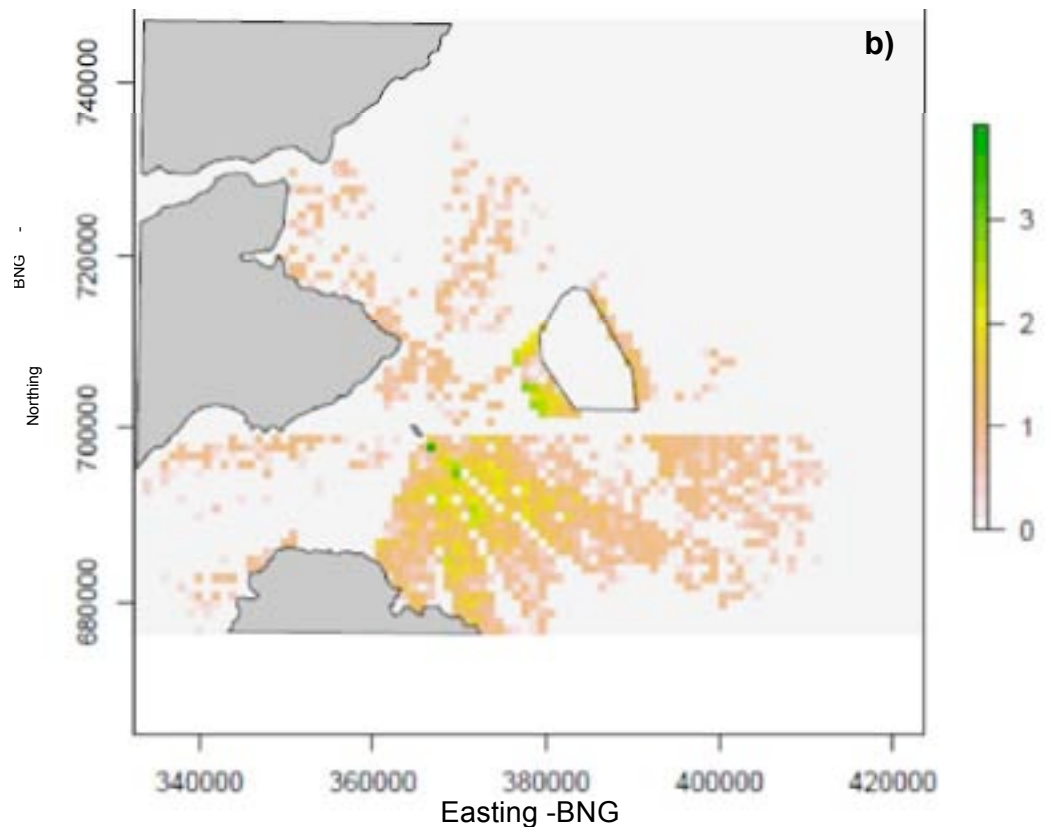
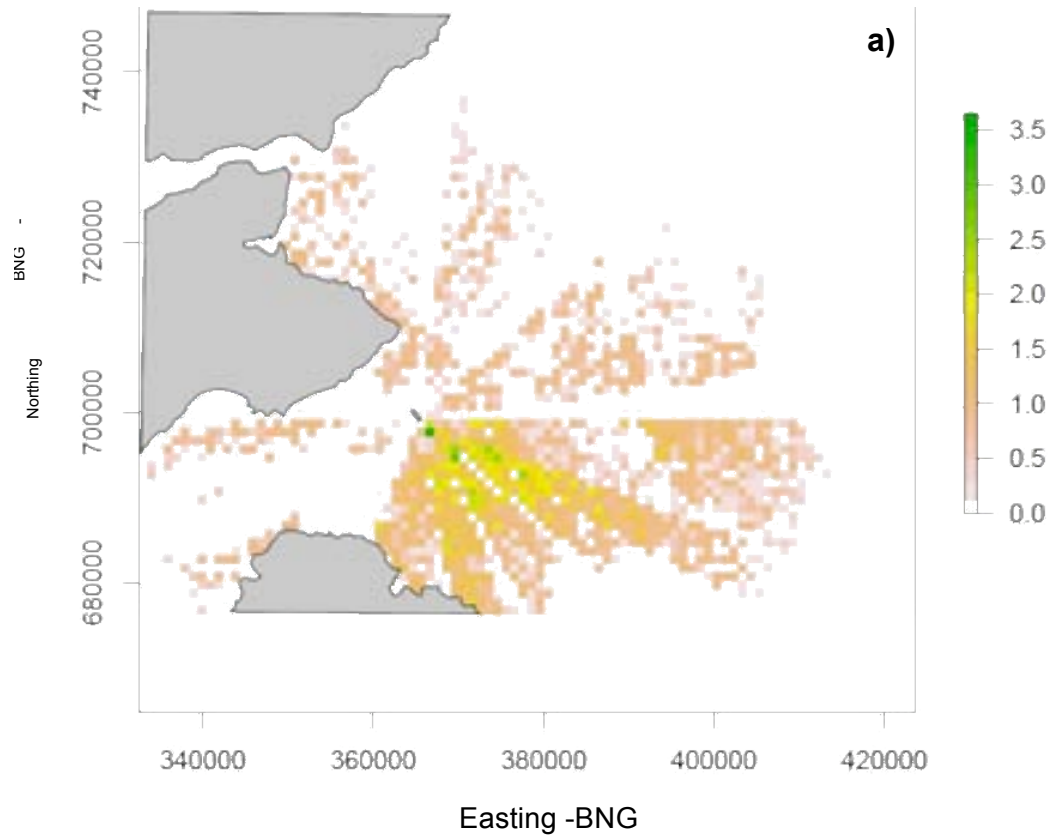


Figure 18. The mean number of guillemots within each cell of the simulation model using a random prey density map and a high interference coefficient from 50 simulations with a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

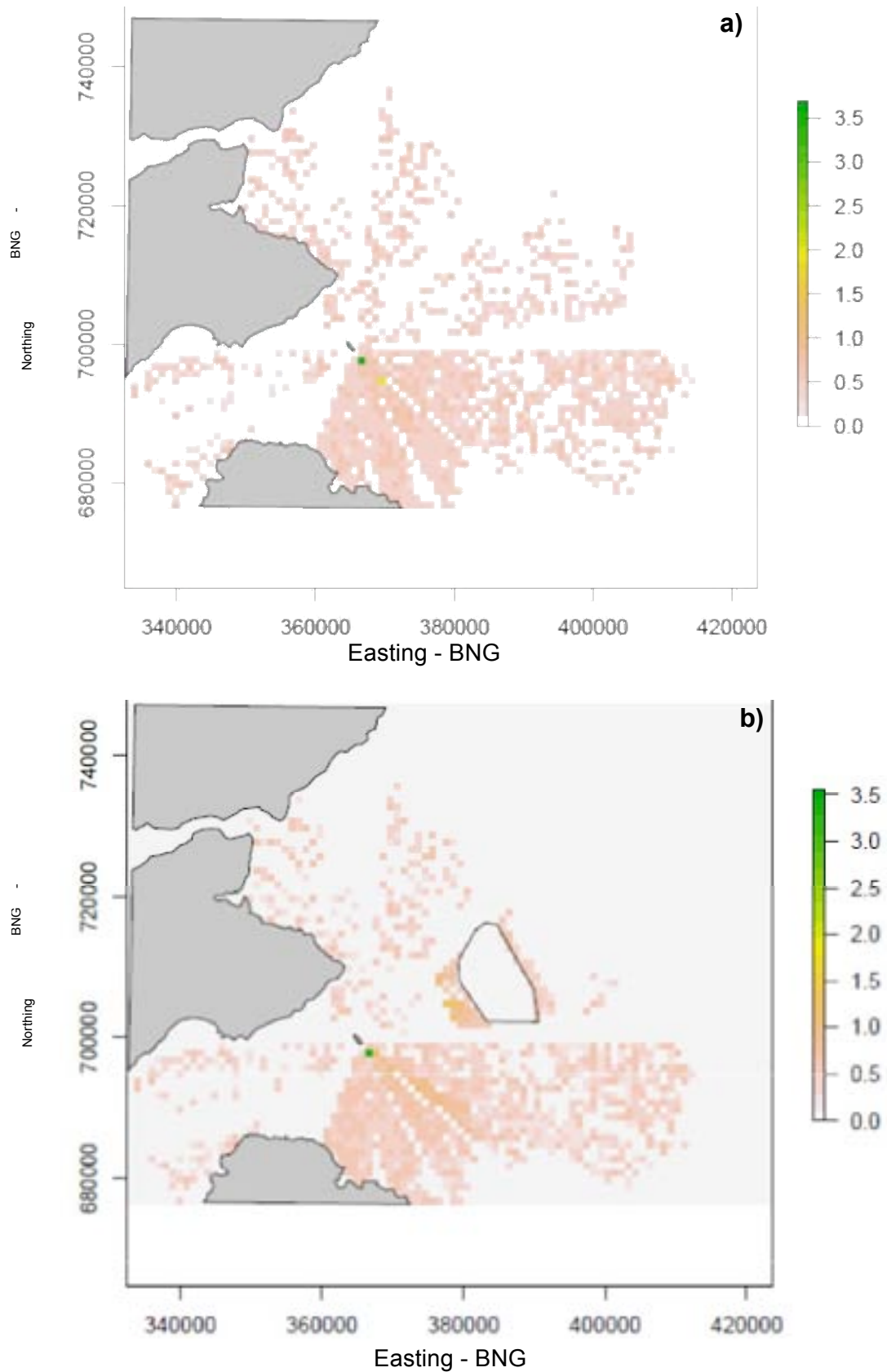


Figure 19. The standard deviation of the mean number of guillemots within each cell from 50 simulations with a random prey density distribution and an increased interference coefficient: a) no wind farm and b) with a wind farm. The scale bars are the number of guillemots per cell and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

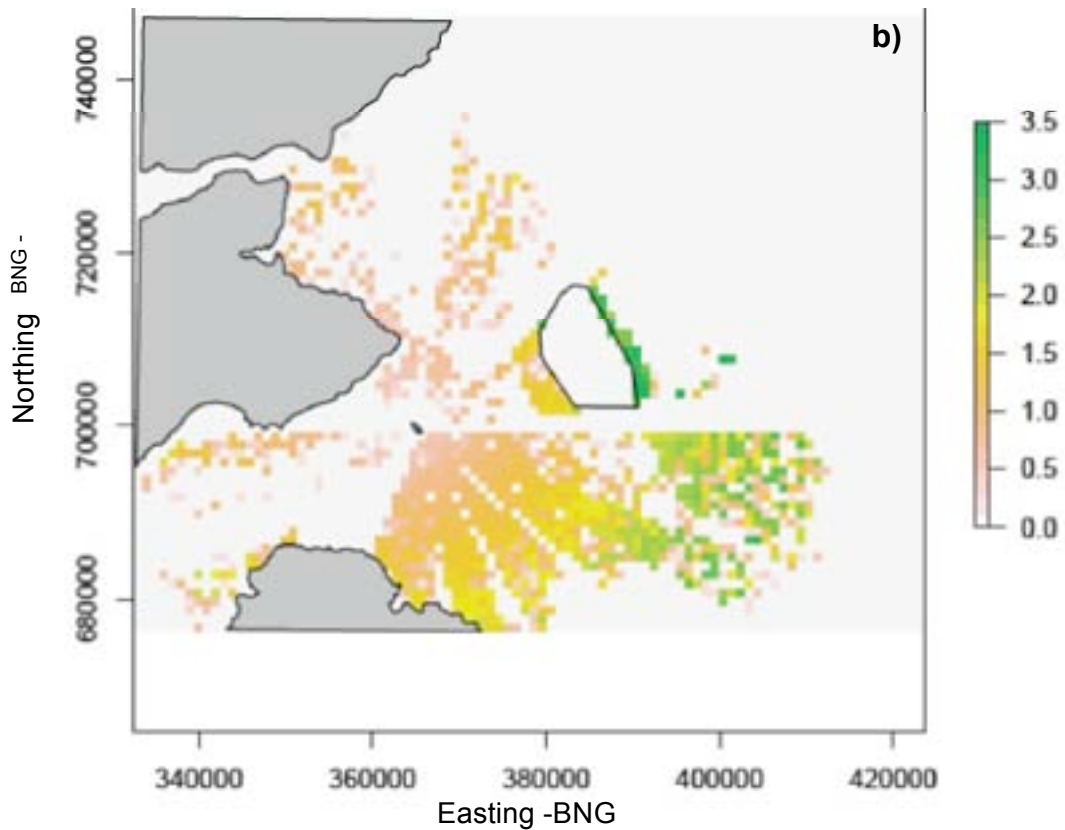
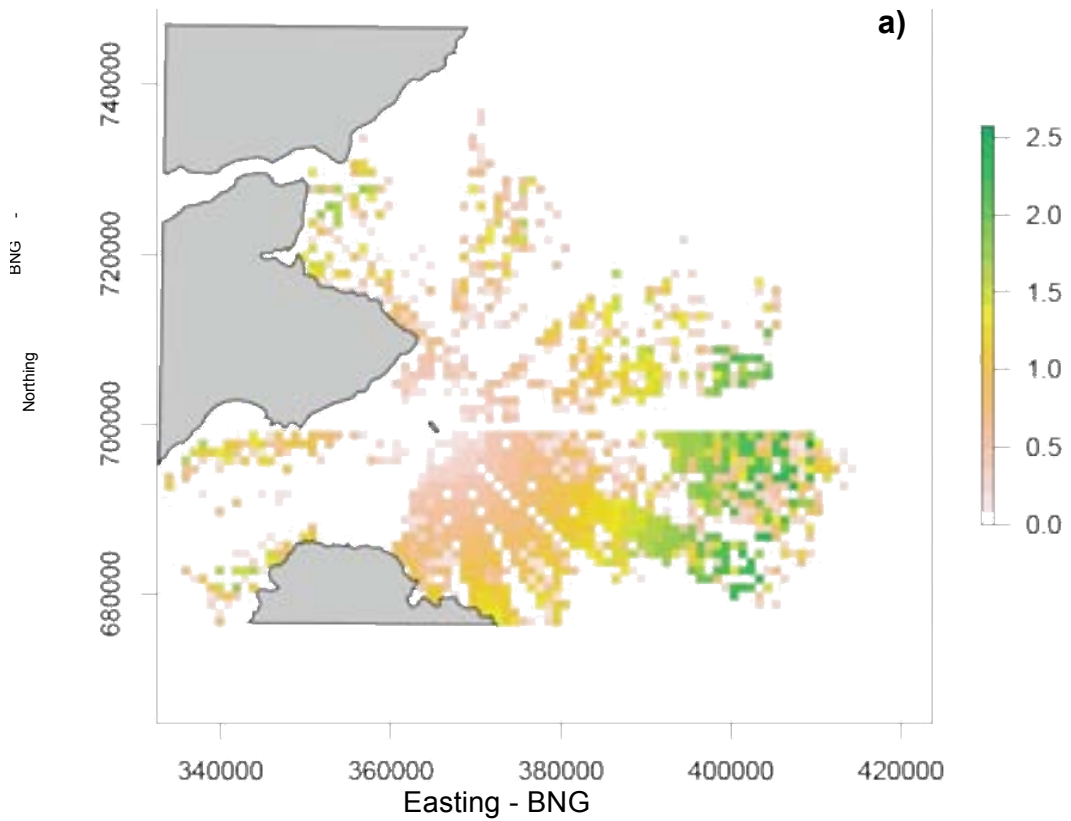


Figure 20. The mean flight cost incurred at each cell after 50 simulations of the model with a random prey density distribution layer, an increased interference coefficient and with a) no wind farm and b) with a wind farm present. The scale bars are the number of hours in flight and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

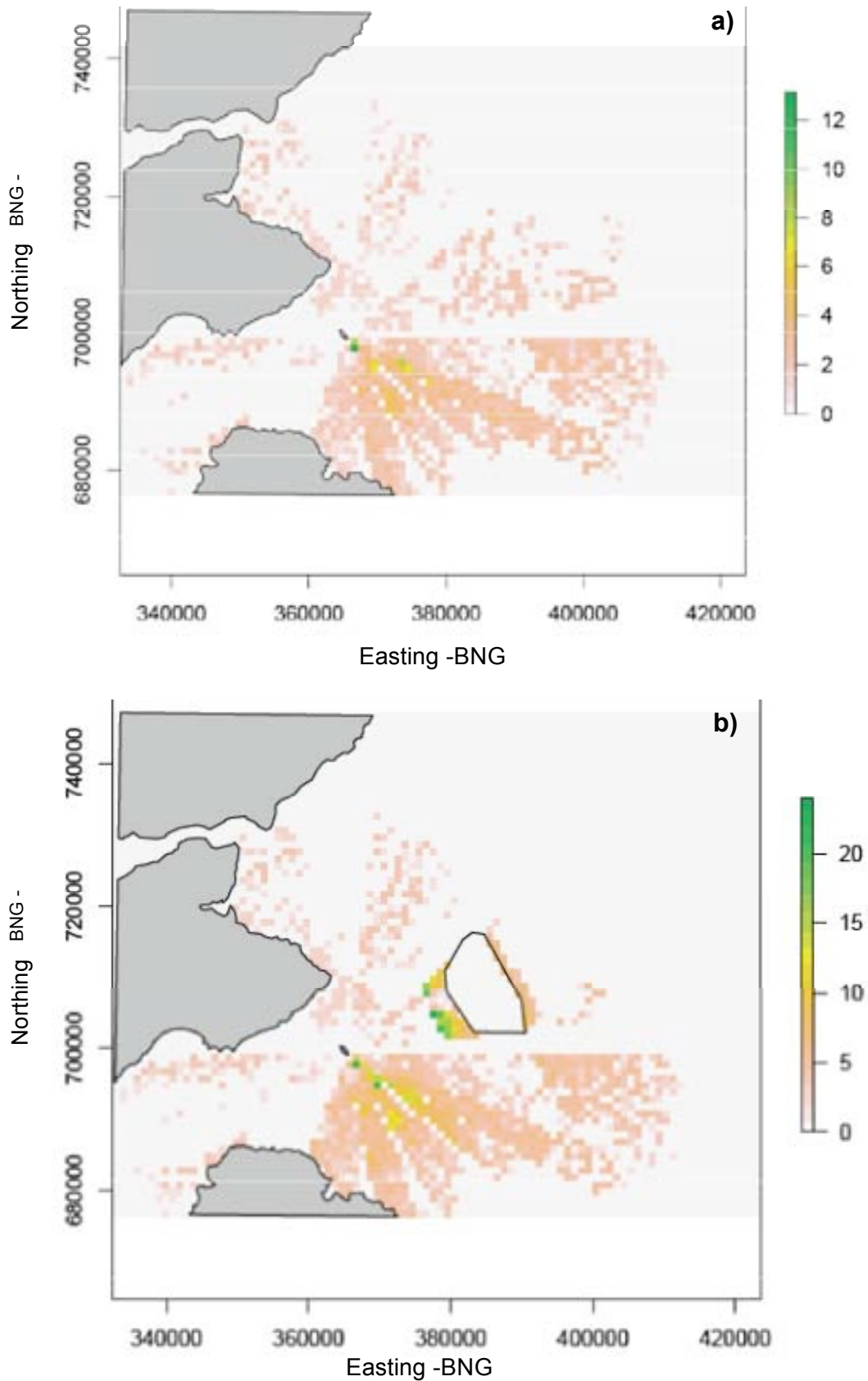
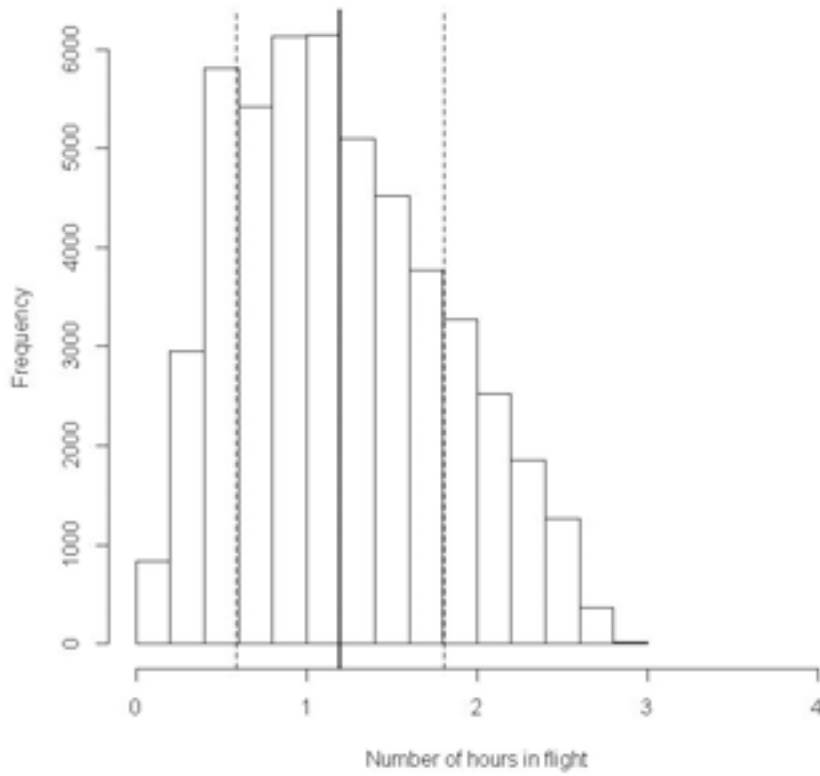


Figure 21. The mean foraging cost incurred at each cell after 50 simulations of the model with a clustered prey distribution layer and with a) no wind farm and b) with a wind farm present. The scale bars are the number hours spent foraging and the grey areas indicate land. The hollow polygon indicates the wind farm position. Northings and Eastings are in the British National Grid (BNG) reference system.

a) No wind farm present



b) With a wind farm present

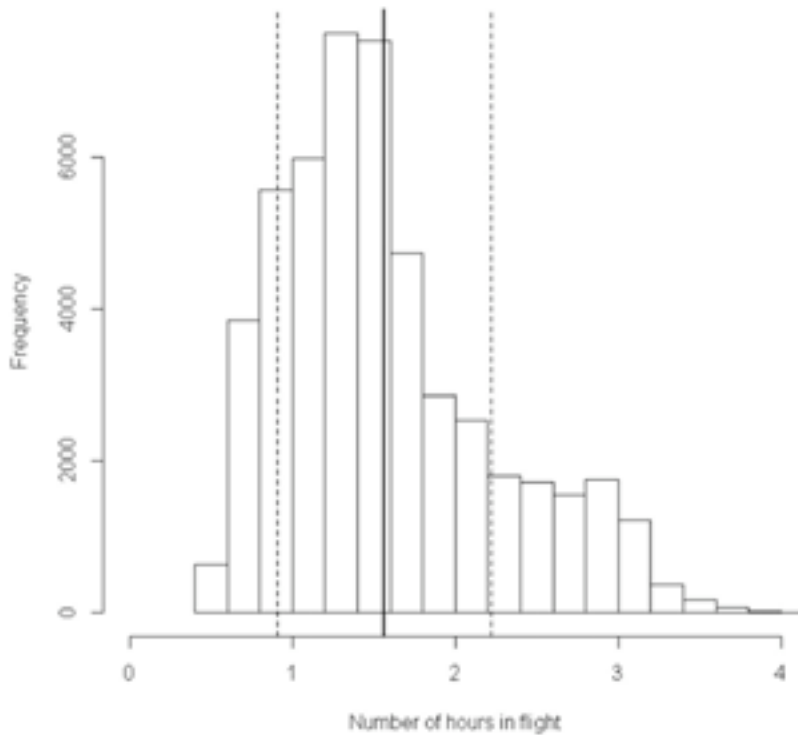
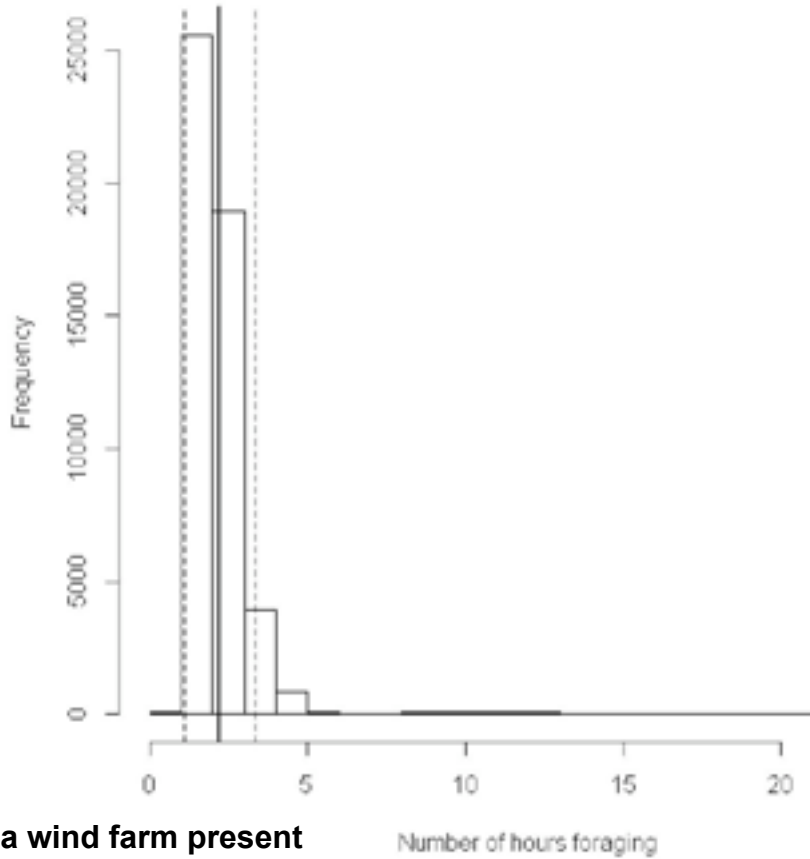


Figure 22. The distribution of flight costs incurred for 50 simulations of 1000 birds with a random prey distribution layer and an increased interference coefficient: a) without a wind farm present and b) with a wind farm present.

a) No wind farm present



b) With a wind farm present

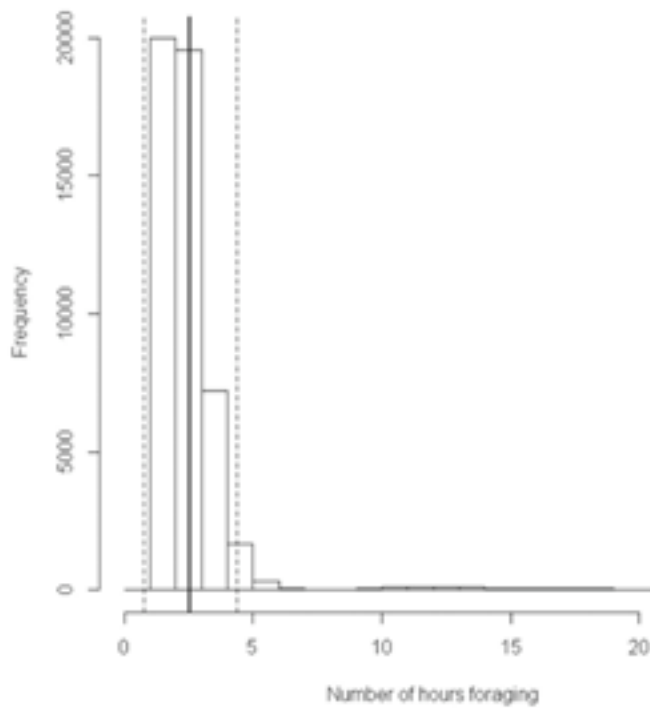


Figure 23. The distribution of foraging costs incurred for 50 simulations of 1000 guillemots with a random prey distribution layer and an increased interference coefficient: a) without a wind farm present and b) with a wind farm present. The bold line indicates the mean foraging cost in hours and the dashed lines are the \pm standard deviations.

4. Discussion

4.1. Displacement model

The model presented in this report represents a significant step forward towards understanding the implications of displacement and barrier effects of wind farms on seabirds breeding at SPAs. To our knowledge, this is the first attempt to model how breeding individuals in a seabird population use their foraging landscape, and, crucially, how this changes when a component of the population is displaced or has to travel round a wind farm development.

In all scenarios, the addition of the Neart na Gaoithe wind farm resulted in an increase in the average costs of foraging. This result is important since it suggests that displacement effects merit further consideration. The impact of displacement was driven by two main processes:

- the increased travelling costs incurred by the subset of the population that is displaced or for which the wind farm forms a barrier to movement, and
- the reduction in average prey densities in the remaining habitat due to intensified intra-specific competition, affecting not just displaced birds but the population as a whole.

Whilst there were some differences amongst the scenarios tested, the effect of the wind farm on time/energy budgets was consistent, suggesting that the displacement effect was apparent at different levels of prey aggregation and degrees of interference between individual guillemots.

Whilst the number of birds that did not achieve their daily energy requirements in the scenarios was comparatively small, the purpose of this project was to provide a proof of concept of the modelling approach. As such, formal examination of the absolute values is not justified since various aspects of the model are not realistic (e.g. 24 hour duration, population density). Future work would focus on developing the approach to explore patterns across a whole season for the SPA population as a whole. The potential effects of displacement over these time scales are hard to predict from the values presented in the model, since the relationships are unlikely to be linear, and may involve a range of outcomes - see section 4.2 part 2).

Although we used the Isle of May guillemot population and the Neart na Gaoithe wind farm to showcase the model, the framework is extremely flexible and could readily be updated, for example to take advantage of improved data on foraging behaviour or prey distribution. Similarly it could be adapted for different seabird or prey species by incorporating appropriate information on foraging behaviour and distribution respectively. Moreover, this model could be adapted to situations where no empirical data are available (e.g. flight direction could be modelled as random), subject to the appropriate caveats. The model could also be scaled up to the whole SPA, and incorporate interannual and seasonal variation including the effects of displacement on wintering birds. With further development, it could also explore outcomes for multiple species simultaneously, enabling inter- as well as intra-specific competition to be accounted for in the calculations. This modification is likely to be particularly insightful since seabird breeding colonies typically comprise several species and inter-specific facilitation and competition among multi-species feeding flocks are well known. Finally alternative scenarios of array location and design could be explored within this framework, and identifying designs that maintain energy balance above a defined threshold (e.g. that maintained population level effects below a threshold as agreed in consultation with interested parties – see next section) could be particularly useful, while sensitivity analyses could be employed to identify minimum data requirements and highlight priorities for future monitoring. The model could also be adapted to other case studies, and is designed so that cumulative effects from multiple developments could be estimated, with a view of informing marine spatial planning as well as decisions on a case by case basis.

Changes in the time/energy budgets of breeding seabirds can have important population consequences. This is because such changes may impact on the body condition of adult breeders which, in turn, can affect breeding success (through abandonment of young), adult survival and, ultimately, population size. Additionally, breeding success may be affected directly if provisioning rates alter significantly. There is an urgent need to estimate these more realistic population consequences of displacement, to provide improved assessments of likely adverse effects on SPA populations. Below, we describe how the outputs of the model can be used to parameterise population models that estimate the population consequences of displacement.

4.2. Population consequences of displacement

The most appropriate method of estimating the population consequences of displacement is to link time-energy budget models of foraging with population models under a range of plausible scenarios of displacement (Figure 24).

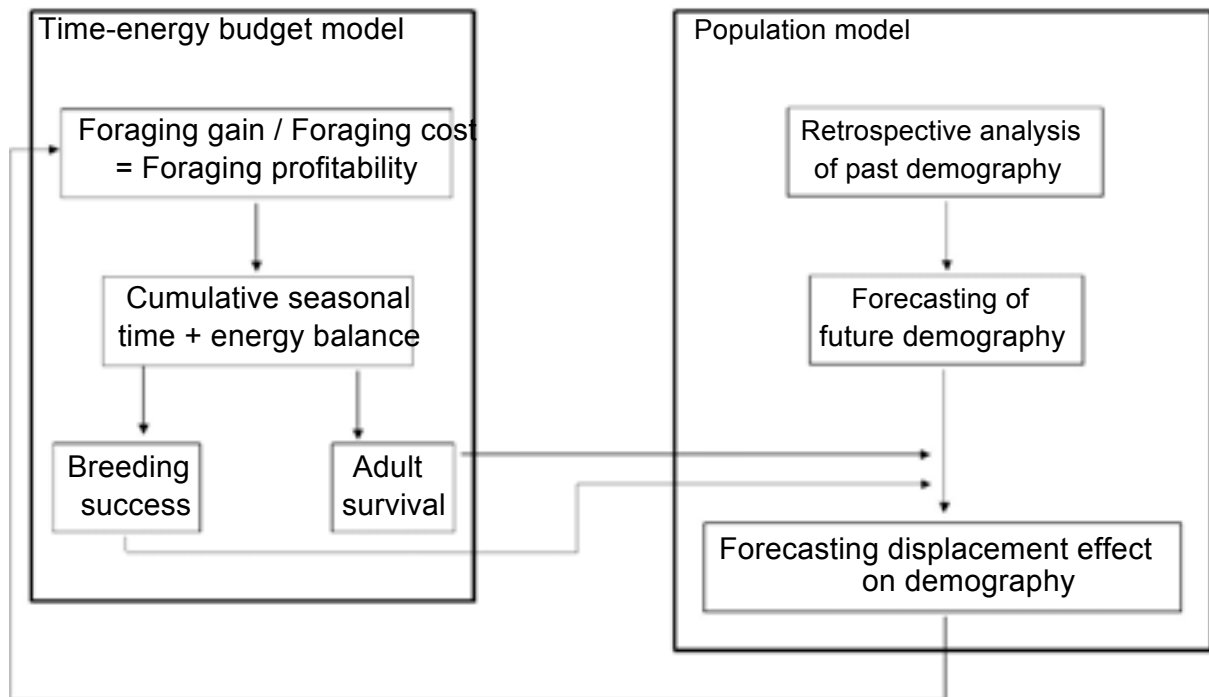


Figure 24. Flow diagram illustrating the linking of time-energy budget and population models to estimate population consequences of displacement.

The framework can be split into three components:

- 1) Time-energy budget model: The time-energy model in the absence of a wind farm, presented in this report over a 24 hour period, would be expanded into a cumulative profitability surface estimated over the course of the breeding season. This seasonal model would be quantified in a range of environmental conditions from optimum to severe, based on the range of conditions experienced in the region and forecasted in climate models.

Sustained time/energy deficits may have consequences both for breeding success and adult survival, two critical drivers of population dynamics. Life history theory predicts a trade-off between investment in current breeding and self-maintenance (Ylönen *et al.* 1998). Available data on the relationships between energy balance and these two parameters would be utilised; alternatively, theoretical understanding would be used (e.g. allometric scaling relationships). To breed successfully, one member of a pair of most species of seabird, including guillemots, needs to be constantly present at the nest site. Thus, increased time required for foraging can result in temporary unattendance of eggs or young which increases the likelihood of failure (Harris & Wanless 1997; Ashbrook *et al.* 2008). These fitness consequences of time and energy budgets underpin the subsequent displacement scenarios.

2) Consequences of displacement on breeding success and adult survival: The impact of changes in time/energy budgets on breeding success and adult survival would be estimated using the same approach as the baseline time-energy budget model. There are a number of challenges in reaching a satisfactory conclusion, given the lack of information on fitness consequences of foraging energetics and the effects of displacement on these parameters. Thus, where possible available empirical data would be used, or theoretical understanding together with experience of the species' ecology. At this stage, the most appropriate set of outcomes (for each set of environmental conditions) may be a matrix of severity against likelihood.

3) Population consequences of displacement. A stochastic time-specific matrix model (Caswell 2001; Frederiksen *et al.* 2008) using data on breeding success and adult survival and, where available, on age at first breeding, age structure and juvenile survival would quantify the population consequences of displacement. The modelling would be undertaken in three steps:

- a. Retrospective analysis: existing time would be evaluated to assess how well they capture observed historical population trends, and what environmental variables correlate with demographic rates.
- b. Forecasting population change: models would simulate future population growth rate. These simulations would be driven by change in breeding success and adult survival resulting from predicted environmental change or current trends where possible, or in the absence of these the distribution of historical parameter values.

- c. Predicted impacts of displacement: using the forecasts for population change with no displacement provides a baseline population trend against which predicted impacts of displacement from energetic models can be compared. These forecasts can be used to identify required decreases to breeding success and survival necessary for causing pre-determined changes in total population size. Different scenarios for the impacts of displacement on breeding success and survival can then be related to these necessary changes. In this way, resulting population change can be evaluated, and displacement scenarios under which negative impacts on the integrity of the SPA network are predicted can be identified. These scenarios would be run for the expected lifespan of the wind farm and an agreed period afterwards to monitor post-closure population trajectories, as part of the EIA/HRA process. Specifically, the time taken to recover from any decline as a result of displacement would be determined. Finally, the population consequences of displacement could be modelled alongside other potential effects such as collision to provide an overall assessment of wind farm impacts on populations.

5. Conclusions

Offshore renewable developments have the potential to impact on seabirds by displacing individuals from optimal foraging areas. The impact of displacement is particularly important for breeding seabirds that, as central place foragers, are constrained to obtain food within a certain distance from the breeding colony. The current worst case scenario is that displacement causes 100% mortality, so there is a need to model more realistic consequences of displacement. In practice, displacement is likely to result in changes to daily energy and time budgets, and the model presented here is a demonstration of how this can be quantified. It also lays the foundation for estimating population consequences of displacement by linking time-energy budget models of foraging with population models.

6. Acknowledgements

We are grateful to the many people that helped collect the empirical data that informed the models, in particular Mike Harris, Maria Bogdanova, Chris Thaxter, Silvano Benvenuti, Alberto Ribolini, Luigi Dall'Antonia, Gerrit Peters and David Gremillet. We also thank the wardens and other staff of Scottish Natural Heritage for logistical support on the Isle of May, and to Jimmy Smith and Andy Easton for providing transport to and from the island. The bathymetry data are derived from 1:250,000 BGS Digital data under Licence 2008/101 (British Geological Survey. ©NERC).

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8. Appendix 1

List of simulation and cost model parameters detailing assumptions and references.

Parameter Group	Parameter Name	Parameter Value	References	Comments
Input layers	Resolution of model	1km ²	-	-
	Prey density	Raster of number of individuals per location	-	Distribution simulated to represent prey
	Distance	Distance from Isle of May to every other cell	-	
	Bathymetry	Depth at every location	British Geological Survey under licence: http://www.bgs.ac.uk/products/offshore.html	
	Rules for selecting foraging location	Prey density >1 Prey individual Dive depth > 0 Distance < 50km	Stephens & Krebs 1986; Daunt <i>et al</i> 2011a,b,c Thaxter <i>et al</i> 2009, 2010. Wanless <i>et al</i> 1990,2000,2005	foraging theory; empirical data from Isle of May
Model details	Prey interference competition model $a^I = Q \cdot P^{-m}$ a is the intake rate of an individual	Q = 0.4; m = 0.6: P = number of guillemots at the location	Hasswell & Varley 1969; Ens & Goss-Custard 1984; Dolman <i>et al.</i> 1995, Goss-Custard <i>et al.</i> 1995).	m increased to 0.9 in clustered prey scenario
Behaviour	Flight direction	Range of directions from empirical data	Daunt <i>et al</i> 2011 a,b Thaxter <i>et al</i> 2009,2010.	Data sampled when direction data is chosen Assume that prey are disturbed due to high density of birds close to the colony
	Flight vs foraging direction	Equivalent values	Daunt <i>et al.</i> 2011 a,b	
	Flock size	Empirical data from 1 birds to 50 birds	Daunt <i>et al</i> 2011 c	
	Prey density decay	decay rate = 0.001	Lewis <i>et al</i> 2001	
Wind farm presence	Displacement rate	100%	-	Only for birds that choose to forage where the wind farm is located
	Displacement distance (within 5km)	Birds remain within 5km	-	Assume that birds would aim to locate a suitable foraging location

Parameter Group	Parameter Name	Parameter Value	References	Comments
				close to the wind farm to minimise added costs
Cost Model	Cost model details	-	Daunt & Wanless 2008, Wanless 1997	Based on guillemots flying out and returning on the same bearing
	Number of trips per day (chick rearing)	2.02	Enstripp <i>et al</i> 2006	
	Distance travelled	From simulation results		
Flight Cost	Flight speed	19.1 ms ⁻¹	Pennycuick 1997	
	Division of labour between mates	-	Daunt & Wanless 2008	
Foraging Cost	Assimilation efficiency	0.78	Hilton <i>et al</i> 2000b	Expert knowledge; assumption that intake rate and therefore foraging is dependent on the availability of prey
	Cost of flight	7361.72 kJ day ⁻¹	Pennycuick 87,89	
	Cost of resting on sea surface	810.28 kJ day ⁻¹	Croll & McLaren 1993	
	Cost of staying at the colony	1168.91 kJ day ⁻¹	Hilton <i>et al</i> 2000a	
	Cost of warming food	51.92 kJ	Gremillet <i>et al</i> 2003	
	Energy requirements of chick	221.71 kJ day ⁻¹	Harris & Wanless 1985	
	Prey density	6.1kJ g ⁻¹	Harris <i>et al</i> 2008	
	Time spent resting at sea and at colony	Empirical data	Wanless <i>et al</i> 2005	
	Time spent foraging, dependent on prey availability	Max prey intake rate of 5g min ⁻¹ Intake rate does not increase until more than 200 individuals per km ²	Enstipp <i>et al</i> 2007	
	Diving efficiency (DE)	DE = 0.36- (0.0021*dive depth(m)) 50% benthic;	Daunt & Wanless 2008	
Diving depth distribution	50% water column from normal dist (mean 11.71, sd 8.07m)	Daunt <i>et al</i> 2006; Daunt & Wanless 2008		
Negative energy budget	> 12 hours foraging	-	Assumption that this is one foraging trip, if more than 12 hours then returns to the colony to relieve mate	

Parameter Group	Parameter Name	Parameter Value	References	Comments
Wind Farm Costs	Birds need to fly around the wind farm (barrier) both on outward and return journey sampled from a normal distribution	Cost sampled from a normal distribution (mean =20km, sd= 5km)	-	Value based on size of wind farm (Approx. 40km perimeter, 14km length, 9km wide)



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