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GPS tracking of common guillemots, razorbills, Atlantic puffins and black-legged kittiwakes on the Isle of May in 2019 in relation to the Neart na Gaoithe offshore wind farm

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Executive summary

- This report presents the results of GPS tracking of adult common guillemots, razorbills, Atlantic puffins and black-legged kittiwakes breeding on the Isle of May (SE Scotland) in 2019 and assessment of connectivity with the consented Neart na Gaoithe offshore wind farm.

- Locational data were obtained from 24 guillemots, 14 razorbills, 24 puffins and 25 kittiwakes (comprising 120, 129, 123 and 167 trips, respectively) in June and July 2019. The data were partitioned into non-flight behaviours (foraging and resting), relevant to displacement effects, and flight behaviours, relevant to collision risk and barrier effects. A resampling procedure suggested that the sample sizes of tracked birds were adequate to estimate the at-sea area used by the Isle of May populations of all four species during the deployment period.

- The at-sea non-flight distributions of the four study species included both inshore and offshore areas, as found in previous GPS tracking studies in 2010-18. Differences among the species were apparent, with guillemots and razorbills using coastal areas more extensively, and puffins and kittiwakes using mainly offshore waters. The core areas used by guillemots were concentrated around and to the east of the Isle of May and within St Andrews Bay. Razorbills used offshore areas mainly to the east of the colony, and to a lesser extent coastal areas within the Firth of Forth and St Andrews Bay. Puffin distribution was concentrated exclusively offshore, spanning areas from a south-easterly to north-easterly direction from the Isle of May. Kittiwakes had a wider distribution than the auk species, including mainly offshore areas spread from south-east to north-east and north of the colony (although some birds used waters within the St Andrews Bay). This was reflected in the larger mean maximum range for this species (81.2 ± 4.2 km) compared to guillemots (38.9 ± 2.1 km), razorbills (44.0 ± 3.1 km) and puffins (51.9 ± 3.0 km).

- The distribution of flight lines matched closely the distributions of non-flight activities. Guillemots departed from and returned to the colony on bearings ranging from

southwest and north/northwest (for inshore foraging trips) to northeast and east (for offshore trips). A similar pattern was observed in razorbills although bearings of commuting flights to offshore areas were concentrated mainly to the east of the Isle of May. Flight bearings of puffins spanned from a north-easterly to south-easterly direction, whereas in kittiwakes they spanned from a north-westerly to south-easterly direction from the colony.

- A small proportion (<2%) of the core areas used (50% UD contours) by razorbills and puffins overlapped with the planned Neart na Gaoithe footprint, whereas in guillemots and kittiwakes the overlap was larger (up to 9%). The proportion of the overall area used at sea (90% kernels) that overlapped with the wind farm footprint was also small (<5% in all species). However, the entire footprint fell within the overall areas used by all four species.

- The overlap of flight activities with the wind farm footprint was generally higher than the overlap of non-flight activities. In terms of number of birds, all four species used the planned Neart na Gaoithe site extensively, particularly kittiwakes and puffins where 75% or more of the study birds passed through the wind farm site. At the trip level, the extent of overlap was smaller but a similar pattern was apparent, with proportion of trips through the wind farm footprint higher in kittiwakes and puffins and lower in razorbills and guillemots. At the level of individual flights, overlap was highest in puffins, followed by kittiwakes and guillemots, and lowest in razorbills. The lower overlap of guillemot and razorbill flight activities with the planned Neart na Gaoithe site is likely due to these species having partially inshore distribution.

- Our study showed negative effects of GPS logger deployment on chick feeding rates in puffins, confirming previous findings on the Isle of May. Our results suggest that colour-ring attachment ('handling') had a modest effect, whereas GPS logger deployment ('device') had a substantial effect on individual feeding rates. There was an indication that among pairs in the 'handling' group, the partner was able to compensate for the slightly reduced feeding rate of the treatment bird. Among pairs in the 'device' group however, compensation by the partner was not fully effective and reduced feeding rate was observed at the pair level too, compared to

unmanipulated ('control') pairs. Within the first four days after logger deployment feeding rates did not improve, indicating that the treatment birds did not return to normal activities whilst carrying a logger. Such negative impacts of device deployment appear to be a feature of this population of puffins. However, we were able to compensate for these effects using a supplementary feeding protocol and the chicks from treatment burrows fledged successfully and in similar condition to those from control burrows. We did not find evidence for negative device effects on kittiwake foraging behaviour (trip duration), chick condition or breeding success.

- *Conclusions:* This study demonstrates variation in seabird distributions at sea among species and, when comparing with previous GPS tracking studies undertaken between 2010 and 2018, variation within species among years. Our study also confirmed connectivity between the guillemot, razorbill, puffin and kittiwake populations breeding on the Isle of May and the planned Neart na Gaoithe offshore wind farm site. As in previous studies on the Isle of May, we found negative effects of logger deployment on chick provisioning rates in puffins resulting in a particular challenge with using this technology on this population. The interannual variation in distribution indicates that the development of a structured monitoring plan, including GPS tracking in the periods before, during and after wind farm construction, would be very valuable and maximise opportunities for quantifying the impacts of the wind farm on these seabird populations.

1 Introduction

1.1 Background

Offshore renewable developments have the potential to impact on protected seabird populations, mainly due to collisions with turbine blades, displacement from important habitat and barrier effects to movements (Drewitt & Langston 2006; Larsen & Guillemette 2007; Masden et al. 2010; Grecian et al. 2010, Langton et al. 2011; Searle et al. 2014, 2018). These effects may be particularly important for breeding seabirds that are constrained to forage within a certain distance from the colony because of the requirement to return regularly to the nest to relieve the attending mate and feed the young (Daunt et al. 2002; Enstipp et al 2006). Accordingly, for the purposes of Habitats Regulations Appraisal, there is a need to estimate the potential impact of offshore renewable developments (ORDs) on seabirds breeding at Special Protection Areas (SPAs). To address this question requires first to establish the extent of interaction between birds from colony SPAs and ORDs and second to estimate whether such interactions are having a detrimental effect at the population level.

GPS tracking offers a very useful approach to tackling these two issues. Deploying GPS loggers on breeding adults at SPAs enables the extent of overlap to be quantified. Quantifying foraging and flight behaviour over the period from before, during and after construction of the wind farms coupled with simultaneous estimates of changes in physiology and demography is a powerful framework for estimating population-level effects.

Baseline information on seabird at-sea distribution and flight lines is fundamental to interpreting potential effects of wind farms. Thus, pre-construction monitoring is a key strand of the structured before-during-after design. Accordingly, we were tasked by EDF Renewables, in the context of their planned Neart na Gaoithe offshore wind farm in Forth/Tay region, to undertake GPS tracking of breeding adults on the Isle of May, part of the Forth Islands SPA, of four species that have been central to HRA/EIA assessments of this development: black-legged kittiwake *Rissa tridactlya* (hereafter 'kittiwake'), Atlantic puffin *Fratercula arctica* (hereafter 'puffin'), common guillemot *Uria*

aalge (hereafter 'guillemot') and razorbill *Alca torda* during the 2019 breeding season. This work constituted the second year of pre-construction monitoring following GPS tracking undertaken on the same species on the Isle of May in the 2018 breeding season (Bogdanova et al. 2018).

Device effects on birds are being increasingly recognised and so is the awareness of the importance of reducing these negative effects (Bodey et al. 2018). Important considerations in this respect are the choice of device (dimensions, weight, shape), optimal placement on the bird and attachment methods, and minimising handling-related disturbance (Vandenabeele et al. 2012, 2014; Thaxter et al. 2014, 2017). It is imperative that studies take these factors into account if possible in order to minimise negative impacts on the study populations and increase the representativeness of resulting data. Previous work has shown that puffins on the Isle of May and other colonies are susceptible to disturbance arising from handling and deployment of data loggers, including the work undertaken in 2018 (Rodway et al 1996, Harris & Wanless 2011; Harris et al. 2012; Bogdanova et al. 2018). Accordingly, we once again used the smallest available loggers. However, we abandoned the method of mist netting used in 2018 to instead capture birds at burrow entrances, thereby ensuring only one adult per pair was tracked per pair and that the chicks of all instrumented birds were identified and could be supplementary fed to secure their wellbeing should provisioning rates be affected. We also carried out deployments when the puffin chicks were older and more robust. We then, as in 2018, undertook an assessment of the effects of GPS deployment on chick feeding rates and chick condition and survival. Recent work (although using substantially larger loggers than the ones used in this project) also indicates that GPS logger deployment can affect both the foraging behaviour and physiology of kittiwakes (Heggøy et al. 2015, Chivers et al. 2016). We therefore tested for device effects on foraging trip duration, chick condition and breeding success in this species for the first time.

1.2 Objectives

The objective of this project was to undertake GPS tracking of guillemots, razorbills, puffins and kittiwakes breeding on the Isle of May during the 2019 breeding season in

order to quantify their at-sea distribution and flight lines, and to estimate overlap with the planned Neart na Gaoithe wind farm. This work built on GPS tracking undertaken on these four species on the Isle of May in 2018 (Bogdanova et al. 2018). A secondary aim was to assess potential effects of GPS deployment on puffins and kittiwakes.

The report contains a series of maps of distributions and flight lines, estimates of overlap with the planned wind farm and analyses of minimum adequate sample size, where we assess whether our data were sufficient to robustly estimate the population distribution over the sampling period. The report also contains an analysis of device effects in puffins and kittiwakes.

2 Methods

2.1 GPS tracking

2.1.1 Data collection

The data were collected on the Isle of May National Nature Reserve (56°11' N, 2°33' W) in June and July 2019 using remote download Pathtrack nanoFix-GEO+RF GPS loggers in three configurations (guillemot: 51x24x9mm, 11g; razorbill: 50x15x10mm, 8.2g; kittiwake: 42x14x8mm, 4.1g; puffin: as kittiwake but weighing 3.2g, all with ~50mm external whip antenna; Fig. 1). Deployment details are provided in Table 1.
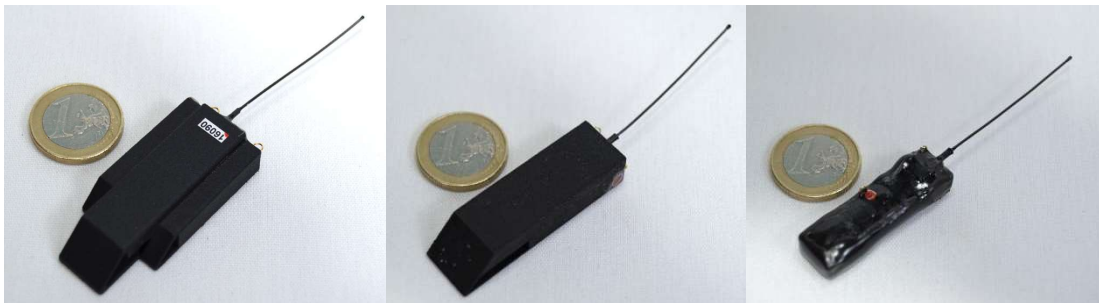

Figure 1: Three Pathtrack devices used in the project: 11g logger used on guillemots; 8.2g logger used on razorbills; 4.1g used on kittiwakes (a modified version of this weighing 3.2g was used on puffins). €1 coin provided for scale. See text for full details.

Species	Logger mass (g)	Deployment period	Number deployed	Number with data retrieved	Number of trips
Guillemot	11	21 – 27 June	24	24	120
Razorbill	8.2	21 June	15	14	129
Puffin	3.2	29 June – 5 July	25	24	123
Kittiwake	4.1	18 – 23 June	25	25	167

Table 1: Details of logger mass, deployment dates and number of birds and trips tracked for the four study species.

For three of the species (guillemot, razorbill and kittiwake), breeding adults were captured at the nest site with a noose at the end of an extendable pole. Puffins were captured using purse nets at the entrance to their nesting burrows. The loggers were attached to lower back feathers (guillemot, razorbill and puffin) or central tail feathers (kittiwake) using waterproof Tesa tape (Fig. 2). Handling time for all species was typically around 5 minutes, and not longer than 11 minutes. Birds carried the loggers for up to *ca.* two weeks before they fell off. Data were collected during chick-rearing in guillemots, razorbills and puffins, and during incubation and chick rearing in kittiwakes.

Figure 2. Completed deployment of data logger on puffin (left panel) and kittiwake (right panel).

GPS data were automatically downloaded to fixed base stations positioned in line of sight of nest sites each time the logger was within range (Bogdanova et al. 2018). The base stations successfully received data from 87/89 loggers (98%). The data stored in the base stations were then downloaded daily onto a computer. The sampling interval was set at 5min for guillemot, 5 or 10min for kittiwake and 10min for razorbill and puffin to maximise deployment duration while retaining sufficient resolution to estimate behaviours. The average length of deployments was 4.8 ± 0.4 days for guillemot, 6.1 ± 0.3 days for razorbill, 3.6 ± 0.2 days for puffin and 6.0 ± 0.5 days for kittiwake.

2.1.2 Data processing

The data processing involved several steps. First, the raw data were cleaned by removing GPS fixes recorded before the loggers were fitted to the birds and fixes with low accuracy (when signal from less than four satellites was received the loggers did not obtain longitude and latitude). Second, locations recorded at the colony (within 500m of the nest site) were also removed from the data set as we were interested in the birds' behaviour and distribution at sea. The remaining fixes, recorded at sea, were assigned to foraging trips. Thus, a foraging trip was assumed to begin when a bird moved from a location within 500m of the nest site to a location more than 500m from the nest site, and to end when the bird returned to a location within this boundary. Periods away from the colony that lasted less than 30mins likely represented short non-foraging excursions from the nest and were therefore not classified as separate trips; trip duration in our study species is typically much longer (Finney et al 1999, Daunt et al 2002, Thaxter et al. 2009; 2010; Harris et al. 2012). Third, at-sea fixes were categorised as 'flight' (commuting) or 'non-flight' (foraging or resting) based on the speed between subsequent fixes, with higher speeds indicating flight. The threshold value for each species was obtained from the distribution of speeds (guillemot and razorbill: 6 ms^{-1}, puffin: 7 ms^{-1}, kittiwake 5.5 ms^{-1}). At-sea data were categorised in this way as the potential impacts of offshore wind farms on seabirds are likely to differ during flight (when collision and barrier effects are expected to be more important; Desholm & Kahlert 2005; Searle et al. 2014. 2018) and during foraging/ resting (when displacement is expected to be more relevant; Masden et al. 2010; Searle et al. 2014, 2018). The final processing step involved removing erroneous fixes for which the geographical location was implausible.

Several birds (2 guillemots, 4 razorbills, 1 puffin and 3 kittiwakes) had longer periods of missing data (mean: 12.3 hrs, range: 3.1 to 33.5 hrs). The logger manufacturers were able to recover all data from the kittiwakes and partial data from the puffin and one of the guillemots but not from the remaining guillemot or any of the razorbills. In these individuals some foraging trips may have been missed.

2.1.3 Data analysis

2.1.3.1 Species utilisation distribution (UD)

Utilisation distribution at sea was determined for each species by calculating the kernel density of locations recorded away from the colony. Locations were projected in Lambert azimuthal equal-area projection and kernel density was calculated in R (R development core team, 2019; package adehabitatHR, Calenge 2006), using a cell size of 500m^2 and a smoothing parameter *h* identified with the *ad hoc* (reference bandwidth) method (Worton 1989). For each species, maps with 50, 70 and 90% density contours (the former representing the core area used, the latter – the overall area used) were produced in ArcGIS 10.4.1 (ESRI). Separate maps were generated for all at-sea locations and for non-flight locations (representing foraging and resting behaviours).

2.1.3.2 Horizontal flight lines

Individual commuting flights within a foraging trip were extracted and horizontal flight lines mapped in ArcGIS 10.4.1. On the maps, breaks in the lines at sea represent periods when the birds were engaged in non-flight behaviours. Also, due to the relatively large GPS sampling intervals only single locations were recorded for some of the shorter commuting flights. These are not shown in the flight line maps but were included in calculations of number of flights passing through the planned wind farm footprint.

2.1.3.3 Minimum adequate sample size

To establish whether the sample size of tracked individuals was adequate to estimate the at-sea area used by the population of each species during the sampling period, we examined the relationship between overall area used (area of the 90% UD contour) and number of individuals using a resampling procedure. This procedure was performed in R, and involved creating 1,000 datasets for each sample size of birds, ranging from 1 to n (where n denotes the total number of birds for which we had data), by choosing birds randomly without replacement (Manly, 2009). Resampling without replacement was used to avoid systematic underestimation of the overall area used by the birds. A UD estimate was then derived from the pooled data from all individuals within each resample (using the adehabitatHR package within R) and the area of the

90% UD contour calculated. The distribution of these areas across the 1,000 resampled datasets was used to quantify the typical at-sea area used for a given sample size of birds and the uncertainty associated with estimating this area.

2.1.3.4 Overlap with Neart na Gaoithe footprint

To quantify overlap between the utilisation distribution of each species and the planned Neart na Gaoithe wind farm, we calculated the proportion of 50% and 90% UD contours (core area and overall area, respectively) lying within the planned wind farm footprint. To assess the extent to which commuting birds travelled through the planned Neart na Gaoithe site we calculated the proportion of birds, trips and flights passing through the wind farm footprint.

The UD areas and flights overlapping with the planned Neart na Gaoithe wind farm were extracted in R and ArcGIS 10.4.1.

2.2 Device effects

2.2.1 Data collection

2.2.1.1 Puffin

Prior to deployment, a large number of active burrows were marked at the study site using small canes. These were then assigned to a treatment or control group. Treatment burrows had one member of the pair tagged or colour-ringed, whereas control burrows had no birds manipulated. Two deployments took place towards the later part of the puffin breeding season when the chicks were older and more robust (Table 2).

Deployment session	Deployment date	Logger	Colour ring only	Total
1	29 June	10	4	14
2	5 July	15	7	22

Table 2. Sample size of birds within each treatment category and deployment session.

Adult birds carrying fish were caught at the burrow entrances using purse nets. The nets (size: *ca.* 50cm^2, mesh size *ca.* 4x4cm) were pegged down and laid over the entrance to the burrow. This method allowed us to catch incoming adults and instantly allocate them to their burrow, in contrast to the mist netting approach used in 2018 where a proportion of burrows of instrumented birds was not found (Bogdanova et al. 2018). The method employed in 2019 also eliminated the risk of catching both members of the pair, which had occurred in 2018 (Bogdanova et al. 2018). Captured puffins were tagged with either a Pathtrack GPS logger (*ca.* 3.2g in weight) and a unique combination of colour rings or with a combination of colour rings only. The two treatment groups were included to investigate potential negative effects of handling and device deployment. Due to the large number of burrows needed, two sites were used for the deployments, approximately 20m apart. This allowed us to avoid any burrow overlap between the deployments. GPS loggers were attached to the lower back feathers using three strips of Tesa tape. To aid subsequent identification of individuals, each bird was also given a letter marked in black on the Tesa tape (Fig. 2). Handling time averaged 5 minutes and never exceeded 8 minutes.

From the day following each deployment, feeding watches were undertaken for 8 hours a day (5am to 1pm) shared by three observers from a fixed, wooden hide. The watches were carried out for a period of 4 days after each deployment. Every feed into a marked burrow was recorded, and for treatment burrows, also which individual fed (tagged or partner). In addition, the behaviour of treatment birds was recorded (e.g. colony attendance, entering the burrow without fish). Details of observation dates and sample sizes of control and treatment burrows in each deployment session's feeding watches are summarised in Table 3.

Deployment session	Observation dates	Control burrows	Treatment burrows
1	30 June – 3 July	24	14
2	6 – 9 July	38	22

Table 3. Summary of puffin feeding watches for each deployment session.

Due to the decrease observed in the provisioning rates of tagged birds, supplementary feeding of puffin chicks with whitebait and seabird supplements took place from the 3rd day of watches after deployment until fledging. Chicks were not fed during the first three days after deployment to ensure the provisioning rates of adults were not affected at the time when GPS data were being recorded. After the third day of watches we weighed and measured all chicks at treatment burrows. The amount of food given to each chick was determined using the provisioning data collected in the previous three days. The criteria we used are described in Table 4.

Amount of food (g)	Criteria	Comments
0	Average feeds ≥ than controls	Feeds by both members of the pair
20	Average feeds ≥ than controls	Feeds only by untagged partner
40	Average feeds < than controls	

Table 4. Amount of supplementary food given to puffin chicks and feeding criteria.

Supplementary food was given to the chicks twice (2x20g) or once (20g) a day. Where possible, the fish were left near the chick inside the burrow. If the chicks were unsuccessful in taking the food this way, they were hand-fed. All chicks were weighed and measured every other day until they fledged to monitor their condition and survival. Body condition was calculated as weight/(wing length)^3 and condition values were scaled (multiplied by 1000) to avoid very small decimal numbers.

2.2.1.2 Kittiwake

Observations were carried out between 18 and 27 June and focused on recording change-over rates of adults at the nest, from which foraging trip duration was later calculated. Treatment nests had one member of the pair tagged with a Pathtrack GPS logger (3.6g in weight), whereas control nests had no birds tagged. Two deployments took place at two different sites. Birds were caught at the nest with a noose at the end

of an extendable pole. They were given a BTO metal ring, a GPS logger and were weighed and measured. The logger was attached to the four central tail feathers with four strips of Tesa tape. Prior to release the birds were marked with yellow dye to facilitate identifying them during watches. Each control and treatment nest was assigned a unique ID using a photo of the colony (Fig. 3). Observations were carried out from a fixed canvas hide (Fig. 3) for four days, 12 hours a day (5am – 5pm), starting the day after each deployment. Sample sizes and deployment details are shown in Table 5.
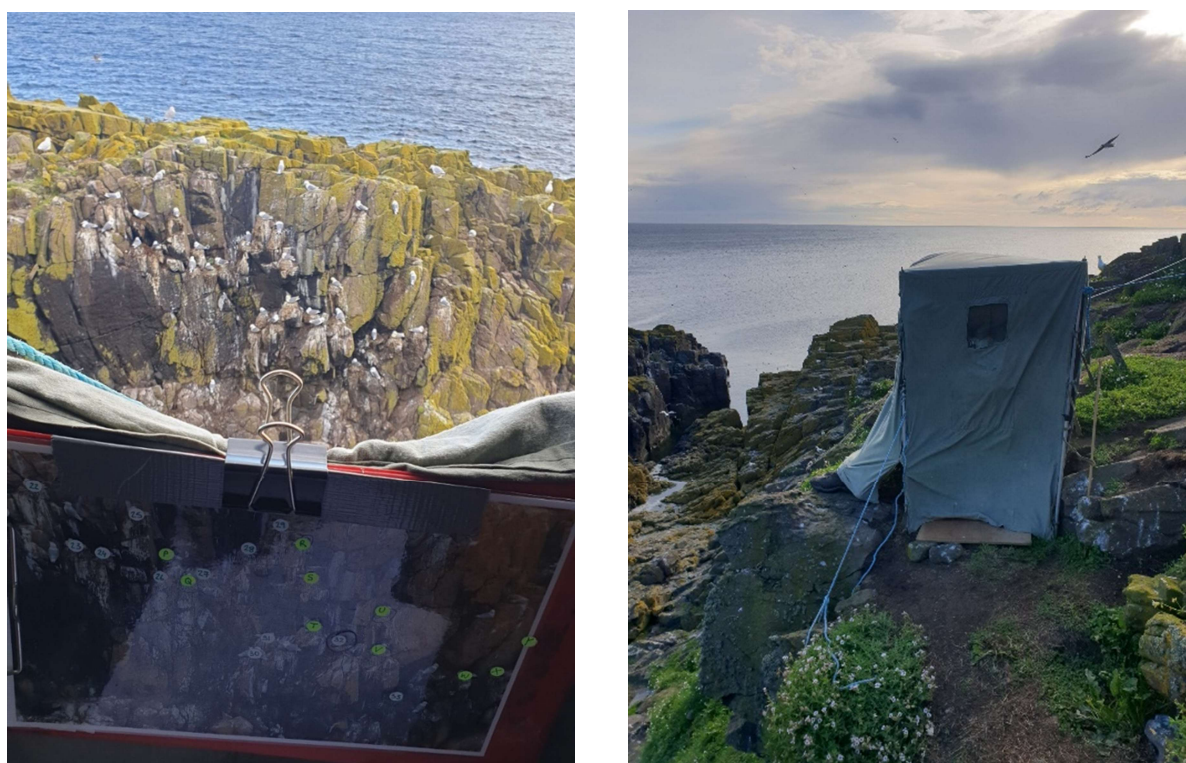
Figure 3. The second deployment site with nest IDs in the foreground and kittiwake plot in the background (left panel), and the observation hide (right panel).

Deployment session	Deployment date	Site	Logger	Control
1	18 June	1	14	18
2	23 June	2	11	13

Table 5. Deployment sessions and number of GPS loggers deployed on kittiwakes.

During the observations, all events involving two adults at any nest were recorded (time the birds spent together at the nest, whether changeover occurred, identity of arriving and leaving bird – this was possible only at treatment nests, where the mates could be distinguished). A change-over was defined as any event in which the leaving bird at a specific nest was not the same as the arriving bird.

The status of each nest (number of eggs/chicks) was recorded on a daily basis during the watches. Two to three weeks after the GPS data collection was completed, a proportion of chicks at control and treatment nests were also weighed and measured to assess their condition (Table 6). Body condition was calculated in the same way as for puffins. Finally, overall breeding success of all nests included in the study was obtained.

Site	Treatment chicks	Control chicks
1	6	13
2	7	7

Table 6. Number of kittiwake chicks that were weighed and measured to assess body condition.

2.2.2 Data analysis

2.2.2.1 Puffin

We investigated effects of treatment and time since deployment on chick feeding rates using linear mixed models. The analysis of feeding rates was conducted at the individual and at the pair level. At the individual level, we tested whether the proportion of daily feeds delivered by birds equipped with a GPS logger (and colour rings) or with colour rings only differs, and therefore to what extent partners would need to compensate for any reduction in feeding rates by the tagged birds. Direct testing for effects of treatment on individual feeding rates was not possible because we could not obtain data from unmarked control birds. At the pair level, we tested whether the number of feeds delivered daily differs in 'colour-ring' and 'logger' pairs compared to

controls, and therefore whether compensation by the partner of the tagged bird is effective.

In the analysis at the individual level, we used generalised linear mixed models (GLMM) with binomial error distribution, where the response was the proportion of feeds per observation day delivered by the tagged bird. Treatment (logger vs colour ring) was a fixed effect, day since deployment was a covariate, and bird identity and day were random effects in the models. In the analysis at pair level, we used GLMMs with Poisson error distribution, where number of feeds per observation day was the response, treatment was a fixed effect, day since deployment was a covariate, and pair identity and day were random effects. Since in the pair-level analysis treatment had three categories (logger, colour ring and control), to aid interpretation we fitted models with the original (3-factor) variable, and separately with two binary variables for 'handling' (control vs colour ring and logger) and 'device' (control and colour ring vs logger) effects. Day was included as a random effect in the models to account for random variation between days common to all individuals. We also initially considered including site as a random effect; however, preliminary analyses showed that variation between the study sites in feeding rates was negligible at both individual or pair level, so data from the two sites were pooled.

To investigate effects of logger deployment on chick fledging condition and survival we used GLMMs with Gaussian and binomial error distribution, respectively. Treatment (tested both as a 3-factor variable and as two binary variables) was a fixed effect and site a random effect in the models.

2.2.2.2 Kittiwake

As kittiwakes do not feed their chicks immediately after returning from a foraging trip, it is difficult to record feeding rates directly in this species. We therefore used foraging trip duration as a measure of provisioning effort and compared this between treatment and control nests. Trip duration was derived using the number of changeovers, time the pair members spent together at the nest and watch duration per observation day. The distribution of trip durations was clearly bimodal, therefore we split the trips into

two categories (short, up to 6 hrs and long, over 6 hrs). To test for device effects on foraging trip duration, we used GLMMs with binomial error distribution where trip type (short/long) was the response, treatment (logger vs control) and breeding stage (incubation vs chick rearing) were fixed effects, day since deployment was a covariate, and pair identity, site and day were random effects. We accounted for breeding stage in the analysis because foraging trips in this species tend to be longer during incubation than during chick rearing. The analysis was also carried out using the original trip duration variable but in this case we could only fit models that contained breeding stage too as this accounted for the bimodality in the data.

We also investigated effects of logger deployment on chick condition and breeding success. We modelled device effects on chick condition (at 2 to 3 weeks after deployment) using GLMMs with treatment (logger vs control) and brood order as fixed effects, and nest identity and site as random effects. The response variable was square-root transformed to achieve approximate normality. Brood order was included in the models to control for differences in condition between first-hatched and second-hatched chicks. Device effects on breeding success were investigated using GLMMs with Poisson error distribution where number of fledged chicks per nest was the response, treatment was a fixed effect and site was a random effect.

2.2.2.3 Model selection

For each analysis, our candidate set included a 'null' model containing only the random effect(s) and no fixed effects, models testing for each of the main effects separately, and a 'full' model containing all main effects and relevant interactions between them. Support for different candidate models was assessed using Akaike's information criterion adjusted for small sample size (AICc). The model with the lowest AICc value was considered best supported. Models were deemed strongly supported if they differed from the best model by less than 2 AICc units (Burnham & Anderson 2002), unless they were otherwise identical to the best model but contained one more parameter, in which case this rule is not appropriate (Burnham & Anderson 2002) and the more complex models were disregarded on the grounds of parsimony. Marginal coefficient of determination (R^2m, representing the variance explained by the fixed

effects) and conditional coefficient of determination (R^2c, representing the variance explained by both fixed and random effects; Nakagawa & Schielzeth 2013) were calculated for the best model in each candidate set. Analyses were performed in R, using packages lme4 (Bates et al. 2019) and MuMIn (Bartoń 2019).

3 Results

3.1 Species utilisation distribution

Maps of locations at sea (all fixes and non-flight fixes) and utilisation distributions based on those are provided in Fig. 4a-d (for guillemot), Fig. 5a-d (for razorbill), Fig. 6a-d (for puffin), and Fig. 7a-d (for kittiwake). Clear differences in distributions were apparent among the four species. The distribution of guillemots included both inshore and offshore areas, with core areas concentrated mainly around and to the east of the Isle of May, and within St Andrews Bay. Razorbills used areas offshore, mainly in an easterly direction from the colony, and to a lesser extent coastal areas within the Firth of Forth (Largo Bay) and St Andrews Bay. Puffin distribution was concentrated exclusively offshore, spanning areas from south-east to north-east direction from the Isle of May. Kittiwakes had a wider distribution than the three auk species, including offshore areas spread from south-east to north-east and north of the colony. Some kittiwakes were also found in waters within the St Andrews Bay, and five of the birds made trips of over 110 km from the colony. Accordingly, the mean maximum range (± SE) from the Isle of May was larger in the kittiwake (81.2 ± 4.2 km) than in any of the remaining species (guillemot: 38.9 ± 2.1 km, razorbill: 44.0 ± 3.1 km and puffin: 51.9 ± 3.0 km).

Within species, UDs generated from all GPS fixes and from non-flight fixes were generally very similar. This is expected since most locations at sea are associated with foraging or resting (i.e. non-flight) behaviours, whereas locations in flight represent a minority of fixes (guillemot 8%; razorbill 18%; puffin: 10% and kittiwake 25% within this dataset). Only in puffins there were some differences, with core areas based on non-flight fixes slightly more spatially segregated than those based on all fixes (Fig. 6 b,d).

3.2 Horizontal flight lines

Maps of horizontal flight lines are shown in Fig. 4e (for guillemot), Fig. 5e (for razorbill), Fig. 6e (for puffin) and Fig. 7e (for kittiwake). As expected, the distribution of flights lines matched closely with the UD distributions. Guillemots departed from and returned

to the colony on bearings ranging from southwest and north/northwest (for inshore foraging trips) to northeast and east (for offshore trips). A similar pattern was observed in razorbills although bearings of commuting flights during offshore trips were concentrated mainly to the east of the Isle of May. Flight bearings of puffins spanned from a north-easterly to south-easterly direction from the colony. Bearings of kittiwake commuting flights spanned from north-west to south-east of the colony.
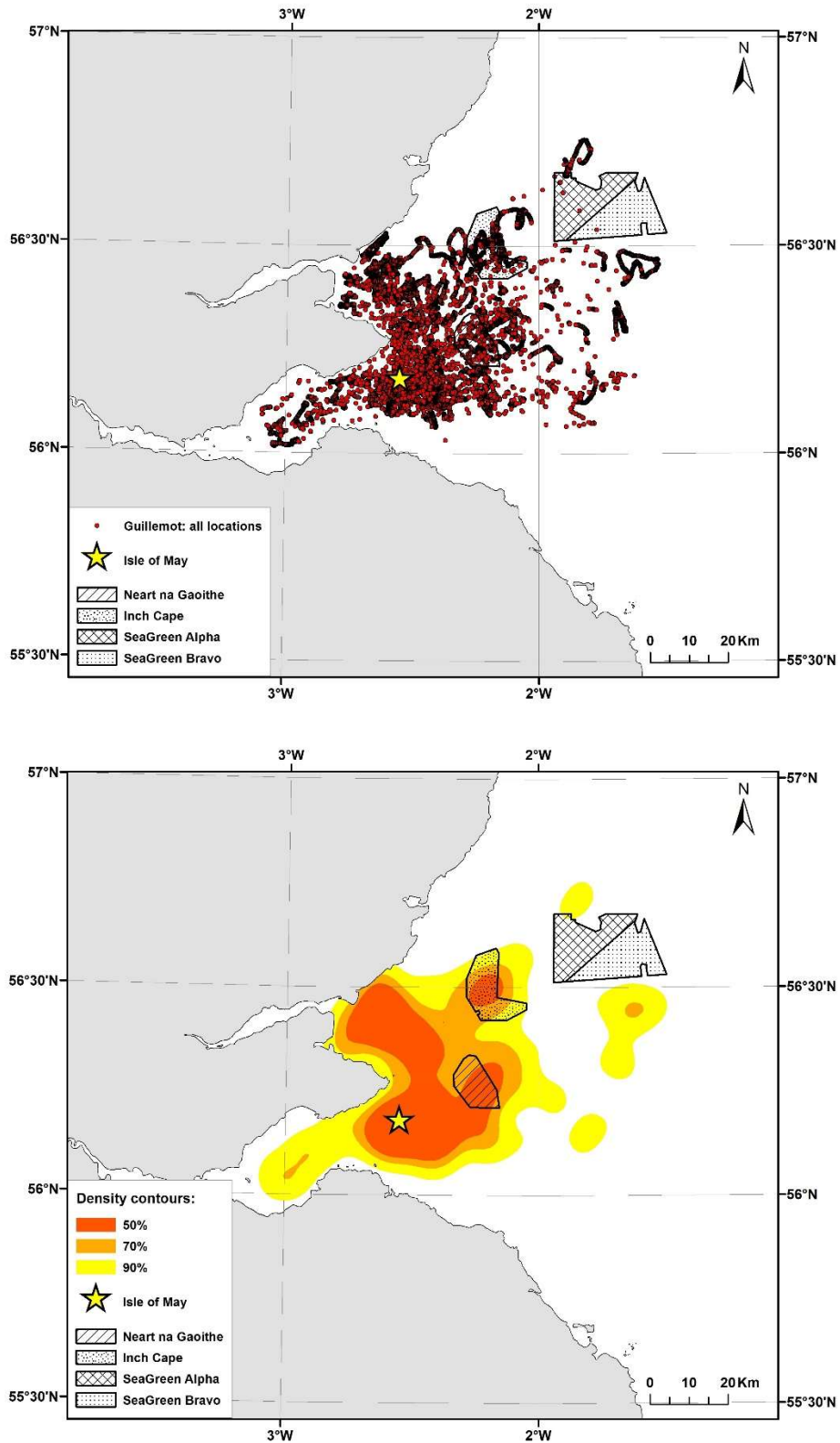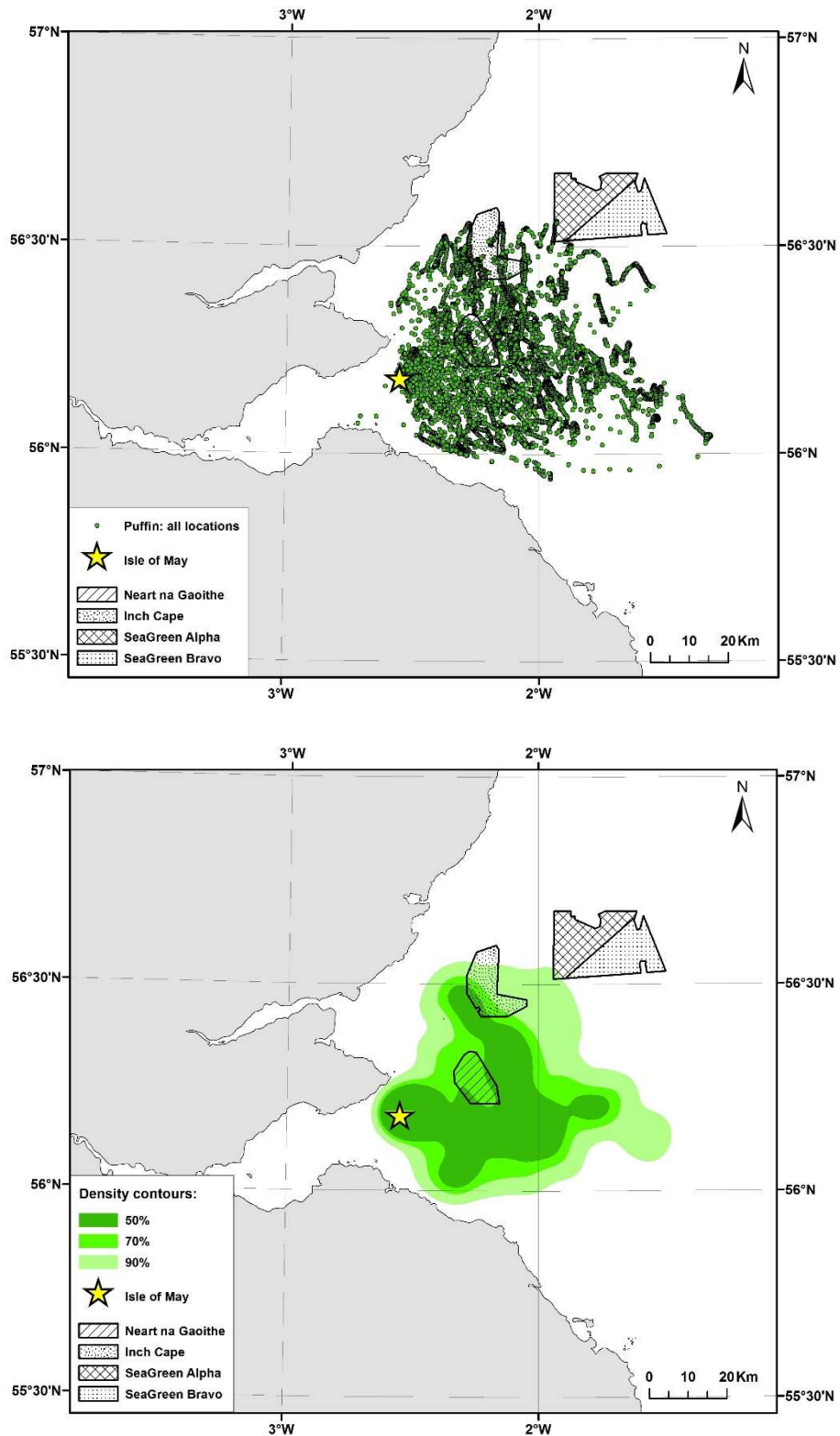
Fig. 4: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for guillemot for flight and non-flight behaviours combined.
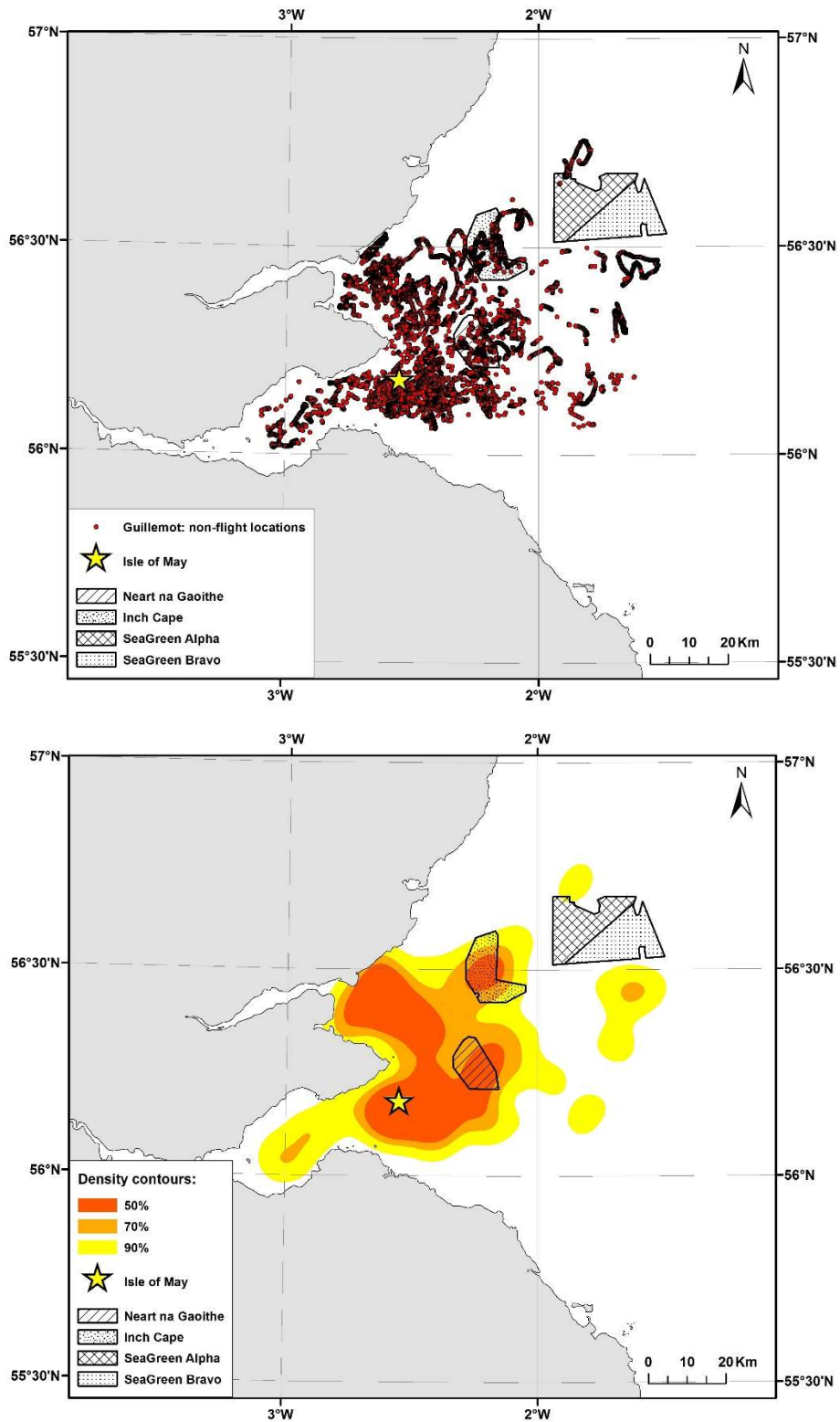
Fig. 4 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for guillemot for non-flight behaviours only.
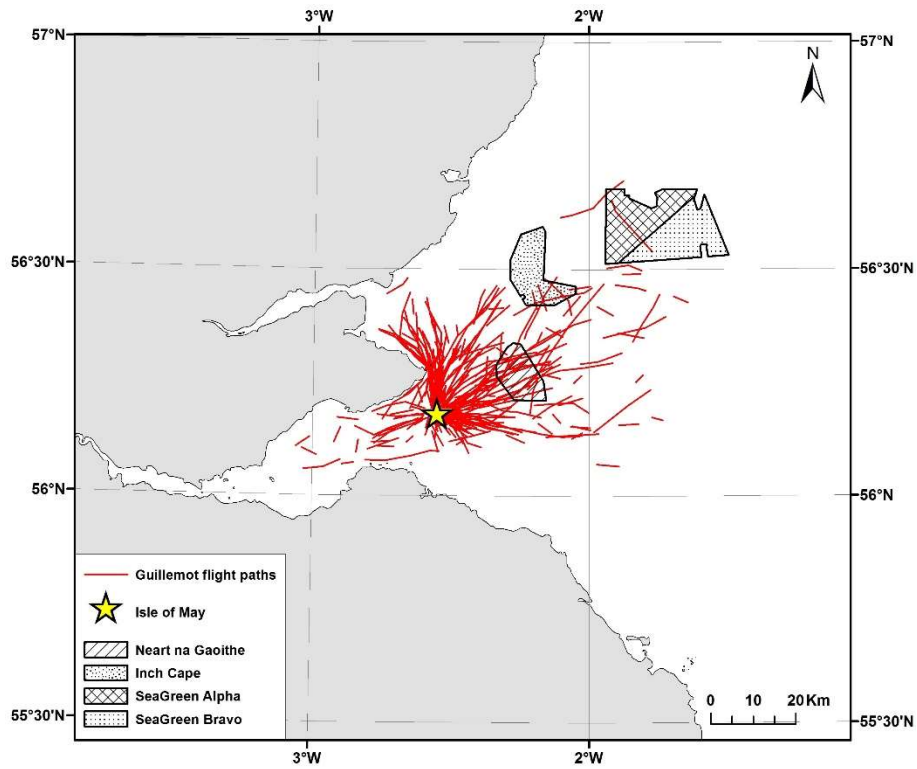
Fig. 4 (cont.): e) Horizontal flights lines for guillemot.
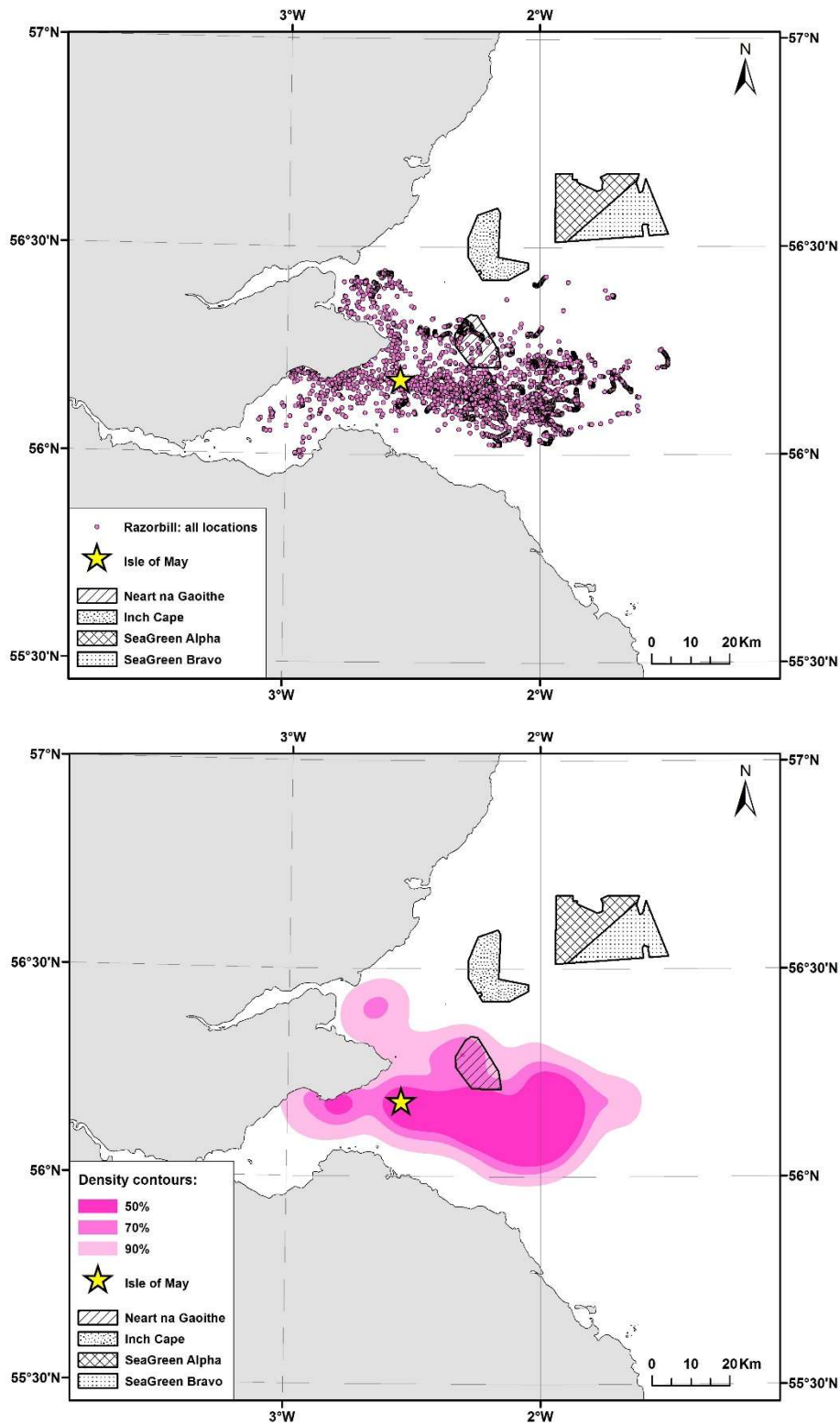
Fig. 5: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for razorbill for flight and non-flight behaviours combined.
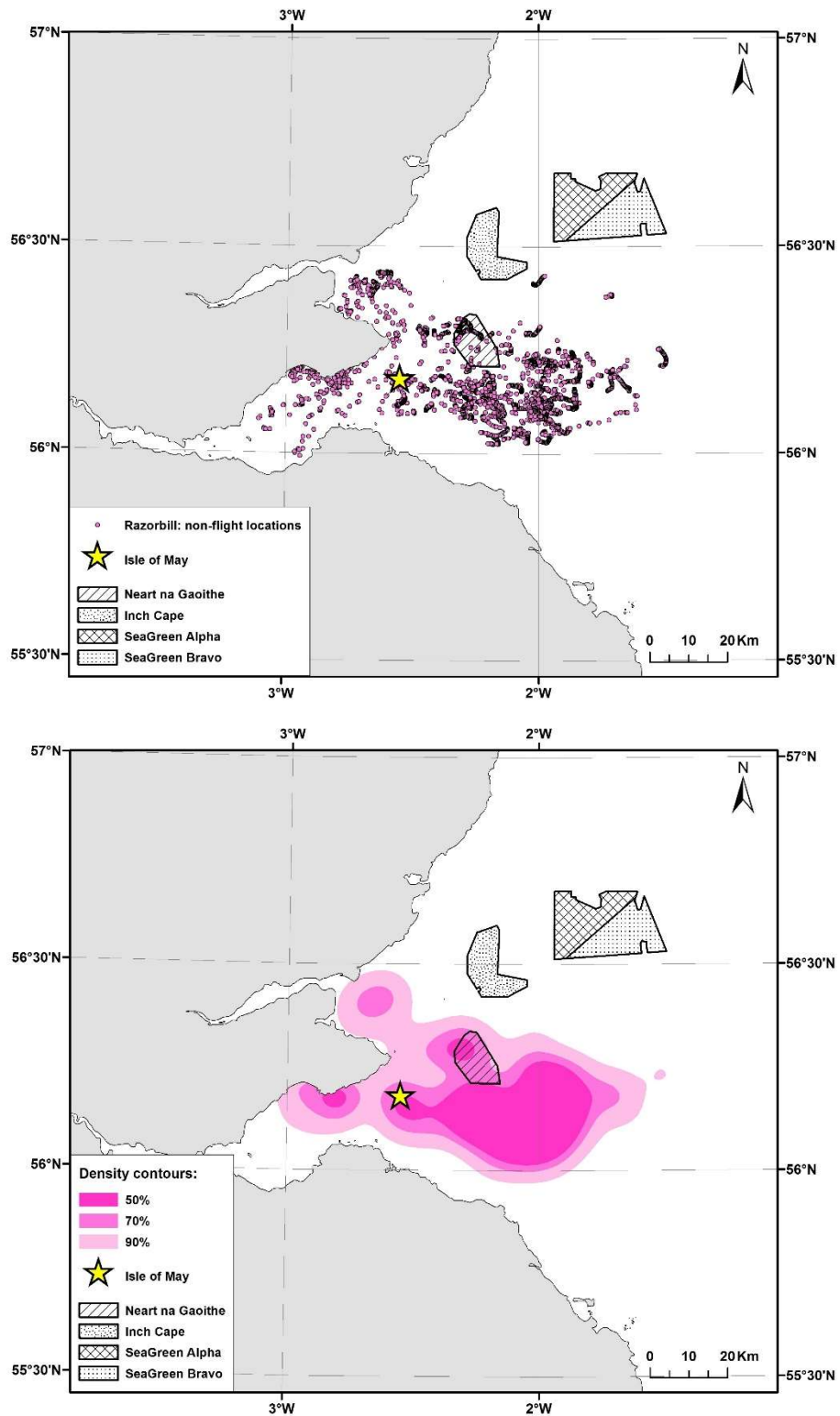
Fig. 5 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for razorbill for non-flight behaviours only.
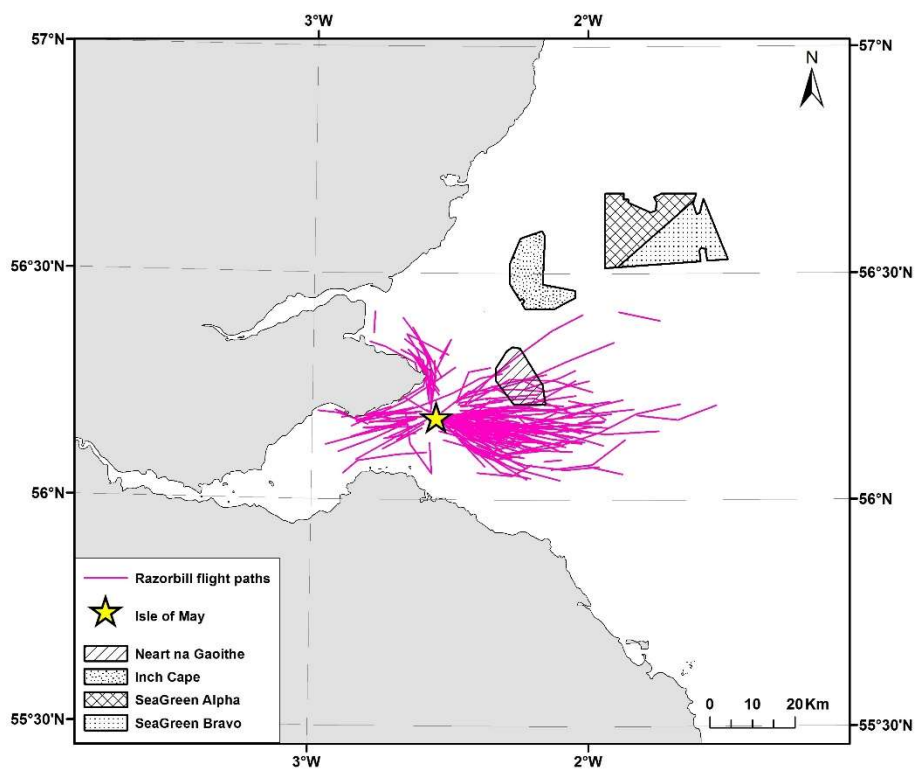
Fig. 5 (cont.): e) Horizontal flights lines for razorbill.

Fig. 6: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for puffin for flight and non-flight behaviours combined.
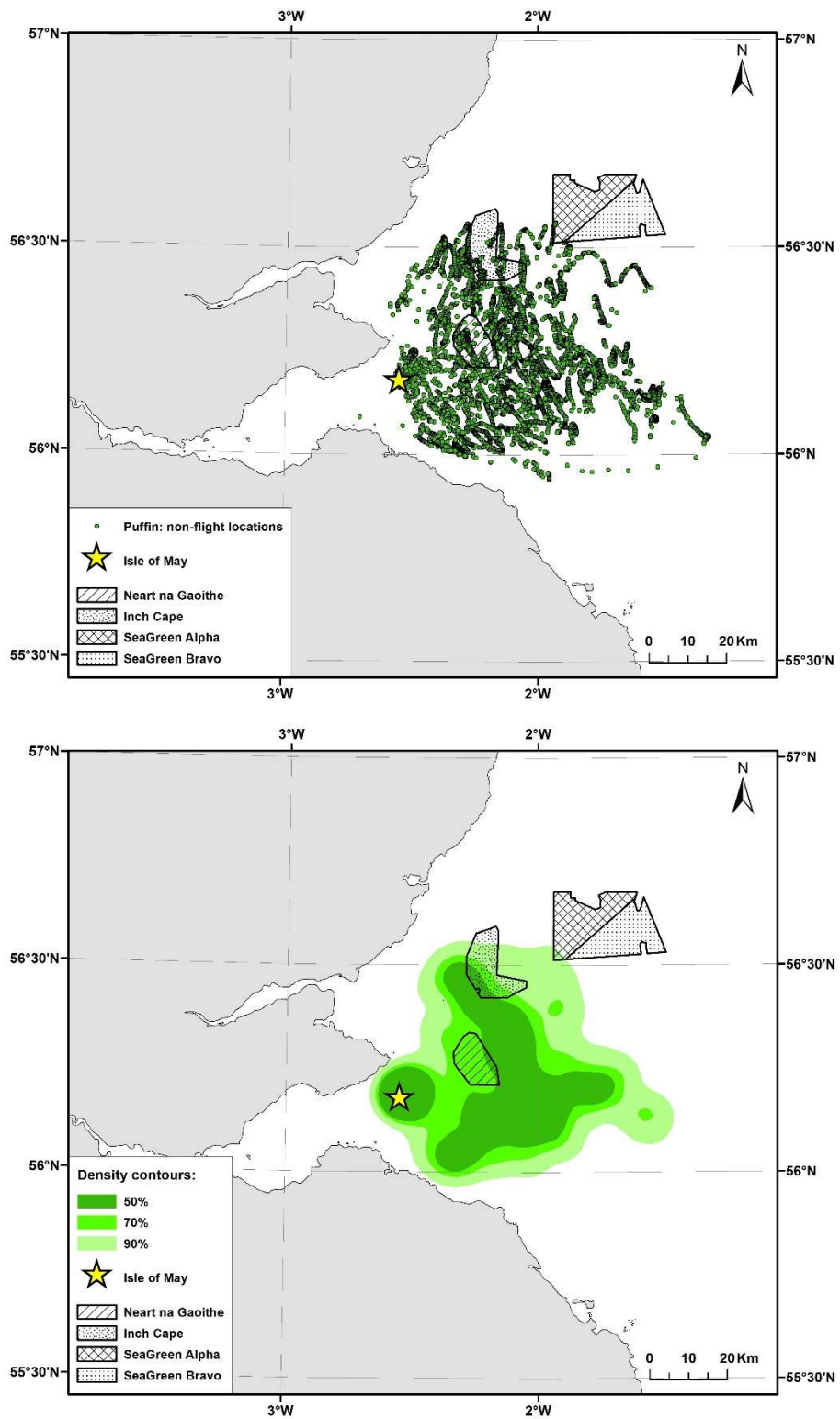
Fig. 6 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for puffin for non-flight behaviours only.
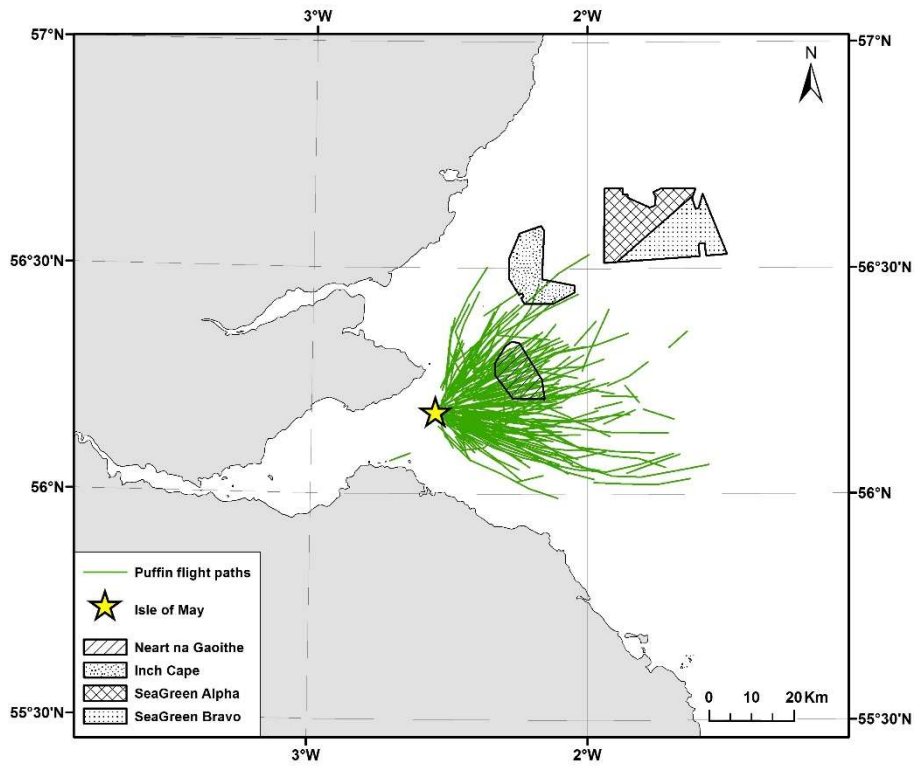
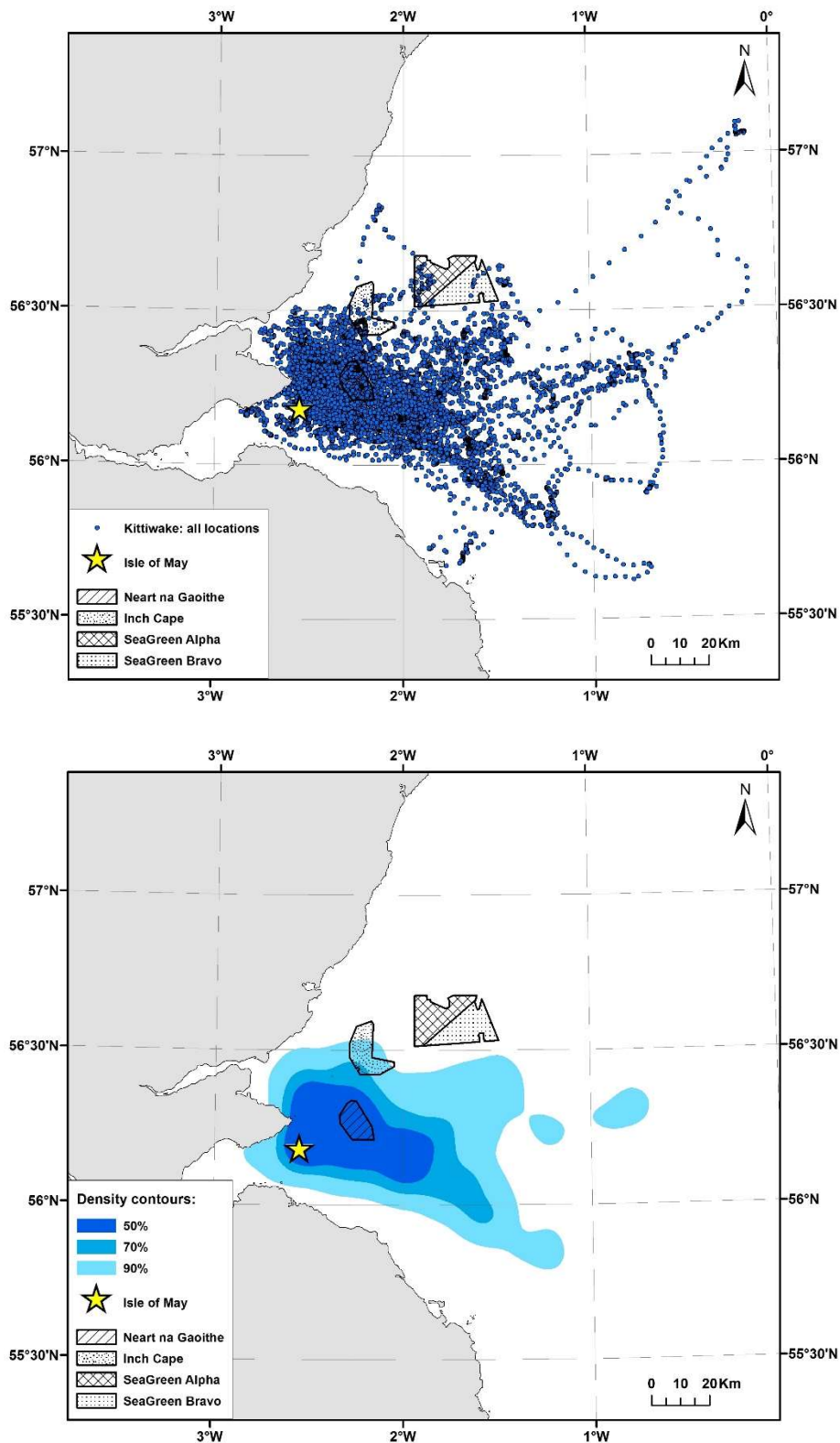*Fig. 6 (cont.): e) Horizontal flights lines for puffin.*

Fig. 7: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for kittiwake for flight and non-flight behaviours combined.
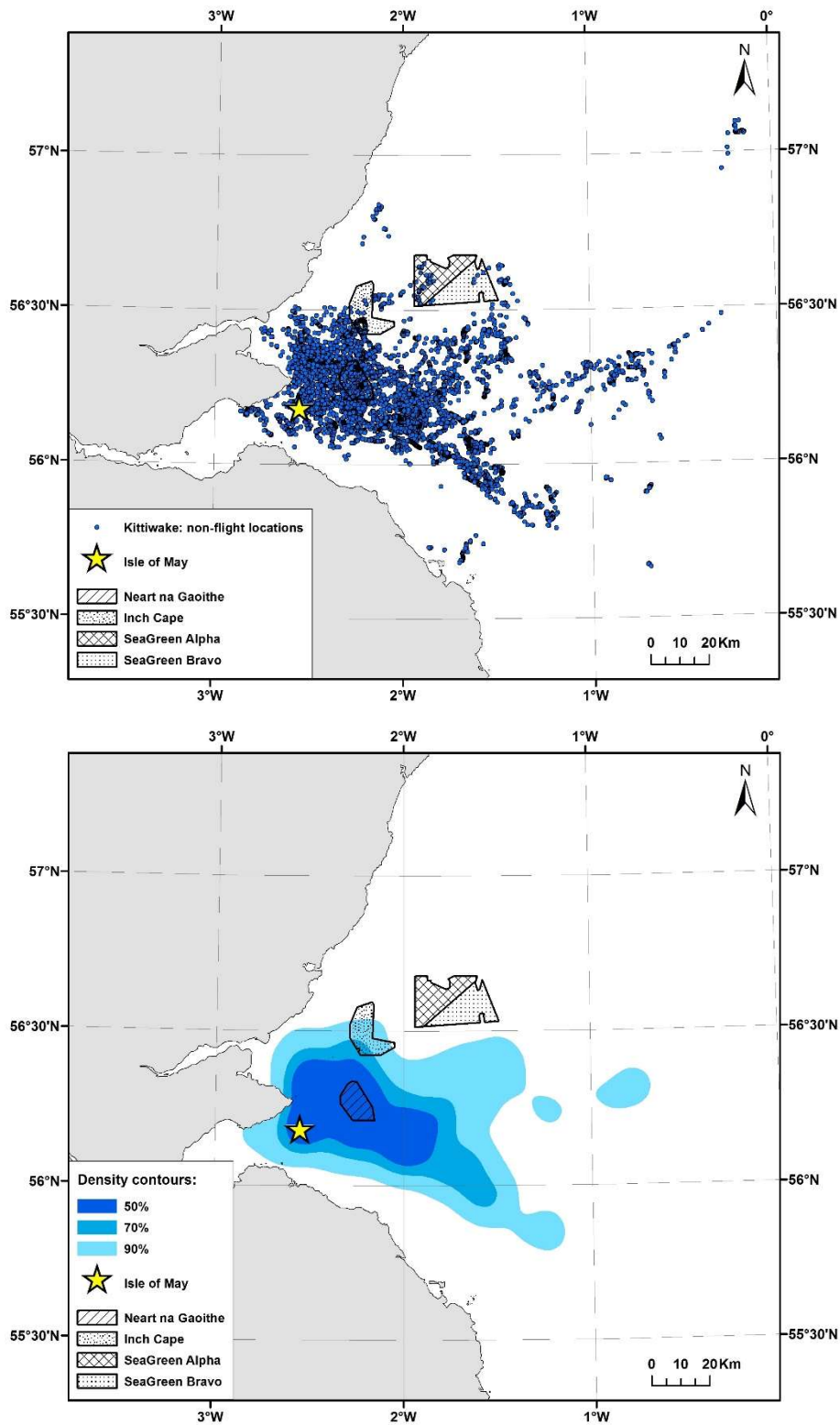
Fig. 7 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for kittiwake for non-flight behaviours only.
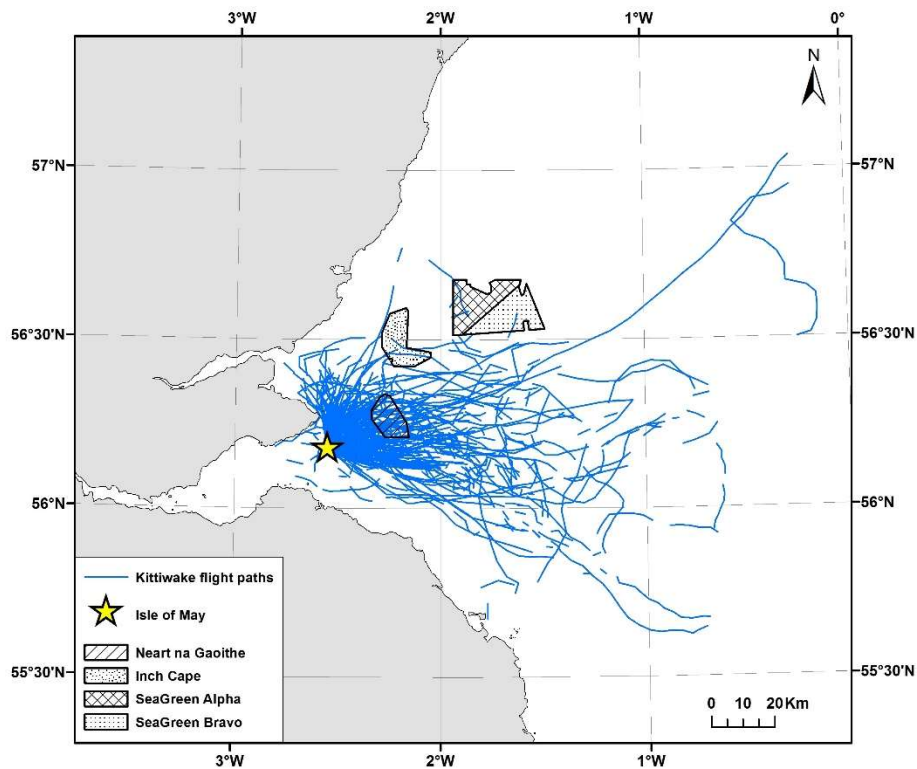
Fig. 7 (cont.): e) Horizontal flights lines for kittiwake.

3.3 Minimum adequate sample size

In guillemots, the resampling procedure using 90% density contours indicated a substantial increase of at-sea area used with sample size up to around 7 birds, after which the increment with each additional bird was smaller (Fig. 8a). Accordingly, the cumulative percentage of area used displayed the expected non-linear increase (Fig. 8b). Randomized samples of 7 birds covered 82.5% of the area identified using all study birds (Fig. 8b). In razorbills, a substantial increase of area used was observed up to a sample size of 6 birds, after which the area size plateaued (Fig. 9a). This pattern was reflected in the cumulative percentage of area used, with randomized samples of 6 birds covering 99.2% of the area identified using all study birds (Fig. 9b). In puffins, area used increased substantially up to a sample size of 7 birds, after which the increment with each additional bird was smaller (Fig. 10a). Randomized samples of 7 birds captured 93.3% of the area identified using all study birds (Fig. 10b). In kittiwakes, area used increased substantially up to a sample size of 7 birds, after which the increment with each additional bird was smaller and eventually the

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area size plateaued at a sample size of around 15 birds (Fig. 11a). Randomized samples of 7 birds captured 94.1% of the area identified using all study birds (Fig. 11b).

It is important to note that the estimates outlined above describe the mean values, yet there was considerable variation in area used at small sample sizes (Figs. 8-11). Resampling was done without replacement, so the percentiles around the median become narrower with increasing sample size and eventually there is no variation in area used with the largest sample size. This is because increasing sample size reduces sampling variance resulting in large samples being increasingly similar to each other and identical at the largest sample size.
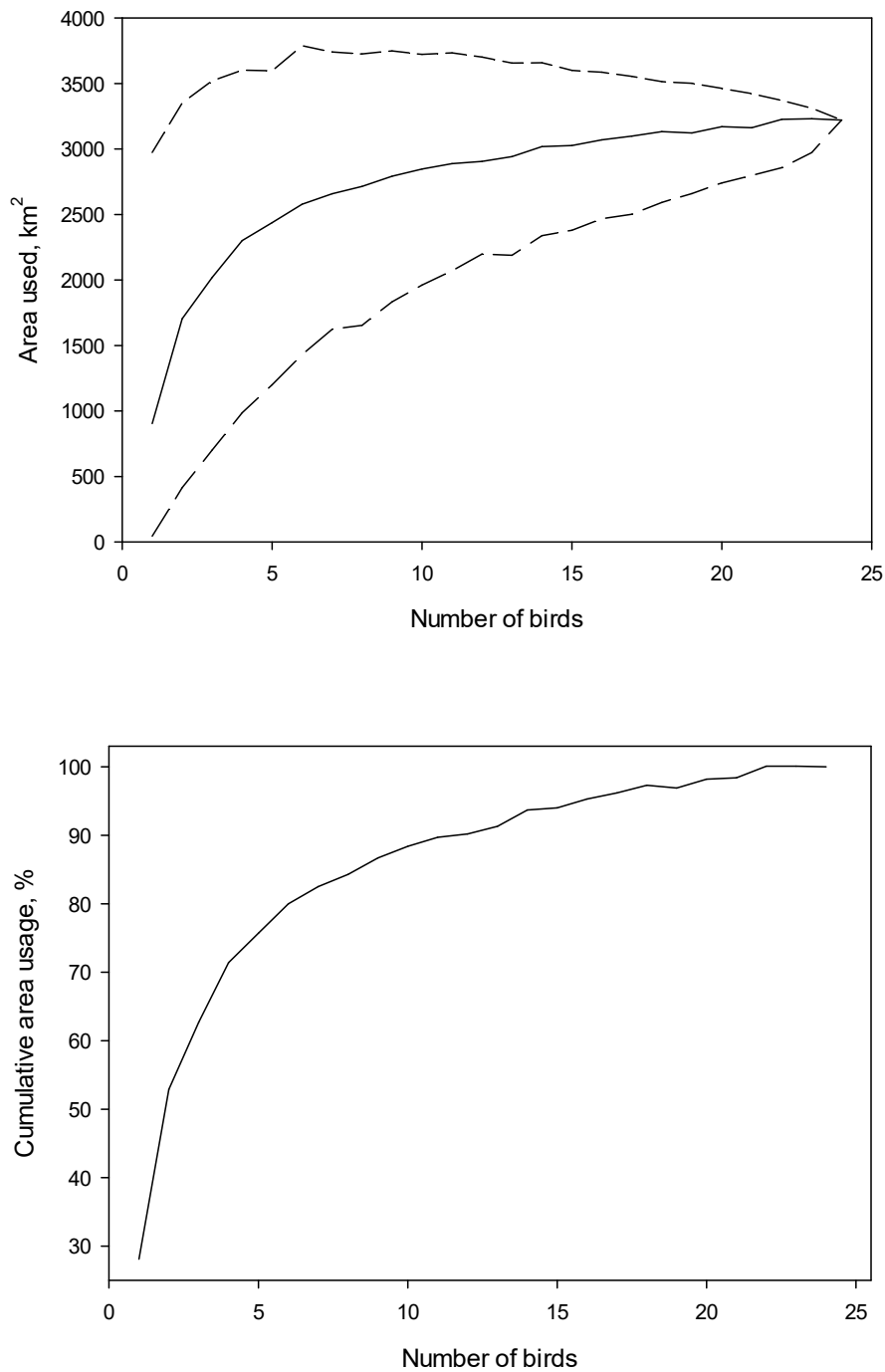
Fig. 8: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in guillemots. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.
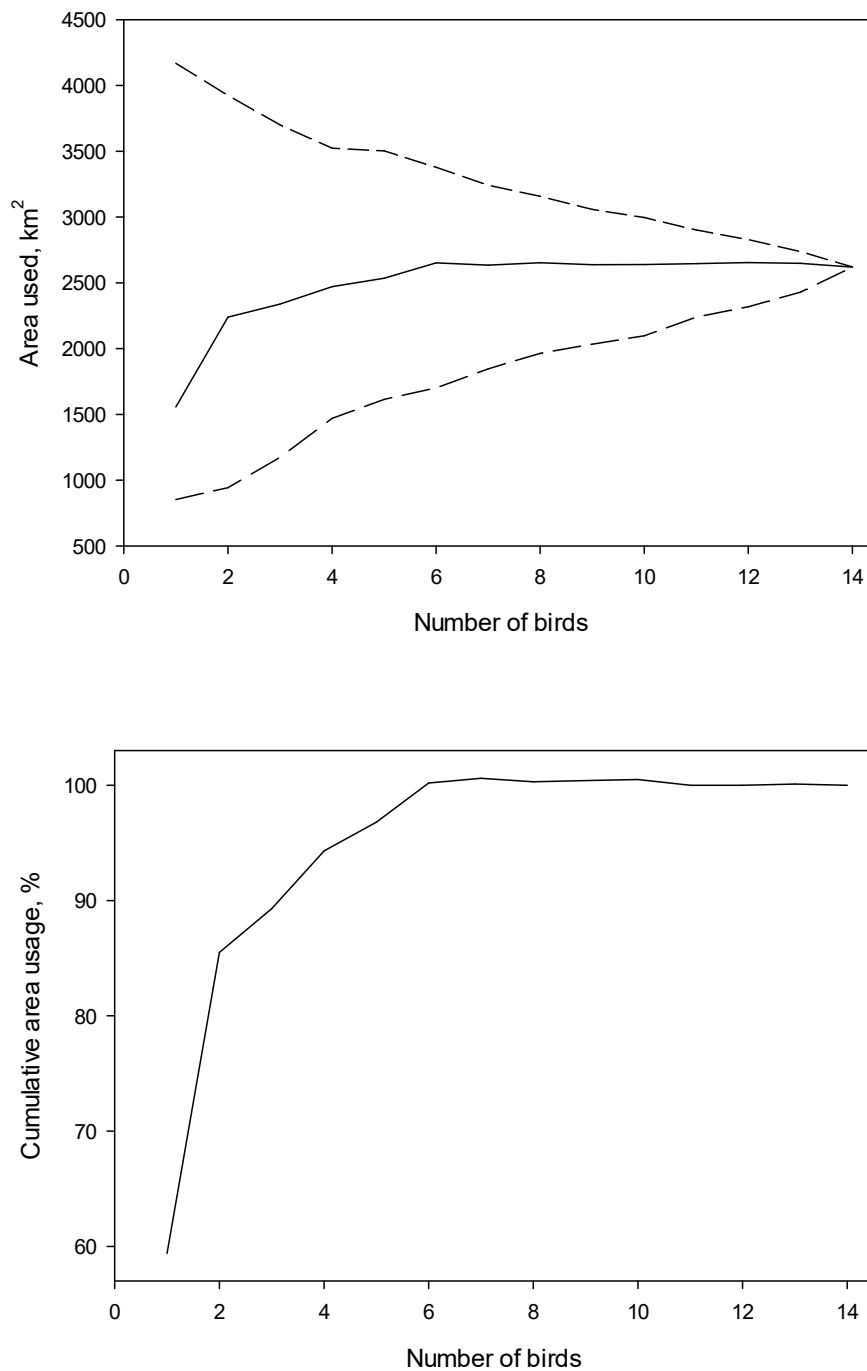
Fig. 9: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in razorbills. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.
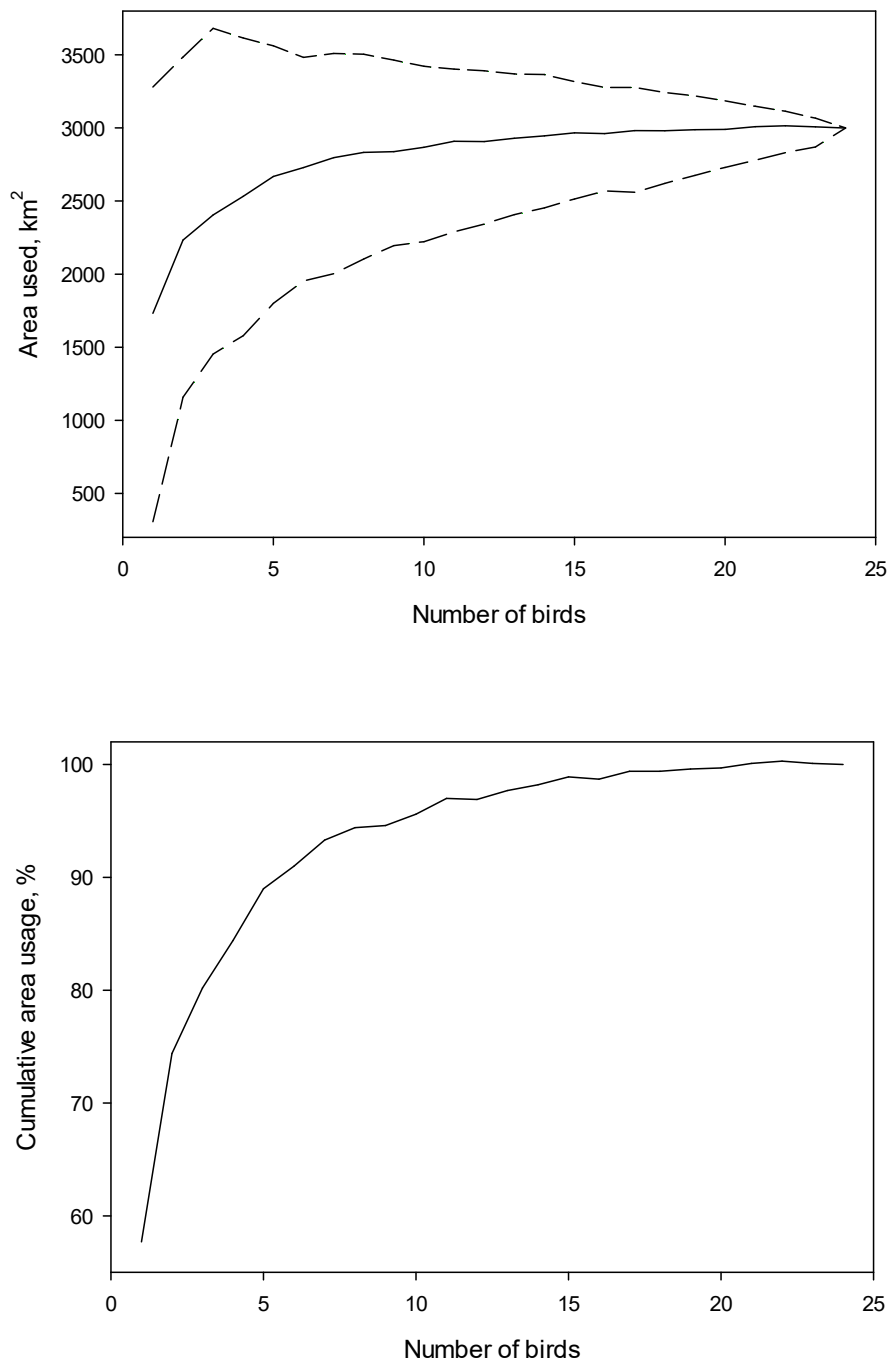
Fig. 10: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in puffins. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.

Fig. 11: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in kittiwakes. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.
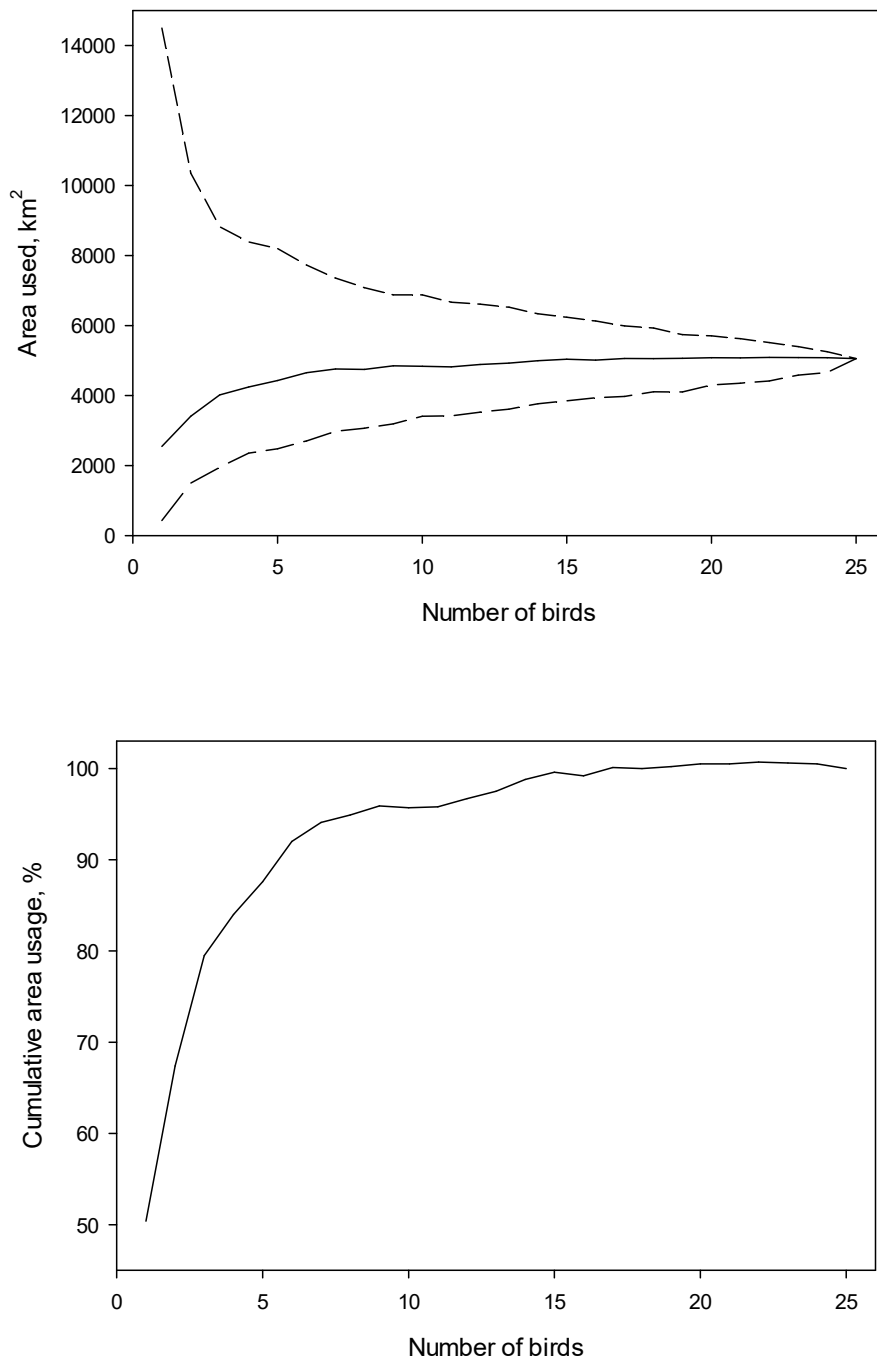
3.4 Overlap with Neart na Gaoithe footprint

3.4.1 Utilisation distribution

The percentage overlap of non-flight UD with the planned Neart na Gaoithe windfarm footprint is shown in Table 7. A very small proportion of the core areas used (50% UD contours) by razorbills and puffins overlapped with the footprint, whereas in guillemots and kittiwakes the overlap was larger. The proportion of the overall area used at sea (90% UD contours) that overlapped with the planned wind farm footprint was also small (less than 5% in all four species). However, note that the entire planned Neart na Gaoithe footprint fell within the 90% UD contours of all four species.

Species UD	Figure	UD area (km^2)	Neart na Gaoithe	
			UD overlap (km^2)	UD overlap (%)
a) Guillemot				
50% contour		948.5	68.7	7.2
90% contour		3221.6	105.2	3.3
b) Razorbill				
50% contour		819.0	3.0	0.4
90% contour		2618.0	105.0	4.0
c) Puffin				
50% contour		1128.0	21.4	1.9
90% contour		2999.4	105.2	3.5
d) Kittiwake				
50% contour		1166.3	105.2	9.0
90% contour		5054.0	105.2	2.1

Table 7. Overlap between bird utilisation distribution (50% and 90% non-flight UD contours) and planned Neart na Gaoithe OWF, expressed as area of overlap and % of the UD area covered by the windfarm footprint.

3.4.2 Horizontal flight lines

The proportion of birds, trips and flights passing through the planned Neart na Gaoithe footprint is shown in Table 8. In terms of number of birds, all four species used the planned Neart na Gaoithe site extensively, and this was particularly so for kittiwakes and puffins where 75% or more of the study birds passed through the planned wind farm area. In comparison, this figure was 50% for guillemots and 57% for razorbills. At the trip level, the extent of overlap was smaller in all species but a similar pattern was apparent, with proportion of trips involving movements through the planned wind farm footprint higher in kittiwakes and puffins and lower in razorbills and guillemots. At the level of individual flights, overlap was highest in puffins, followed by kittiwakes and guillemots, and lowest in razorbills. The lower overlap of guillemot and razorbill flight activities with the planned Neart na Gaoithe footprint is likely due to these species having a partially inshore distribution.

Category	Figure	n	% flights within Neart na Gaoithe
a) Guillemot			
Bird		24	50.0
Trip		120	17.5
Flight		521	7.7
b) Razorbill			
Bird		14	57.1
Trip		129	10.9
Flight		340	4.7
c) Puffin			
Bird		24	75.0
Trip		123	31.7
Flight		352	15.9
c) Kittiwake			
Bird		25	80.0
Trip		167	33.5
Flight		928	8.3

Table 8. Percentage of flight lines crossing the planned Neart na Gaoithe windfarm for each bird, trip and flight for each species.

Figure 12 shows the distribution of commuting flights that overlapped with the planned windfarm footprint. The correspondence between flight directions and the location of the Isle of May is apparent for all four species.

a)
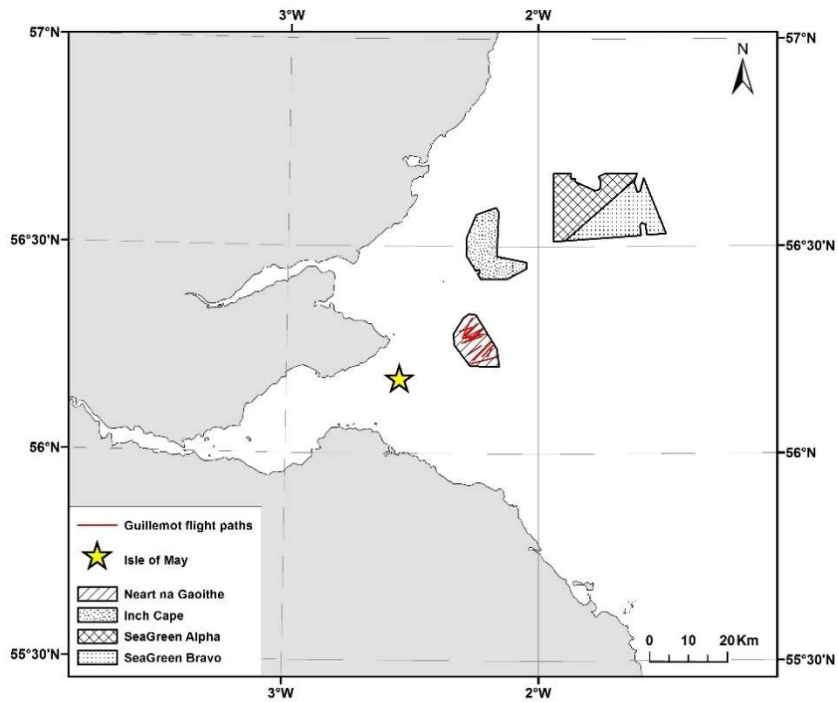
b)
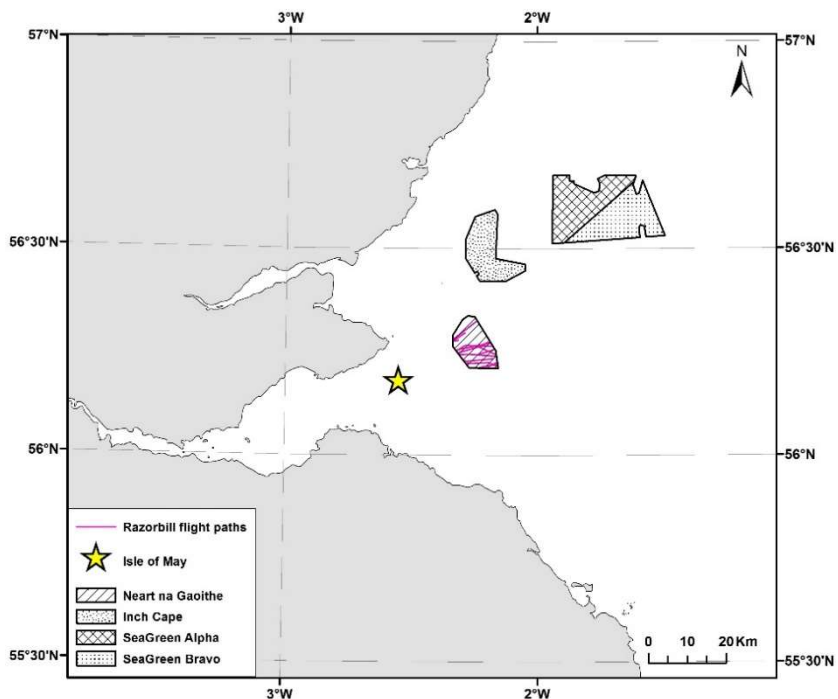
c)

d)

Fig. 12: Flights passing through the planned Neart na Gaoithe wind farm for a) guillemot, b) razorbill, c) puffin and d) kittiwake.

3.5 Device effects in puffins

3.5.1 Chick feeding rates

We were not able to test directly for effects of treatment on individual feeding rates because we could not obtain data from unmarked control birds. Among puffins that received colour rings or a combination of GP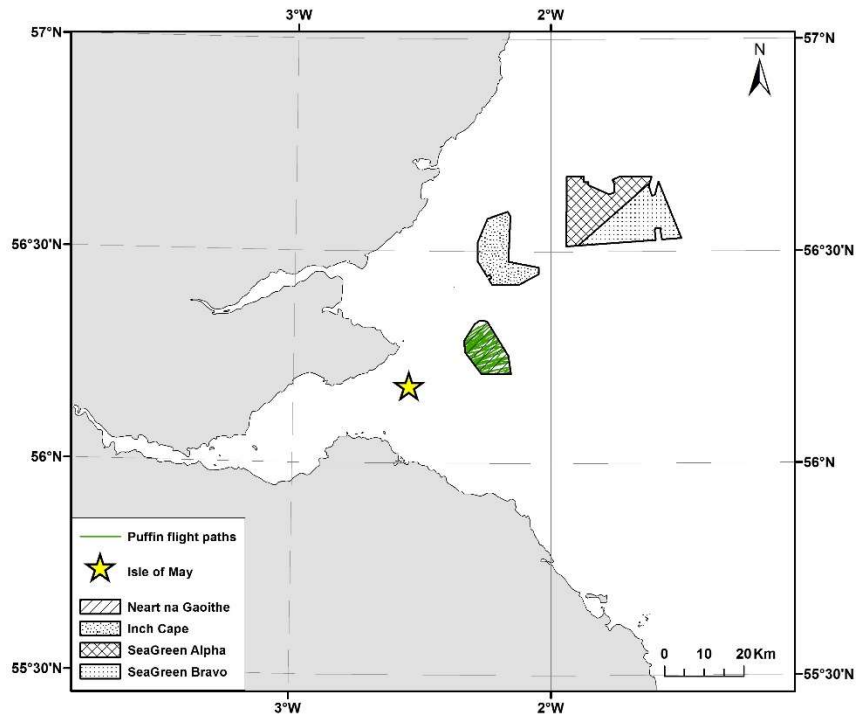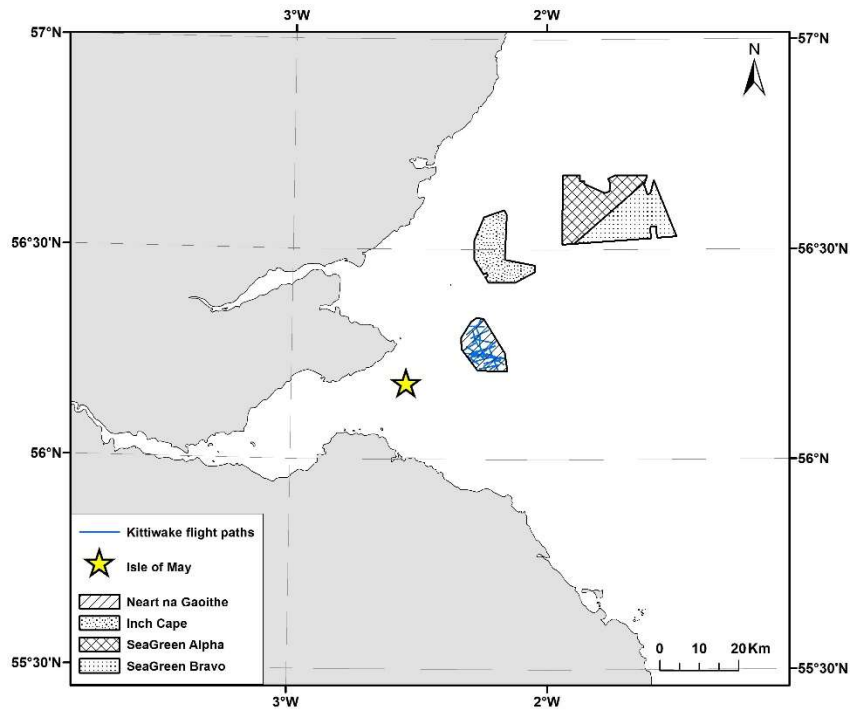S logger and colour rings, there was weak evidence for an effect of treatment on feeding rate. The proportion of feeds per observation day delivered by birds tagged with GPS loggers was slightly lower compared to ones that received colour rings only (Fig. 13, Table 9). However, pair members normally share chick provisioning duties equally (Harris & Wanless 2011), therefore if the tagged birds were unaffected they would be expected to provide on average 50% of the daily feeds. Instead, colour-ringed birds provided a median of 25% and logger birds 0% of the daily feeds, suggesting there may be substantial negative effects of device deployment at the individual level.
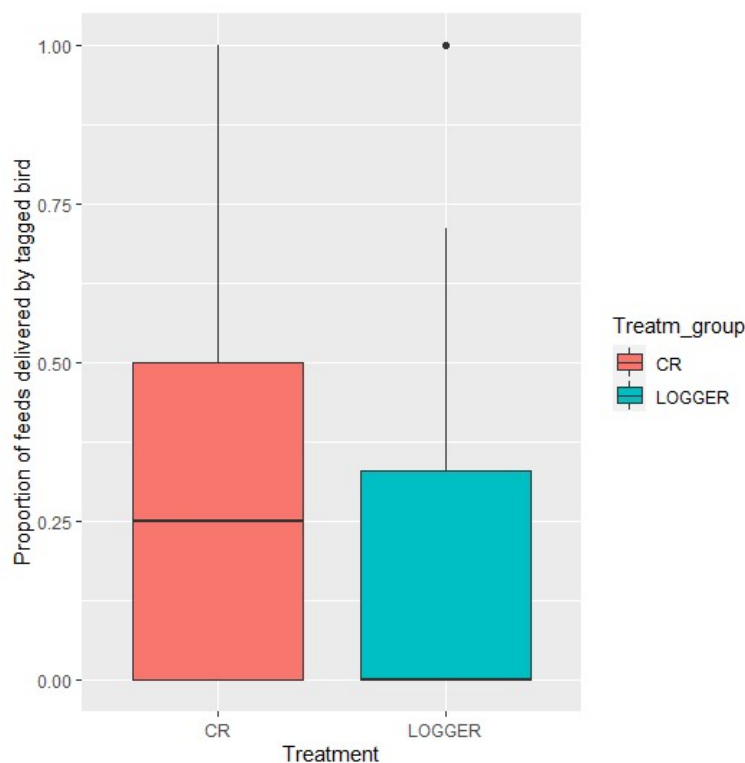

Fig. 13: Proportion of feeds delivered to chicks per observation day in relation to treatment (colour-ringed (CR): n=11; logger: n=23 pairs).

The proportion of daily feeds delivered by individuals in the two treatment groups did not change within the first four days since the tag was deployed/colour ring fitted (Table 9). There was some indication for an interaction between treatment and time since deployment but the evidence was again weak (Table 9).

The predictor variables explained negligible amount (1 to 2%) of the variation in proportion of daily feeds delivered to the chick (Table 9, see marginal coefficient of determination R^2m), indicating that feeding rates were largely determined by other variables not measured in this study. Linked to this, within the candidate set of models the intercept-only model (M5) had the lowest AICc value, followed by the model containing treatment only (M3) and the model containing treatment, day since deployment and the interaction between them (M1). Similar to the fixed effects, the random effects of 'burrow identity' and 'day' explained very little of the variation in proportion of daily feeds (Table 9, see conditional coefficient of determination R^2c).

Model	AICc	N parameters	Parameter estimate (± SE)			R^2m	R^2c
			Treatment	Day since deployment	Treatment × day since depl.		
M5	**212.9**	**3**	**-**	**-**	**-**	**0**	**0.05**
M3	213.6	4	-0.43 ± 0.35	-	-	0.01	0.05
M1	214.3	6	0.99 ± 0.85	0.93 ± 0.51	- 0.54 ± 0.29	0.02	0.06

Table 9. Generalised linear mixed models testing for effects of treatment and time since deployment on proportion of daily feeds delivered to puffin chicks. The best model (in bold) and models within 2 AICc units of the best model are presented.

At the pair level, chick feeding rate was affected by treatment but not by time since logger deployment/ring attachment. The number of daily feeds was reduced in pairs where one bird was tagged with a GPS logger compared to control (unmanipulated) pairs (Fig. 14, Table 10). There was no major difference in number of feeds between pairs where one bird was colour-ringed and control pairs (Fig. 14, Table 10).
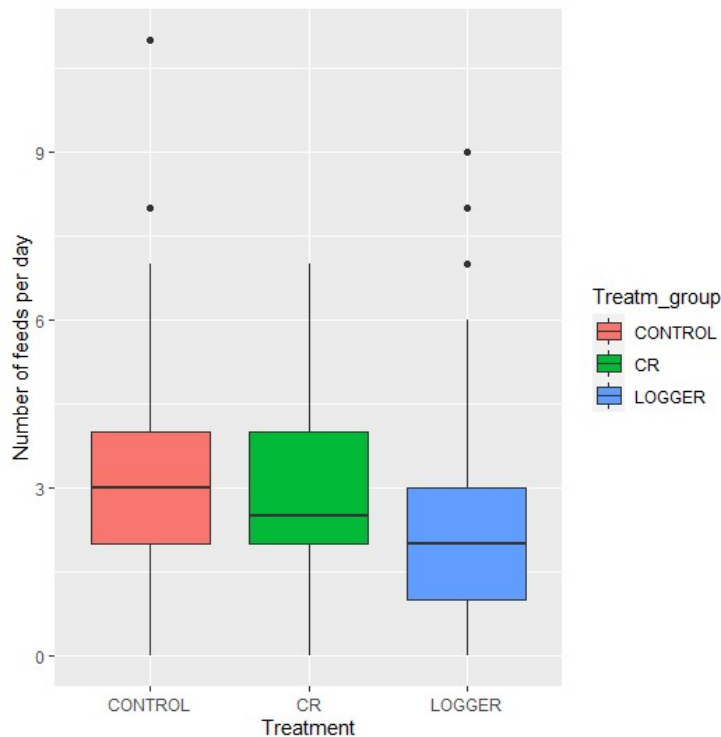
Fig. 14: Number of feeds per observation day delivered by the pair in relation to treatment (control: n=57, colour-ringed (CR): n=11, logger: n=23 pairs).

Despite the difference in feeding rate between 'logger' and control pairs, treatment explained a very small amount (2%) of the variation in number of daily feeds delivered to the chick (Table 10, R^2m). A much larger amount of the variation in the response variable was explained by the random effects in the models ('burrow identity' and 'day'; Table 10, R^2c).

| Model | AICc | N parameters | Parameter estimate (± SE) | | | R^2m | R^2c |
			Treatment *	Day since deployment	Treatment × day since depl.		
M3	**1429.2**	**5**	**CR (-0.06 ± 0.17)** **Logger (-0.27 ± 0.13)**	**-**	**-**	**0.02**	**0.31**
M4	1429.5	3	-	-	-	0	0.31

* Parameter estimates for each treatment level are relative to the control group

Table 10. Generalised linear mixed models testing for effects of treatment and time since deployment on the number of daily feeds delivered to puffin chicks. The best model (in bold) and models within 2 AICc units of the best model are presented.

Models including two binary variables for 'handling' (control vs colour ring and logger) and 'device' (control and colour ring vs logger) effects supported the conclusions from the first analysis where we used a 3-factor treatment variable, suggesting the treatment effect on feeding rates was mainly driven by logger deployment. Time since deployment (within the first 4 days) did not affect feeding rates. The best model within the candidate set included 'device' effect only (Table 11). Two other models were within 2 AICc units of the best model (Table 11).

Model	AICc	N parameters	Parameter estimate (± SE)			R^2m	R^2c
			Treatment device	Treatment handling	Day since deployment		
M9	**1427.3**	**4**	**-0.26 ± 0.12**	**-**	**-**	**0.02**	**0.31**
M8	1428.4	4	-	-0.19 ± 0.11	-	0.01	0.31
M6	1429.1	5		-0.30 ± 0.14	0.07 ± 0.06	0.02	0.31

Table 11. Generalised linear mixed models testing for effects of treatment type (handling vs device) and time since deployment on the number of daily feeds delivered to the chick. The best model (in bold) and models within 2 AICc units of the best model are presented.

3.5.2 Chick condition and survival

Despite the reduction in feeding rates by pairs in the logger compared to control group, there was no effect of treatment on chick fledging condition (likelihood ratio test between the model with treatment and an intercept only model: χ^2= 1.31, df=2, P=0.52) or survival (χ^2=1.33, df=2, P=0.51), indicating that the supplementary feeding carried out as part of the study was successful at compensating for the negative effects of device deployment.

Puffin chicks in the three treatment groups fledged in similar condition and had high survival rate (Table 12). At control burrows all chicks except 3 fledged, at 'colour-ring' burrows all fledged, and at 'logger' burrows all except one fledged successfully. The

single chick that died in the 'logger' group looked unwell and was not growing normally so its death was most likely unrelated to our study.

	Control	CR	Logger
Fledging condition	0.120 ± 0.003 (37)	0.116 ± 0.003 (8)	0.115 ± 0.004 (17)
Chick survival	93 (40)	100 (8)	96 (26)

Table 12. Condition at fledging (mean ± SE) and survival (%) of puffin chicks in relation to treatment. Sample sizes are shown in brackets.

3.6 Device effects in kittiwakes

3.6.1 Foraging trip duration

Foraging trip duration in kittiwakes was not associated with treatment but differed between breeding stages. As previously shown in this species, trips during incubation were longer than those during chick rearing (the best-supported model contained breeding stage only: parameter estimate ± SE: -2.43 ± 0.45, R^2m: 0.24, R^2c: 0.25; Table 13a). There was no difference between treatment and control pairs in trip duration (Table 13b). Time since logger deployment had no effect on trip duration either.

Predictor	N pairs	N trips	% short	% long
a) Breeding stage				
- incubation	47	129	36	64
- chick rearing	20	57	86	14
b) Treatment				
- logger	25	83	43	57
- control	42	103	58	42

Table 13. Percentage of short and long foraging trips in kittiwakes in relation to breeding stage and treatment.

The analysis using trip duration as a continuous response produced very similar results and supported these conclusions.

3.6.2 Chick condition and breeding success

There was no evidence for treatment effect on chick condition 2 to 3 weeks after logger deployment (Table 14b). In nests where both chicks survived at the time of measurement, second-hatched chicks were in better condition compared to first-hatched chicks (the best-supported model contained brood order only: parameter estimate ± SE: 0.19 ± 0.05, R^2m: 0.05, R^2c: 0.93; Table 14a). There was no interactive effect between treatment and brood order.

Explanatory variable	N pairs	N chicks	Median condition
a) Brood order			
- first-hatched	-	22	0.49
- second-hatched	-	10	1.01
b) Treatment			
- logger	8	12	0.75
- control	14	20	0.54

Table 14. Median condition of kittiwake chicks 2 to 3 weeks after logger deployment in relation to position in the brood order and treatment.

Treatment and control pairs had a similar breeding success (in both groups the median number of chicks fledged per nest was 1; likelihood ratio test between the model with treatment and an intercept only model: χ^2=0.61, df=1, P=0.44).

4 Discussion

4.1 Data collection

As in 2018, the remote-download GPS technology performed very well. Tracks were obtained from 98% of study individuals (vs 93% in 2018) whereas only 60% of individuals contributed data using archival loggers in 2010 (Daunt et al. 2011a). Data gaps where data could not be recovered by the logger manufacturers and may have resulted in missing a small number of foraging trips were present only in seven birds (8% of all successful deployments).

4.2 Utilisation distributions

The at-sea distributions of the four study species encompassed both inshore and offshore areas, as previously found on the Isle of May (Daunt et al. 2011a, Harris et al. 2012, Bogdanova et al. 2018) and at other UK breeding colonies (Robertson et al. 2014, Shoji et al. 2016, Wakefield et al. 2017). Differences among the species were apparent, in that guillemots and razorbills used coastal as well as offshore areas whereas puffins and kittiwakes were concentrated mainly in offshore areas. These differences most likely reflect variation in foraging strategies (including factors such as flight costs, foraging effort, foraging mode and diet; Thaxter et al. 2013, Wanless et al. 2018). The core areas used by all four species included the area around the Isle of May, suggesting that food resources were available in the vicinity of the colony. Horizontal flight lines during commuting flights showed the predicted directional movement to and from the colony, particularly for foraging trips offshore. At the foraging grounds, the headings of flight lines became more variable most likely due to birds moving between foraging patches.

The resampling analysis suggests that the sample size of individuals we tracked is adequate to estimate the at-sea area used by the local populations of all four species during the period of deployment. It is therefore likely that we have captured the key areas used by Isle of May seabirds for both flight and non-flight activities at that time. An exception may be the puffin because of the device effects observed, which we

discuss in detail in Section 4.4. It is important to note that the period over which the birds were tracked was relatively short (deployments took place over 1 to 7 days; average deployment duration was up to 6 days) so caution is required if interpreting these distributions as representative of periods outside the study period.

In 2019, distributions in all four species were similar to those observed in 2018 (Bogdanova et al. 2018). However, a comparison to earlier years (2010, 2012-2014; Daunt et al. 2011a, Harris et al. 2012, Appendix to this report) shows that there is significant inter-annual variation within each of the species. The inter-annual differences are likely due to variation in environmental conditions among years, particularly the distribution and availability of prey. Adult lesser sandeels are one of the main prey species of the Isle of May seabirds (Wanless et al. 2018), and tend to be closely associated with sandy substrates (Wright et al. 2000), so areas where the birds forage on these (and hence overlap with sandy benthic habitats) can be expected to be relatively consistent/predictable among years. However, during chick rearing (when the majority of logger deployments took place) most species switch to feeding on the young of the year (0 group) sandeels that are not so closely associated with sandy habitats (Wright et al. 2000). Furthermore, large-scale processes such as climate warming have resulted in dramatic changes in the North Sea over the last few decades (Beaugrand et al. 2008). As a result, the abundance and quality of lesser sandeels has declined and, linked to that, new evidence shows that seabird diet has diversified to include other prey such as Clupeids (Wanless et al. 2018). Such changes in diet, with an increasing focus on alternative prey to adult sandeels, are likely to result in inter-annual differences in foraging distributions.

4.3 Connectivity with Neart na Gaoithe

A relatively small proportion of the core utilisation distributions of Isle of May seabirds overlapped with the planned Neart na Gaoithe footprint (<10% in all study species). Key foraging areas were concentrated around the colony, near the coast and at offshore sand banks but also substantially overlapped with the wind farm footprint in the case of kittiwakes and guillemots. Furthermore, the entire planned wind farm

footprint fell within the overall areas used by all four species indicating the potential for interaction with the seabird breeding populations on the Isle of May. Substantial overlap was observed also for flight activities, with at least 50% of individuals from each species crossing the wind farm footprint at least once during the deployment period. This suggests that Neart na Gaoithe may potentially pose a higher risk for collision and barrier effects than displacement. Recent research of flight heights (Johnston et al. 2014) indicates that collision risk is higher for kittiwakes than for the auk species. Barrier effects may operate on all four species, for birds en route to foraging areas further offshore. However, our data suggest that this effect may be less apparent for guillemots and razorbills due to their partially inshore distribution. The strong directionality of flights passing through the planned Neart na Gaoithe footprint, associated with the location of the Isle of May, could potentially help inform the use of array designs that reduce collision and barrier effects. However, if birds from other SPAs commute to and from their respective colonies through the same areas, their flight directions would be different which could make the choice of optimal array design a more complex task (Daunt et al. 2011b).

The impacts of offshore wind farms on seabirds can be positive or negative (Inger et al. 2009). A recent review of post-construction studies in European waters (Dierschke et al. 2016) demonstrates that responses of seabirds to offshore wind farms can vary substantially, ranging from strong avoidance to strong attraction, with some species showing little change in behaviour. Guillemots and razorbills were among the species showing avoidance, whereas kittiwakes showed mixed responses at different wind farm sites; data on puffins were lacking. Furthermore, the strength of the response differed among populations of the same species most likely linked to factors such as local food availability and distance of the development from the colony (Dierschke et al. 2016). Given the extent of variation in seabird distributions and responses to offshore wind farms (both among and within species), to gain a robust understanding of the effects proposed offshore wind farms are likely to have on local seabird communities, ideally GPS data and associated data on physiology and demography should be collected over several years spanning before, during and after construction from multiple relevant breeding populations.

4.4 Device effects

4.4.1 Puffin

Based on our experience in 2018 (Bogdanova et al., 2018), we modified the puffin capture and logger deployment protocol to minimise negative effects of the associated disturbance on chick provisioning rates. We used only the smallest available loggers, captured the birds at their burrows to ensure only one adult per pair was tagged and the location of all chicks of instrumented birds was known, and carried out deployments when the chicks were older and more robust. This study design also meant that we could undertake supplementary feeding of all chicks of tagged birds if/as needed as the burrows of all tagged birds were known.

Chick feeding rates were slightly reduced in individuals fitted with GPS loggers compared to those that received colour rings only. Even though it was not possible to obtain data from unmarked control birds at the individual level, the proportion of daily feeds provided by tagged birds suggested they reduced their provisioning effort compared to the expected if pair members shared chick provisioning duties equally as is typical in this species (Harris & Wanless 2011). Puffins are known to be sensitive to disturbance (Harris & Wanless 2011) and our findings fit with previous work on the Isle of May and elsewhere that has shown that the foraging behaviour of instrumented birds can be adversely affected (Harris et al. 2012, Bogdanova et al. 2018, Symons & Diamond 2019). Further, feeding rates were reduced in pairs where one member carried a GPS logger but not in pairs where one member was colour-ringed compared to controls (where neither bird was manipulated). This may suggest that among pairs in the colour-ringed group, the partner was able to compensate for the slightly reduced feeding rate of the treatment bird. Among pairs in the device group, however, compensation by the partner was not effective and reduced feeding rate was observed at the pair level too. Puffins are known to compensate if their mate reduces their provisioning rate (Harris & Wanless 2011, Symons & Diamond 2019), however it is possible that there is a threshold below which full compensation cannot be achieved, especially if foraging effort is close to or at capacity. Chick feeding rates did not change within the first four days after logger deployment, suggesting that the birds did not

habituate to the presence of the logger. There is therefore the potential for negative effects of device deployment to last until the logger falls off. Despite the reduction in feeding rates by birds carrying devices, our supplementary feeding programme ensured that chicks from treatment burrows fledged successfully and in similar condition to chicks in control burrows.

Given the changes in chick provisioning behaviour in puffins carrying devices, it is possible that the at-sea distributions we recorded are not fully representative of the distribution of unmanipulated birds. Tagged birds may have modified their behaviour, which could result in differences in the direction or range of foraging trips compared to unmanipulated birds. It is very challenging to assess the representativeness of the data without information on the distribution of the latter. What can be stated is that the offshore distribution is plausible for foraging of Isle of May breeding adults, based on our understanding of their diet and ecology (Harris & Wanless 2011). However, we are concerned that tagged individuals may have been distributed further offshore on average than the population as a whole, and that shorter trips to locations closer to the colony, often associated with foraging for the chick (Harris & Wanless 2011), may have been under-represented in these data. We drew a similar conclusion in the previous studies of GPS tracking of puffins on the Isle of May in 2010 and 2018 (Harris et al. 2012, Bogdanova et al. 2018). If this is the case, our estimate of the overlap with offshore renewable developments may be exaggerated.

4.4.2 Kittiwake

We did not find evidence for negative effects of GPS logger deployment on foraging behaviour (trip duration), or chick condition and breeding success in kittiwakes. Previous studies in this species have found device effects on physiological and behavioural parameters, with tagged birds having significantly elevated levels of stress hormones, reduced nest attendance and longer foraging trips (Heggøy et al. 2015) or reduced time spent flying (Chivers et al. 2016). However, in both of these studies the GPS loggers used were substantially larger and heavier than the ones we used (15.5g and 21g vs 4.1g) so the presence of device effects is perhaps not surprising.

4.5 Conclusions

In this project we undertook GPS tracking of kittiwakes, guillemots, razorbills and puffins breeding on the Isle of May. Sample sizes were sufficient to ensure that distributions at sea and flight lines were representative for the deployment period. As in 2018, the technology was very successful, ensuring that data were obtained for nearly all individuals, and deployment durations were longer than previously achieved using archival loggers. There was considerable variation among species in at-sea distribution. Although these differences accorded with current understanding of foraging ranges from past GPS tracking from 2010-2014 and 2018, the results highlight that there is marked variation among years within species, both in terms of directionality and foraging range. The study demonstrated negative effects of device deployment on puffins, in line with past findings from this and other populations.

The extent of interannual variation in at-sea distributions, during a period when the North Sea is experiencing marked environmental variation, suggests that additional GPS data during the pre-construction period would be valuable to maximise our understanding of at-sea distribution of breeding birds in the absence of a wind farm. Further, it would be important to develop a structured before-during-after monitoring protocol, involving additional physiological and demographic parameters that can be collected at the breeding colony, ideally at the individual level to maximise the power to detect effects and thus quantify population-level impacts of wind farms in the study region.

However, GPS tracking work on puffins at this colony requires careful interpretation. Although we have developed a mechanism for safeguarding the welfare of chicks of birds carrying devices through supplementary feeding, questions still remain about the short-term effects on adults, and representativeness of the at-sea distributions of these birds.

5 Acknowledgements

6 References

Bartoń K (2018) MuMIn: multi-model inference, R package version 1.42.1 https://cran.r-project.org/web/packages/MuMIn/.

Bates D, Maechler M, Bolker B & Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67: 1−48.

Beaugrand G, Edwards M, Brander M, Luczak C & Ibanez F (2008) Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic. Ecol Lett 11: 1157-1168.

Bodey TW, Cleasby IR, Bell F, Parr N, Schultz A , Votier SC & Bearhop S (2018) A phylogenetically controlled meta-analysis of biologging device effects on birds: Deleterious effects and a call for more standardized reporting of study data. Methods Ecol Evol 9: 946–955.

Bogdanova MI, Gunn C, Langlois Lopez S, Phillpot P, Newell M, Harris M, Wanless S & Daunt F (2018) GPS tracking of common guillemot, razorbill, Atlantic puffin and black-legged kittiwake on the Isle of May, summer 2018. Contract report to EDF Renewables.

Burnham, KP, Anderson, DR (2002) *Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach*. Springer-Verlag, New York.

Calenge C (2006) The package 'adehabitat' for the R software: a tool for the analysis of space and habitat use by animals. Ecol Model 197: 516−519.

Chivers LS, Hatch SA & Elliott KH (2016) Accelerometry reveals an impact of short-term tagging on seabird activity budgets. Condor 118: 159-168.

Daunt F, Benvenuti S, Harris MP, Dall'Antonia L, Elston DA & Wanless S (2002) Foraging strategies of the black-legged kittiwake *Rissa tridactyla* at a North Sea colony: evidence for a maximum foraging range. Mar Ecol Prog Ser 245: 239–247.

Daunt F, Bogdanova MI, Newell M, Harris M & Wanless S (2011a) GPS tracking of common guillemot, razorbill and black-legged kittiwake on the Isle of May in 2010. Contract report to the Forth and Tay Offshore Developer Group.

Daunt F, Bogdanova MI, Redman P, Russell S & Wanless S (2011b) GPS tracking of black-legged kittiwake and observations of trip durations and flight directions of

common guillemot at Fowlsheugh and St Abb's Head, summer 2011. Report to Forth & Tay Offshore Wind Developers Group (FTOWDG)

Desholm M & Kahlert J (2006) Avian collision risk at an offshore wind farm. Biol Lett 1: 296-298.

Dierschke V, Furness RW & Garthe S (2016) Seabirds and offshore wind farms in European waters: Avoidance and attraction. Biol Cons 202: 59–68.

Drewitt AL, & Langston RHW (2006) Assessing the impacts of wind projects on birds. Ibis 148: S29–42

Enstipp MR, Daunt F, Wanless S, Humphreys E, Hamer KC, Benvenuti S & Gremillet D (2006) Foraging energetics of North Sea birds confronted with fluctuating prey availability. In: Top predators in marine ecosystems: their role in monitoring and management. (Eds I.L. Boyd, S. Wanless & K. Camphuysen). Cambridge University Press, Cambridge, pp191-210

Finney SK, Wanless S & Harris MP (1999) The effect of weather conditions on the feeding behaviour of a diving bird, the Common Guillemot Uria aalge. J Avian Biol 30: 23-30.

Grecian WJ, Inger R, Attrill MJ, Bearhop S, Godley BJ, Witt MJ & Votier SC (2010) Potential impacts of wave-powered marine renewable energy installations on marine birds. Ibis 152: 683-97

Harris M, Bogdanova MI, Daunt F & Wanless S (2012) Using GPS technology to assess feeding areas of Atlantic Puffins Fratercula arctica. Ringing Migr 27: 43-49.

Harris MP & Wanless S (2011) The Puffin. T & A D Poyser, London, 256pp.

Heggøy O, Christensen-Dalsgaard S, Ranke PS, Chastel O, Bech C (2015) GPS-loggers influence behaviour and physiology in the black-legged kittiwake Rissa tridactyla. Mar Ecol Prog Ser 521: 237–248.

Inger R, Attrill MJ, BearhopS, Broderick AC, Grecian WJ, Hodgson DJ, Mills C, Sheehan E, Votier SC, Witt MJ, Godley BJ (2009) Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J Appl Ecol 46: 1145–1153.

Johnston A, Cook ASCP, Wright LJ, Humphreys EM & Burton NHK (2014) Modelling flight heights of marine birds to more accurately assess collision risk with offshore wind turbines. J Appl Ecol 51: 31–41.

Langton R, Davies IM & Scott BE (2011) Seabird conservation and tidal stream and wave power generation: information needs for predicting and managing potential impacts. Mar Policy 35: 623-30

Larsen JK & Guillemette M. (2007) Effects of wind turbines on flight behaviour of wintering common eiders: implications for habitat use and collision risk. J Appl Ecol 44: 516-522

Manly BFJ (2009) *Randomization, bootstrap and Monte Carlo methods in biology*. Chapman Hall.

Masden EA, Haydon DT, FoxAD & Furness, RW (2010) Barriers to movement: Modelling energetic costs of avoiding marine wind farms amongst breeding seabirds. Mar Pollut Bul 60: 1085–1091.

Nakagawa S & Schielzeth H (2013) A general and simple method for obtaining R^2 from generalized linear mixed effects models. Methods Ecol Evol 4: 133−142.

Robertson GS, Bolton M, Grecian WJ & Monaghan P (2014) Inter- and intra-year variation in foraging areas of breeding kittiwakes (*Rissa tridactyla*). Mar Biol 161: 1973–1986.

Searle K, Mobbs D, Butler A, Bogdanova MI, Freeman S, Wanless S & Daunt F (2014) Population consequences of displacement from proposed offshore wind energy developments for seabirds breeding at Scottish SPAs (CR/2012/03). Report to Scottish Government.

Searle KR, Mobbs DC, Butler A, Furness RW, Trinder TN & Daunt F (2018) Finding out the Fate of Displaced Birds. Scottish Marine and Freshwater Science Vol 9 No 8.

Shoji A, Aris-Brosou S, Owen E, Bolton M, Boyle D, Fayet A, Dean B, Kirk H, Freeman R, Perrins C & Guilford T (2016) Foraging flexibility and search patterns are unlinked during breeding in a free-ranging seabird. Mar Biol 163: 72.

Rodway MS, Montevecchi WA & Chardine JW (1996) Effects of investigator disturbance on breeding success of Atlantic puffins *Fratercula arctica*. Biol Cons 76: 311-319.

Symons SC & Diamond AW (2019) Short-term tracking tag attachment disrupts chick provisioning by Atlantic Puffins Fratercula arctica and Razorbills Alca torda. Bird Study 66: 53-63.

Thaxter CB, Daunt F, Gremillet D, Harris MP, Benvenuti, S,cWatanuki, Y, Hamer, KC & Wanless, S (2013) Modelling the effects of prey size and distribution on prey capture rates of two sympatric marine predators. PLOS ONE 8: e79915.

Thaxter CB, Daunt F, Hamer KC, Watanuki Y, Harris MP, Grémillet D, Peters G & Wanless S. (2009) Sex-specific food provisioning in a monomorphic seabird: nest defence, foraging efficiency or parental effort? J Avian Biol 40: 75-84.

Thaxter CB, Ross-Smith VH, Clark JA, Clark NA, Conway GJ, Marsh M, Leat EHK & Burton NHK (2014) A trial of three harness attachment methods and their suitability for long-term use on Lesser Black-backed Gulls and Great Skuas. Ring & Migr 29: 65-76.

Thaxter CB, Wanless S, Daunt F, Harris MP, Benvenuti S, Watanuki Y, Grémillet D & Hamer KC (2010) Influence of wing loading on trade-off between pursuit-diving and flight in common guillemots and razorbills. J Exp Biol 213: 1018-1025.

Thaxter CB, Ross-Smith VH, Clark JA Clark NA, Conway GJ, Masden EA, Wade H., Leat EHK, Gear SC, Marsh M, Booth C, Furness RW, Votier SC & Burton NHK (2017) Contrasting effects of GPS device and harness attachment on adult survival of Lesser Black-backed Gulls *Larus fuscus* and Great Skuas *Stercorarius skua*. Ibis 158: 279-290.

Vandenabeele SP, Shepard EL, Grogan A & Wilson RP (2012) When three per cent may not be three per cent: device equipped seabirds experience variable flight constraints. Mar Biol 159: 1–14.

Vandenabeele SP, Grundy S, Friswell MI, Grogan A, Votier SC & Wilson RP (2014) Excess baggage for birds: Inappropriate placement of tags on gannets changes flight patterns. PLOS One 9: e92657.

Wakefield ED, Owen E, Baer J, Carroll MJ, Daunt F, Dodd SG, Green JA, Guilford T, Mavor RA, Miller PA, Newell MA, Newton SF, Robertson GS, Shoji A, Soanes LM,

Votier SC, Wanless S & Bolton M (2017) Breeding density, fine-scale tracking, and large-scale modelling reveal the regional distribution of four seabird species. Ecol Appl 27: 2074–2091.

Wanless S, Harris MP, Newell MA, Speakman JR & Daunt F (2018) Community-wide decline in the occurrence of lesser sandeels *Ammodytes marinus* in seabird chick diets at a North Sea colony. Mar Ecol Prog Ser 600: 193–206.

Worton BJ (1989) Kernel methods for estimating the utilization distribution of home range studies. Ecology 70: 164–168.

Wright PJ, Jensen H & Tuck I (2000) The influence of sediment type on the distribution of the lesser sandeel *Ammodytes marinus*. J Sea Res 44: 243-256.

Zuur AF, Ieno EN, Walker NJ, Saveliev AA, Smith GM (2009). *Mixed Effects Models and Extensions in Ecology with R.* Springer, New York.

7 Appendix

Inter-annual variation in at-sea distribution of four seabird species breeding on the Isle of May: a) guillemot; b) razorbill; c) puffin; d) kittiwake. 50%, 70% and 90% UD contours shown, yellow star denotes the location of the island.

a)

b)

c)

d)