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GPS tracking of common guillemots, razorbills, Atlantic puffins and black-legged kittiwakes on the Isle of May in 2018 in relation to the Neart na Gaoithe offshore wind farm

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Contents

Executive summary

- This report presents the results of GPS tracking of adult black-legged kittiwakes Atlantic puffins, common guillemots and razorbills breeding on the Isle of May (SE Scotland) in 2018 and assessment of overlap with the consented Neart na Gaoithe offshore wind farm. Locational data were obtained from 16 kittiwakes, 23 puffins, 24 guillemots and 13 razorbills (comprising 71, 175, 207 and 142 trips, respectively) in June and July 2018. 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 indicated 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 2010-14. 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 the Isle of May and within the Firth of Forth and 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 offshore, from a south-easterly to north-easterly direction from the colony. Kittiwakes had a wider distribution than the three auk species, including mainly offshore areas spanning from a south-easterly to north-easterly direction from the colony. This was reflected in the larger mean maximum range for this species (60.3 ± 7.0 km) compared to guillemot (39.1 ± 2.4 km), razorbill (46.0 ± 2.6 km) and puffin (48.8 ± 2.5 km). The distribution of flight lines matched the distributions of non-flight activities. Guillemots departed from and returned to the colony on bearings ranging from southwest and northwest (for inshore foraging trips) to northeast and east (for offshore trips). A similar pattern was observed in razorbills although flight bearings

in an easterly direction were more common. Flight bearings of puffins and kittiwakes spanned from a north-easterly to easterly/south-easterly direction from the colony.

- A small proportion (up to 1.5%) of the core areas (50% kernels) used by guillemots, razorbills and puffins for non-flight activities overlapped with the planned Neart na Gaoithe footprint. In contrast, the overlap in kittiwakes was substantially larger (>10%). 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. At all three levels that we explored (bird, trip and flight), overlap was lowest in guillemots and highest in kittiwakes (and puffins, at the flight level only). The lower overlap observed in the guillemot is likely due to the predominantly inshore distribution of the species during our study.

- In the light of past evidence that Isle of May puffins are susceptible to disturbance when captured in burrows, we adopted an alternative deployment method by mist netting breeding birds close to burrows. Despite this, we recorded negative effects of GPS logger deployment on chick provisioning rates and chick survival, in particular in cases where both members of the pair carried loggers. Our results indicate that both handling and device deployment may contribute additively to these effects. We found similar effects in birds fitted with a heavier (8.2g) and lighter (4.1g) logger model, suggesting that the attachment of a device may be a key issue causing disturbance, or there is a threshold mass that puffins will tolerate that is lower than the smaller of the two loggers used. Feeding behaviour was related also to the amount of time that had passed since logger deployment, with feeding rates declining and trip duration and range slightly increasing over time. Such strongly negative impacts of device deployment are rarely observed in seabirds. However, we were able to improve the welfare of chicks through supplementary feeding.

- *Conclusions*: This study demonstrates variation in seabird distributions at sea among species and, when comparing with previous GPS tracking studies undertaken in 2010-2014, variation within species among years. Our study also confirmed overlap between the distributions of guillemot, razorbill, puffin and kittiwake populations breeding on the Isle of May and the planned Neart na Gaoithe offshore wind farm. Our results indicate substantial negative effects of logger deployment on chick feeding rates and chick survival in puffins and demonstrates a particular challenge with using data loggers in this population. We recommend for future GPS tracking studies that puffins are captured at burrow entrances, not in mist nets, to ensure that all chicks of instrumented birds are identified, and that only one member of a pair is deployed with a data logger. The interannual variation in distribution seen in all species indicates that further GPS tracking in future years prior to construction would be very valuable, as well as the development of a structured monitoring plan spanning the periods before, during and after wind farm construction to 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, principally from 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). These effects may be particularly important for breeding seabirds that are constrained to forage within a certain distance from the breeding colony because of the requirement to return regularly to the nest to relieve the attending mate and feed the offspring (Daunt et al. 2002; Enstipp et al 2006).

For the purposes of Habitats Regulations Appraisal, there is a need to estimate the potential impact on seabirds breeding at Special Protection Areas. Addressing this question comprises two core elements: first, to establish the extent of interaction between birds breeding at SPAs and offshore renewable developments; second: to estimate whether any 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. Developing GPS deployment programmes to quantify foraging and flight behaviour over the period before, during and after construction coupled with parallel estimates of changes in physiology and demography is a powerful framework for estimating population-level effects.

Baseline information on 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 offshore wind farm at Neart na Gaoithe, 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.

Due to technological developments in recent years, GPS tracking devices are now available as remote download loggers. This means that the data logger transmits the data (via VHF or GSM) so the logger does not need to be retrieved to obtain the data. This approach offers considerable advantages over the former technology, whereby the data was stored on the logger and it had to be retrieved. There is less disturbance to the birds because repeated visits to retrieve the logger are not necessary. In addition, the amount of data obtained is greater because the proportion of birds from which data are obtained is higher, and because data are obtained until the logger falls off or the battery runs out, which typically occurs later than logger retrieval that was required with archival loggers.

We undertook an assessment of effects of GPS devices, in which we compared feeding rates of birds carrying loggers with unmanipulated control birds, and monitored chick survival, since past work has shown that puffins on the Isle of May and other colonies are sensitive to handling and deployment of data loggers (Rodway et al 1996, Harris & Wanless 2011; Harris et al. 2012). In many of these studies puffins were caught whilst in their burrows and it was suggested that this deterred instrumented birds from re-entering their burrows and thus ceasing to feed their chicks. In an attempt to overcome this problem we used an alternative capture method (mist nets set in front of the burrows; E. Owen pers. comm.) and planned for supplementary feeding of chicks in the event of detrimental impacts still being detected. We then undertook an assessment of effects of GPS devices, in which we compared feeding rates of birds carrying loggers with unmanipulated control birds, and monitored chick survival.

1.2 Objectives

The objective of this project was to undertake GPS tracking of kittiwake, puffin, guillemot and razorbill breeding on the Isle of May during the 2018 breeding season. The purpose of the work was to quantify at-sea distribution and flight lines, and to estimate overlap with the planned Neart na Gaoithe wind farm and other consented wind farms in the Forth/Tay region.

The report contains a series of maps of distributions and flight lines, estimates of overlap with the planned wind farms 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.

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 2018 using remote download Pathtrack nanoFix-GEO GPS loggers in three configurations (guillemot: 50x23x10mm, 11g; razorbill/puffin: 50x13x10mm, 8.2g; puffin/kittiwake: 40x12x10mm, 4.1g; all with ~50mm external whip antenna; Fig 1). Deployment details are provided in Table 1.

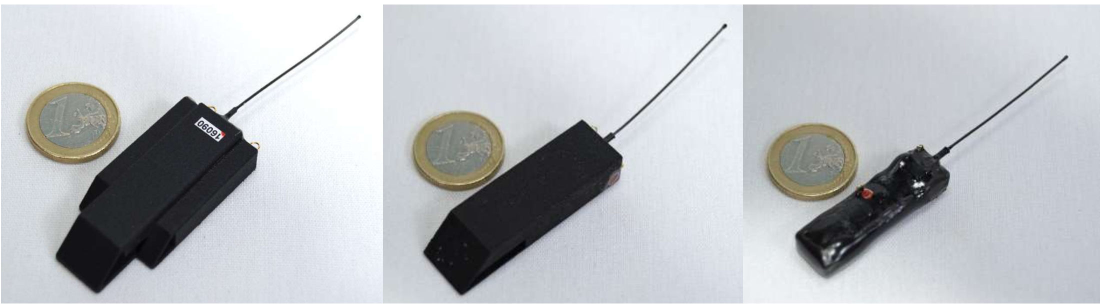


Fig 1: Three Pathtrack devices used in the project: 11g logger used on guillemots (left panel), 8.2g logger used on razorbills and puffins (middle panel), and 4.1g used on puffins and kittiwakes (right panel). €1 coin provided for scale. See text for full details.

Species	Logger mass (g)	Deployment dates	Number deployed	Number with data retrieved	Number of trips
Guillemot	11	26 – 27 June	25	24	207
Razorbill	8.2	26 June	15	13	142
Puffin	8.2/4.1	20 June – 10 July	26	23	175
Kittiwake	4.1	21 – 27 June	16	16	71

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 a telescopic pole. Puffins carrying fish (i.e. returning to the colony to feed young) were captured outside the nesting burrows using mist nets (Fig. 2), adopting a method developed by the RSPB (E. Owen, pers.comm.). This method was considered to cause less disturbance than the traditional method of catching breeding birds in burrows. For all species, the loggers were attached to back feathers using waterproof Tesa tape (Fig. 3). In all cases, handling time was typically less than 5 minutes, and never longer than 10 minutes. Birds carried the loggers for up to *ca.* two weeks before they fell off (Fig 4). Data were collected during chick-rearing in guillemots, razorbills and puffins, and during incubation and chick rearing in kittiwakes.

Fig. 2. Preparation of mist nets for capture of puffins for deployment.

Fig 3. Deployment of data logger using Tesa tape on puffin (left panel); completed deployment on guillemot (right panel).

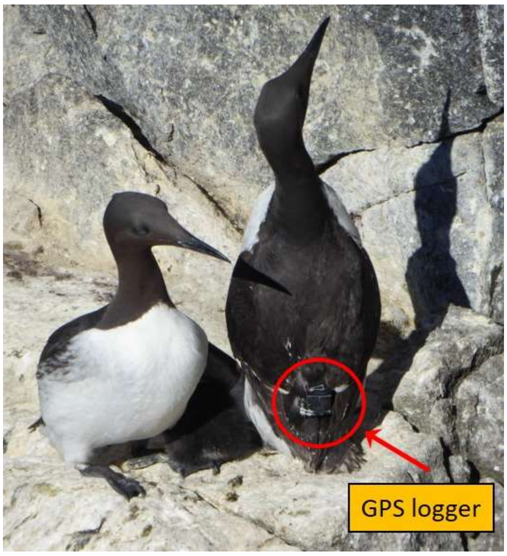


Fig. 4. Breeding guillemot carrying GPS logger.

GPS data were automatically downloaded to fixed base stations positioned in line of sight of nest sites each time the logger was within range (Fig. 5). The base stations successfully received data from 76/82 loggers (93%). The data stored in the base stations were then downloaded daily onto a computer. The sampling interval was set at 5min for guillemot and kittiwake, 10min for razorbill, and 10 or 20min for puffin, to maximise deployment duration while retaining sufficient resolution to estimate behaviours. The average deployment period was 6.8 ± 0.4 days for guillemot, 6.0 ± 0.7 days for razorbill, 6.0 ± 0.8 days for puffin and 3.3 ± 0.2 days for kittiwake.

Fig. 5: GPS tracking set up for remote download loggers. Left panel: base station positioned in proximity to breeding ledges; right panel: close-up of base station.

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, fixes with low accuracy (when signal from less than four satellites was received the loggers did not obtain longitude and latitude, which resulted in 0.45% of the total deployment period being lost) and erroneous fixes for which the geographical location was implausible. Second, locations recorded at the colony (within 500m of the nest site) were also removed from the data set, to ensure that short non-foraging excursions from the nest that are not erroneously classified as foraging trips. 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 were not classified as separate trips as 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 speed threshold for each species was available from previous work on the Isle of May (guillemot and kittiwake: 5 ms-1; razorbill and puffin: 4 ms-1; Daunt et al 2011a, Harris et al 2012). 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) and during foraging/resting (when displacement is expected to be more relevant; Masden et al. 2010; Searle et al. 2014).

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, 2018; 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

Each individual commuting flight within a foraging trip was 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.

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 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 using Feature Manipulation Engine (FME 2017.0, Safe Software Inc) and ArcGIS 10.4.1.

2.2 Device effects in puffins

2.2.1 Data collection

Puffins including those in the Isle of May population, are known to be particularly sensitive to disturbance from handling and carrying data loggers (Rodway et al 1996, Harris & Wanless 2011; Harris et al. 2012). Accordingly, we collected data to test for potential device effects on the provisioning rate (the number of feeds per active burrow) in this species. The data collection was carried out between 20th June and 27th July 2018, and was focussed on comparisons between control burrows (adults not handled) and burrows where adults had been captured. Of these, there are three treatment categories: individuals deployed with a GPS device (of two different sizes), individuals deployed with Tesa tape only (to replicate the handling and deployment process without including a data logger) and individuals deployed only with colour-rings (to separate handling effects from handling and device effects; GPS logger birds and tape-only birds were also colour-ringed).

The study consisted of three deployment sessions across which these multiple treatment categories were introduced (Table 2). As previously explained, we used a new method developed by the RSPB of catching breeding adults carrying fish in mist nets (E. Owen pers.comm; Fig. 2), as opposed to the traditional method of catching in the burrow to try to minimise disruption of behaviour. Thus, the initial session was carried out on the assumption that catching the birds in mist nets would substantially reduce disturbance effects from those previously recorded when birds were extracted from burrows, and only the GPS logger treatment was included in the protocol. However, our observations revealed that this was not the case, and we adapted the second and third deployment sessions in the light of observations of device effects in earlier sessions.

In the first session, we deployed only GPS loggers of the razorbill/puffin configuration (mass 8.2g; Fig. 1). This logger had been designed for shallow diving auks with a robust housing that would ensure that the logger was not damaged by the water pressure at depth. However, due to markedly lower chick provisioning rates observed in the treatment birds in comparison to controls, we included additional treatment categories in sessions 2 and 3 (Table 2). First, we switched to using the lighter loggers at 4.1g originally intended for kittiwakes (Fig. 1) in a subset of instrumented birds. Lighter loggers were used because size and mass of loggers are typically important in determining the extent of device effects. These did not have such a robust housing as the larger loggers, and so there was a risk that they may be damaged by being transported underwater to the depths that puffins can attain (>30m, Harris & Wanless 2011). However, the manufacturers Pathtrack indicated that they thought this was unlikely, and we sought the approval of Ewan Walker of EDF Renewables to make the switch given the results obtained with the larger loggers in session 1, and he approved. This had knock on consequences for the sample size that we could achieve on kittiwakes, which we had to divert these loggers from, which Ewan Walker also understood and approved. As it transpired, the lighter loggers also functioned well so Pathtrack were proved correct that they would not be damaged during diving. We also deployed with Tesa tape only and with colour-rings (note: GPS logger birds and tape-only birds were also colour-ringed) during the second and third session, respectively (Table 2). These other treatment groups were included to tease apart potential negative effects of handling and device deployment. The intention was to deploy on only one bird per burrow, but since birds were caught away from their burrows, by chance, both members of four pairs had devices attached.

Deployment session	Deployment date	8.2g Logger	4.1g Logger	Tesa Tape Only	Colour Ring Only	Total
1	20 June	8	-	-	-	8
2	29 June	3	3	3	-	9
3	10 July	6	6	-	6	18

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

The same study plot was used for deployment sessions 1 and 2. The study plot was marked with a boundary rope and the nets placed within this area to maximise the probability that the burrow of birds captured and thus given a logger was inside the study plot. For session 3, the study area was moved ~30m to the east thus providing a new set of control and treatment burrows, and again a boundary rope was laid and catching was concentrated within the rope boundary. This change was to reduce the possibility of deploying on the mate of a bird carrying a device from the first two deployments. In addition, to reduce dual deployments happening during session 3, we set the nets over a larger area, and marked the net where any bird had been caught with a small cane and did not deploy on a bird captured at the same location, because of the possibility that it was the mate of the deployed bird.

Loggers were attached to the lower back feathers using four strips of white Tesa tape (Fig 3). To aid subsequent identification of individuals, birds were given a unique combination of colour rings and a single number or letter marked in black on the Tesa tape (Fig. 6). Birds also received a BTO ring. In session 1, 3-4 breast feathers were taken for sexing, bill grooves recorded to obtain an approximate estimate of maturity, and stock marker sprayed on the chest. These steps were omitted in the second and third deployment sessions to reduce disturbance and handling time (which dropped from 7 min to 4 min on average).

Fig. 6: Marking of device with a unique letter.

After the birds were released, we carried out intensive observational watches over the following 24 period (Fig. 7), to identify active burrows (i.e. those in which adults were delivering fish) in the study plot. All active burrows within the plot were subsequently included in watches of feeding rates. Each active burrow was marked with a numbered cane (Fig. 8) and we attempted to identify in which burrows the treatment birds were breeding (Fig. 9). Once this process had been completed, two observers did alternate 2 hour watches spanning the period 05:00 – 13:00 BST in the days that followed, except on four occasions when watches had to be shortened by 1-3 hours due to restrictions in accessing the hide. Every feed into a marked burrow was recorded, and the behaviour of treatment birds was noted (in addition to bringing feeds e.g. colony attendance, entering the burrow without fish). Burrows of treatment birds outside the study plot could not be included in the feeding watches without compromising the accuracy of the results. Details of the dates and sample sizes of control and treatment burrows in each deployment session's feeding watches are summarised in Table 3. Numbers of treatment individuals are greater than numbers of burrows because of the four cases in which both adults from the same burrow were caught. One individual from deployment 1 was still active in deployment 2.

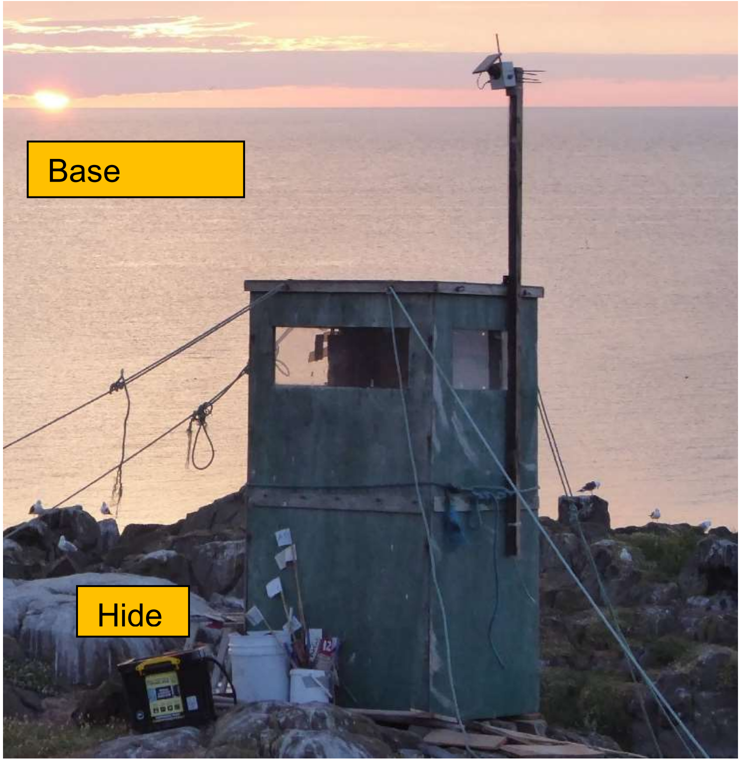


Fig. 6: Observation hide with base station attached.

Fig. 7: observation plot showing active nests marked with a numbered cane. The boundary rope is visible on the right of the picture.

Fig. 8: puffin carrying GPS logger.

Deployment session	Observation dates	Observation days	Control burrows	Treatment burrows	Treatment individuals
1	24 – 29 June	6	20	4	6
2	2 – 6 July	5	17	5	7
3	13 – 22 July	10	22	8	9

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

Supplementary feeding

As a comparison of feeding rates between control and treatment burrows during deployment session 1 showed a substantially reduced feeding rate to treatment burrows, especially in cases where both partners had been caught, supplementary feeding of the chicks was initiated. In sessions 1 and 2, 50g of defrosted whole small fish (whitebait Clupeidae) was given spread over three feeds per day until fledging or death of the chick at burrows where reduced feeding was observed. In practice, this meant that all burrows with two treatment adults received the additional food. During session 3, we put 15g of defrosted fish in all treatment burrows, to support the partner who was compensating for the reduced feeding by the treatment bird.

Observation from cameras

Four motion detector cameras (Ucam247 NC328SW-1080P) were trialled to see if they could automatically record adult puffins returning to the burrow with fish. The trigger sensitivity was tested until suitable levels were established and then the cameras were deployed at the entrances to known treatment burrows (Fig. 9).

Fig. 9. Motion detector camera set up. Upper photo shows camera on short wooden post trained on a puffin burrow, with battery placed in waterproof black box. Lower photo shows full set up with contents of box visible.

To test the cameras' reliability, notes were made on events which we expected would have been recorded by the cameras during the observational watches in deployment sessions 1 and 2 (e.g. puffins or rabbits going down the burrow or walking past the burrow entrance). Of the 64 camera validation events recorded by the observers, 42 (66%) were caught on camera and 22 (34%) were not. Of the missed events, 5 were feeds, 6 were potential feeds where a bird went into a burrow entrance and 11 were animals walking past the camera/burrow entrances. In contrast, in 317 hours of observational watches, 3 feeds were missed by the observer which were captured by the cameras. Therefore, the cameras were not deemed reliable to automatically record feeding rates and observational watches were solely used in deployment session 3.

2.2.2 Data analysis

Effects of treatment and time since deployment on feeding rates and foraging trip characteristics (duration and maximum range) were investigated using linear mixed models. The analysis of feeding rates was conducted at the individual and at the pair level, using generalised linear mixed models with Poisson error distribution. Number of feeds per observation day was the response, treatment was a fixed effect, day since deployment was a covariate, and bird or pair identity was a random effect in the models. In the analysis at the individual level, treatment had three categories ('puffin logger', denoting the 8.2g logger; 'kittiwake logger', denoting the 4.1g logger; and 'colour ring'). The 'tape only' category was not included as we had data from only one bird within this group. In the analysis at the pair level, treatment had five categories based on the treatment to which pair members were assigned; the large number of categories arose because two individuals from the same burrow were instrumented in some cases: 'control + control', 'logger + logger' (either puffin or kittiwake logger – sample sizes dictated that these had to be combined), 'puffin logger + control', 'kittiwake logger + control' and 'colour ring + control'. The 'logger + tape' category was again excluded due to having data only from a single pair.

The analysis of trip characteristics was conducted at the individual level and involved only birds that had been equipped with loggers. For this analysis, we used general linear mixed models with trip duration or maximum foraging range as the response, treatment (puffin or kittiwake logger) as a fixed effect, day since deployment as a covariate and bird identity as a random effect. Trip duration was square root transformed to achieve approximate normality.

For each analysis, our candidate set included four models: the simplest ('null') model contained only a random effect for bird or pair identity and no fixed effects, the next two models tested for effects of treatment or day since deployment individually, and the full model contained both these explanatory variables. For the purposes of model comparison, models were fitted using maximum likelihood as they had different fixed effects but the same random structure (Zuur et al 2009). 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). The best model was re-fitted using restricted maximum likelihood to obtain more unbiased parameter estimates and their standard errors (Zuur et al. 2009). 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 nlme (Pinheiro et al. 2018), lme4 (Bates et al. 2018) and MuMIn (Bartoń 2018).

3 Results

3.1 Species utilisation distribution

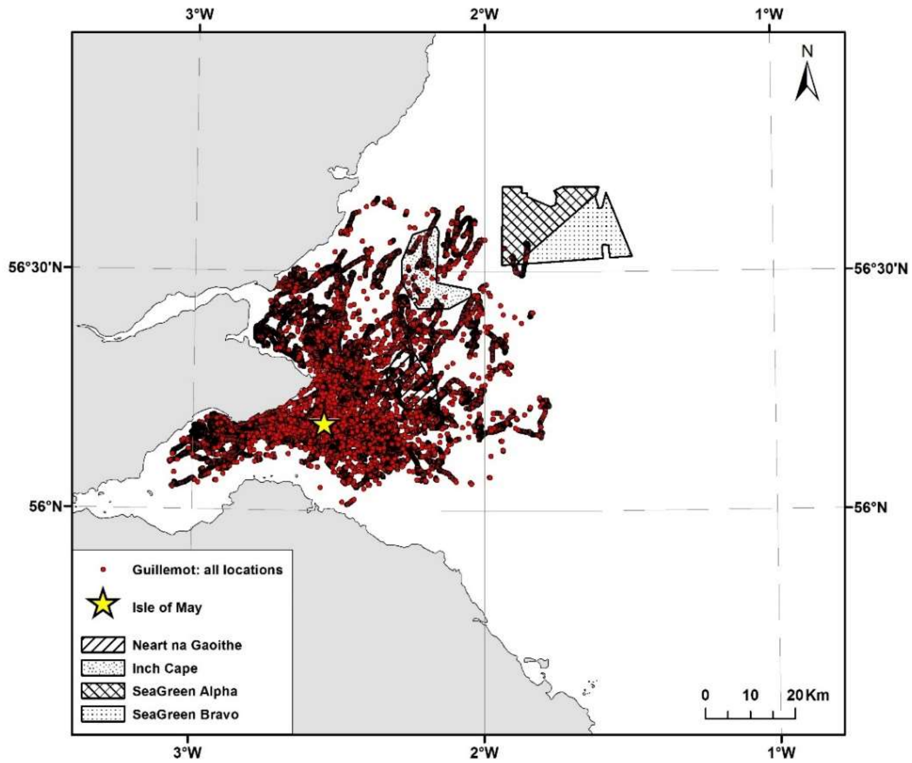
Maps of locations at sea (all fixes and non-flight fixes) and utilisation distributions based on these data are provided in Fig 10a-d (for guillemot), Fig 11a-d (for razorbill), Fig 12a-d (for puffin), and Fig 13a-d (for kittiwake). Clear differences in distributions were apparent among the four species. The distribution of guillemots included both inshore and offshore areas but core areas used were around the Isle of May and within the Firth of Forth and 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, from a south-easterly to a north-easterly direction with respect to the Isle of May. Kittiwakes had a wider distribution than the three auk species, including mainly offshore areas spanning south-east to north-east from the colony. Some kittiwakes also used coastal areas within the St Andrews Bay. Accordingly, the mean maximum range among individuals (± SE) from the Isle of May was larger in the kittiwake (60.3 ± 7.0 km) than in any of the remaining species (guillemot: 39.1 ± 2.4 km, razorbill: 46.0 ± 2.6 km and puffin: 48.8 ± 2.5 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 20%; puffin: 9% and kittiwake 30% within this dataset). The only species where some differences were apparent was the razorbill, where core areas based on non-flight fixes were more spatially segregated than the core areas based on all fixes (Fig. 11 b,d).

3.2 Horizontal flight lines

Maps of horizontal flight lines are shown in Fig 10e (for guillemot), Fig 11e (for razorbill), Fig. 12e (for puffin) and Fig 13e (for kittiwake). As expected, the distribution of flights lines matched closely the UD distributions. Guillemots departed from and returned to the colony on bearings ranging from south-west and north-west (for inshore foraging trips) to northeast and east (for offshore trips). A similar pattern was observed in razorbills although flight bearings in an easterly direction from the Isle of May (corresponding to offshore trips) were more common. Flight bearings of puffins and kittiwakes spanned from a north-easterly to easterly/south-easterly direction from the colony.

a)



b)

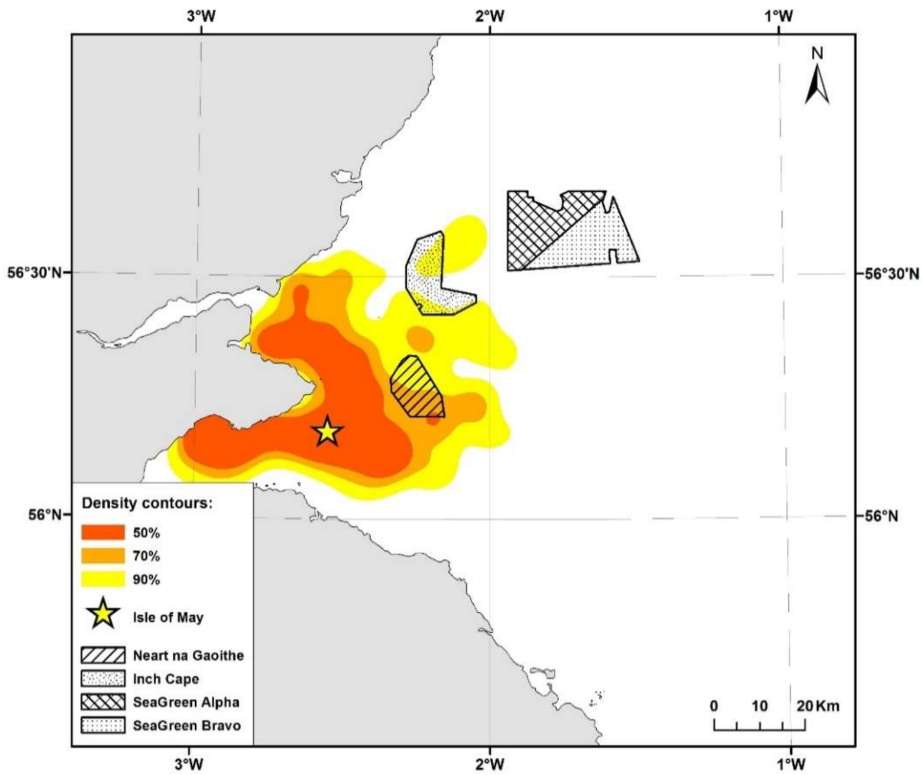
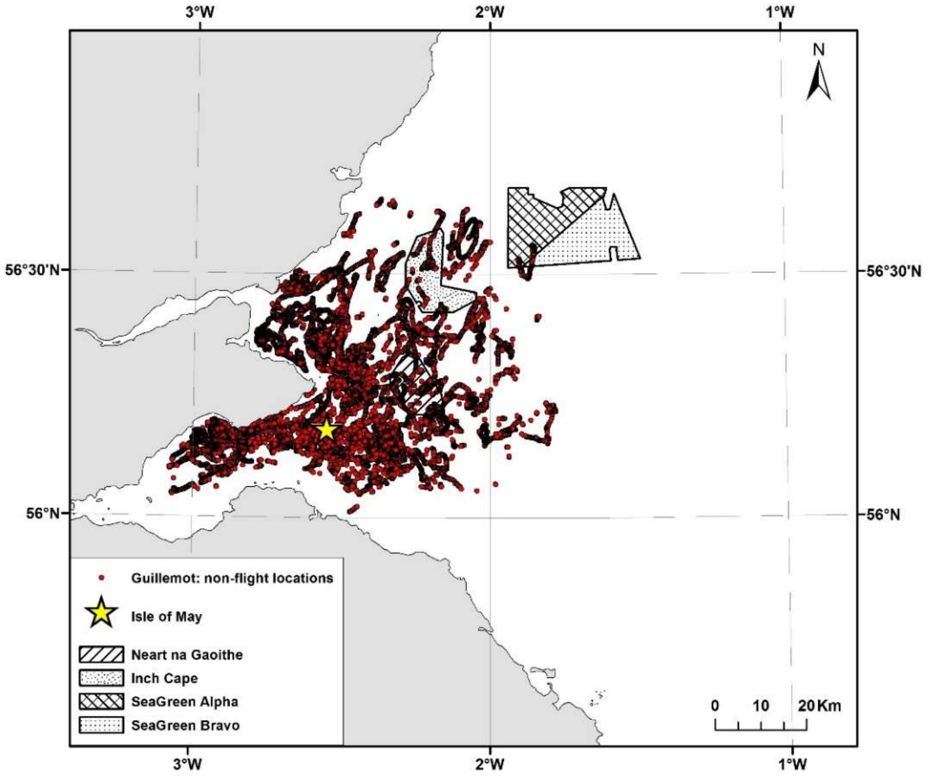


Fig. 10: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for guillemot for flight and non-flight behaviours combined.

c)



d)

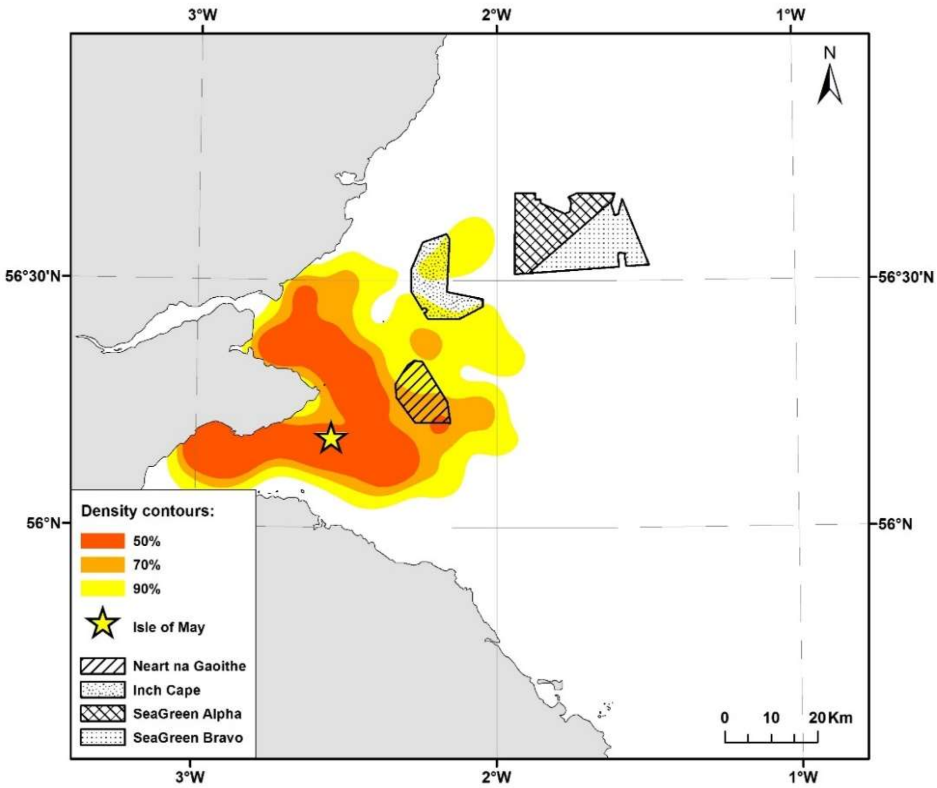


Fig. 10 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for guillemot for non-flight behaviours only.

e)

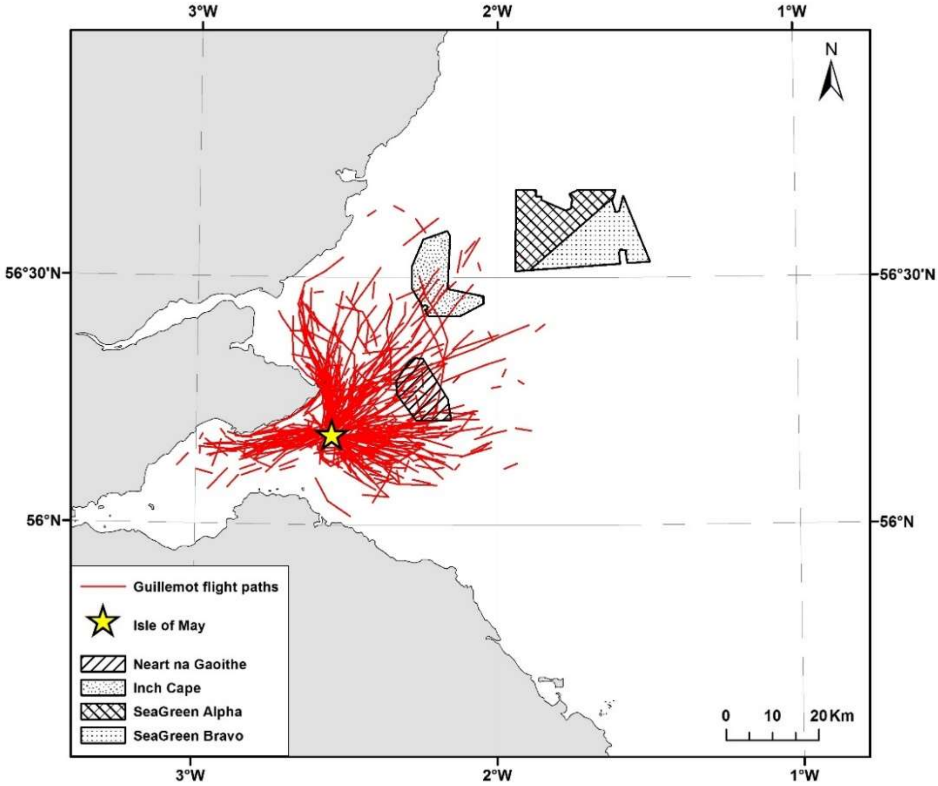
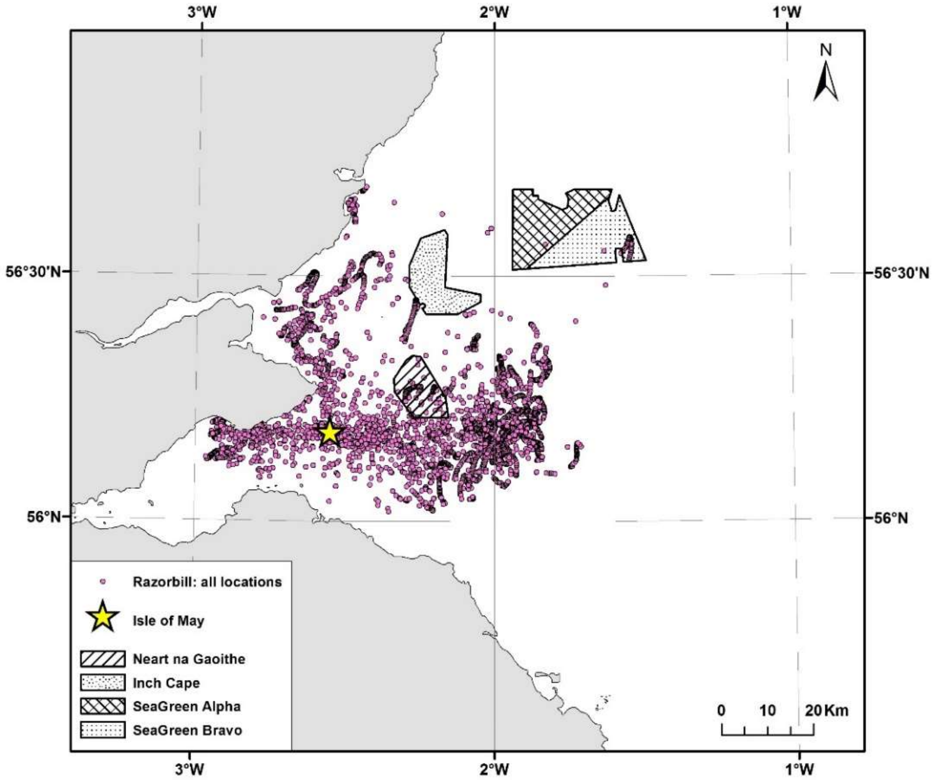


Fig. 10 (cont.): e) Horizontal flights lines for guillemot.

a)



b)

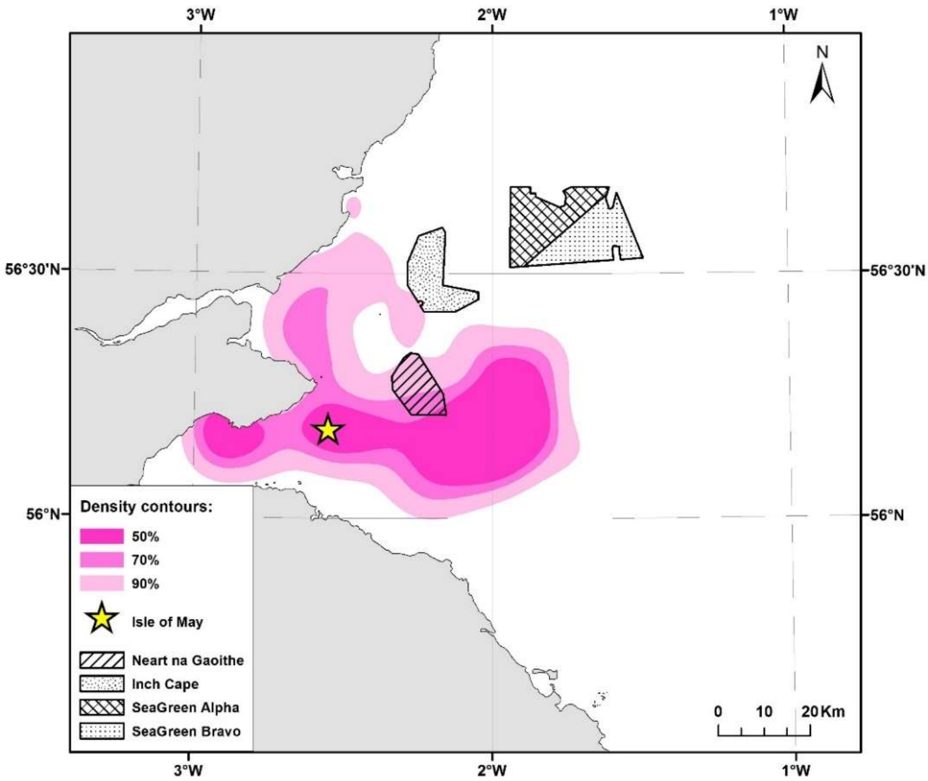
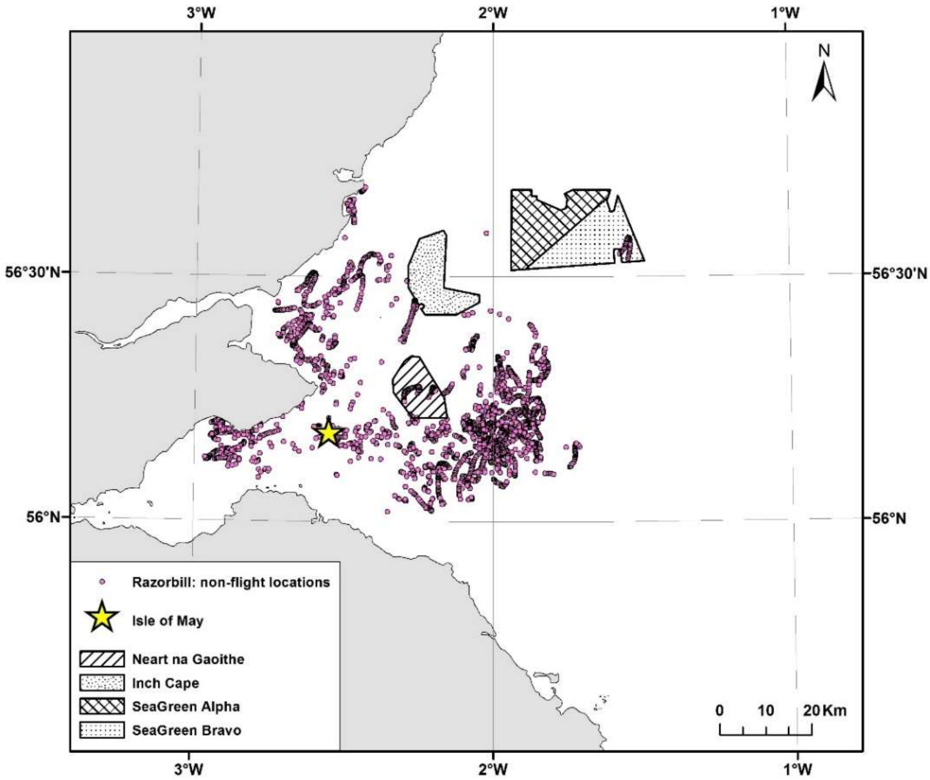


Fig. 11: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for razorbill for flight and non-flight behaviours combined.

c)



d)

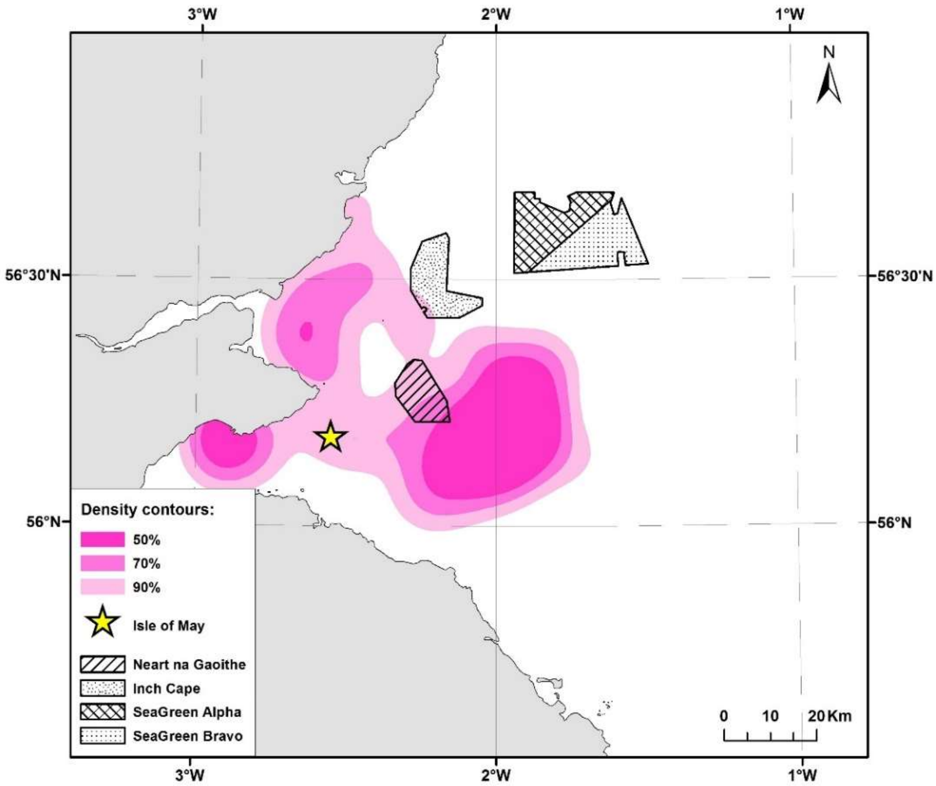


Fig. 11 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for razorbill for non-flight behaviours only.

e)

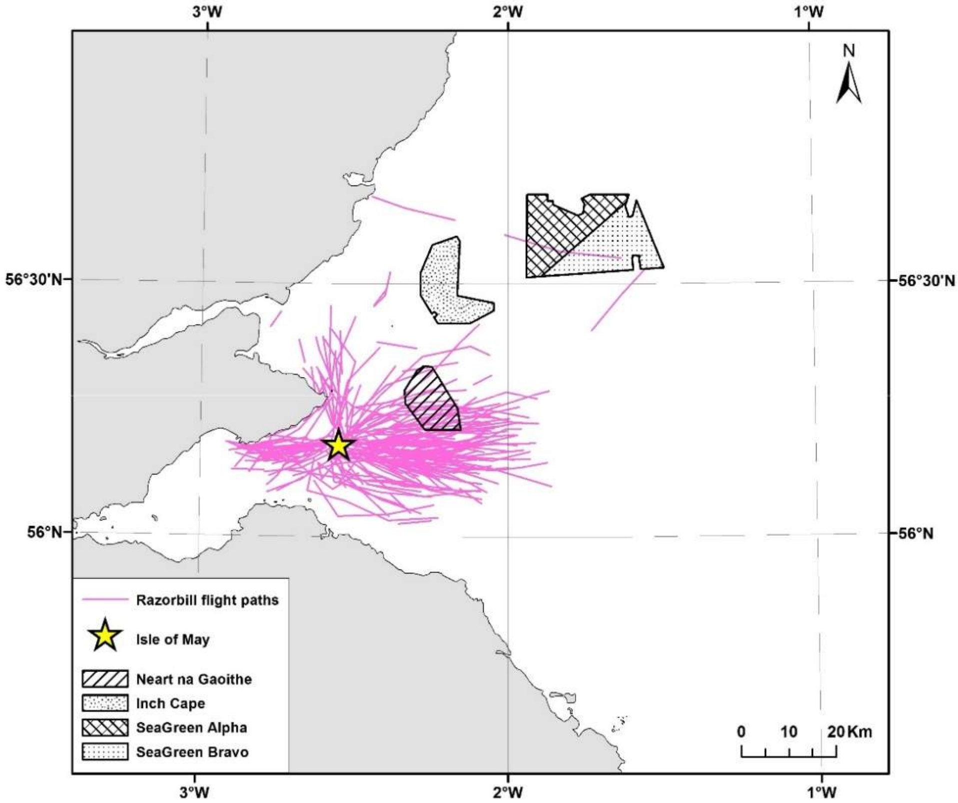
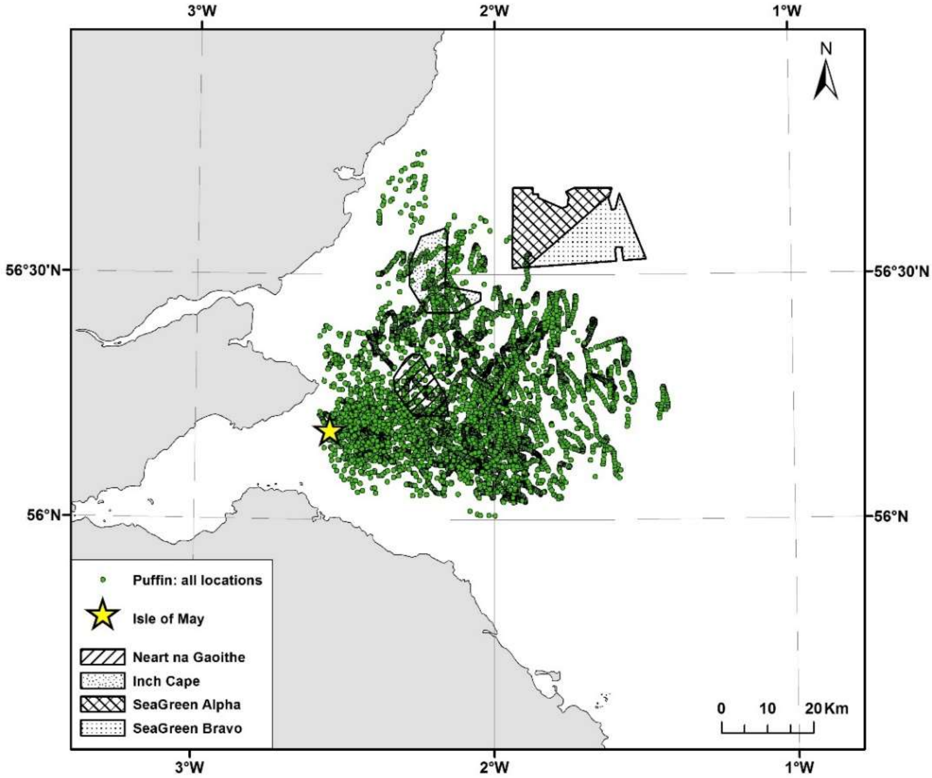


Fig. 11 (cont.): e) Horizontal flights lines for razorbill.

a)



b)

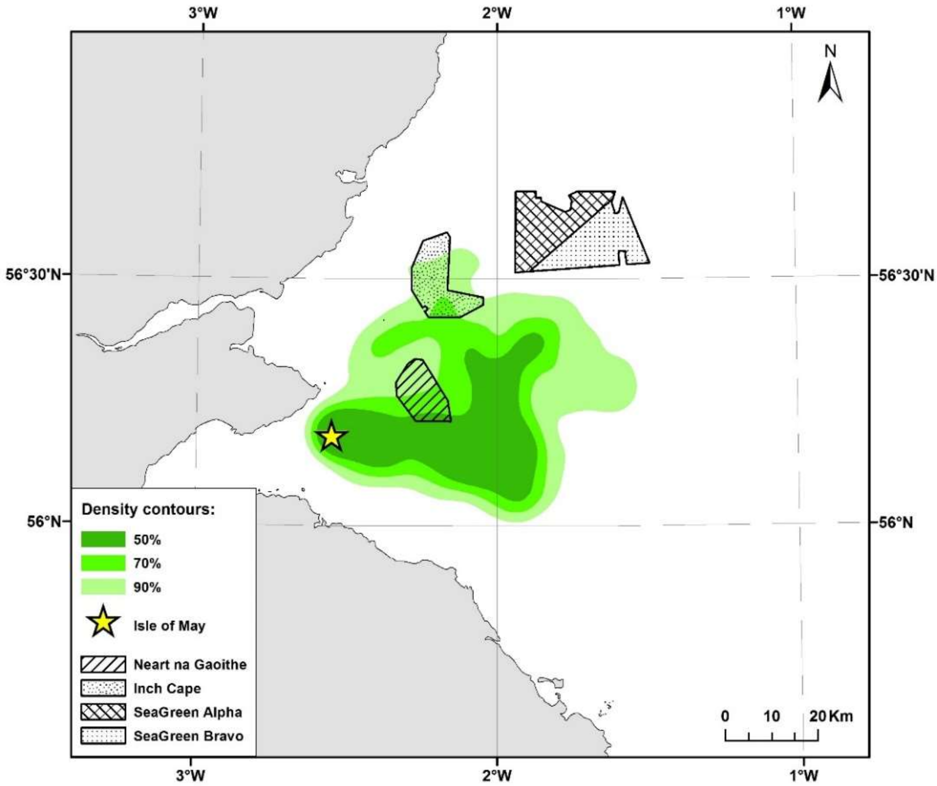
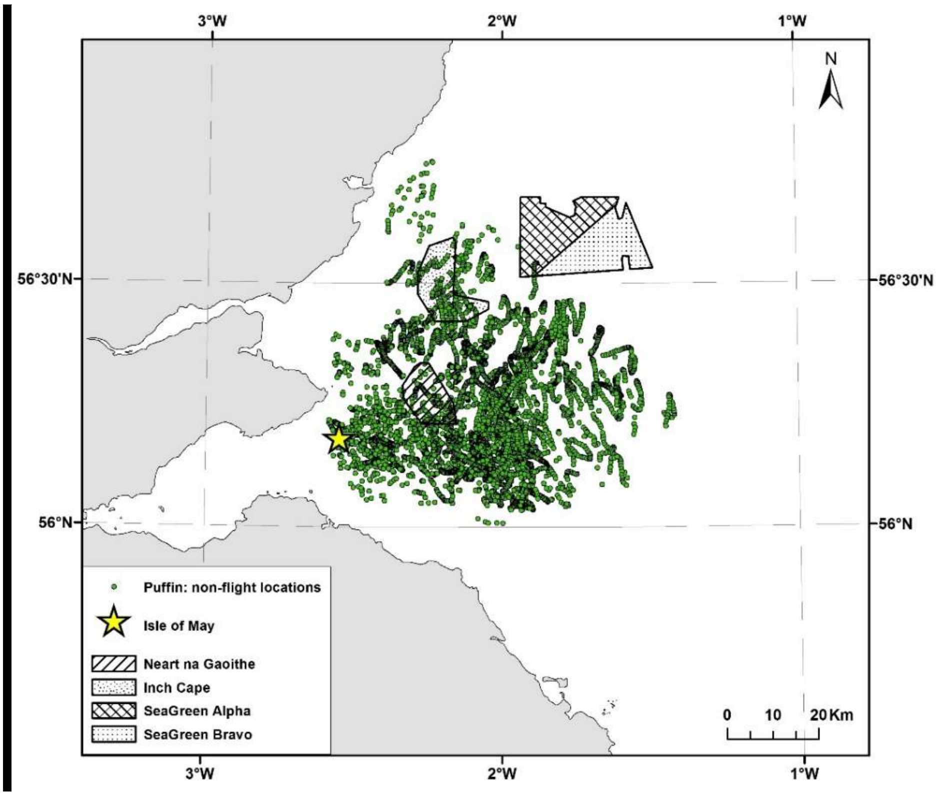


Fig. 12: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for puffin for flight and non-flight behaviours combined.

c)



d)

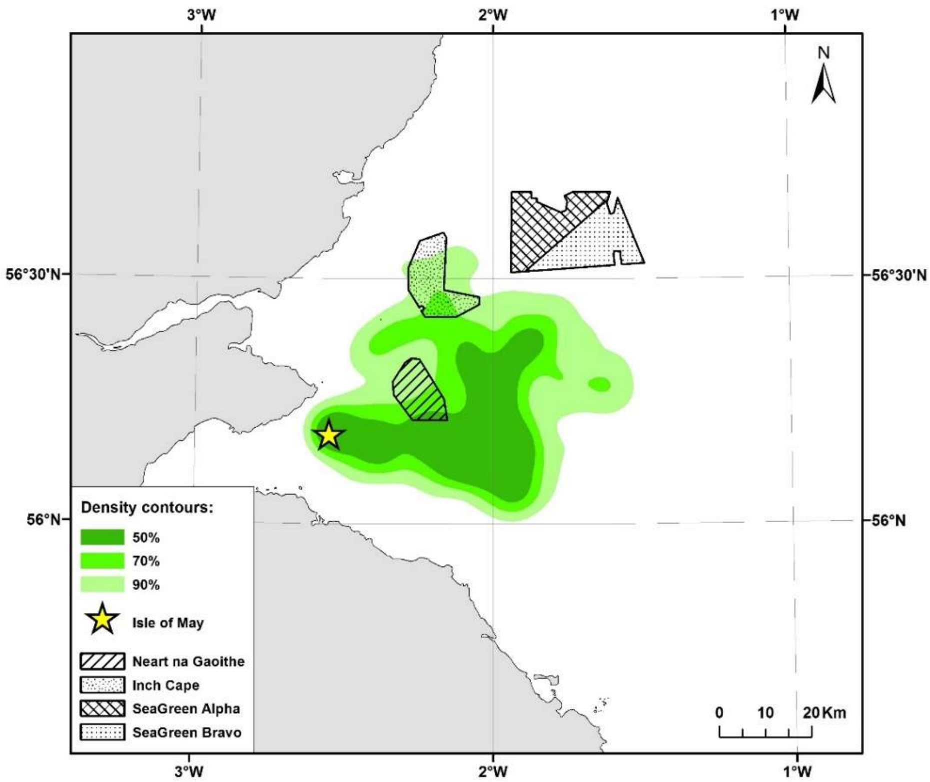


Fig. 12 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for puffin for non-flight behaviours only.

e)

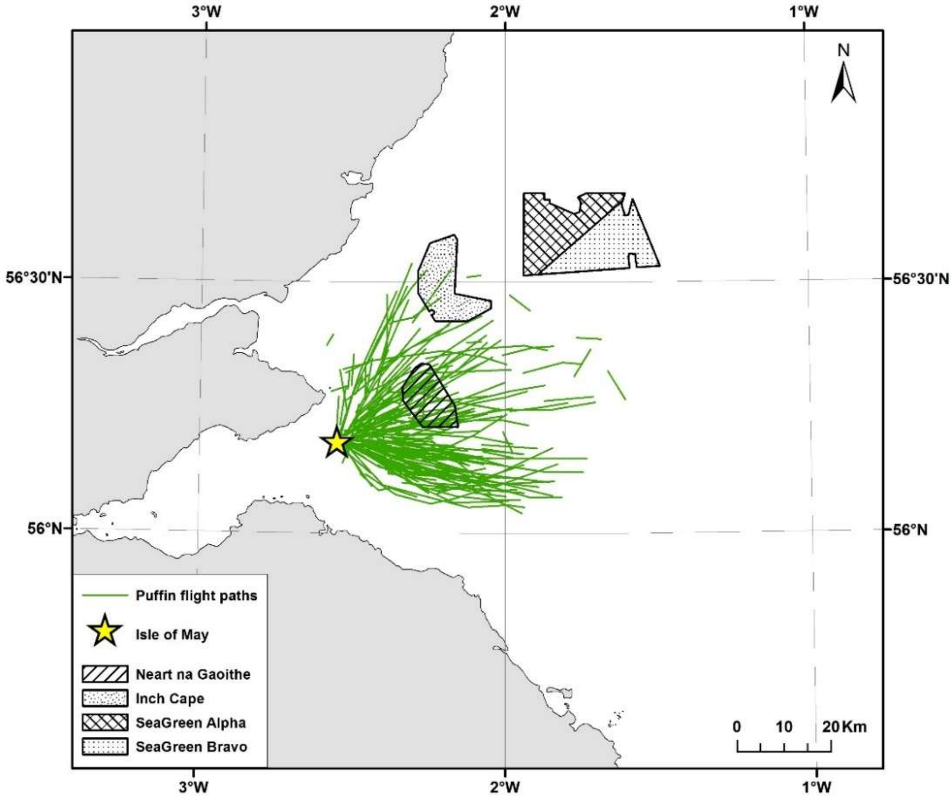
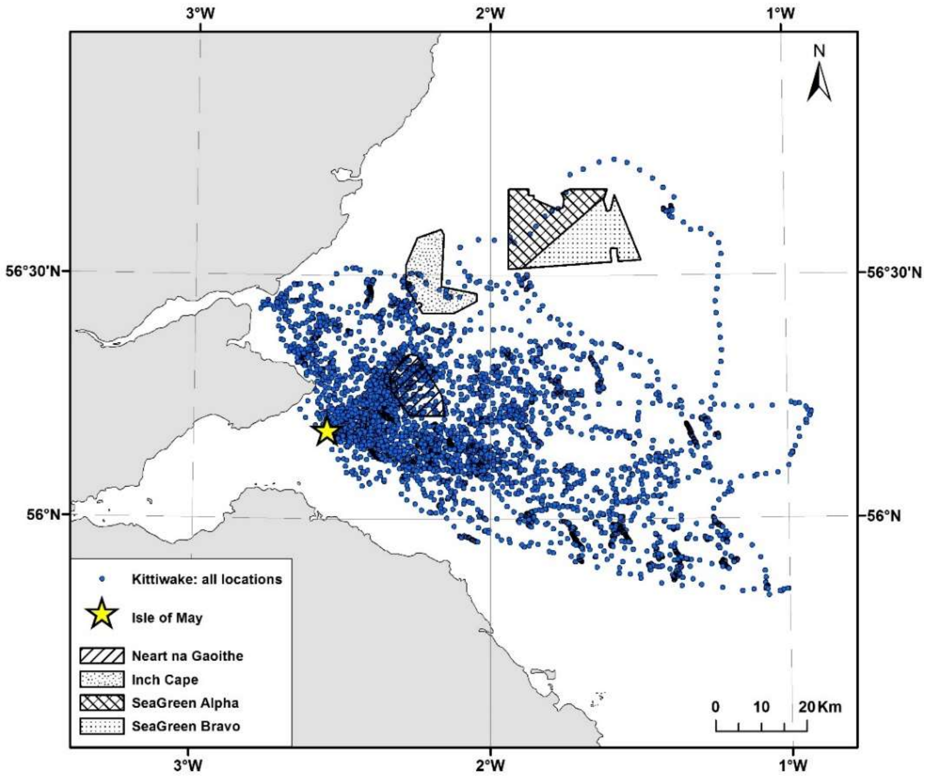


Fig. 12 (cont.): e) Horizontal flights lines for puffin.

a)



b)

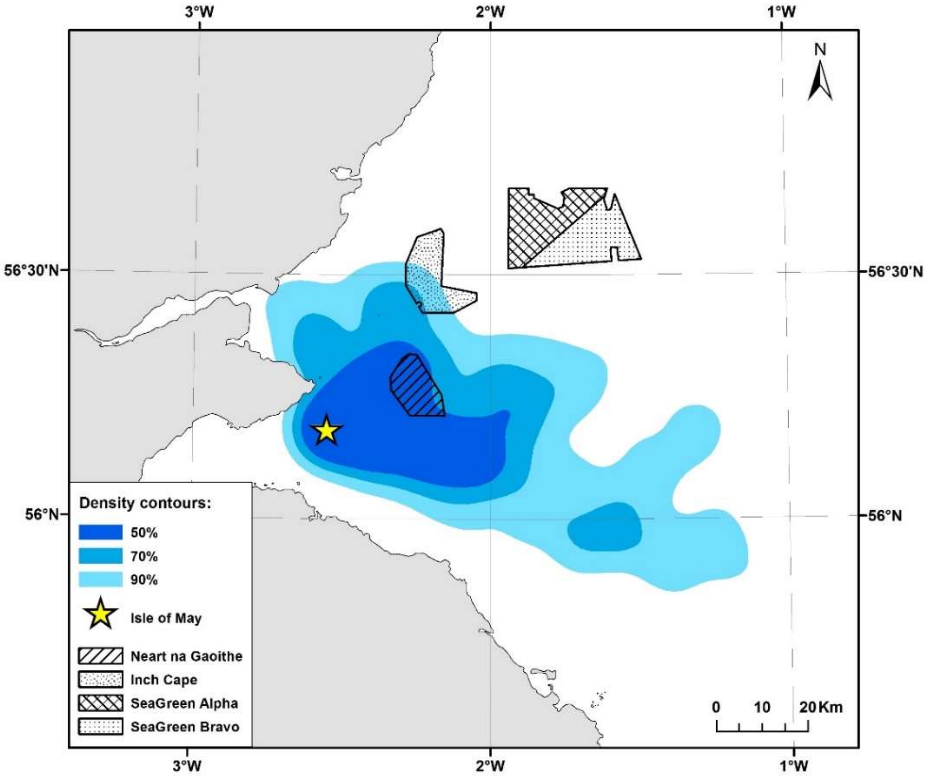
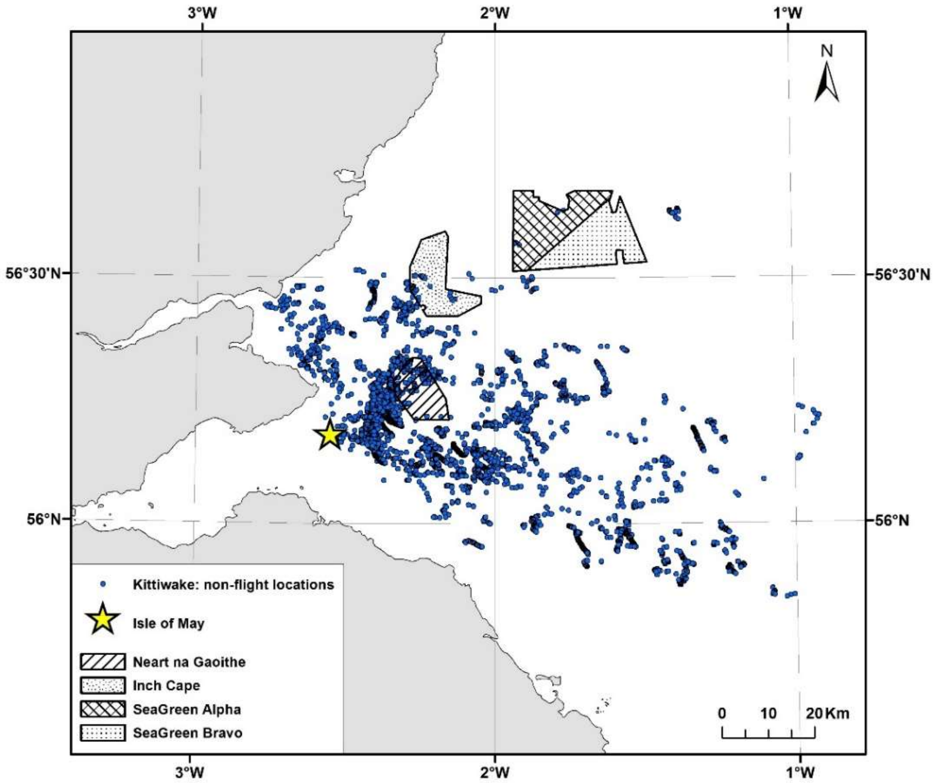


Fig. 13: a) Individual GPS fixes and b) utilisation distributions (50%, 70%, 90% contours) for kittiwake for flight and non-flight behaviours combined.

c)



d)

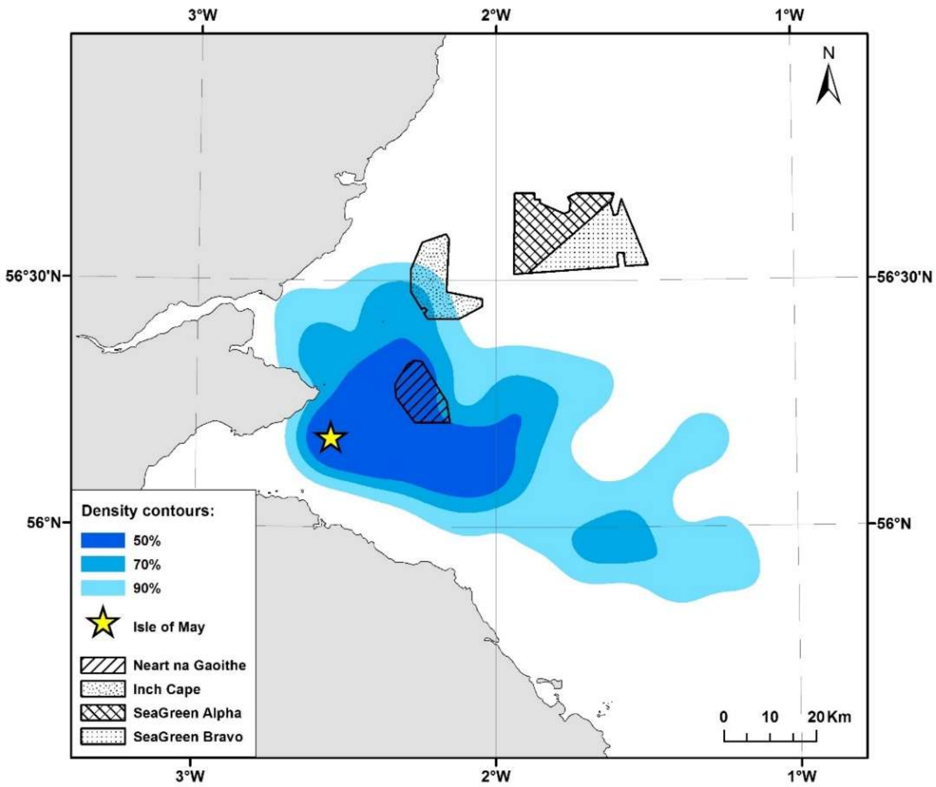


Fig. 13 (cont.): c) Individual GPS fixes and d) utilisation distributions (50%, 70%, 90% contours) for kittiwake for non-flight behaviours only.

e)

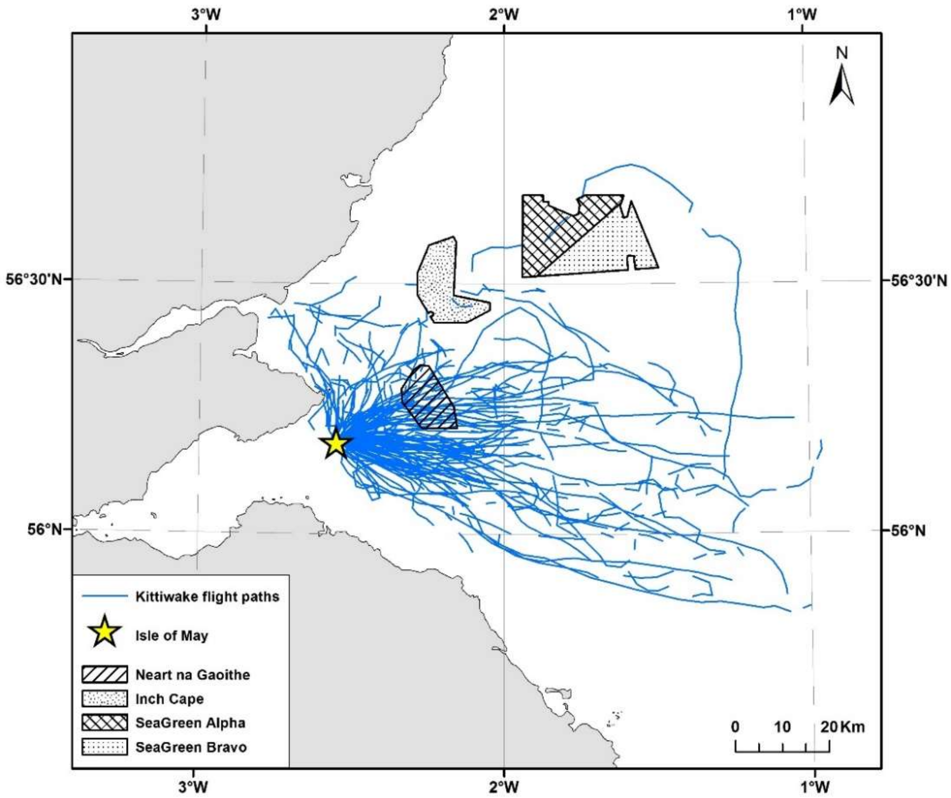


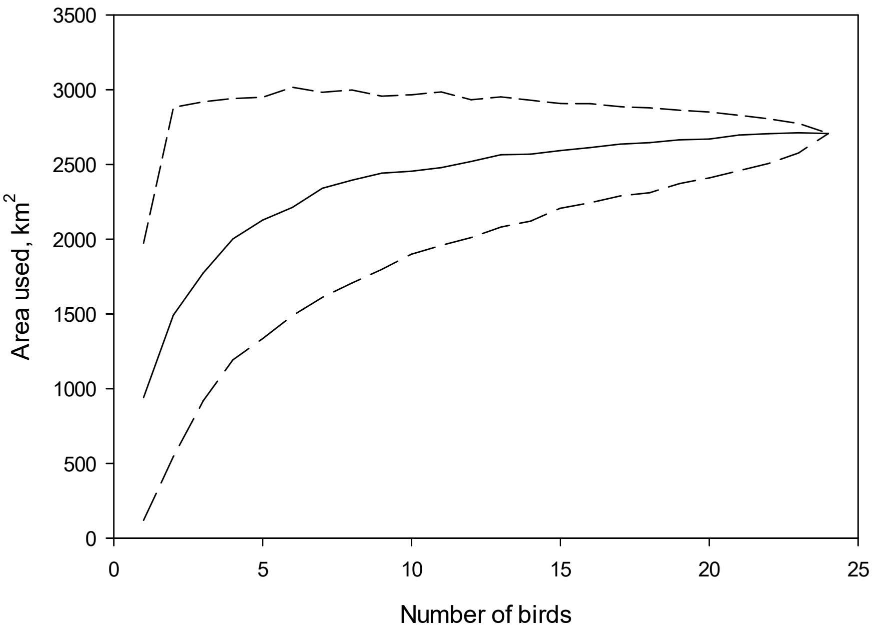
Fig. 13 (cont.): e) Horizontal flights lines for kittiwake.

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 8 birds, after which the increment with each additional bird was much smaller (Fig. 14a). Accordingly, the cumulative percentage of area used displayed the expected non-linear increase and eventually approximately plateaued at sample size of 20 birds (Fig. 14b). Randomized samples of 8 birds covered 88.5% of the area identified using all study birds (Fig. 14b). In razorbills, a substantial increase of area used was observed up to a sample size of 6 birds, with a further small increase up to 8 birds, after which the area size plateaued (Fig. 15a). This pattern was reflected in the cumulative percentage of area used, with randomized samples of 6 birds covering 97.8% of the area identified using all study birds (Fig. 15b). In puffins, area used increased substantially up to a sample size of 6 birds, after which the increment with each additional bird was much smaller (Fig. 16a). Randomized samples of 6 birds captured 94.4% of the area identified using all study birds (Fig. 16b). In kittiwakes, area used increased substantially up to a sample size of 8 birds, after which the increment with each additional bird was much smaller (Fig. 17a). Randomized samples of 8 birds captured 93.3% of the area identified using all study birds (Fig. 17b).

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. 14-17). 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.

a)



b)

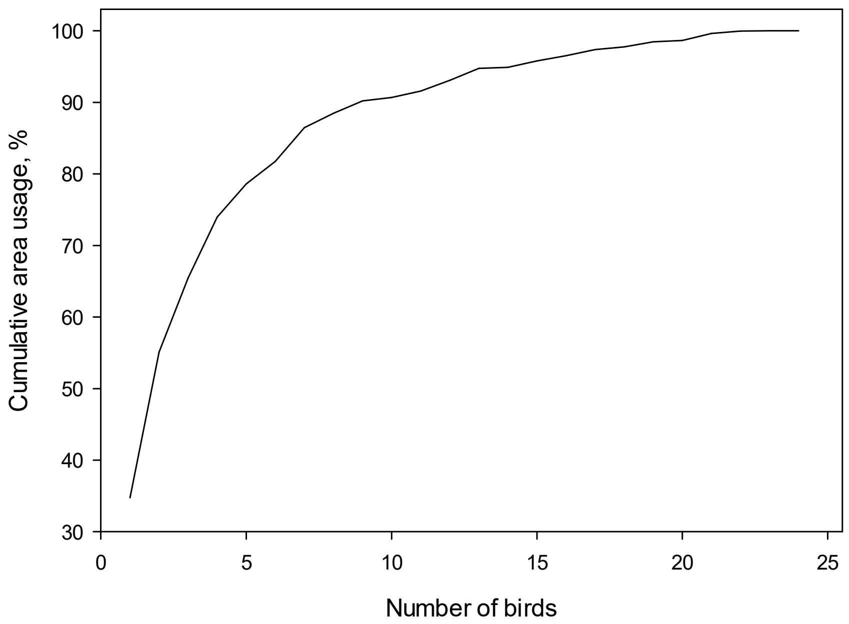
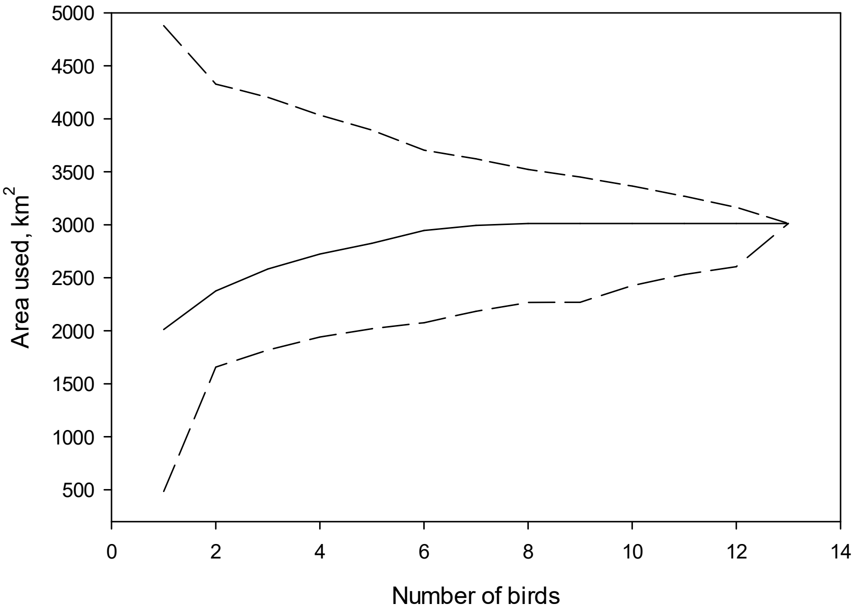


Fig. 14: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in guillemots. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.

a)



b)

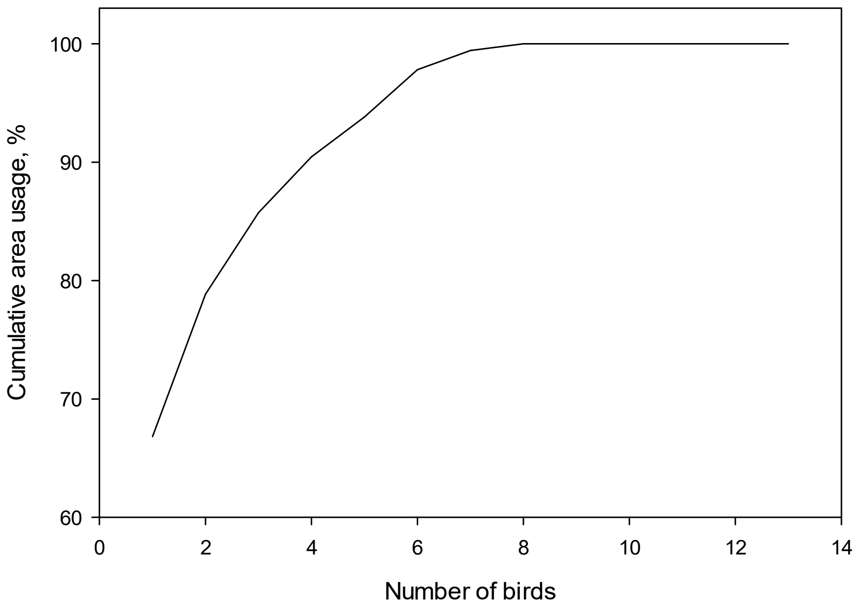
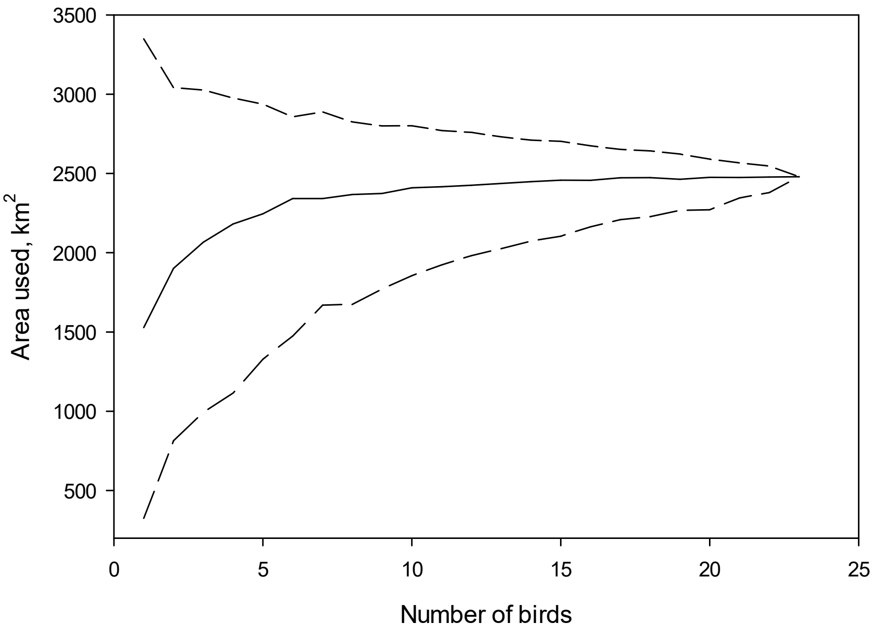


Fig. 15: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in razorbills. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.

a)



b)

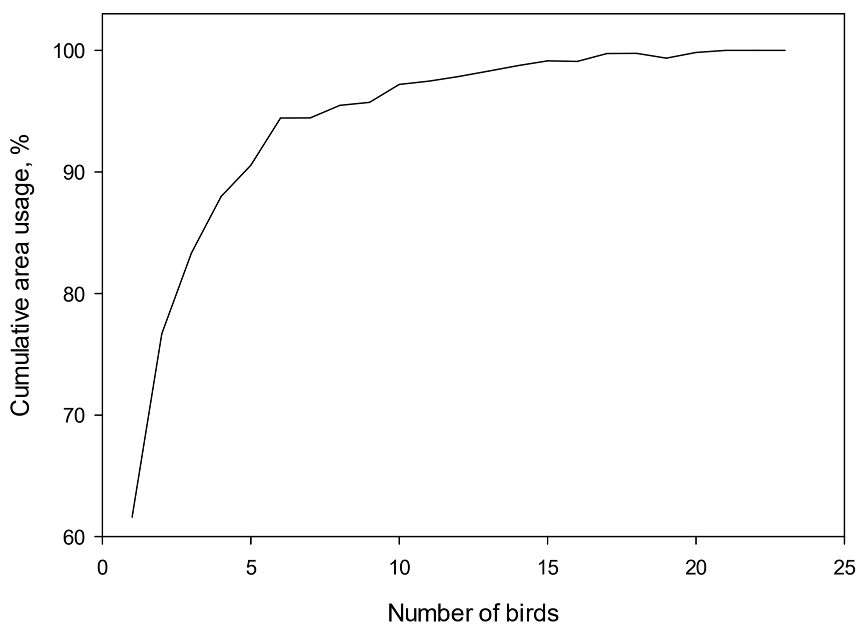
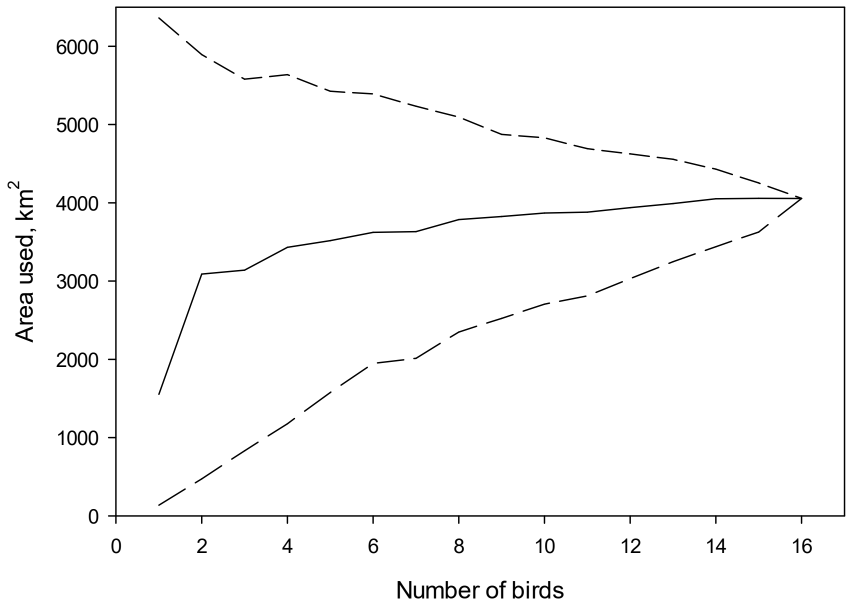


Fig. 16: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in puffins. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.

a)



b)

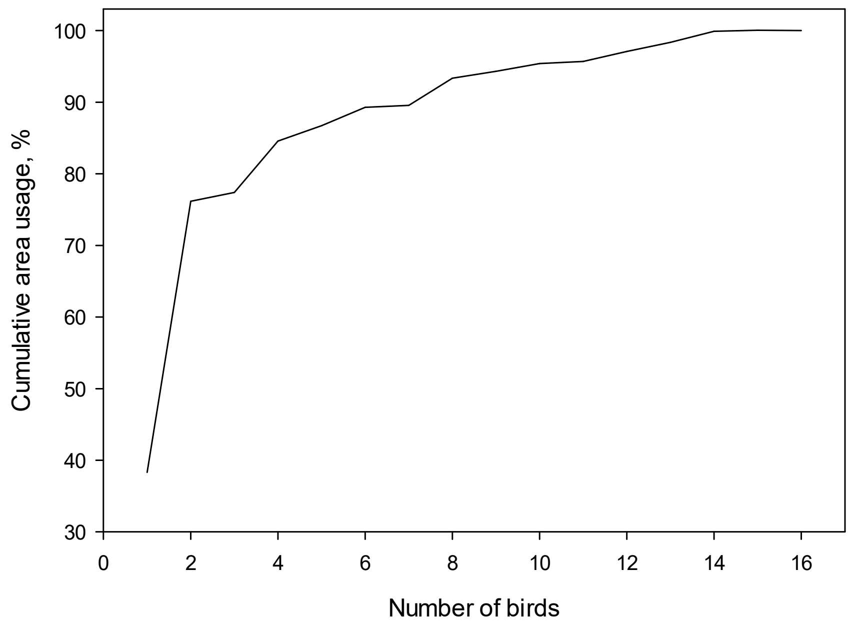


Fig. 17: Relationship between at-sea area used and sample size of birds estimated from a resampling procedure in kittiwakes. a) median area (solid line) and 2.5 and 97.5 percentiles (dashed lines) shown for each randomized sample size; b) cumulative percentage of area used by the population.

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 wind farm footprint is shown in Table 4. A small proportion of the core areas used (50% UD contours) by guillemots, razorbills and puffins overlapped with the footprint, whereas in 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	3d	920.4	5.0	0.5
90% contour	3d	2791.8	105.2	3.8
b) Razorbill				
50% contour	4d	799.0	3.4	0.4
90% contour	4d	3209.6	105.2	3.3
c) Puffin				
50% contour	5d	794.6	12.0	1.5
90% contour	5d	2505.9	105.2	4.2
d) Kittiwake				
50% contour	6d	923.5	94.7	10.3
90% contour	6d	3971.0	105.2	2.6

Table 4. 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 wind farm footprint.

3.4.2 Horizontal flight lines

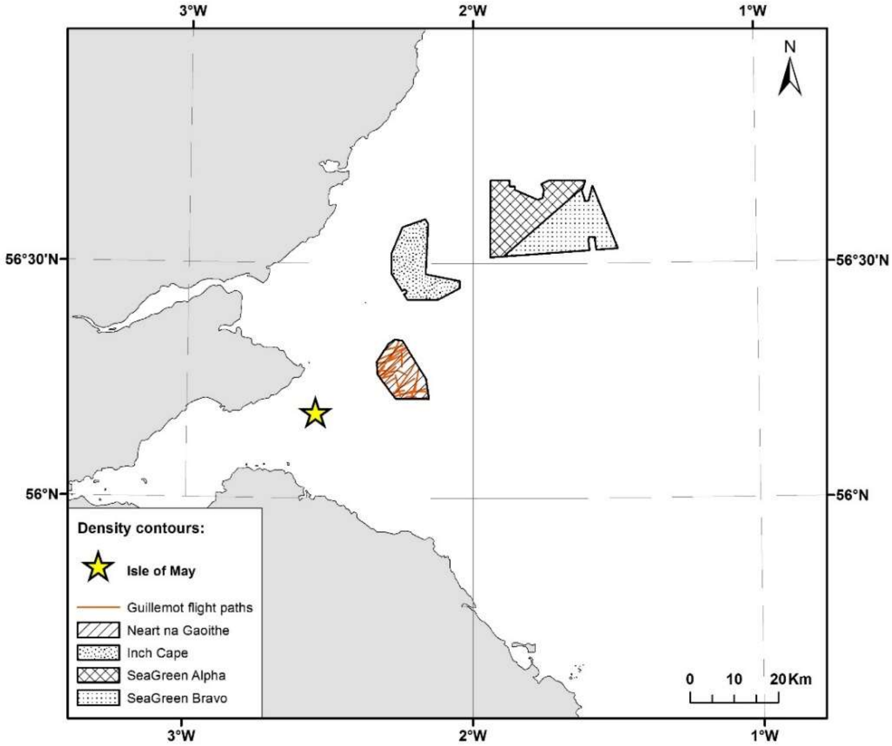
The proportion of birds, trips and flights passing through the planned Neart na Gaoithe footprint is shown in Table 5. The overlap of flight activities with the wind farm footprint was generally higher than the overlap of non-flight activities. In terms of the number of birds, all four species used the planned Neart na Gaoithe site extensively, and this was particularly so for kittiwakes and razorbills where over 75% of the study birds passed through the planned wind farm area. In comparison, for guillemots this figure was less than 50%. 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 highest in kittiwakes and lowest in guillemots. At the level of individual flights, overlap was again lowest in guillemots, and increasingly higher in razorbills, kittiwakes and puffins. The lower overlap of flight activities of guillemots with the planned Neart na Gaoithe footprint is likely due to the predominantly inshore distribution of the species during our study.

Category	n	% within Neart na Gaoithe
a) Guillemot		
Bird	24	45.8
Trip	207	11.1
Flight	722	4.7
b) Razorbill		
Bird	13	76.9
Trip	142	15.5
Flight	356	7.9
c) Puffin		
Bird	23	69.6
Trip	175	19.4
Flight	387	13.2
d) Kittiwake		
Bird	16	87.5
Trip	71	36.6
Flight	525	9.9

Table 5. Percentage of flight lines crossing the planned Neart na Gaoithe windfarm for each bird, trip and flight for each species.

Figure 18 shows the distribution of commuting flights that overlapped with the planned wind farm footprint. The correspondence between flight directions and the location of the Isle of May is apparent for all four species.

a)



b)

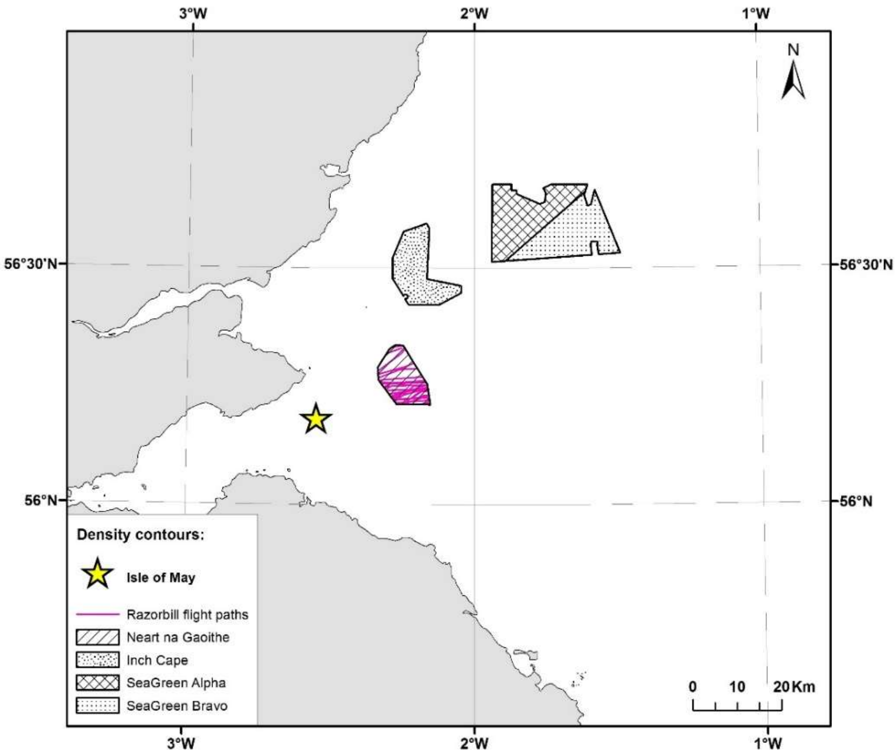
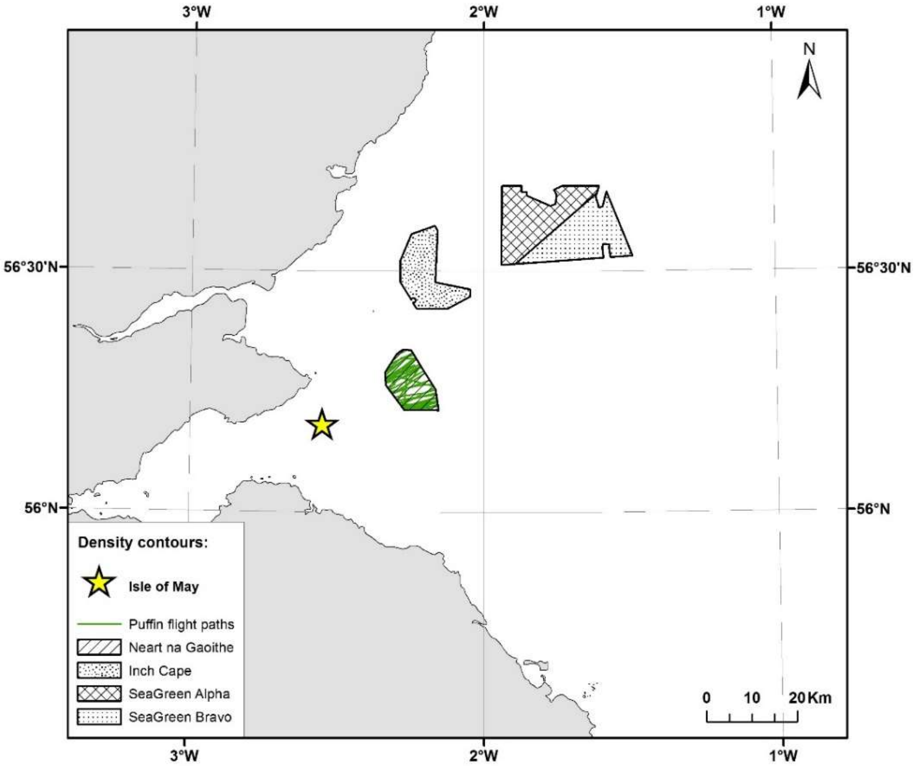


Fig 18: Flights passing through the planned Neart na Gaoithe wind farm for a) guillemot and b) razorbill.

c)



d)

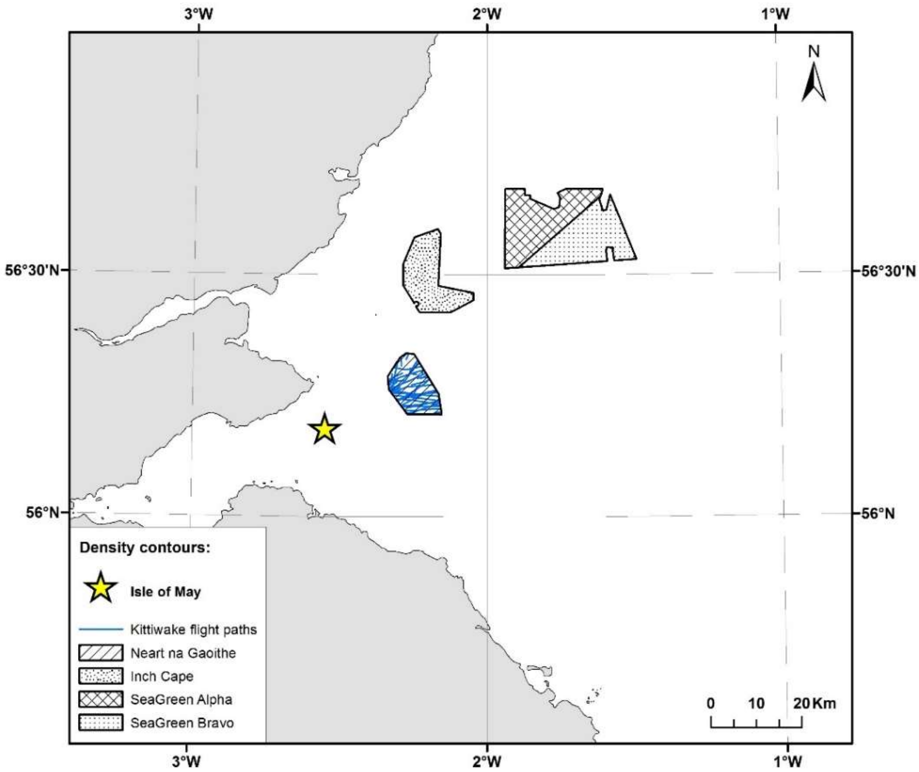


Fig 18 (cont.): Flights passing through the planned Neart na Gaoithe wind farm for c) puffin and d) kittiwake.

3.5 Device effects in puffins

3.5.1 Chick feeding rates

At the individual level, daily chick feeding rates were related to both deployment treatment and time since logger deployment. Feeding rates were markedly reduced in puffins that were fitted with GPS loggers compared to ones that received a colour ring only (Fig. 19, Table 6a). Furthermore, feeding rates declined with time since logger deployment (Table 6a). Together, these two variables explained 27% of the variation in feeding rates.

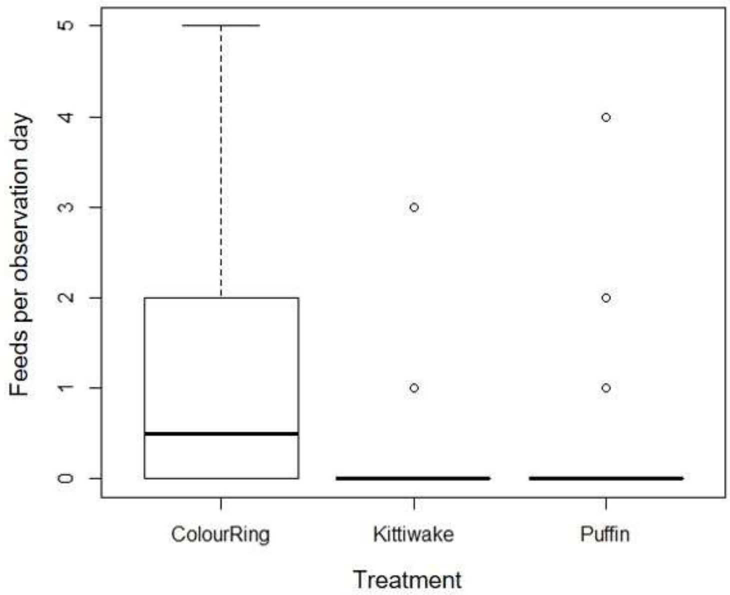


Fig.19: Median number of feeds individuals delivered to chicks per observation day in relation to deployment treatment.

At the pair level, feeding rates were affected by both deployment treatment and time since deployment. Feeding rates were most reduced in pairs where both adults were fitted with GPS loggers, whereas decline in feeding rates was less pronounced in pairs where one of the partners was unmanipulated (Fig. 20, Table 6b). Again, a decline in feeding rates with time since deployment was observed (Table 6b). These two variables together explained 22% of the variation in feeding rates.

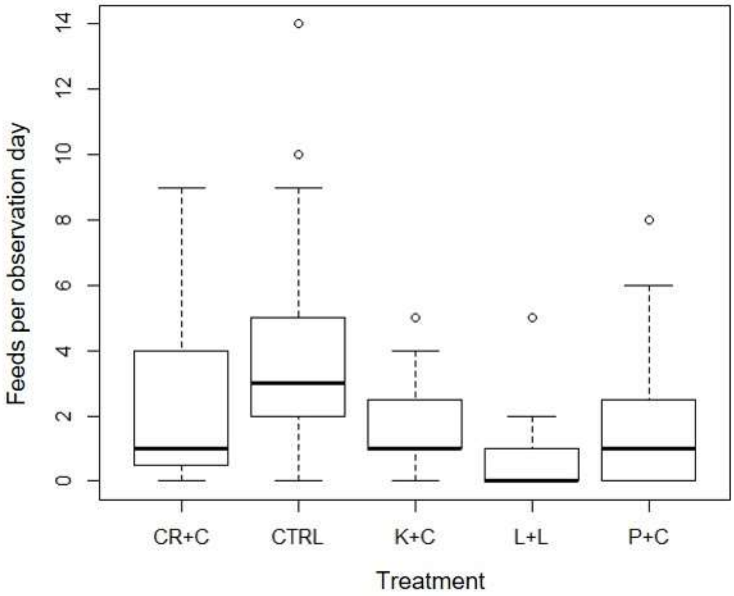


Fig.20: Median number of feeds pairs delivered to chicks per observation day in relation to deployment treatment (CR+C = colour ring + control; CTRL = control; K+C = kittiwake logger + control; L+L = logger + logger; P+C = puffin logger + control).

Feeding rate	N birds	N parameters	Parameter estimate (± SE)		R^2m	R^2c
			Treatment	Day since deployment		
(a) individual	18	4	0.73 ± 0.21	- 0.24 ± 0.06	0.27	0.38
(b) pair	56	4	0.35 ± 0.07	-0.04 ± 0.01	0.22	0.56

Table 6. Generalised linear mixed models testing for effects of deployment treatment and time since deployment on puffin feeding rates at (a) the individual level and (b) the pair level. Only the best model for each analysis is presented. R^2m: marginal coefficient of determination (representing the variance explained by the fixed effects); R^2c: conditional coefficient of determination (representing the variance explained by both fixed and random effects, see Methods for details).

3.5.2 Chick survival

The marked reduction in feeding rates after capture and deployment of GPS loggers resulted in breeding failure for some of the puffin pairs, particularly in the first deployment session (Table 7). This negative outcome was avoided for other pairs and in the third deployment session all monitored chicks from treatment burrows fledged successfully. Supplementary feeding was used in all deployment sessions. In session 1, it was not initiated immediately after deployment, and uptake by the chicks was less successful with a greater incidence of fish being left untouched, likely because the chicks were younger. In sessions 2 and 3, uptake was more successful and, thus, supplementary feeding may have contributed substantially to the higher survival rates in these sessions. The summary statistics in Table 7 include burrows both inside the study plots where feeding rates could be recorded and outside where feeding rates could not be estimated, but survival rates could be ascertained. We were unable to locate the burrows of 10 (29%) puffins carrying loggers, so the survival rates of their chicks is unknown but it is likely that these adults would have been seen carrying fish if they had been successful. Thus, working on the assumption that the chicks of these birds did not survive, the minimum success rate of study burrows was 50% (15/30).

Deployment session	Survived to fledging	Died before fledging	Unknown	Total
1	0	4	2	6
2	4	1	2	7
3	11	0	6	17

Table 7. Breeding success of puffin treatment burrows from each deployment session. Burrows included those outside the areas covered by feeding watches.

3.5.3 Foraging trip duration and maximum range

Deployment treatment did not affect foraging trip duration (mean ± SE, square root transformed, puffin logger: 3.3 ± 0.2 hrs, kittiwake logger: 3.2 ± 0.2 hrs; Table 8a). Trip duration increased slightly with time since deployment but this relationship was weak (Table 8a). Accordingly, this variable explained only 2% of the variation in trip duration.

Similarly, maximum range of foraging trips was not related to deployment treatment (mean ± SE puffin logger: 26.3 ± 1.8 km, kittiwake logger: 29.9 ± 2.2 km; Table 8b) but increased slightly with time since deployment (Table 8b). This variable explained only 4% of the variation in trip range.

Trip characteristic	N birds	N parameters	Parameter estimate (± SE)		R^2m	R^2c
			Treatment	Day since depl.		
(a) duration	23	3		0.1 ± 0.05	0.02	0.06
(b) max range	23	4		1.3 ± 0.5	0.04	0.16

Table 8. Generalised linear mixed models testing for effects of deployment treatment and days since deployment on puffin foraging trip characteristics (a) trip duration and (b) maximum range. Only the best model for each analysis is presented.

4 Discussion

4.1 Data collection

The remote download GPS technology performed well, and the anticipated increase in proportion of individuals contributing data was achieved, with tracks obtained from 93% of study individuals whereas only 60% of individuals contributed data using archival loggers in 2010 (Daunt et al. 2011a). In addition, the number of trips/bird in 2018 was more than twice that in 2010. Data gaps due to poor satellite connection accounted for <0.5% of the deployment period. There was also significantly less disturbance to the study birds, since no recapture was required. In summary, the remote download technology was a successful approach with a number of important advantages over archival loggers.

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) 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 areas more extensively 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 matched the distribution patterns and demonstrated the predicted directional movement to and from the colony, particularly for foraging trips offshore. At the maximum ranges of foraging trips, the headings of flight lines became more variable.

The resampling analysis indicates 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. We are therefore confident we have captured the key areas used by Isle of May seabirds for both flight and non-flight activities at that time, with the exception of puffin because of the marked device effects observed, which we consider in detail in Section 4.4. The period over which the birds were tracked was relatively short (deployments took place over 1-6 days except in puffins where they spanned 3 weeks; average deployment length was up to 7 days) so caution is required when interpreting these distributions as representative of periods outside deployment windows.

A comparison of the seabird distribution patterns in 2018 to those observed on the Isle of May in previous years (2010, 2012, 2013 and 2014; Daunt et al. 2011a, Harris et al. 2012; Appendix 1) shows that there is significant inter-annual variation within species. These 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, 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, when feeding young (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 Overlap with Neart na Gaoithe

With the exception of kittiwakes, the overlap of core utilisation distributions of the Isle of May seabirds with the planned Neart na Gaoithe footprint was <1.5%. This reflected the birds' choice of key foraging areas that were concentrated around the colony, near the coast and around offshore sand banks beyond the wind farm footprint. However, the entire planned wind farm footprint fell within the overall areas used by all four species suggesting the potential for interaction for a proportion of the time. Stronger overlap was observed for flight activities, with birds from all four species crossing the wind farm footprint to a greater or lesser extent. 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 is least apparent for guillemots due to their more coastal 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 data should be collected over several years and from multiple relevant populations.

4.4 Device effects in puffins

Our study of device effects in puffins provided further evidence of marked negative effects of GPS logger deployment on chick provisioning rates and subsequent chick survival. Feeding rates in individuals fitted with GPS loggers were markedly reduced compared to birds that received a colour ring only. Further, pair level feeding rates were most substantially reduced in pairs where both partners were fitted with loggers and to a lesser extent in pairs where one of the partners was unmanipulated, compared to controls (where neither bird was manipulated). Puffins are known to be sensitive to disturbance (Harris & Wanless 2011) and previous pilot work on the Isle of May suggested that the foraging behaviour of instrumented birds can be adversely affected (Harris et al. 2012). Comparing our results at the individual and pair level indicate that both handling and device deployment may contribute to the negative device effects. Feeding rates were lower among instrumented birds than those just carrying colour-rings, yet pairs where one member had a colour ring attached (handling effect) and those where one member had a logger deployed (handling and deployment effect) had reduced provisioning rates compared with controls. Birds are known to compensate if the mate reduces provisioning rates (Harris & Wanless 2011). As such, it would appear that the mates of GPS-deployed individuals compensated more than those of colour-ringed individuals, resulting in no strong difference in provisioning rates between these two groups at the pair level. The lack of opportunity for compensation where both birds were instrumented is likely to have contributed to the very low provisioning rates of these pairs.

We were also interested in whether the strength of the deployment effect was related to logger weight and size. Birds fitted with either the heavier and larger ‘puffin’ logger or with the lighter and smaller ‘kittiwake’ logger showed substantially reduced chick feeding rates. Furthermore, we found no evidence that key foraging trip characteristics such as duration and maximum range differed between birds from these two treatment groups, suggesting that the attachment of a foreign object to the bird’s back may be a key issue causing disturbance, or that some threshold mass and shape exists below that of both logger types deployed here.

Feeding behaviour was also related to time that had passed since logger deployment with feeding rates declining and trip duration and range slightly increasing. Thus there was no evidence that the birds had habituated to the presence of the logger, or that the effects of handling would reduce over time.

Such severe negative impacts of device deployment are somewhat rarely reported from seabirds and are a cause of concern since they have the potential to impact on chick survival. Most previous studies demonstrate more subtle effects such as increased stress levels and altered activity budgets, including reduced nest attendance and flight time (e.g. Chivers et al. 2016, Heggøy et al. 2017 but see Thaxter et al. 2017). However, the body of evidence regarding device effects on birds is growing as 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, attachment method and minimising handling-related disturbance (Vandenabeele et al. 2012, 2014, Thaxter et al. 2014). It is imperative that future studies take these factors into account in order to minimise negative impacts on the study populations and increase the representativeness of resulting findings.

With respect to GPS tracking of the Isle of May puffin population in 2018, we were successful in undertaking the planned capture and deployment protocol using mist nets. However, the desired reduction in device effects in comparison to past approaches, when breeding birds were captured in breeding burrows, did not materialise. It would appear that puffins did not respond well to loggers of either size (4.1 and 8.2g), but that handling was also a factor. Over the course of the three deployment sessions, we adapted our capture protocol to minimise the possibility that both members of the pair were carrying devices, and to ensure the welfare of the chicks of deployed adults through supplementary feeding from deployment. As a result of this, we did not experience both members of any pairs being instrumented in the last deployment session, and all chicks of instrumented birds where the burrow was identified fledged successfully. The age of chicks may also have been a contributory factor – it is likely that older/large chicks are better able to withstand intervals without food. However, we were unable to locate the burrows of 29% of individuals carrying devices, and therefore were not able to supplementary feed those chicks. The survival rates of these nests was unknown, but it is possible that chicks at these burrows may have died because of the absence of supplementary food. Further, despite our adjustments to capture protocols, using mist nets cannot guarantee that both members of a pair do not receive a device, something that is particularly important to avoid because provisioning of unmanipulated mates proved important in ensuring that chicks received feeds throughout the period a bird was carrying a GPS logger.

We recommend that, should GPS tracking be undertaken in the future, adults should be caught in nets laid at burrow entrances rather than using mist nets. That way, we can ensure that we do not deploy on both members of the pair, and we know the location of all study burrows and can therefore undertake supplementary feeding of all chicks of instrumented birds. We also recommend that deployments are delayed until later in the chick-rearing period to avoid deploying on adults with very young chicks. A further refinement that could be considered is to delay supplementary feeding until three days after deployment, at which point the data loggers would have stopped recording data at the faster sampling interval of 10 min. This method would ensure that the data are as representative as feasible, since puffins alter their behaviour when their chicks are supplementary fed (Harris & Wanless 2011), yet the duration would be sufficiently short that, should provisioning rates decline as a result of device effects, the long-term wellbeing of the chick would not be compromised.

Irrespective of the method of capture, handling and deployment, it would appear that puffins in this population will show marked device effects with respect to colony attendance and chick provisioning with all GPS loggers currently available on the market. This situation may change if loggers become smaller still, or if the option for deploying loggers on leg rings becomes possible (there is potential in principal, but some technological development is required; Pathtrack pers. comm.). However, in the meantime, we need to consider whether the at-sea distributions that we obtained are representative of the distribution of unmanipulated birds. It is possible that instrumented birds adopted different foraging behaviours, for example by showing different directionality or range than unmanipulated birds. Effects do not appear to decline over time, so programming the loggers so that they start several days into the deployment would not to appear to be a solution to this issue. It is very challenging to assess the representativeness of the data without information on the distribution of the unmanipulated birds. What can be stated is that the offshore distribution, in particular the maximum ranges in comparison to other study species, is plausible for foraging of Isle of May breeding adults, based on our understanding of their diet and ecology (Harris & Wanless 2011). However, we remain concerned, given the lower provisioning rates compared with control birds, that study 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 may have been unrepresented in these data. We drew a similar conclusion in the previous study of GPS tracking of puffins on the Isle of May in 2010 (Harris et al. 2012). If this is the case, our estimate for the overlap with offshore renewable developments may represent a worse case scenario. One possible avenue for testing this possibility is to compare the distributions we observed with those recorded from aerial surveys that were being undertaken at the same time. These aerial surveys were only carried out in a subset of the puffin foraging range, and constitute all individuals, not just breeding adults from the Isle of May. However, given that the area surveyed was sufficiently large, and the breeding adult population on the Isle of May is likely to constitute a significant proportion of all puffins foraging in the area, the comparison is likely to be worthwhile.

4.5 Conclusions

This project 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. The use of remote download GPS loggers was very successful, ensuring that data were obtained for nearly all individuals, and deployment durations were longer than have previously been 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, the results highlight that there is marked variation within species among years for all Isle of May populations, both in terms of directionality and foraging range. The study demonstrated marked negative effects of device deployment on puffins, supporting past findings with this population, suggesting that the new method of capture employed (mist netting versus the standard approach of extracting from the burrow), was still insufficient to alleviate the problem. The method also introduced two new challenges, that both members of the pair could potentially receive a device, and that a proportion of burrows of instrumented birds were not identified and therefore could not be supplementary fed.

The extent of interannual variation, coupled with the age of the earlier GPS data (4-8 years' old) 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, to maximise the opportunities for quantifying wind farm effects in the study region.

However, any proposals for future GPS tracking work on puffins at this colony require careful consideration. Although we have developed a mechanism for safeguarding the welfare of chicks of birds carrying devices through supplementary feeding, questions still remain about short-term effects on adults, and representativeness of the at-sea distributions of these birds. This assessment should include the most appropriate method of capture of puffins. Given the lack of success with the new method, it would be advisable to reconsider former methods, notably capture of adults at burrows, since these offer key advantages over the current method in terms of ensuring that the location of chicks of all study adults is known, and ensuring that deployment does not occur on both adults of a pair.

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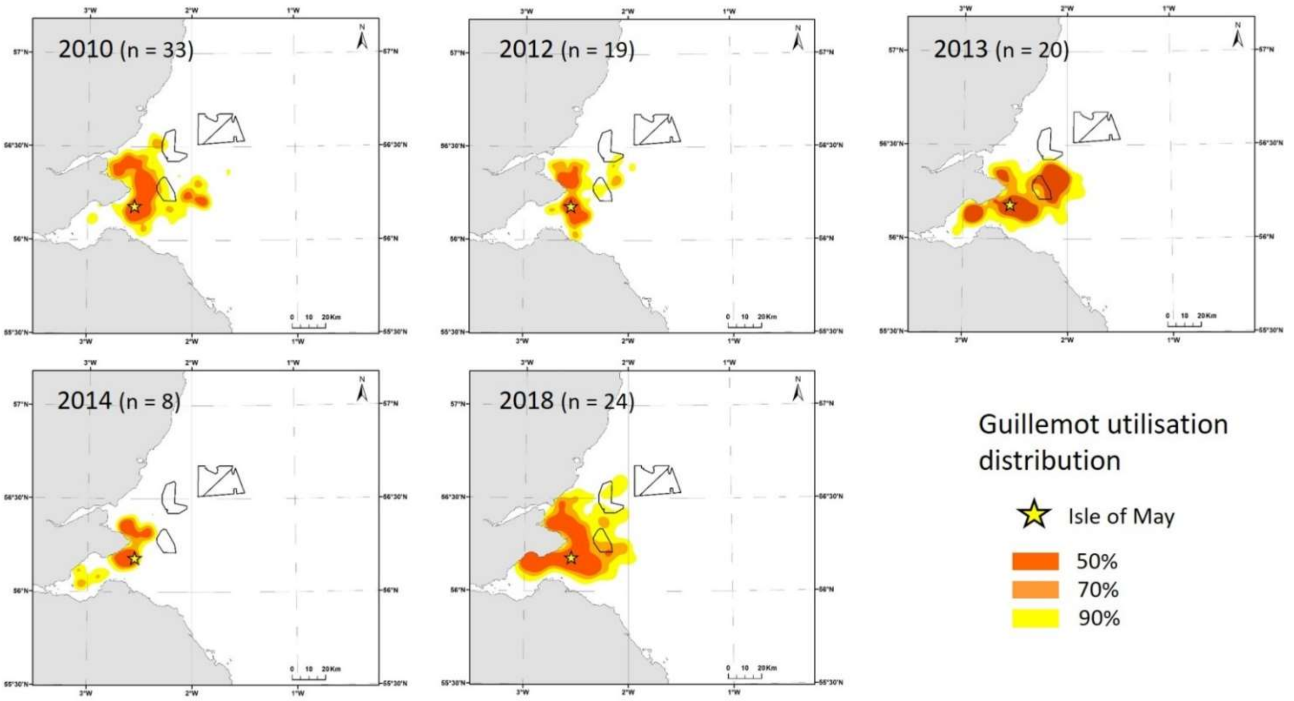
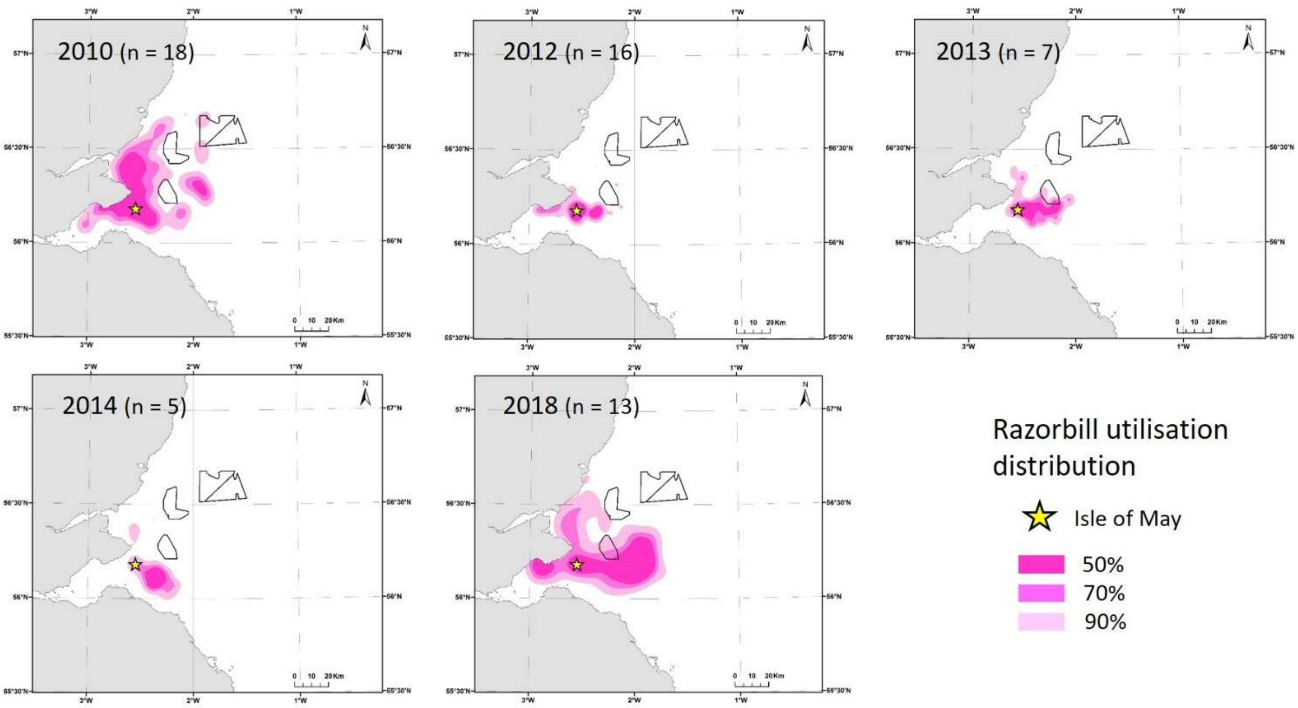
7 Appendix

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.

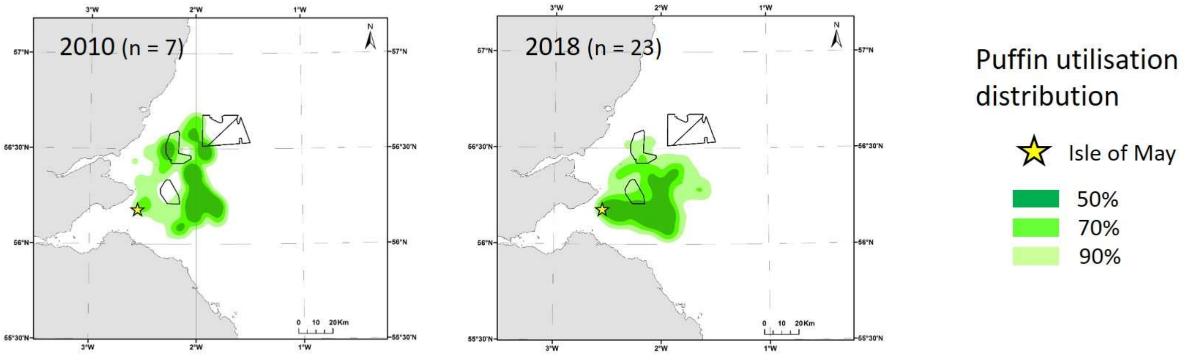
a)



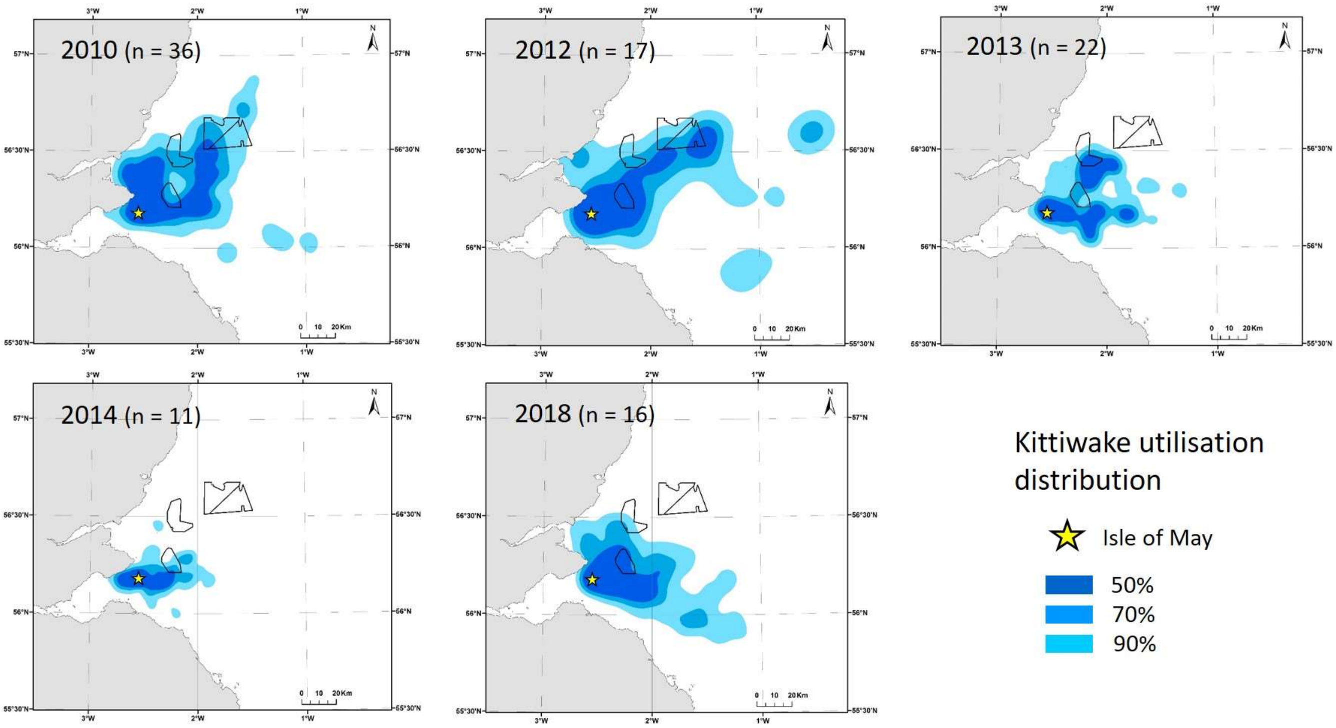
b)



c)


2010 (n = 7)
2018 (n = 23)
Puffin utilisation distribution
Isle of May
50%
70%
90%

d)


2010 (n = 36)
2012 (n = 17)
2013 (n = 22)
2014 (n = 11)
2018 (n = 16)
Kittiwake utilisation distribution
Isle of May
50%
70%
90%

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