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Gannets at Bempton Cliffs, note antenna of tagged adult, top centre

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## **Foraging ranges of northern gannets *Morus bassanus* in relation to proposed offshore wind farms in the North Sea: 2010-2012**

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### ABSTRACT

In each of the three years 2010-2012, adult northern gannets (*Morus bassanus*) from Bempton Cliffs, on the northeast coast of England, were fitted with satellite tags to investigate their foraging ranges during chick-rearing and early post-breeding periods. This was done to establish whether there is overlap with potential development zones for offshore wind energy generation in the North Sea. The three seasons of study, in 2010 ( $n=14$  birds), 2011 ( $n=13$ ) and 2012 ( $n=15$ ), have identified the previously unknown sea areas used by adult gannets from Bempton Cliffs. Locations of tagged birds during chick-rearing coincided with the Hornsea offshore wind energy zone in particular, with some birds recorded on Dogger Bank and a few records in the East Anglia zone, and within the Greater Wash strategic area for offshore wind energy generation. Post-breeding locations overlapped with the Hornsea, Dogger Bank, and East Anglia zones before dispersal out of the North Sea or cessation of recording. This report presents comparative results for all three chick-rearing and, for a reduced sample of birds, early post-breeding periods. Breeding success at Bempton Cliffs was high in all three years. Locations during the three chick-rearing periods show a marked similarity in the area of active use, but a notable difference in the extent of the core area used in 2012. Distance to colony had the over-riding influence on foraging range. Relatively small annual samples mean that we remain unsure how representative the data are of year to year foraging activity by breeding gannets from Bempton Cliffs, especially in years of lower breeding productivity. However, the collective foraging range of the forty two tagged birds encompassed the full seaward radius around Bempton Cliffs, so we are reasonably confident that our results represent the sea areas used by adult gannets, at least in seasons of good breeding productivity.

**Keywords:** gannet, wind energy, satellite telemetry, chick-rearing, post-breeding

## BACKGROUND

The European Union Renewable Energy Directive target requires the UK to meet 15% of its energy supply from renewable sources by 2020 (Directive 2009/28/EC). This is equivalent to 35–45% of electricity and places heavy reliance on wind energy for its delivery, requiring a substantial increase over the current 10.4 GW installed capacity (RenewableUK, [www.renewableuk.com](http://www.renewableuk.com), accessed 21 November 2013). Estimates vary as to the exact scale of expansion needed, but it is generally thought that onshore wind generation will need to increase to 13–15 GW by 2020, and offshore wind generation to 25–30 GW installed capacity during the same period (DECC 2011). In response to these ambitious targets, there has been an order-of-magnitude increase in potential offshore wind energy projects, in particular the large proposed Round 3 development zones (Figure 1) (The Crown Estate, 2012: <http://www.thecrownestate.co.uk/energy-infrastructure/offshore-wind-energy/> accessed 18 November 2013).

Britain and Ireland are of outstanding international importance for their breeding seabirds and migratory waterbirds, for which they host a high proportion of the biogeographical populations of several species, especially breeding Manx shearwater *Puffinus puffinus*, northern gannet *Morus bassanus* (hereafter, gannet), great skua *Catharacta skua* and lesser black-backed gull *Larus fuscus* (Mitchell *et al.* 2004). The UK hosts approximately 59% of the world population of gannets at several colonies distributed mainly around the western and northern coasts of Britain (*e.g.* Wakefield *et al.* 2013). The Special Protection Area (SPA) at Flamborough Head and Bempton Cliffs (hereafter, Bempton Cliffs) includes gannet as part of the breeding seabird assemblage that forms a qualifying feature of the site and is the only gannet colony in England. Several proposed offshore wind energy development zones lie within the expected foraging range of breeding seabirds from this SPA, notably for gannets, for which studies from the Bass Rock indicate regular foraging ranges in excess of 100 km (*e.g.* Hamer *et al.*, 2007). The foraging areas used by gannets from Bempton Cliffs were unknown prior to 2010, when this project started (Langston & Boggio 2011, Langston & Teuten 2012). Breeding gannets are central place foragers (Grémillet *et al.* 2006). Consequently, their foraging ranges are likely to be most constrained when provisioning growing chicks, although they can still cover large distances during this period.

There were an estimated 261,000 Apparently Occupied Nests (AONs) of gannets in Britain and Ireland (218,500 in the UK) when the last complete census was carried out in 2003/04 (Wanless

*et al.* 2005). The gannet is amber-listed on the Birds of Conservation Concern (BoCC, Eaton *et al.* 2009). There has been a consistent rise, of 2% *per annum*, in the world population of gannets throughout the period since regular censuses began in 1900. Bempton Cliffs had 3,940 AONs in 2004, rising to 7,859 AONs in 2009, and 11,061 AONs in 2012 (<http://www.jncc.gov.uk/page-2875>, accessed 27 July 2013). The steady rate of increase at Bempton Cliffs, since its colonisation in the 1960s, has become more rapid since 2000. The potential for further growth is considerable in view of the large number of non-breeding immatures associated with the colony; 1,470 in 2009, and 798 in 2012. This contrasts with the situation across Britain and Ireland as a whole, where the rate of population growth dropped to 1.33% *pa* during 1995-2005, from the previously recorded 2% *pa*, consistent with the expectation that the rate of increase would plateau (WWT Consulting 2012, Project report SOSS-04 to The Crown Estate<sup>1</sup>).

An essential part of environmental impact assessment (EIA) for offshore wind farms is to determine the bird populations that might be affected, and in particular to assess the risk of adverse impact on relevant SPAs and their interest features (EU Birds Directive 79/409/EEC, as amended in Directive 2009/147/EC). Gannets may be vulnerable to collision with offshore wind turbines (Furness & Wade 2012, Furness *et al.* 2013). They have poor manoeuvrability, and their long, narrow wings and high wing-loading are adaptations to using the wind to assist fast flight (Nelson 1978). The risk is unclear, depending on levels of flight activity within the wind farm footprints and within the rotor swept area, and the extent of avoidance behaviour. It is known that gannets fly at and plunge-dive from elevations within rotor swept height (Nelson 1978, Krijgsveld *et al.* 2011). Flight activity, within a given area, may increase either as a result of feeding aggregations *e.g.* in response to fish shoals or discards from fishing vessels, or individuals commuting to the same foraging locations. It is anticipated that any risk is likely to be increased during chick-rearing, a higher-pressure time when adult birds are constrained by the need to return to the nest, albeit gannets would appear to be less energetically constrained than several other seabird species. Aerial or boat-based surveys provide information about the overall distribution and abundance, including feeding aggregations, but do not enable colony origins of birds seen at sea to be determined, nor provide information on the frequency of foraging trips by individuals. Satellite tracking is a reliable method for tracking gannets from their breeding colonies (Hamer *et al.*, 2000, 2001, 2007). Satellite tags can be deployed without the need for recapture of the bird, which reduces

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<sup>1</sup>SOSS is the Strategic Ornithological Support Services to The Crown Estate, [www.bto.org/soss](http://www.bto.org/soss)

disturbance to the colony and reduces the risk of data loss. Bempton Cliffs' crumbly chalk presents particularly challenging conditions, requiring skilled climbers to minimise risks both to climbers and breeding birds from rock fall. A single visit to the Staple Newk section of the colony was the preferred approach in each year; hence the choice of satellite telemetry, using platform transmitter terminals (PTTs) rather than the use of GPS data loggers which would have required recapture or close approach, with clear line of sight, to remotely download data.

The study had the following objectives: to determine foraging ranges, flight directions, and foraging destinations of adult gannets from the breeding colony at Bempton Cliffs; to determine whether adult gannets from Bempton Cliffs forage within or pass through, on their way to foraging locations, areas of the North Sea proposed for wind energy development, notably the Round 3 zones of Dogger Bank, Hornsea and East Anglia; and to seek to obtain a measure of relative importance of the sea areas used, bearing in mind that the data presented here apply mainly to the latter half of three chick-rearing seasons, together with early post-breeding records for a reduced sample of birds. In reality, owing to the staggered breeding season for gannets, a range of chick ages was present during the study windows, but a small proportion were younger age chicks. Preliminary results for 2010 are presented in Langston & Boggio (2011), and preliminary results for 2011 in Langston & Teuten (2012); this report supersedes both and provides a comparative analysis of the data from all three years.



Above: fitting a PTT to a gannet.

Right: gannet flies away after PTT has been fitted to the undertail.



## METHODS

### SATELLITE TELEMETRY

The tags used in 2010 were Microwave Telemetry Inc (MTI) Platform Terminal Transmitters (PTTs) weighing 45g (approximately 1.7% of gannet body weight including fittings), with a duty cycle of continuous transmission (Appendix I). On 20 July 2011, four of these same 45g tags were deployed on continuous transmission throughout, and a further five tags were programmed on a variable duty cycle, using a multi-season nano timer (Appendix I). These tags were programmed to be on for six hours and off for 24 hours for 2 cycles, followed by continuous transmission for five cycles, then six hours on/24 hours off for the next 64 cycles, followed by 6 hours on/48 hours off for the remainder of the battery life. This schedule permits daily drift of the time when the tag is on thereby increasing the likelihood of coinciding with a satellite passing overhead. The variable duty cycle was utilised to extend battery life beyond the chick-rearing period, with the aim of obtaining information post-breeding when gannets are no longer constrained to return to Bempton Cliffs. In addition, four gannets were fitted with MTI LC4 GPS PTT-100 tags, each weighing 40g, programmed to give hourly positional information (Votier *et al.* 2010), to provide higher spatial resolution data on the adult bird's position during chick-rearing. In 2012, a further sixteen tags were fitted, comprising 15 of the 45g PTTs, ten on continuous transmission and five on the same variable duty cycle described above, and the one remaining LC4 GPS tag that we were unable to deploy in 2011. These tags were fitted to adult gannets, at Bempton Cliffs, on 16 July 2012 (Appendix I). The tags were attached by means of Tesa© tape and two cable ties to the underside of the central three or four tail feathers, close to the base of the tail, with the antenna pointing upwards through the tail feathers, following Hamer *et al.* (2007). This arrangement was found to minimise drag when the birds were in flight and prevented displacement of tags when birds plunge-dive (Hamer *et al.* 2007). Fitting tags to the undertail in this way necessitated a low tag weight to body weight ratio and precluded the use of solar-powered tags.

Birds were caught at or near the nest, using a pole with a brass noose, by climbers roped securely to the cliff top. Each bird was transferred to the cliff top, in a sack tied at the top, for fitting of the PTT, individually numbered metal ring (BTO ringing scheme), and collection of biometrics (age, wing length, mass), before release from the cliff top, within 15 minutes of capture and delivery to the cliff top. The fitting of PTTs was done sitting down with the gannet held by a second,

experienced seabird handler so that it had a secure foothold on the tag-fitter's knees, facing outwards. A large cloth bag or similar draped over the head and eyes of the bird was used to calm the bird during handling (this follows the standard practice of placing birds in cloth bird bags/sacks preparatory to ringing and taking measurements).

Adult gannets were tracked during the chick-rearing period and during the early post-breeding period, into October and, exceptionally for one bird, up to late November (in 2012). Regular observations were made at several monitoring plots at Bempton Cliffs, including Staple Newk at which several of the tagged birds could be seen from the cliff top, when they were at the nest. This provided observations of a small sample of tagged birds, and timing of fledging of their chicks, compared with untagged birds.

#### DATA PROCESSING AND ANALYSIS

Initial processing of satellite data was carried out by ARGOS (CLS, France). Regular downloads were made from the ARGOS online system and the resulting data compiled into a seamless dataset for each year and then into a combined dataset for the three years of the project. GPS locations were obtained by running the data through MTI's parsing software (MTI, unpublished, supplied with the LC4 tags), which includes an error filtering mechanism, before incorporation in the main dataset. Duplicate data points were removed.

In 2010, one tag failed after 13 days, whilst three tags continued to function for 80 days (Table AI.1), considerably longer than the 30g tags originally recommended but no longer manufactured (Hamer *et al.* 2000), but still well-within the recommended tag to bird weight ratio of 3% (Phillips *et al.* 2003). In 2011, one tag failed after just seven days, presumed lost. Excluding this tag, the overall operational duration for PTTs, ranged from 40 to 92 days (continuous and variable duty cycle tags, Table AI.2). As expected, the LC4 GPS tags generally provided data for a shorter time period (range 17-54 days, Table AI.2). In 2012, one tag failed or was lost after six days, generating just 11 records during this time and so excluded from analysis. However, also in 2012, one variable duty cycle tag exceptionally functioned for 132 days, approximately four months, tracking this gannet's migration to NW Africa (range 6 to 132 days, continuous and variable duty cycle tags, Table AI.3). Most tags either failed or were lost. Observations at the colony of birds that had lost tags, inspection of the data, and comparison of continuous and variable duty cycle tags indicates that tag loss was the most likely cause of termination of data capture. Tags would in any



case fall off when rectrices (tail feathers) were moulted. Only in the case of one GPS tag did the engineering data indicate possible death of the bird, as neither activity nor location changed and tag temperature was low for the last few days in which data were returned. Deployment of tags programmed with a variable duty cycle did not lead to any appreciable improvement in the duration of tracking data when compared with tags on continuous settings, with the notable exception of the one tag that returned positions for 132 days.

To account for positional error, initially only locations with ARGOS quality codes 3, 2, 1, 0, A were used, following Hamer *et al.* (2000, 2001) (Appendix II). However, subsequent studies have recognised that discounting class B records excludes a lot of potentially valid data, which accounts for a high proportion of the data obtained from satellite tags on highly mobile organisms, such as seabirds (Nicholls *et al.* 2007, Wakefield *et al.* 2013) (Table 1, Appendix II). Furthermore, interpretation of individual trips is made considerably more complicated by excluding B records, leaving temporal and spatial gaps which increase the likelihood that a bird's return to the breeding colony might be missed, leading to likely inflation of estimates of foraging trip parameters. In view of the small number of tagged birds visible from the cliff top at Bempton, we have not recalculated the error associated with location quality observed in our study, *i.e.* by comparison of recorded location with true position (see Hamer *et al.* 2007, Wakefield *et al.* 2013).

The data cleaning process applied to the raw data from ARGOS downloads was considered to deal with the main sources of error. Data cleaning involved removal of unrealistic records, on the basis of implausible flight speed, in instances where the calculated bird flight speed between adjacent registrations exceeded 90 kmh (Nelson 1978, Hamer *et al.* 2007), which deals with the most extreme errors (Wakefield *et al.* 2013). Usually the first point in the sequence was retained, unless this was unlikely in relation to the previous location, or of a lower location class. Duplicate records, "mirror" records and invalid locations classified as Z by ARGOS (ARGOS, unpublished instruction manual), were removed prior to analysis. Furthermore, comparison of the Kernel Density Estimation for different location classes indicate similar patterns of distribution for cleaned data (Figure AII.1), so we continue here to include B records, but also present locations excluding B records in Appendix II (Figures AII.2 & AII.3), in view of the differing precision of ARGOS location classes (Nicholls *et al.* 2007).

All locations recorded within 5 km of the central location of Staple Newk were considered to be at the breeding colony. Allowing for this and the exclusion of records > 5 km inland, all locations

> 5 km from the breeding colony were considered to relate to activity at sea, notably foraging trips. Data for chick-rearing and post-breeding were separated taking the approximate departure date from Bempton Cliffs for each individual, based on the last recorded date at Bempton Cliffs. The resulting data were plotted in ArcGIS (ArcGIS Desktop 10 ©ESRI), on a backdrop showing the indicative offshore wind energy project boundaries. Radial distance bands were added showing 50 km, 100 km, 150 km, and 200 km. For the chick-rearing period only, summary statistics for foraging range, trip length and trip duration were calculated from data obtained from tags set on a continuous duty cycle, as these provided more frequent positions. The longer time interval for data capture by variable duty cycle tags reduces the utility of the data from these tags for detailed investigation of individual foraging trips as intervening returns to the breeding colony may be missed. The maximum foraging range was taken to be the maximum radial distance from the centroid of Bempton Cliffs and was calculated using the spherical law of cosines, using Excel. Trip length was calculated from the combined distances between locations for each trip, from the last location at the colony to the first record back at the colony for each trip. Only complete foraging trips at sea were included, *i.e.* those that started and finished at the colony. Data from all three years were analysed for this report, using data meeting these criteria, hence summary data presented here differ from those in Langston & Boggio 2011 and Langston & Teuten 2012.

Fixed Kernel Density of 50, 75 and 95% isopleths were calculated for combined PTTs in each year and separately for individual PTTs, using the kernel density tool in ArcGIS (Desktop 10), applying a default 8 km smoothing parameter and cell size of 1 km<sup>2</sup>, using just the locations at sea. The 50% and 95% kernel density estimates were considered to represent the core area of activity (50% of locations) and area of active use (95% of locations), respectively (Hamer *et al.* 2007). Sea areas under the contour lines were calculated separately for each year. Trip end points represent a conservative sample of foraging destinations based on repeatable, standardised criteria, and were distributed throughout the areas of active use. Birds also feed during foraging flights. Satellite data provide limited discrimination of bird activity, so it is more difficult to define foraging areas used in transit, although sometimes several locations occur close together in space and time indicating other diurnal foraging areas and these occur widely within the range of detected locations, as do foraging endpoints of individual foraging trips.

Analysis of habitat associations for foraging endpoint locations used location classes 3, 2, 1, 0, A & B. We used logistic regression models to compare the characteristics of foraging locations,

during chick-rearing, against the characteristics of a set of control points (Aarts *et al.*, 2008; Aarts *et al.* 2012). The 218,242 control points were taken to be the marine locations on a regular 30 arc-second by 30 arc-second grid that lay within 250km of the Bempton colony. All of the models that we considered contained distance to colony as an explanatory variable. We considered models that included all possible combinations of three additional explanatory variables: depth (as derived from the GEBCO\_08 Grid dataset; [http://www.gebco.net/data\\_and\\_products/gridded\\_bathymetry\\_data/](http://www.gebco.net/data_and_products/gridded_bathymetry_data/)), the logarithm of depth gradient (derived from depth using a Sobel filter) and sediment type. Sediment type was a categorical variable that represented the dominant sediment type within each square of the 30 arc-second by 30 arc-second grid, and which had four possible categories: 'coarse' (sublittoral coarse sediment), 'fine/sandy' (sublittoral fine or sandy sediment), 'mud' (sublittoral mud sediment) or 'mixed' (sublittoral mixed sediment). The sediment type data were derived from the 'UK marine landscapes' layer of the MESH data (Mapping European Seabed Habitats; <http://www.searchmesh.net/>).

Data on foraging locations ideally would be modelled as a spatial point process, such as an inhomogeneous Poisson point process, but, for simplicity, we modelled them using logistic regression (Binomial GLMs or GAMs) since this enables the use of standard software. It has been shown (Warton & Shepherd, 2010) that the estimates of environmental effects obtained from logistic regression models will, if the control points lie on a regular grid and the number of control points is large, be approximately equal to the estimates that would have been obtained by fitting an inhomogeneous Poisson point process model. We considered two types of model: (1) Binomial generalised linear models (GLMs) which contained between one and four explanatory variables, and which were fitted in R using the 'glm' function; and (2) Binomial generalised additive models (GAMs) which contained between one and four explanatory variables and also obtained a two-dimensional spatial smooth term to represent residual spatial variation. The models were fitted to a combination of foraging locations and control points, with the response variable being a binary variable that indicated whether the location is a control (0) or an actual foraging location (1). This model can be used to predict the probability that every location of a regular grid will be a foraging location, and to calculate the odds of being a foraging location rather than control, since “odds = (probability / (1 - probability))”. It has been shown that the odds are proportional to the density of foraging locations (Aarts *et al.*, 2008), and they therefore can be used to provide the contours of the estimated foraging distribution – these contours are comparable to those that are produced via

kernel density estimation. These models were fitted in R using the 'bam' function from within the 'mgcv' library. Each model was fitted to pooled data for all three years, and was then, separately, applied to data for individual years, or pairs of years in order to explore their predictive capability for the third year.

Individual and interannual variation in various trip parameters (foraging range, trip length, trip duration, distance to trip endpoint, return distance to colony, time to reach trip endpoint, and time to return) were investigated using a linear mixed model. The linear mixed model (for each of the eight variables) contained random effects for 'year' (a categorical variable with three levels, 2010, 2011, 2012) and 'bird' (a categorical variable with 26 levels – each of the 26 tags on continuous duty cycle). The variance associated with 'trip' corresponds to the residual variance. The model was fitted in R, using the function 'lme' from the package 'nlme'. Owing to the highly skewed distribution of untransformed variables, all trip variables were log-transformed.

#### DATA STORAGE

The main repository for data from this project is the BirdLife extended “Procellariiform” database (BLI 2004). The data from this project also will be held on the BGS DECC SEA data portal, with metadata on the Medin (Marine Environmental Data & Information Network (<http://www.oceannet.org/>)). The recorded locations are available as GIS ESRI shapefiles, from the Conservation Data Management Unit (CDMU) at the RSPB (<http://www.rspb.org.uk>).

## RESULTS

The LC4 GPS data had large gaps in the data record, extending to several days when the tags reverted to ARGOS data. Only approximately 12% of the GPS locations passed the MTI checksum test in 2011 (Appendix I), suggesting that these data should not be regarded as reasonable. Furthermore, a high proportion of GPS locations were obtained at the breeding colony, other locations reverting primarily to ARGOS Doppler locations, indicating recording bias, the reason for which has not been fully resolved. These findings undermined confidence in the data from these LC4 GPS tags which were excluded from further analysis. Figures illustrating the overall distribution of gannet locations at sea, during chick-rearing and post-breeding periods, are plotted using data from both continuous and variable duty cycle PTTs. Analysis of foraging trips, during chick-rearing, is based on data from continuous tags only. Three continuous PTTs were excluded from analysis on the basis of small samples of trips that could be determined as starting and ending at the colony – two in 2010, and one in 2012.

### Chick-rearing

Approximately 41-45% of locations from PTTs (location classes 3, 2, 1, 0, A & B) were recorded at the breeding colony and 55-59% at sea during chick-rearing (Table 1). The overall distribution of locations during chick-rearing was broadly similar in all three years, although at higher density further out to sea in 2012 (Figure 2). Most locations were within 200 km of Bempton Cliffs, with the highest density of locations mostly within 50-100 km, influenced by activity close to the colony. The tendency was for the highest densities of locations to occur to the east and ESE of Bempton Cliffs, with location density declining markedly beyond 150 km. Summary statistics on foraging parameters for each of the three years, from continuous tags, are presented (Table 2). These values differ from those presented in progress reports (Langston & Boggio 2011, Langston & Teuten 2012) owing to the inclusion of B records and using data only from tags on continuous duty cycle (Appendix I). The maximum foraging range was within approximately 300-400 km, whilst the maximum trip length ranged from approximately 1,200 – 1,700 km. Foraging trip duration was highly variable, on average lasting approximately eight hours, or roughly one third of a 24 hour “day”. The distributions of all foraging parameters were heavily skewed, owing to the over-riding effect of proximity to colony (Appendix IV). Consequently, 95% confidence intervals to arithmetic

means were derived by  $\log_{10}$  transformation (Table 2, after Fowler & Cohen 1996). The mean foraging range was less than 50 km, whilst the average foraging trip length was less than 150 km (Table 2). There was a strong relationship between trip duration and both foraging range and trip length, with no sign of asymptote for distance travelled, but the data points indicate a possible asymptote in 2012 for foraging ranges beyond approximately 200 km (Figure 3).

Flight endpoints, putative foraging locations, occurred throughout most of the area in which birds were recorded (Figure 4; see also Figure AII.2, based on location classes 3, 2, 1, 0, A, *i.e.* excluding B records). In relation to the proposed offshore wind energy development zones, flights occurred through and to the Hornsea Round 3 proposal zone in particular (Figures 2 & 4). There were also flight end points, and likely flights through, the Dogger Bank zone, mainly in the western half, a few records within the East Anglia Round 3 zone, and a few within and close to Round 1, *e.g.* Westernmost Rough, and Round 2 sites (see discussion) in the Greater Wash strategic area (Figure 4). The Kernel Density Estimation figures (Figure 5; see also Figure AII.3, based on location classes 3, 2, 1, 0, A, *i.e.* excluding B) illustrate that a high proportion of locations extended further east within the Hornsea zone in 2012, utilising more of this zone, compared with earlier years, based on the 50% density contour. The 95% density contours in 2010 and 2011 incorporated clusters of locations within the periphery of the Greater Wash, but do not show much penetration into this area, whereas in 2012 one individual made repeated forays into the Wash from Bempton Cliffs. There were no recorded locations further south than the coast of north Norfolk during chick-rearing. The core foraging range represented by the 50% kernel density extended to 2,547 km<sup>2</sup> in 2010, 3,371 km<sup>2</sup> in 2011, and 4,570 km<sup>2</sup> in 2012 (Table 2). In 2010 and 2011 the 50% kernel mainly extended to approximately 50 km from Bempton Cliffs, whereas in 2012 it extended to about 150 km into the sea.

The areas of active use represented by the 95% density contour extended to 18,002 km<sup>2</sup> in 2010, 15,852 km<sup>2</sup> in 2011 and 17,744 km<sup>2</sup> in 2012 (Table 2) and indicate a more continuous distribution of activity further eastwards in 2012 than in 2010 and 2011 (Figure 5). Comparison of the fixed kernel density estimation for individual PTTs (Table 3, Appendix III), on  $\log_{10}$  transformed data, found a statistically significant difference between annual mean areas under the 50% (One-way ANOVA,  $P = 0.036$ ) isopleths, arising from a significantly larger  $\log_{10}$  transformed mean value in 2012 compared with 2010 (difference = 0.142,  $t = 2.843$ ,  $P = 0.014$ ). No statistically significant difference was found between  $\log_{10}$  transformed annual mean areas under the 95% isopleths (One-

way ANOVA,  $P = 0.940$ ), although the power of the performed test was low, so a significant difference in the area of active use between years cannot be ruled out. There is variation in the areas used by individual birds, both in terms of core and overall areas of active use and the extent of overlap with the Hornsea and Dogger Bank zones in particular (Appendices III & IV).

The environmental variables incorporated in the analysis of foraging locations are plotted in Figure 6. There was a marked decline in density of foraging locations with distance from colony which was the over-riding influence on gannet distributions at sea (Figure 7a). Bathymetry provided a useful additional explanatory variable, notably the change in water depth to the south-east of the colony (Figure 7b). Smoothing, using GAMS, improved the fit to gannet distribution at sea, with little additional explanatory fit from any of the environmental variables included, alone or in any combination (Figures 7c-7h). Using different combinations of pairs of years to predict the third year gave a broadly similar overall pattern of decline in density away from the colony. However, the exclusion of 2012 curtailed the at sea distribution and, unsurprisingly, did not indicate use of the Wash, which was recorded as a foraging destination in 2012 but not in 2010 or 2011 (Figures 8a-8f). The predictive capability was good for closely similar years but limited for the year showing a greater difference in tracking locations. Visual inspection indicates that the GAM with the addition of water depth may give some improvement in predictive ability (Figures 9a-9f).

For all variables relating to trip duration and length, variation between years was much less than variation between birds, and variation between birds was less than variation between individual trips (Table 4). Individual trip was the greatest source of variability, there being approximately four times more variability at trip level than at bird level and no evidence of a year effect. Frequency distribution of trip parameters for individual birds show similar, skewed distributions and patterns of decay, with a high proportion of short trips and a long tail (Appendix V, Figures AV.1-AV.3).

### **Post-breeding locations**

In 2010, four birds provided post-breeding locations for a few days to a few weeks (Figure 10). Most records were close to Bempton Cliffs. The last data were transmitted on 6 October 2010. In 2011 and 2012, records were obtained from seven birds, over several weeks, in each year. In 2011, one bird headed north, around the Orkney islands and the coasts of northern and western Scotland, then down the west coast of Ireland before crossing the Bay of Biscay to western France whereupon

further contact was lost (Figure 11). The other six birds remained in the North Sea for at least one to two weeks before either tags ceased to operate or, in the case of one individual, onward migration to northwest Africa. These movements are comparable to those recorded by Kubetzki *et al.* (2009) and Fort *et al.* (2012), also described in WWT Consulting *et al.* (2012) for gannets from Bass Rock. Time spent in the North Sea tended to be relatively clustered for each individual, and records overlapped especially with the Hornsea and East Anglia zones. They also overlapped several Round 1 and Round 2 wind farm footprints, notably Westermost Rough and Humber Gateway. The pattern of locations was similar in 2012, although there was greater overlap with the Dogger Bank zone. One tag exceptionally delivered information up to 24<sup>th</sup> November, registering its complete southward migration to NW Africa and initial forays in African waters (Figure 12).



## DISCUSSION

The main concerns relating to birds in association with wind farms are: (1) disturbance displacement, leading to effective habitat loss (2) collision mortality, (3) habitat loss/change influencing prey availability, and (4) barriers to movement potentially increasing flight energy demands for daily foraging flights or longer migratory flights (Drewitt & Langston 2006). Of greatest concern are the cumulative and in combination effects across multiple wind farms, which if unchecked may lead to significant risk of population reduction.

This study reflects gannet foraging tracks prior to placement of wind turbines in the Round 3 zones. Of the wind farm footprints coinciding with the range of gannet locations recorded by this study during chick-rearing, only Lynn & Inner Dowsing and Sheringham Shoal were operational; Lincs and Teesside were under construction. These are all outside the main area of active use identified during chick-rearing in 2010 to 2012 (Figures 2, 4 & 5). The rest were in planning or consented ([www.renewableuk.com](http://www.renewableuk.com), accessed 24 July 2013). So, it is too early to determine flight responses to constructed wind farms by gannets from Bempton Cliffs, based on the small number of locations in the vicinity of operational wind farms and the relatively coarse resolution of much of the satellite tracking data obtained during this study. During post-breeding dispersal and migration, gannets may encounter several wind farms or proposal areas, including those in Dutch waters, as indicated here by the locations of the tagged individuals (Figures 10, 11, 12).

Recent studies of gannets, during spring and autumn migration, at Egmond aan Zee offshore wind farm in the Netherlands, indicate strong avoidance of wind turbines (Krijgsveld *et al.* 2011), which may suggest that flight avoidance of wind turbines is likely, at least during migration. It is not known whether this response will apply to foraging flights of breeding gannets, especially during chick-rearing, due to the need to make frequent, repeat trips to the colony. Avoidance *per se* may, or may not, be detrimental, even if applicable to breeding gannets, unless it leads to a reduction in available foraging habitat, *i.e.* displacement, birds cannot compensate by feeding elsewhere, and do not habituate to the presence of wind turbines. Cumulative effects arising from multiple wind farms may lead to adverse effects if access to high quality habitat is restricted or prevented. Collision and displacement may have differential effects, depending on the season, age, sex, breeding status, and behaviour of individual gannets, but may both occur albeit at different times. Gannets are considered to be at moderate to high risk of collision with wind turbines, owing

to their flight elevation and plunge dive height, from 10-50 m or more, which overlap with rotor swept height (Langston 2010, Krijgsveld *et al.* 2011, Furness & Wade 2012, Furness *et al.* 2013, R. Langston pers. obs.). Risky flights were identified to be those during foraging and searching, when individuals were observed up to 50m height, but direct flight was often observed to be below 10m, except in high winds when gannets used dynamic soaring to gain lift (Krijgsveld *et al.* 2011). There is considerable uncertainty at present about likely cumulative effects of the proposed scale of offshore wind farm development on gannets. Collision hazard could become significant, given the substantial scale of proposed wind energy development across the North Sea, not just in UK waters.

A Population Viability Analysis (PVA) has been produced for gannets from the UK breeding population (WWT Consulting *et al.* 2012). For the Bempton Cliffs colony, based on the estimate of 3,940 Apparently Occupied Nests (AONs) in 2004 and demographic parameters from Bass Rock, this model indicated that additional mortality in excess of 150 gannets per year would be expected to lead to a decline in colony size, with the probability of decline increasing rapidly with any further increase in mortality. The colony has continued to grow (Figure 13), 7,859 AONs in 2009 and 11,061 AONs in 2012, which may have increased its resilience to additive mortality to some degree. It is not clear whether there is a straightforward proportional increase in additional mortality that the increased colony size may be able to withstand; this requires testing by re-running the model for Bempton Cliffs, incorporating such demographic data as are available for this site. However, any potential impact leading to the prospect of population decline is of concern, notably because the tracking studies at Bempton Cliffs, as documented here, indicate a disproportionate effect on chick-rearing gannets from Bempton Cliffs arising from wind farms within their area of active use. Tracking studies of gannets from the Bass Rock show little overlap with gannets from Bempton Cliffs in the foraging areas used during chick-rearing, there being some overlap north of Bempton Cliffs (Hamer *et al.* 2007, 2009 and unpubl.; Wakefield *et al.* 2013). In contrast, post-breeding movements of birds from different breeding colonies overlap, as demonstrated by comparing results from Bempton Cliffs presented here with data from the Bass Rock presented in Kubetzki *et al.* (2009) and Fort *et al.* (2012).

Understanding the spatial and temporal coincidence of gannets with proposal areas for wind turbines is the first step in understanding any potential impact of offshore wind energy generation on gannets. The limitations of this study result primarily from the relatively small number of birds tracked during the chick-rearing periods in 2010 to 2012, and the small sample

obtained for early post-breeding dispersal. Nonetheless, the results from this project provide the first records of foraging ranges and destinations for breeding gannets from Bempton Cliffs. Approximately 70% of foraging trips were within 50 km of Bempton Cliffs (Appendix V; mean range all three years,  $43.0 \pm \text{SD } 49.1$  km, range 5-404 km,  $n = 2,721$  trips), only 25 exceeding 200 km, of which just two exceeded 300 km. This represents a smaller foraging range than recorded for breeding gannets from the Bass Rock (mean range  $155.2 \pm \text{SD } 65.3$  km, range 68-276 km, Hamer *et al.* 2009, based on GPS data). The 95% kernels for Bempton, also were considerably smaller in extent than those recorded for Bass Rock (45,890 – 211,120 km<sup>2</sup>, Hamer *et al.* 2007).

The overall similarity of results for the three chick-rearing periods studied at Bempton Cliffs may stem from the fact that all were good breeding seasons, with breeding productivity per AON of 0.82 in 2010, 0.83 in 2011, and 0.85 in 2012, compared with 0.86 in 2009 (D. Aitken pers. comm.). The observations at Bempton Cliffs fit with the theories of intraspecific competition and colony size, whereby birds from larger colonies have to forage further afield because of intraspecific competition and prey depletion (Lewis *et al.* 2001). This is also likely to suppress foraging extent to the north of Bempton Cliffs, especially as there is pronounced spatial segregation of foraging areas used by gannets from different breeding colonies (Wakefield *et al.* 2013). There were an estimated 3,940 AONs (apparently occupied nests) of gannets at Bempton Cliffs, compared with 48,065 AONs at Bass Rock in 2003/04 (Wanless *et al.* 2005). As the Bempton colony grows in size, it might be expected that foraging ranges will increase, owing to increased intraspecific competition at the colony.

At sea activity includes a mix of loafing, preening, bathing, foraging and flight activity, all important maintenance behaviours. Off-duty gannets at sea during the hours of darkness are thought to be resting on the surface (Hamer *et al.* 2000). GPS loggers from Bass Rock indicate that, during foraging trips, gannets tend to intersperse rapid direct flights with slower sinuous tracks over foraging areas associated with the tidal mixing front (Hamer *et al.* 2009). Distinguishing foraging locations from in-flight locations is more challenging using ARGOS PTTs, but foraging end points are cues to likely foraging areas. Gannets also feed during foraging trips, so end points are not the only foraging locations. Results from Bempton Cliffs indicated that foraging behaviour occurred throughout the area of active use (Figure 4). The preliminary analysis of environmental variables presented here did not add greatly to the influence of distance to colony in explaining variability in foraging locations, although the addition of water depth gave some improvement to

model fit. The limitations of the environmental covariates modelling may have been due to a combination of the environmental data available to us for this study and the relatively coarse spatial resolution of those data, consistent with the spatial resolution of the bird locations. Alternatively, it may be that gannets and their prey species are responding to features of the water column, such as seasonal fronts, rather than seabed habitat *per se*. The Flamborough Front coincides with the observed distributions of tracked gannets and is an area of enhanced productivity around the interface between the seasonally stratified cooler waters of the northern North Sea and the waters of the southern North Sea which do not stratify thermally. The data collected by this project do not enable the extent of foraging associated with fishing vessels to be determined, but it is likely that this forms at least part of the gannets' foraging strategy. The few regurgitates obtained from caught birds were of whole mackerel, which the birds probably caught themselves.

Recent research at Grassholm has recorded sexual segregation in foraging behaviour at sea by breeding adult gannets (Stauss *et al.* 2012). They observed consistent differences in the isotopic signatures indicating dietary segregation, including a likely higher proportion of fishery discards in the diets of breeding males, which also foraged closer inshore than females. Further studies confirmed the greater association with fisheries vessels by males than females (Votier *et al.* 2013). No such sexual segregation was apparent during the non-breeding season, nor among non-breeding, immature (2-4 yrs) gannets which showed evidence of central place foraging, regularly attending club-sites at their natal colony (Votier *et al.* 2010). These findings have implications for interactions with offshore wind farms, leading to potentially differential risks to male and female gannets, and to adult and immature birds. Furthermore, the pronounced spatial segregation of feeding areas used by gannets from adjoining breeding colonies emphasises the colony-specific effects likely from offshore wind farms, especially during chick-rearing (Wakefield *et al.* 2013).

The peak fledging period at Staple Newk in 2010 was between 20 August and 7 September. In contrast peak fledging in 2011 occurred during the first three weeks of August, approximately 2 weeks earlier (L. McKenzie pers. comm.), with most of the rest fledging by the end of September. The earliest fledging date in 2011 was 29 July, considerably earlier than most gannets at Bempton Cliffs and associated with one particular pair which are generally early; the last, really late chick, fledged in mid-November (L. McKenzie pers. comm.). In 2012, most fledged between 14 and 27 August, with the last few fledging by 25 September, whilst the chick from the early pair fledged on 31 July, close to the equivalent date in 2011 (L. McKenzie pers. comm.).

There was no indication of a difference in behaviour or breeding performance by gannets with or without a PTT, although the sample for comparison was small, constrained by tagged birds observable from the cliff top observation point. Birds flew strongly when released with their PTT fitted, the weight ratio of which, at approximately 1.7% of body mass, was well within the recommended range (less than 3% of body mass, Phillips *et al.* 2003). Birds observed at the colony ignored the tag and antenna, even when preening. Four of the birds tagged in 2011 had eggs/chicks at different stages of development when the adults were tagged, ranging from an egg hatched on 20 July, to a well-grown chick due to fledge in early August. All these chicks fledged within the expected time for their stage of development at the time of capture of the adults, *e.g.* the chick hatched on 20 July fledged during the third week of October. Many adults remain at Bempton Cliffs for a while after their chicks have fledged. Tracking studies indicated that most adults departed Bempton Cliffs during the second half of September in 2011 and all adults had left by early October. This compares well with observations, the last adults were seen at Staple Newk in late September and all were gone by 4 October. Gannets started to return to Bempton in mid-January 2012, presumably more likely to be birds that stayed in the North Sea over winter, with most birds back at their nests during March and egg-laying in April. The earliest hatching date was 4 May. In 2013, observations at monitoring plots indicated delayed egg-laying and quite a few instances of non-breeding (L. McKenzie pers. comm.), in contrast to previous years. It remains to be seen how breeding productivity compares with recent years.

Cliff-top observations indicated that PTTs were eventually lost; three of the birds identified at the nest in 2011, with tags in place, were observed later in the season without tags. Mounting the PTTs on tail feathers, they were expected to shed tags at least when moulting, if not sooner. Attempts to extend the recording period, using a variable duty cycle setting for 5 tags in 2011, was only partially successful as the last location was obtained on 19 October. It is unclear whether battery failure or tag loss was the cause of curtailment although the latter may be more likely as last dates were comparable for tags on continuous transmission or variable duty cycle, and given the observations at the breeding colony. Votier *et al.* (2010) also considered that tail-moult induced tag loss was likely. Tail moult is irregular (Nelson 1978) although it is thought to commence around egg-laying time, and in 2011 several adults were observed to be in the process of growing at least one or two new tail feathers at the time of fitting tags. Harnesses were ruled out for this study of

gannets due to their plunge-diving and entry into the water at considerable speed, as well as the increased risk for the birds of entanglement with any underwater gear, fishing nets etc.

ARGOS data in location classes 3, 2, 1, 0, A and B from PTTs tracking fast-moving pelagic seabirds have an estimated accuracy (mean distance error from the actual position of the transmitter) of between 0.1 and 5.0 km, and estimated precision (the clustering of locations, measured as one standard deviation of the mean of the distance between the ARGOS location and the actual position of the transmitter) for different location classes of < 2.5 km for 3, 2, and 1, 15 km for A, 25 km for 0, and for B, 56 km (latitude) and 94 km (longitude) (Nicholls *et al.* 2007). Our experience indicates that, as expected, clustering of locations was tighter for the higher quality locations, but the overall pattern of locations was similar following the removal of implausible trips based mainly on flight speed (Appendix II; also see methods).

In view of the disappointing performance of the LC4 GPS tags, together with their generally shorter operational life and higher unit price, the decision was taken not to deploy further LC4 tags in 2012, with the exception of the one remaining tag that we were unable to deploy in 2011 (due to deterioration in weather conditions during fieldwork). The lower resolution data associated with locations from ARGOS PTTs, compared with GPS units is most likely to be a potentially significant limitation when determining gannet responses to wind farms under construction or operational wind turbines, so relevant to future tracking studies.



Left: checking for wing moult and age characteristics of a gannet.

Below: Staple Newk section of Bempton Cliffs during 2012 gannet breeding season.



## CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

Forty two breeding adult gannets, tracked via satellite Platform Transmitter Terminals, from Bempton Cliffs in 2010, 2011 and 2012, yielded information about their foraging ranges during chick-rearing, and the extent of overlap of their foraging trips with potential development zones for offshore wind energy generation in the North Sea. Distance to colony had the over-riding influence on foraging range. Most foraging trips were within 150 km of Bempton Cliffs, and considerable overlap during chick-rearing was noted in particular with the Hornsea Round 3 development zone for offshore wind energy generation. Some information was obtained for the early post-breeding period in each year, indicating variability in dispersal and migration away from Bempton Cliffs, and the potential for interaction with several different wind farms at this stage of the gannet's annual cycle. In particular, increased numbers of locations were recorded in the East Anglia zone in the post-breeding period, contrasting with few locations during chick-rearing. Relatively few locations were recorded within the Dogger Bank zone during chick-rearing but there were more post-breeding.

Further data collection at Bempton Cliffs is highly recommended, to obtain additional data to investigate inter-annual variation in gannet foraging range and destinations during chick-rearing and the post-breeding period. However, there appears to be limited scope for further extension of the study period using PTTs. At the present time, there does not appear to be an obviously suitable tagging method available to further extend the study period without back-mounting with a harness which is undesirable in a plunge-diving species (see earlier). A harness may interfere with plunge-diving and increase the risk of entanglement with underwater fishing gear or other objects. Further developments of remote download capability together with additional on-site or boat-based recording would help to overcome the specific difficulties of obtaining the necessary clear line-of-sight at Bempton Cliffs to facilitate the use of alternative tracking technology to the PTT-100 tags used here for future studies, for example GPS data loggers, notably for studies relating to operational wind farms. This approach has been used at Ailsa Craig (E. Wakefield pers. comm.). The RSPB is developing its own remote download GPS archival tag, suitable for use at sites which are difficult to access, which could be deployed on gannets at Bempton, or elsewhere. The potential to use GPS technology to permit better discrimination of foraging as opposed to other behaviours, and track birds' responses to wind turbines could be particularly useful, albeit likely to be for

shorter deployments during the breeding season. A further valuable addition would be the use of miniaturised high resolution altimeters, to record flight height. The FAME<sup>2</sup> project and associated projects have spear-headed the use of GPS archival tags for tracking several seabird species at multiple colonies around the UK, developing techniques and integrating oceanographic data to interpret distributions and behaviour at sea. We will be developing further research project ideas, drawing on the experience of satellite tracking from the study documented here, together with experience from FAME and other tracking studies. We are also investigating the availability of other environmental datasets that might enable extension of the analysis presented here.



Above: Staple Newk, Bempton Cliffs RSPB Reserve – for scale, note gannets to lower right and members of catching team at cliff top.

Right: climbers from JSMTW in action.



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<sup>2</sup> Future of the Atlantic Marine Environment (FAME), a collaborative project involving the RSPB, <http://www.rspb.org.uk/ourwork/projects/details/255106-future-of-the-atlantic-marine-environment-fame->  
[www.fameproject.eu/en/](http://www.fameproject.eu/en/)



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Above: QMSI Haslam & Andy Phillips from JSMTW

Right: Major Tony Crease (retd.)



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## TABLES

**Table 1:** Breakdown of locations at the breeding colony and at sea, by location class, for gannets tracked from Bempton Cliffs in each chick-rearing season 2010-2012.

**Table 2:** Summary statistics, from continuous tags, describing foraging trip parameters for round trips, starting and ending at the breeding colony, for gannets during chick-rearing in 2010 ( $n = 1,272$  trips, 12 birds), 2011 ( $n = 574$  trips, 4 birds) and 2012 ( $n = 945$  trips, 9 birds). 95% confidence intervals to arithmetic means derived by  $\log_{10}$  transformation. See text for details.

**Table 3:** Kernel density estimation summary for individual PTTs (continuous and variable duty cycle tags) during chick-rearing at Bempton Cliffs 2010-2012

**Table 4:** Output from linear mixed model for various trip parameters of gannets during chick-rearing (continuous tags)

## FIGURE LEGENDS

**Figure 1:** Offshore renewable energy projects around the UK, proposed, in planning, under construction and operational (courtesy of The Crown Estate, November 2013, [www.thecrownestate.co.uk](http://www.thecrownestate.co.uk)).

**Figure 2:** Combined tracking locations for adult gannets from Bempton Cliffs, based on a) 6,272 at sea locations in 2010 ( $n = 14$  birds), b) 4,914 locations in 2011 ( $n = 13$  birds), and 8,674 locations in 2012 ( $n = 15$  birds) during the chick-rearing period. The concentric blue rings are the 5km buffer around the central location of Bempton Cliffs, with added 50km, 100km, 150km and 200km buffers to aid interpretation of foraging distances. Inset shows the location of Bempton Cliffs. ARGOS location classes 3, 2, 1, 0, A, B.

**Figure 3:** Relationship between a) foraging range (km) and trip duration (days/24h period) and between b) trip length (km) and trip duration (days) for gannets from Bempton Cliffs during chick-rearing in 2010 ( $n = 1,285$  trips, 13 birds), 2011 ( $n = 574$  trips, 4 birds), and 2012 ( $n = 945$  trips, 9 birds). (Continuous tags).

**Figure 4:** Highlighted flight end points indicating foraging destinations of adult gannets from Bempton Cliffs during chick-rearing: a) 2010 (6,272 at sea locations,  $n = 14$  birds), b) 2011 (4,914 locations,  $n = 13$  birds), c) 2012 (8,674 locations,  $n = 15$  birds). Different colours signify different individual birds. ARGOS location classes 3, 2, 1, 0, A & B (see also Figure AII.2 for equivalent plots excluding B records).

**Figure 5:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for adult gannets during chick-rearing: a) 2010 ( $n = 14$ ), b) 2011 ( $n = 13$ ) & c) 2012 ( $n = 15$ ), showing the 50%, 75% and 95% density contours. ARGOS location classes 3, 2, 1, 0, A, B (see also Figure AII.3 for equivalent plots excluding B records).

**Figure 6:** Distribution plots of environmental variables used in the analysis, a) bathymetry/water depth, b) log depth gradient, c) sediment type. See text for further explanation.

**Figure 7:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing 2010-2012. Contours show the estimated density of trip endpoint locations from logistic regression models that contain 'distance to colony' and, apart from (a), additional environmental variables as covariates; (a,b) are fitted as Binomial GLMs; (c-g) are fitted as Binomial GAMs and include a bivariate smooth in latitude and longitude. See Figure 8 for figure legend.

**Figure 8:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing, assessing predictive ability of the GAM with distance to colony but no environmental variables included. Maps show the predicted density based on a) 2010, b) 2011, c) 2012, d) 2011-2012, e) 2010 & 2012, and f) 2010-2011.

**Figure 9:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing, assessing predictive ability of the GAM with distance to colony and water depth included. Maps show the predicted density based on a) 2010, b) 2011, c) 2012, d) 2011-2012, e) 2010 and 2012, and f) 2010-2011.

**Figure 10:** Post-breeding locations in 2010 of four individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery powered satellite tags, based on 153 locations.

**Figure 11:** Post-breeding locations in 2011 of seven individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery powered satellite tags, based on 843 locations.

**Figure 12:** Post-breeding locations in 2012 of seven individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery powered satellite tags, based on 887 locations.

**Figure 13:** Population trend in gannets (Apparently Occupied Nests) at Bempton Cliffs, 1981 to 2012. **NB** in 1969, there were 21 AONs.



## APPENDICES

**Appendix I:** Summary information for each satellite tag and individual adult gannet 2010-2012 (before data cleaning, *i.e.* raw data, see text).

**Table AI.1:** Summary information for each satellite tag and individual adult gannet in 2010.

**Table AI.2:** Summary information for each satellite tag and individual adult gannet in 2011.

**Table AI.3:** Summary information for each satellite tag and individual adult gannet in 2012.

**Appendix II:** Comparison of Argos location classes for adult gannets tracked from Bempton Cliffs during 2010-2012 chick-rearing seasons.

**Figure AII.1** Kernel Density Estimation for adult gannets tracked from Bempton Cliffs during chick-rearing, comparing different ARGOS location classes, from highest to lowest quality, 3 & 2 combined, 1, 0, A & B, a) 2010, b) 2011, c) 2012.

**Figure AII.2:** Highlighted flight end points at sea indicating foraging destinations of adult gannets from Bempton Cliffs, during chick-rearing: a) 2010 (4,006 locations,  $n = 14$  birds), b) 2011 (3,565 locations,  $n = 13$  birds), c) 2012 (5,898 locations,  $n = 15$  birds). Different colours signify different individual birds. ARGOS location classes 3, 2, 1, 0, A (see also Figure 4 for equivalent figures including location class B).

**Figure AII.3:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for adult gannets during chick-rearing seasons in each year: a) 2010 ( $n = 14$ ), b) 2011 ( $n = 13$ ), c) 2012 ( $n = 15$ ), showing the 50%, 75% and 95% density contours. ARGOS location classes 3, 2, 1, 0, A (see also Figure 5 for equivalent figures including location class B).

**Appendix III:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for individual adult gannets from Bempton Cliffs during chick-rearing 2010-2012 (continuous and variable duty cycle tags).

**Appendix IV:** Tracking locations of individual adult gannets during chick-rearing 2010-2012

**Appendix V:** Frequency distributions of trip parameters, a) range, b) length, and c) duration for individual adult gannets tracked from Bempton Cliffs during chick-rearing in 2010-2012 (continuous tags).

**Table 1:** Breakdown of locations at the breeding colony and at sea, by location class, for gannets tracked from Bempton Cliffs in each chick-rearing season 2010-2012.

<b>Year/location class</b>	<b>At colony (%)</b>	<b>At sea (%)</b>
<b>2010, <i>n</i> = 10,731 locations</b>	<b>4,459 (41.55%)</b>	<b>6,272 (58.45%)</b>
3	45	76
2	325	204
1	967	416
0	804	1899
A	1246	1411
B	1072	2266
<b>2011, <i>n</i> = 8,365 locations</b>	<b>3,451 (41.25%)</b>	<b>4,914 (58.74%)</b>
3	134	196
2	511	481
1	829	628
0	431	1401
A	949	859
B	597	1349
<b>2012, <i>n</i> = 15,839 locations</b>	<b>7,165 (45.24%)</b>	<b>8,674 (54.76%)</b>
3	363	321
2	798	550
1	1090	1121
0	667	2546
A	1559	1360
B	2688	2776



**Table 2:** Summary statistics, from continuous tags, describing foraging trip parameters for round trips, starting and ending at the breeding colony, for gannets during chick-rearing in 2010 ( $n = 1,272$  trips, 12 birds), 2011 ( $n = 574$  trips, 4 birds) and 2012 ( $n = 945$  trips, 9 birds). 95% confidence intervals to arithmetic means derived by  $\log_{10}$  transformation (after Fowler & Cohen 1996). See text for details.

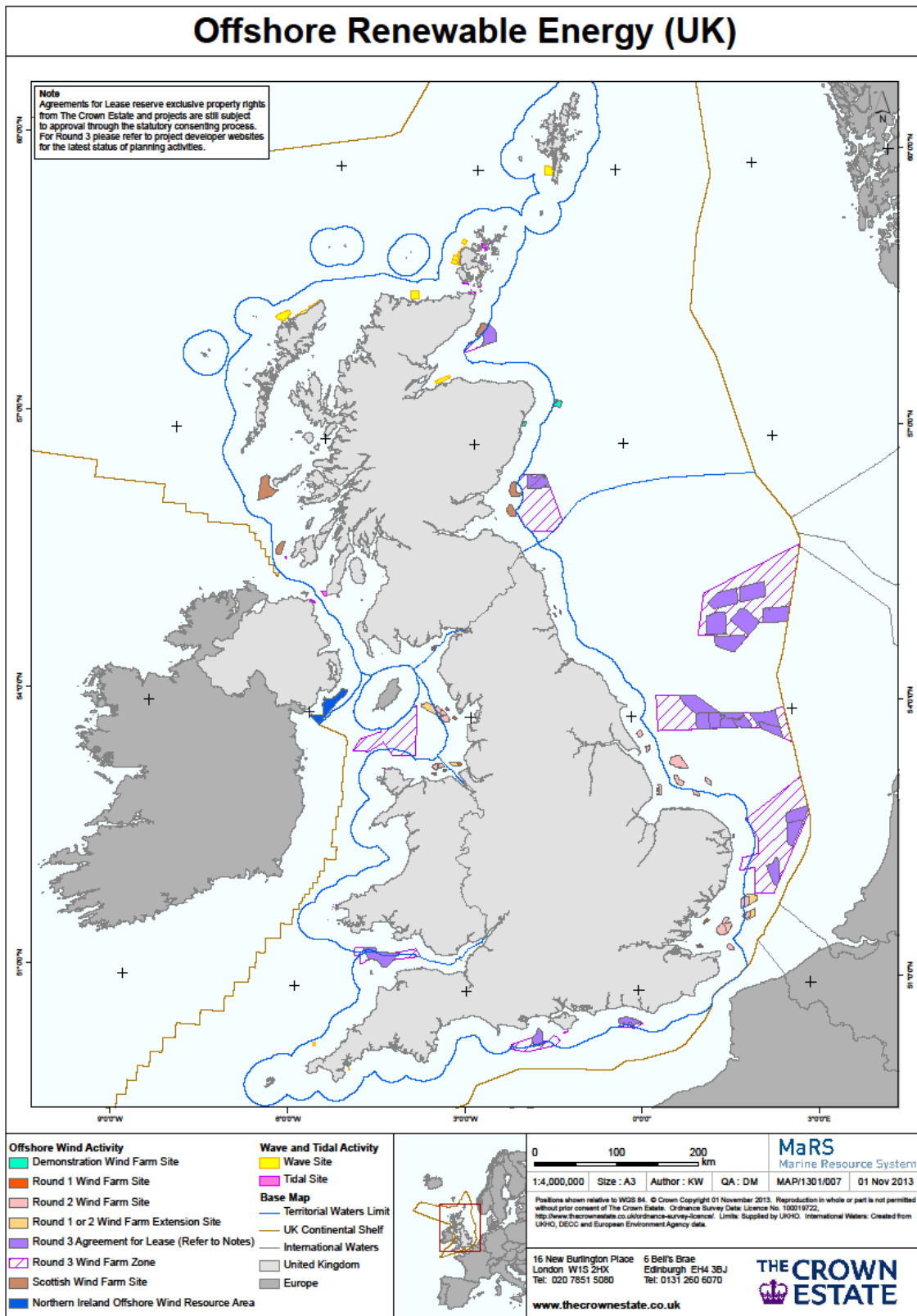
	2010	2011	2012
%			
Maximum foraging range (km)	404.35	320.98	275.14
Mean foraging range (km) 95% CI	43.22 $\times_{\pm}$ 1.06	37.22 $\times_{\pm}$ 1.09	46.22 $\times_{\pm}$ 1.08
Median foraging range (km)	22.24	13.58	17.12
Maximum trip length (km)	1164.23	1288.99	1691.73
Mean trip length (km) 95% CI	126.54 $\times_{\pm}$ 1.07	119.62 $\times_{\pm}$ 1.11	133.27 $\times_{\pm}$ 1.09
Median trip length (km)	57.48	30.43	39.00
Maximum trip duration (days)	3.60	4.42	4.89
Mean trip duration (days) 95% CI	0.36 $\times_{\pm}$ 1.01	0.34 $\times_{\pm}$ 1.02	0.37 $\times_{\pm}$ 1.02
Median trip duration (days)	0.20	0.10	0.15
Fixed kernels all locations	Including B (ex B)		
95% kernel area km <sup>2</sup>	18,002 (14,867)	15,852 (15,485)	17,744 (15,902)
75% kernel area km <sup>2</sup>	5,495 (5,567)	6,131 (6,254)	6,933 (6,464)
50% kernel area km <sup>2</sup>	2,547 (2,416)	3,371 (3,862)	4,570 (4,881)

**Table 3:** Kernel density estimation summary for individual PTTs (continuous and variable duty cycle tags) during chick-rearing at Bempton Cliffs 2010-2012

<b>50%</b>	<b>All3Yrs</b>	<b>2010</b>	<b>2011</b>	<b>2012</b>
Mean	2,224.3	1,975.6	2,056.0	2,569.1
SD	833.3	915.4	864.2	646.0
Max	3,721.6	3,568.8	3,498.4	3,721.6
Min	992.8	992.8	1,099.0	1,560.7
Range	2,728.8	2,575.9	2,399.4	2,160.9
Median	2,125.9	1,632.2	1,750.3	2,490.5
N	36	14	8	14
<b>95%</b>				
Mean	5,918.2	5,784.5	5,857.9	6,086.3
SD	2,062.2	1,989.5	2,354.8	2,110.5
Max	11,001.9	10,084.3	8,619.7	11,001.9
Min	2,328.9	2,458.8	2,328.9	2,687.9
Range	8,673.0	7,625.5	6,290.8	8,314.0
Median	5,958.3	6,129.5	5,915.9	5,723.9
N	36	14	8	14

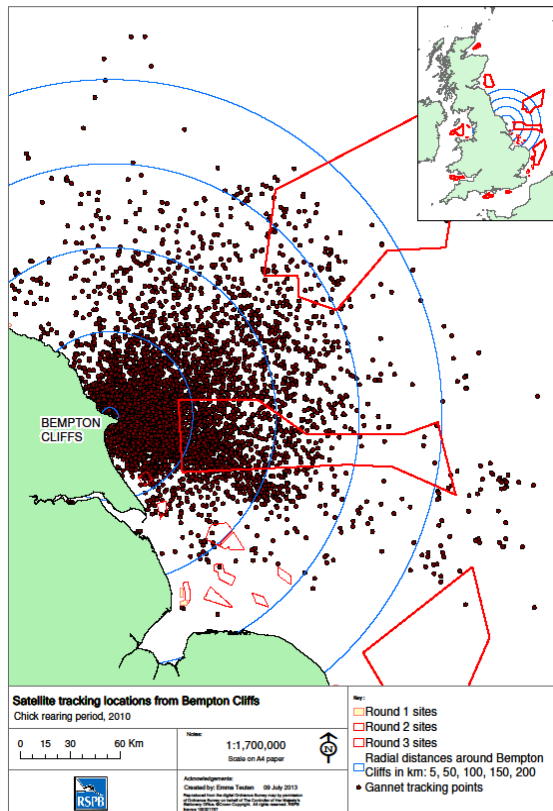
**Table 4:** Output from linear mixed model for various trip parameters of gannets during chick-rearing (continuous tags)

Unit type	Variable	Mean2010	Mean2011	Mean2012	Output from mixed model of log(y)				
					SD (Year)	SD (Bird)	SD (Trip)	SD ratio (Bird:Year)	SD ratio (Trip:Bird)
Distance (km)	Foraging range	43.27433	37.22057	46.21952	0.000128	0.285884	1.08993	2233.46875	3.812487
Distance (km)	Trip length	127	119.6254	133.2737	0.000149	0.331363	1.28065	2223.912752	3.864798
Distance (km)	Distance travelled to max distance (trip endpoint)	64.84881	62.93132	70.41012	0.000148	0.33963	1.31725	2294.797297	3.878474
Distance (km)	Distance travelled to return	62.15199	56.69359	62.86359	0.000149	0.319749	1.28603	2145.966443	4.021989
Time (days)	Trip duration	0.36551	0.339479	0.374602	0.000181	0.405488	1.18036	2240.265193	2.910957
Time (days)	Time to max distance	0.188095	0.180937	0.210433	0.000171	0.378899	1.36183	2215.783626	3.594174
Time (days)	Time to return	0.177402	0.158577	0.164179	0.000303	0.416904	1.31691	1375.920792	3.158773

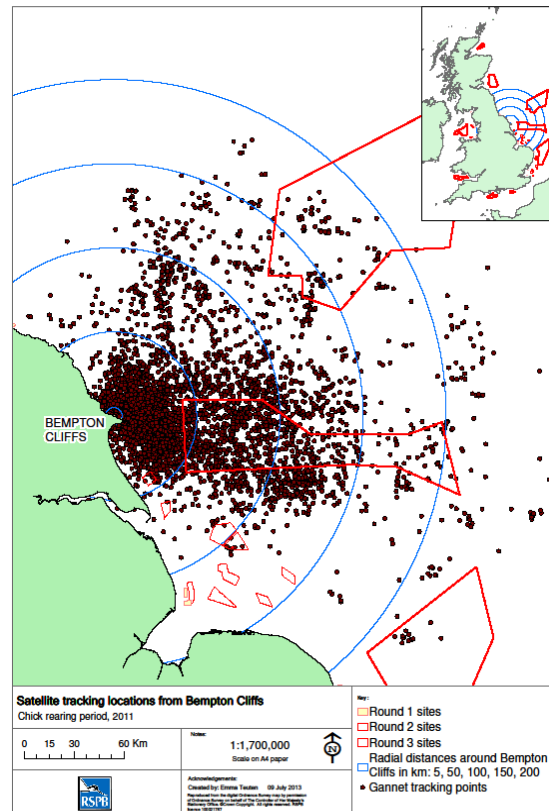


**Figure 1:** Offshore renewable energy projects around the UK, proposed, in planning, under construction and operational (courtesy of The Crown Estate, November 2013, [www.thecrownestate.co.uk](http://www.thecrownestate.co.uk)).

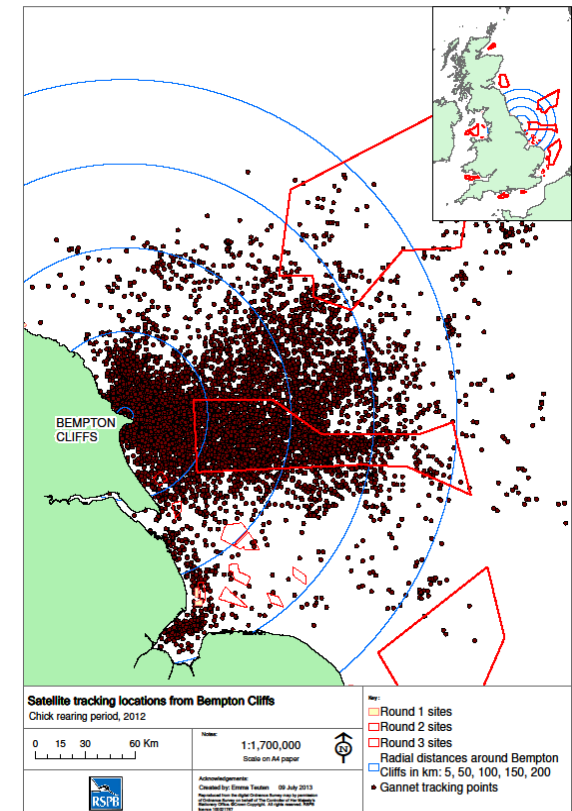
a)



b)

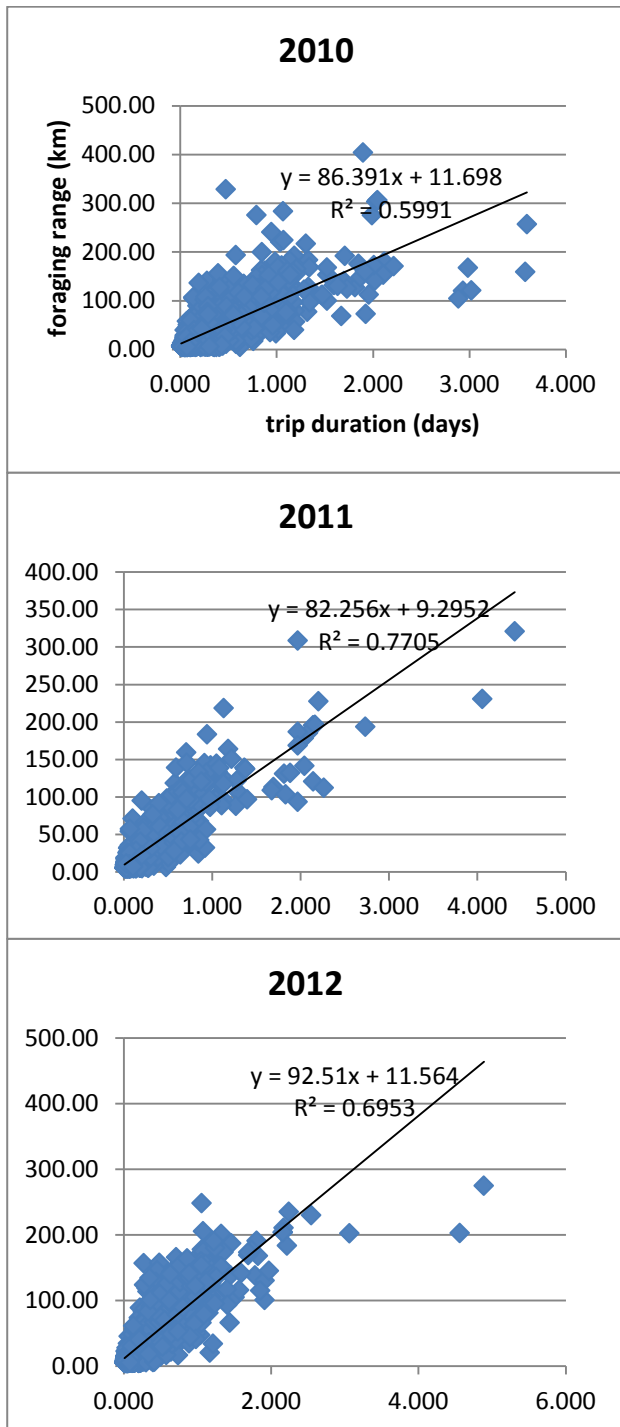


c)

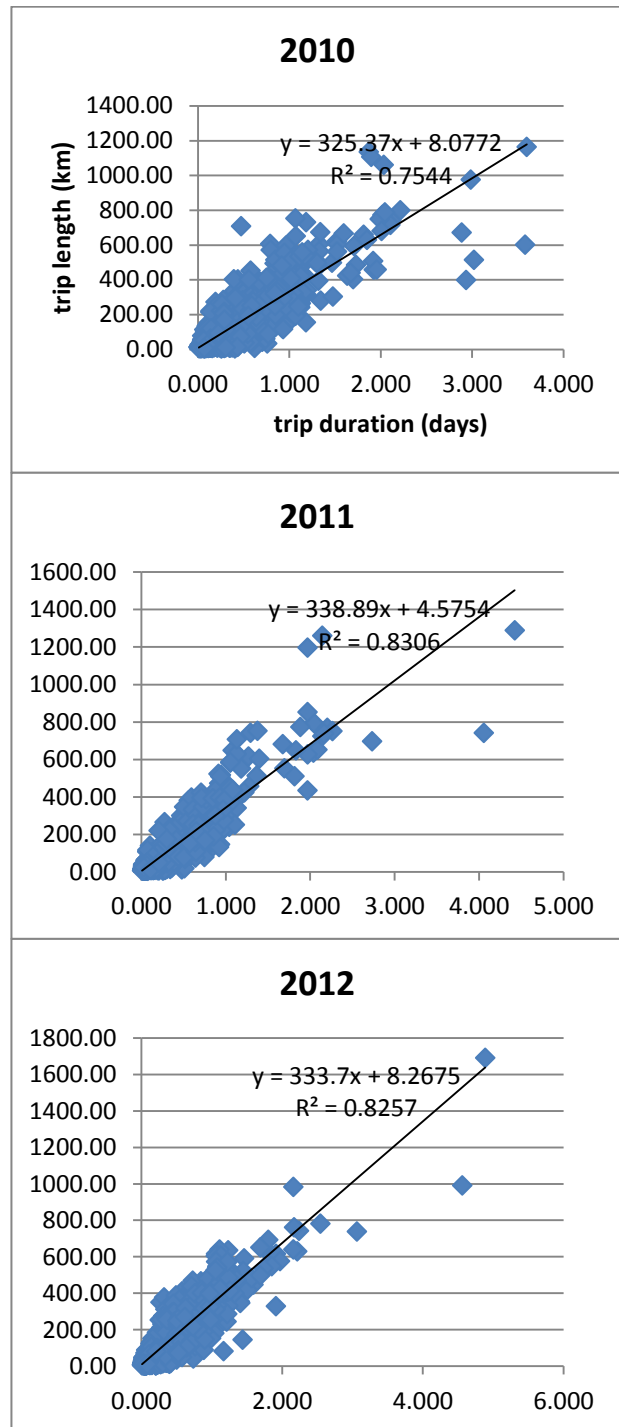


**Figure 2:** Combined tracking locations for adult gannets from Bempton Cliffs, based on a) 6,272 at sea locations in 2010 ( $n = 14$  birds), b) 4,914 locations in 2011 ( $n = 13$  birds), and 8,674 locations in 2012 ( $n = 15$  birds) during the chick-rearing period. The concentric blue rings are the 5km buffer around the central location of Bempton Cliffs, with added 50km, 100km, 150km and 200km buffers to aid interpretation of foraging distances. Inset shows the location of Bempton Cliffs. ARGOS location classes 3, 2, 1, 0, A, B.

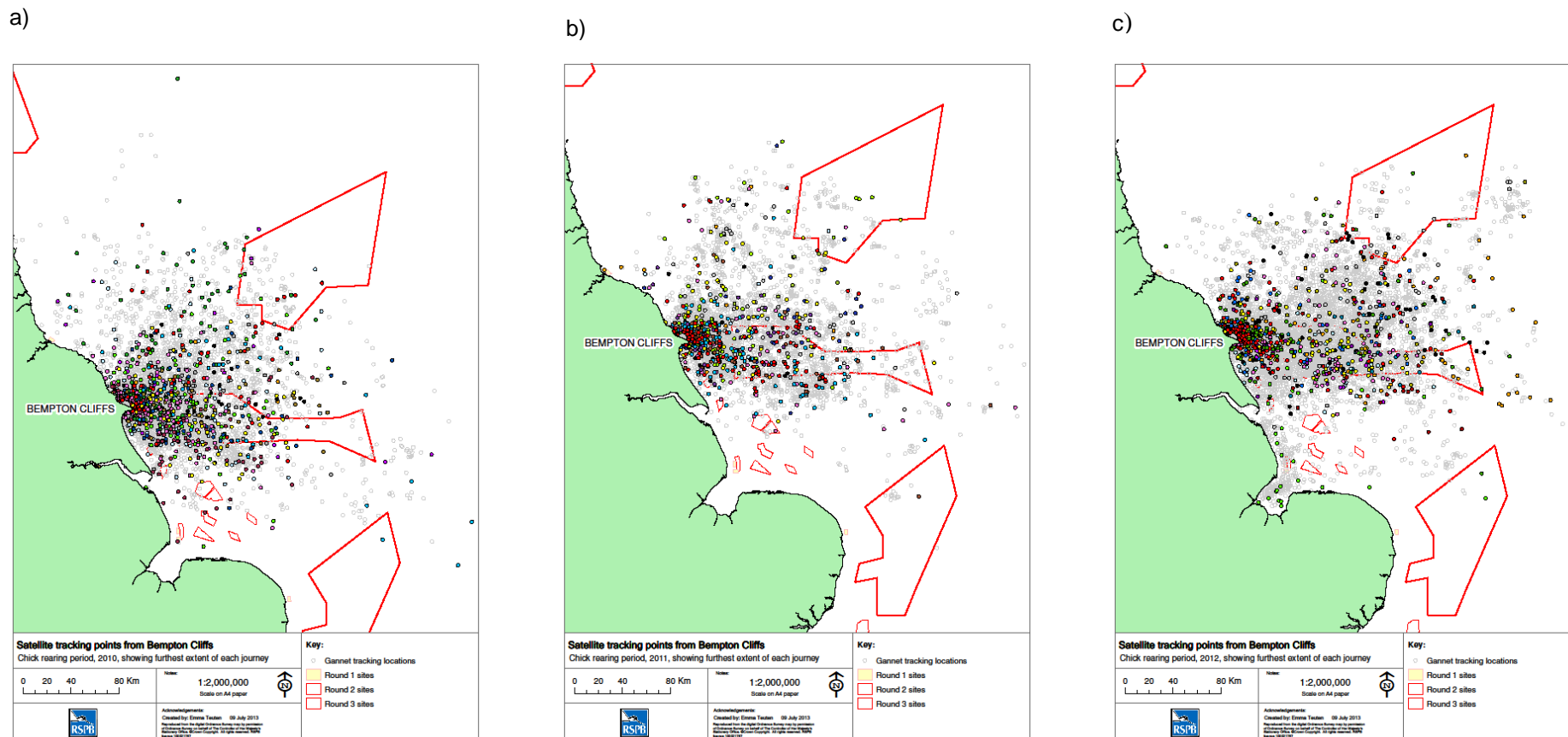
a)



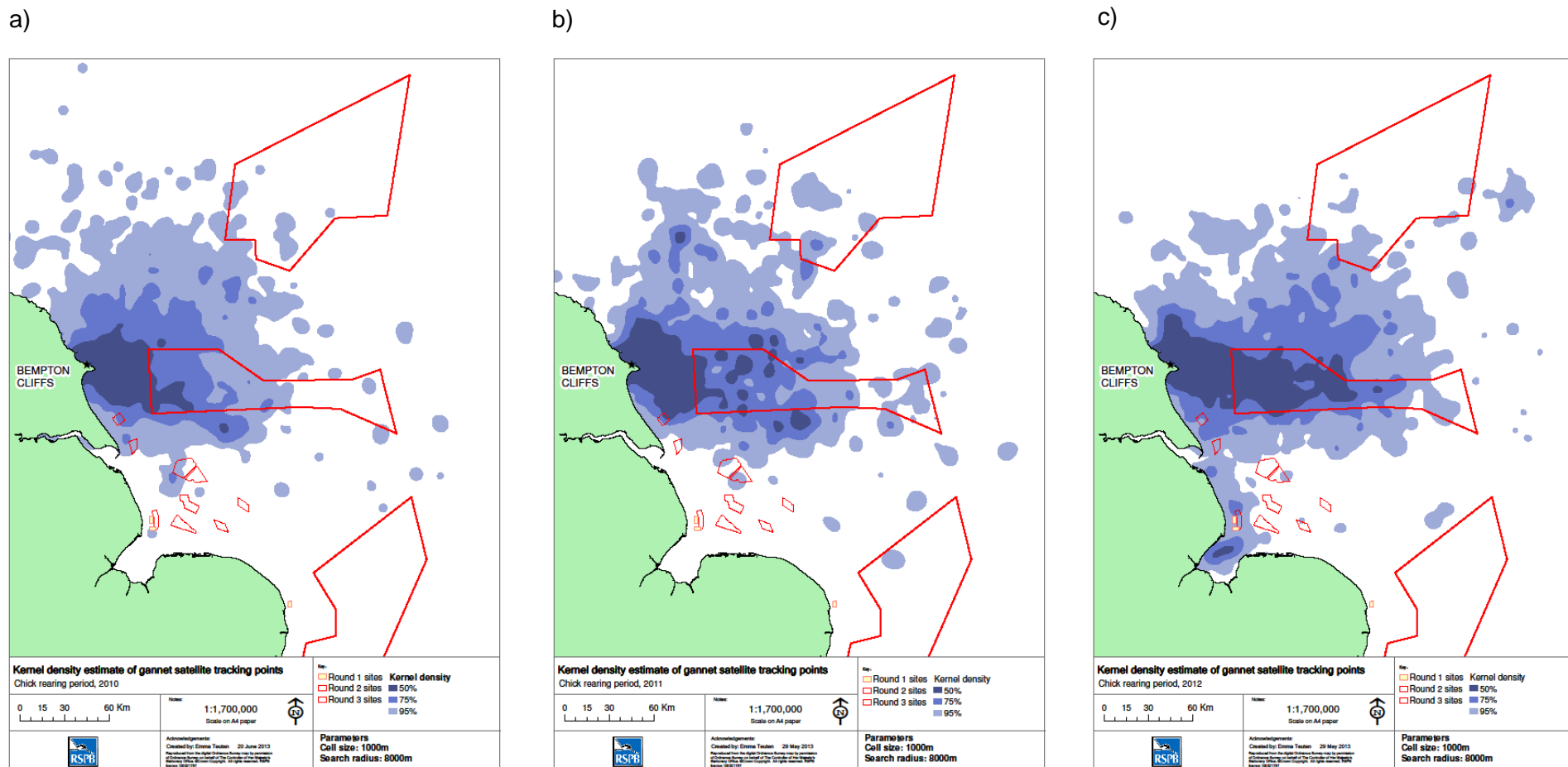
b)



**Figure 3:** Relationship between a) foraging range (km) and trip duration (days/24h period) and between b) trip length (km) and trip duration (days) for gannets from Bempton Cliffs during chick-rearing in 2010 ( $n = 1,285$  trips, 13 birds), 2011 ( $n = 574$  trips, 4 birds), and 2012 ( $n = 945$  trips, 9 birds). (Continuous tags).

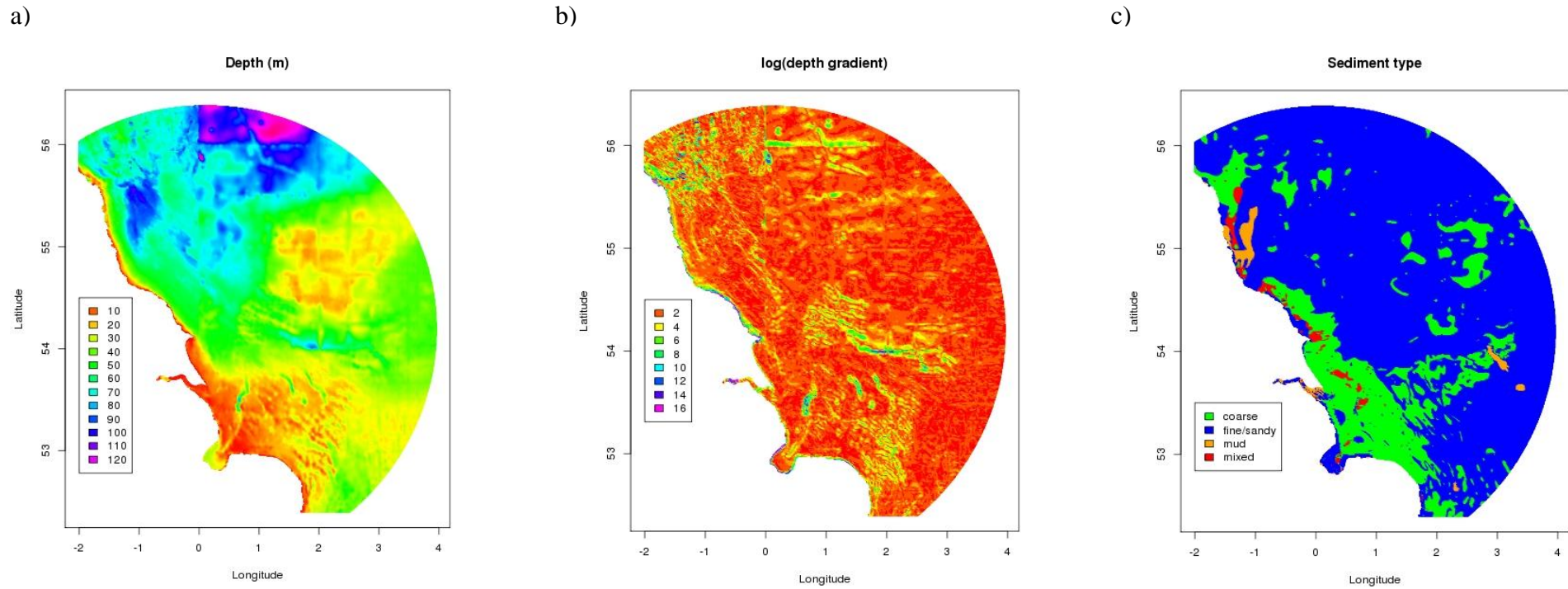


**Figure 4:** Highlighted flight end points indicating foraging destinations of adult gannets from Bempton Cliffs during chick-rearing: a) 2010 (6,272 at sea locations,  $n = 14$  birds), b) 2011 (4,914 locations,  $n = 13$  birds), c) 2012 (8,674 locations,  $n = 15$  birds). Different colours signify different individual birds. ARGOS location classes 3, 2, 1, 0, A & B (see also Figure All.2 for equivalent plots excluding B records).

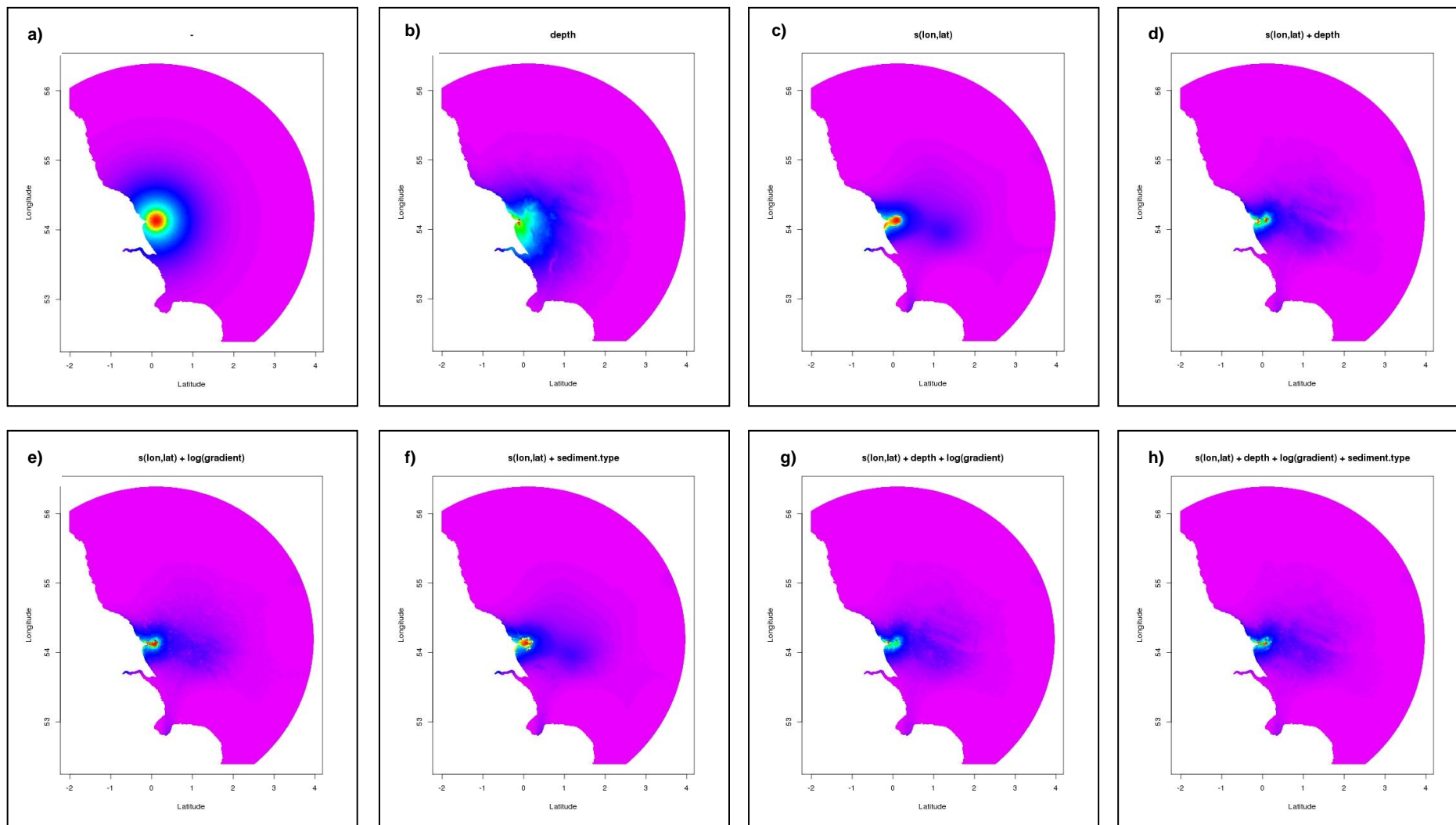


**Figure 5:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for adult gannets during chick-rearing: a) 2010 ( $n = 14$ ), b) 2011 ( $n = 13$ ) & c) 2012 ( $n = 15$ ), showing the 50%, 75% and 95% density contours. ARGOS location classes 3, 2, 1, 0, A, B (see also Figure All.3 for equivalent plots excluding B records).

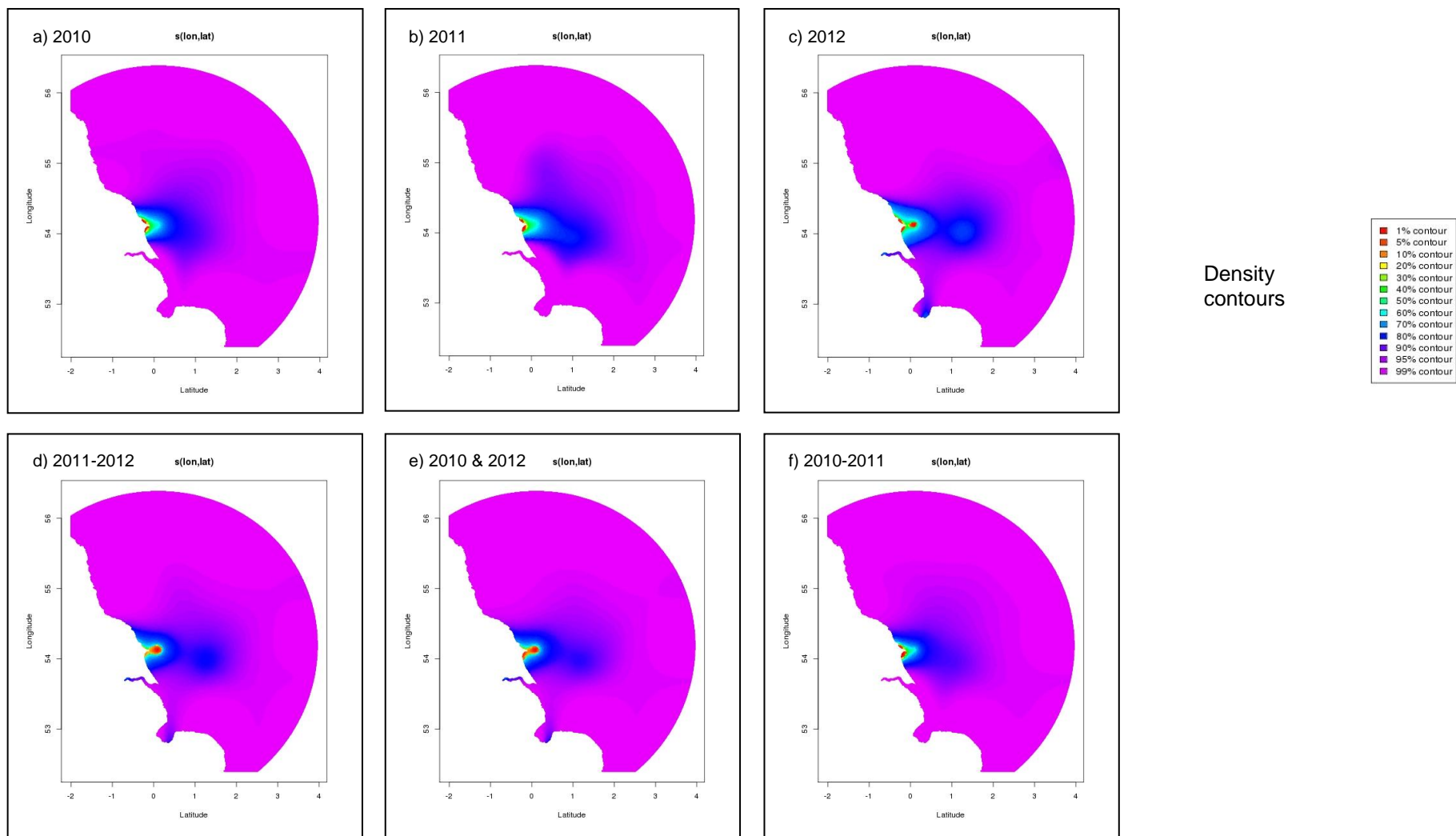




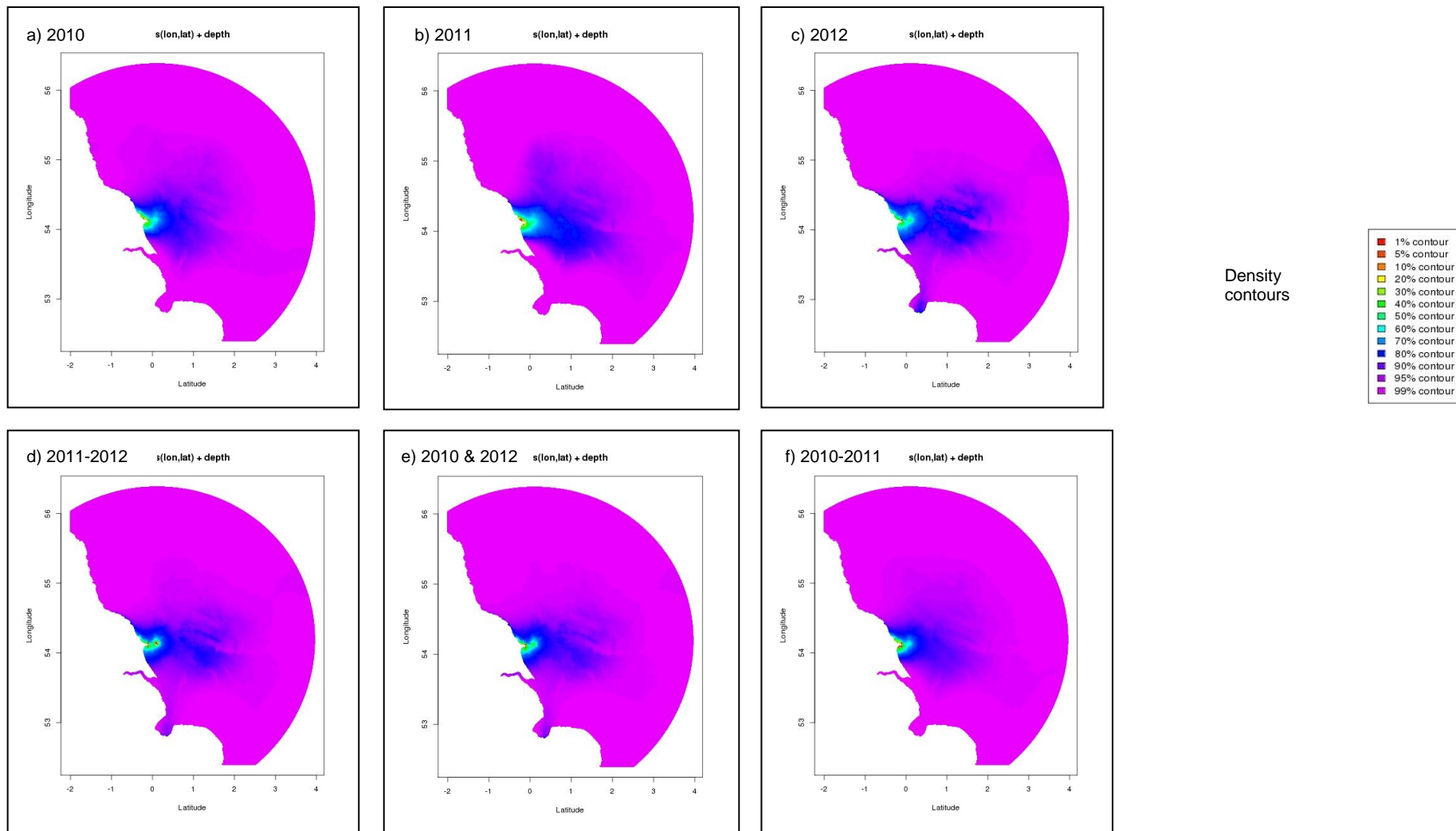
**Figure 6:** Distribution plots of environmental variables used in the analysis, a) bathymetry/water depth, b) log depth gradient, c) sediment type. See text for further explanation.



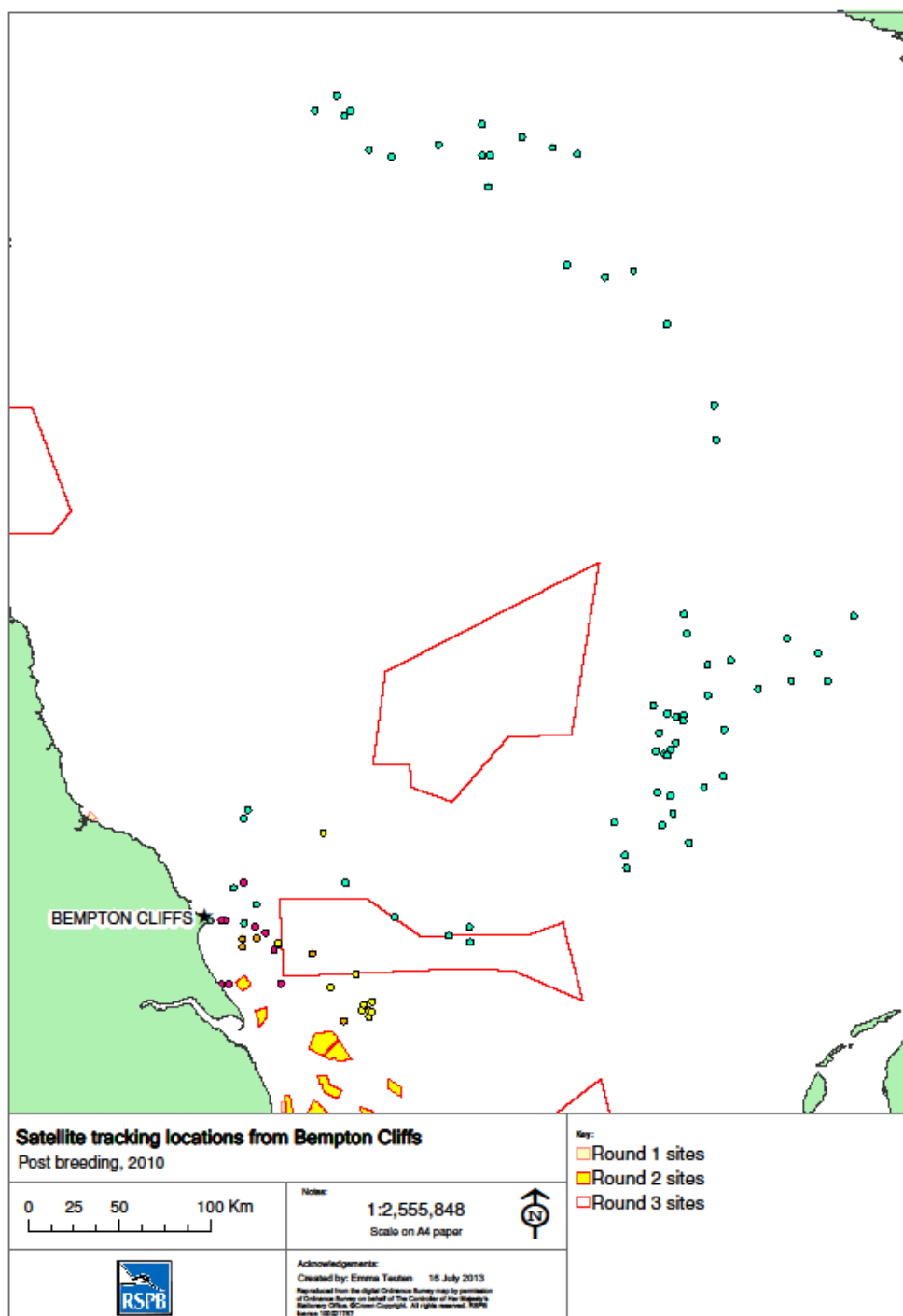
**Figure 7:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing 2010-2012. Contours show the estimated density of trip endpoint locations from logistic regression models that contain ‘distance to colony’ and, apart from (a), additional environmental variables as covariates; (a,b) are fitted as Binomial GLMs; (c-g) are fitted as Binomial GAMs and include a bivariate smooth in latitude and longitude. See Figure 8 for figure legend.



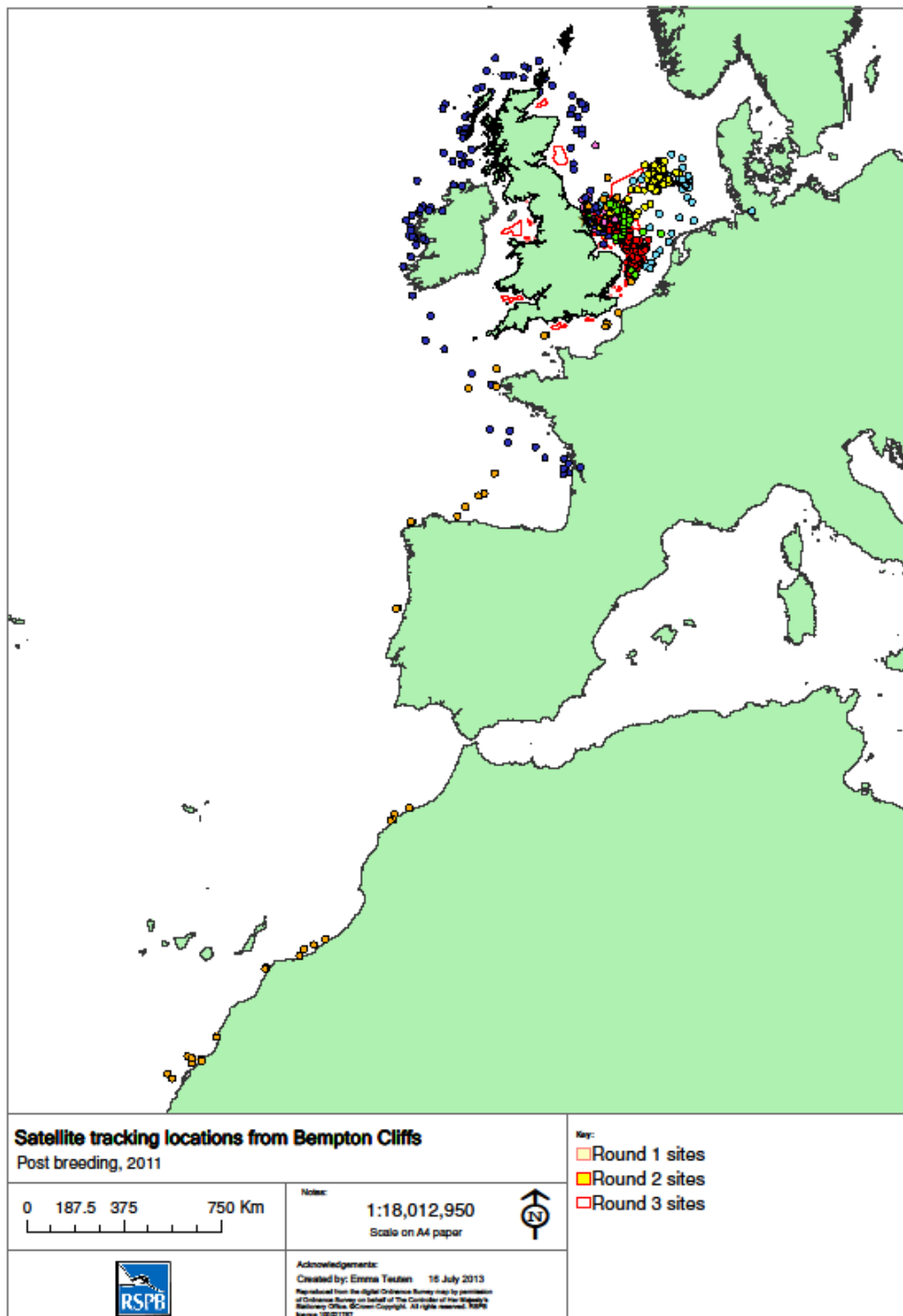
**Figure 8:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing, assessing predictive ability of the GAM with distance to colony but no environmental variables included. Maps show the predicted density based on a) 2010, b) 2011, c) 2012, d) 2011-2012, e) 2010 and 2012, and f) 2010-2011.



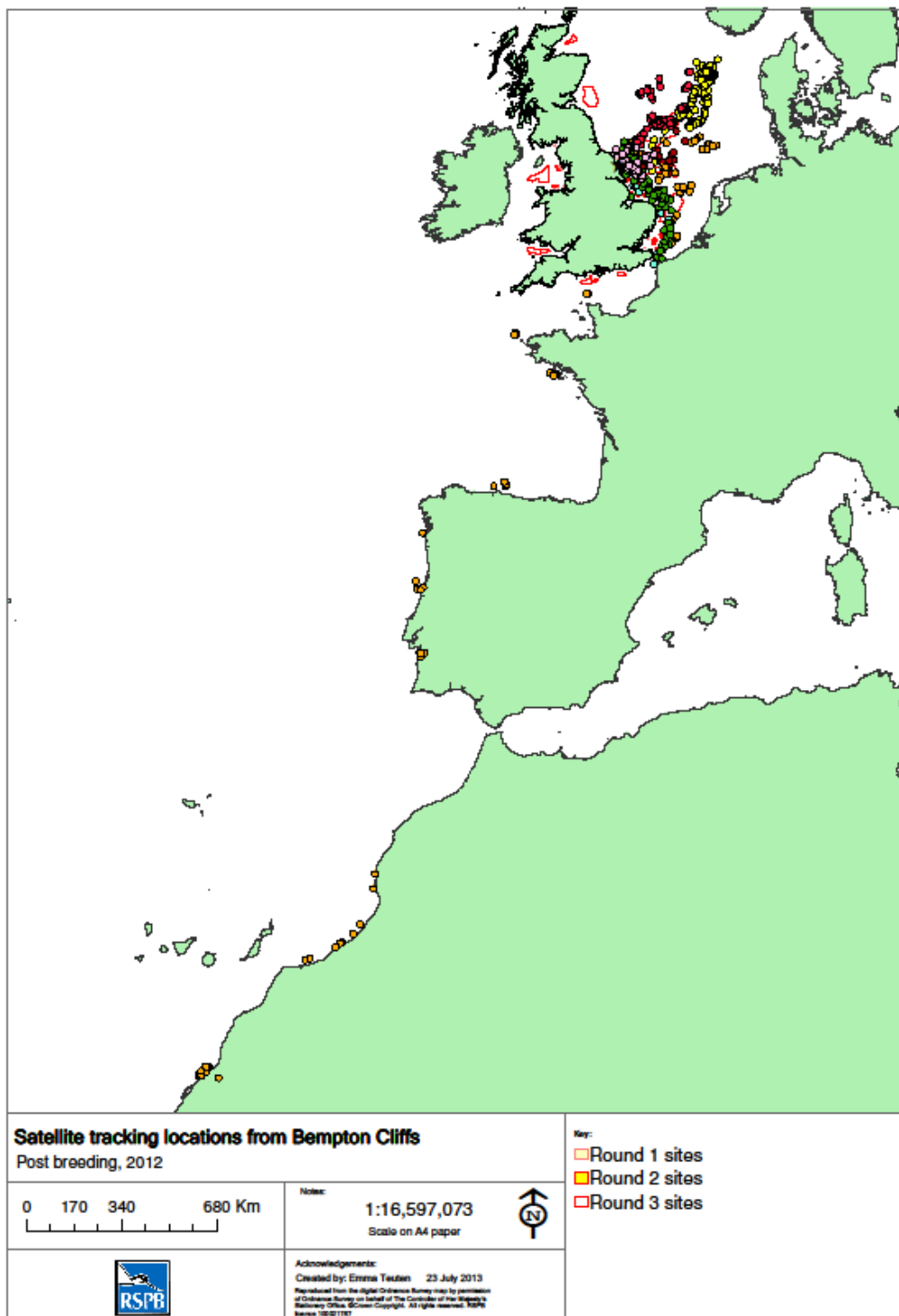
**Figure 9:** Outputs of the analysis of possible environmental determinants of foraging locations for adult gannets during chick-rearing, assessing predictive ability of the GAM with distance to colony and water depth included. Maps show the predicted density based on a) 2010, b) 2011, c) 2012, d) 2011-2012, e) 2010 and 2012, and f) 2010-2011.



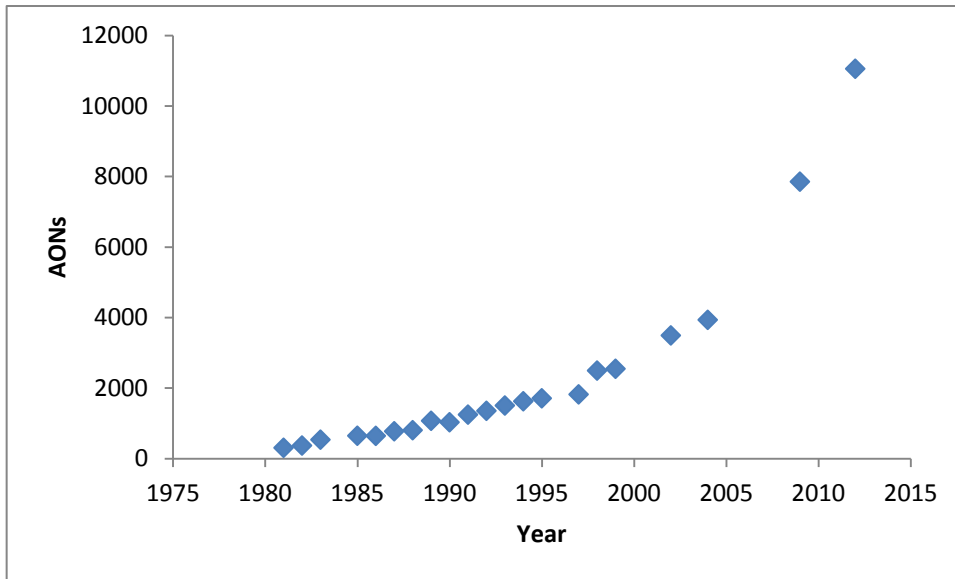
**Figure 10:** Post-breeding locations in 2010 of four individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery powered satellite tags, based on 153 locations.



**Figure 11:** Post-breeding locations in 2011 of seven individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery-powered satellite tags, based on 843 locations.



**Figure 12:** Post-breeding locations in 2012 of seven individually tagged gannets from Bempton Cliffs breeding colony, fitted with 45g PTT-100 battery-powered satellite tags, based on 887 locations.



**Figure 13:** Population trend in gannets (Apparently Occupied Nests) at Bempton Cliffs, 1981 to 2012. **NB** in 1969, there were 21 AONs.



**Appendix I: Summary information for each satellite tag and individual adult gannet 2010-2012  
(before data cleaning, *i.e.* raw data – see text)**

**Table AI.1:** Summary information for each satellite tag and individual adult gannet in 2010

Platform ID	60503	60504	60505	60506	60507	60508	60509	60510	60511	60512	60514	60515	60516	60517	n=14
Tag type	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	
Duty cycle	contin	contin	contin	contin	contin	contin	contin	contin	contin	contin	contin	contin	contin	contin	
GPS total fixes (passed checksum)															
Argos total fixes quality codes 3,2,1,0,A	447	1046	119	337	689	973	1094	1111	974	319	373	673	625	137	8917
LC 3	9	1	5	3	12	3	29	6	20	9	2	8	15	0	122
LC 2	46	15	10	18	43	21	89	51	110	20	20	44	56	1	544
LC 1	72	89	17	72	147	118	194	212	213	35	61	85	129	8	1452
LC 0	136	496	44	111	208	464	349	433	316	131	132	232	184	72	3308
LC A	184	445	43	133	279	367	433	409	315	124	158	304	241	56	3491
LCB	291	615	91	200	411	521	634	570	419	247	248	547	349	105	5248
Total number of all Argos fixes <sup>1</sup>	738	1662	210	537	1100	1494	1731	1685	1393	566	621	1222	974	242	14175
Mean Argos fixes per day (Quality codes 3,2,1,0,A)	13.55	14.33	8.50	13.48	14.06	17.07	13.68	13.89	21.17	7.78	10.08	8.41	14.20	4.28	
Days operational	33	73	13	25	49	57	80	80	46	41	37	80	43	26	
Last record date	15- Aug	24- Sep	26-Jul	07- Aug	31- Aug	08- Sep	01- Oct	01- Oct	28- Aug	23- Aug	19- Aug	01- Oct	25- Aug	08- Aug	
Inferred last date of chick- rearing period <sup>2</sup>		23- Sep					30- Sep	24- Sep				30- Sep			

<sup>1</sup>includes Argos Z records

<sup>2</sup>last date recorded at Bempton

**Table AI.2** Summary information for each satellite tag and individual adult gannet in 2011

Platform ID	107224	107225	107226	107227	110467	110468	110469	110470	110472	110473	110474	110475	110476	n = 13
Tag type	LC4	LC4	LC4	LC4	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	
Duty cycle					contin	contin	contin	contin	var	var	var	var	var	
GPS total fixes (passed checksum)	118(18)	141(14)	408(48)	0										
Argos total fixes quality codes														
3,2,1,0,A	64	54	165	155	1493	612	1910	1840	61	362	282	400	520	7918
LC 3	0	0	0	0	98	8	115	45	3	23	15	19	30	356
LC 2	1	2	7	1	272	19	327	197	5	63	44	60	79	1077
LC 1	1	5	13	13	294	48	428	464	9	77	51	74	129	1606
LC 0	54	30	103	94	387	298	468	569	30	86	81	117	144	2461
LC A	8	17	42	47	442	239	572	565	14	113	91	130	138	2418
LCB	55	48	123	137	539	424	655	716	28	161	99	168	207	3360
Total number of all Argos fixes <sup>1</sup>	120	104	293	294	2048	1072	2590	2588	90	527	388	573	733	11420
Mean Argos fixes per day (Quality codes 3,2,1,0,A)	3.20	2.70	3.30	2.87	16.78	7.20	22.74	20.44	8.71	5.17	7.05	4.44	5.65	
Days operational	20	17	50	54	89	85	84	90	7	70	40	90	92	
Last record date	08-Aug	05-Aug	07-Sep	11-Sep	16-Oct	12-Oct	11-Oct	17-Oct	26-Jul	27-Sep	28-Aug	17-Oct	19-Oct	
Inferred last date of chick-rearing period <sup>2</sup>				05-Sep	29-Sep	17-Sep	25-Sep	03-Oct		25-Sep		16-Sep	30-Sep	

<sup>1</sup>includes Argos Z records

<sup>2</sup>last date recorded at Bempton

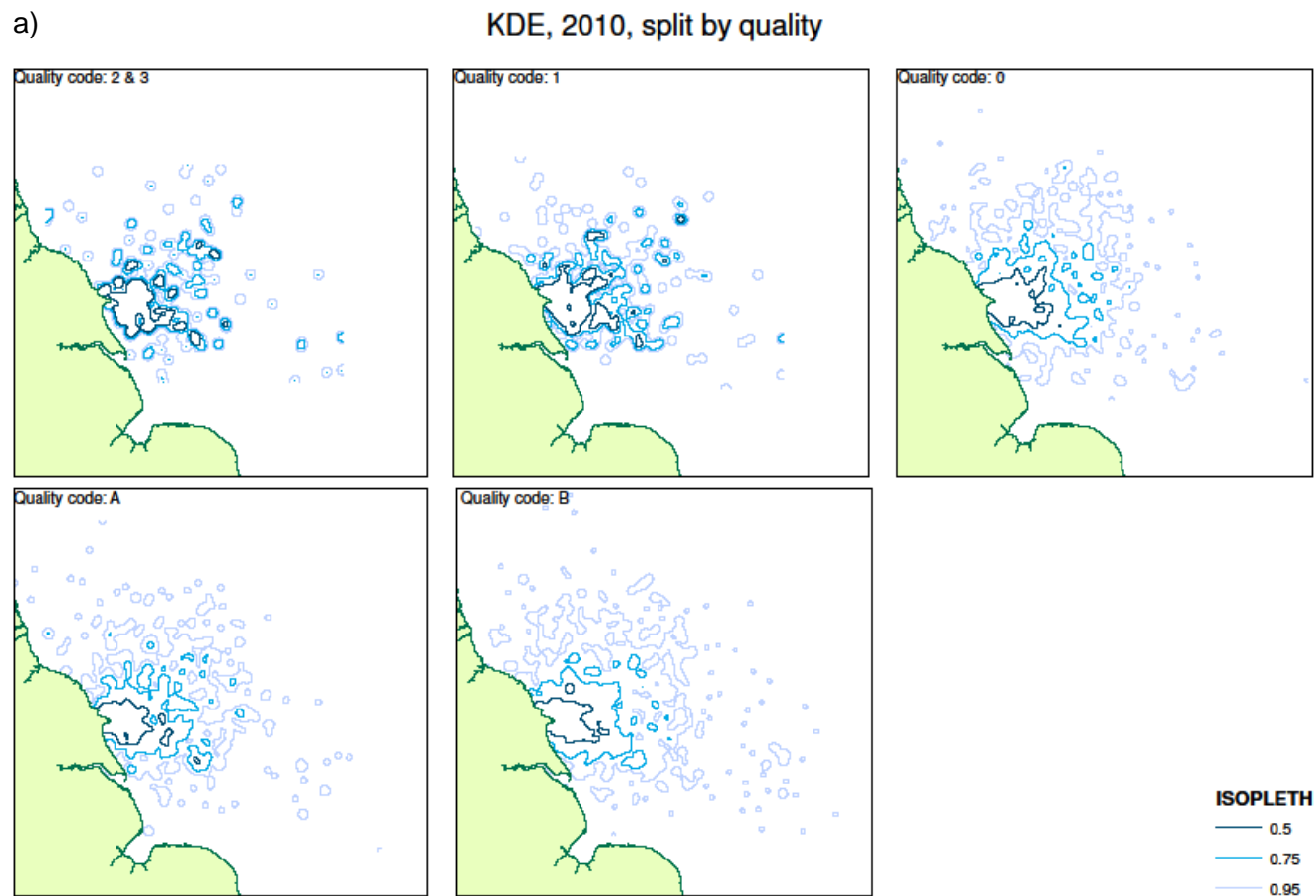
**Table AI.3** Summary information for each satellite tag and individual adult gannet in 2012

Platform ID	60513	107214	107215	107216	107217	107218	107219	107220	107221	107222	107223	107228	110471	118972	118973	118974	n=16
Tag type	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	PTT	LC4	PTT	PTT	PTT	PTT
Duty cycle	contin	contin	contin	contin	contin	contin	var	var	var	var	var	var	hourly	contin	contin	contin	contin
GPS total fixes (passed checksum)																	382(46)
Argos total fixes quality codes																	
3,2,1,0,A	1734	1069	684	1220	1011	6	119	171	296	504	625	100	1255	1133	535	1351	11813
LC 3	47	39	41	88	59	1	7	5	31	50	72	12	44	91	35	93	715
LC 2	177	98	89	181	97	1	13	6	32	80	103	17	171	148	61	156	1430
LC 1	422	206	160	274	195	0	23	27	66	109	107	18	241	168	83	238	2337
LC 0	641	286	186	325	348	3	47	78	101	141	182	24	397	475	202	422	3858
LC A	447	440	208	352	312	1	29	55	66	124	161	29	402	251	154	442	3473
LCB	578	1182	621	891	1018	5	85	136	196	356	299	80	578	350	194	541	7110
Total number of all Argos fixes <sup>1</sup>	2333	2252	1305	2120	2030	11	205	307	495	862	925	180	1857	1500	737	1911	19030
Mean Argos fixes per day (Quality codes 3,2,1,0,A)	21.15	14.07	19.54	22.59	17.74	1.00	3.13	5.52	5.10	3.82	7.53	2.56	14.76	14.91	11.15	17.55	
Days operational	82	87	35	54	57	6	38	31	53	132	83	39	85	76	48	77	
Last record date	05Oct	10 Oct	19Aug	07Sep	10Sep	21Jul	22Aug	15Aug	06Sep	24Nov	06Oct	23Aug	08Oct	29Sep	01Sep	30Sep	
Inferred last date of chick- rearing period <sup>2</sup>	23Sep	01 Oct								14Sep	20Sep		02Oct	19Sep		23Sep	

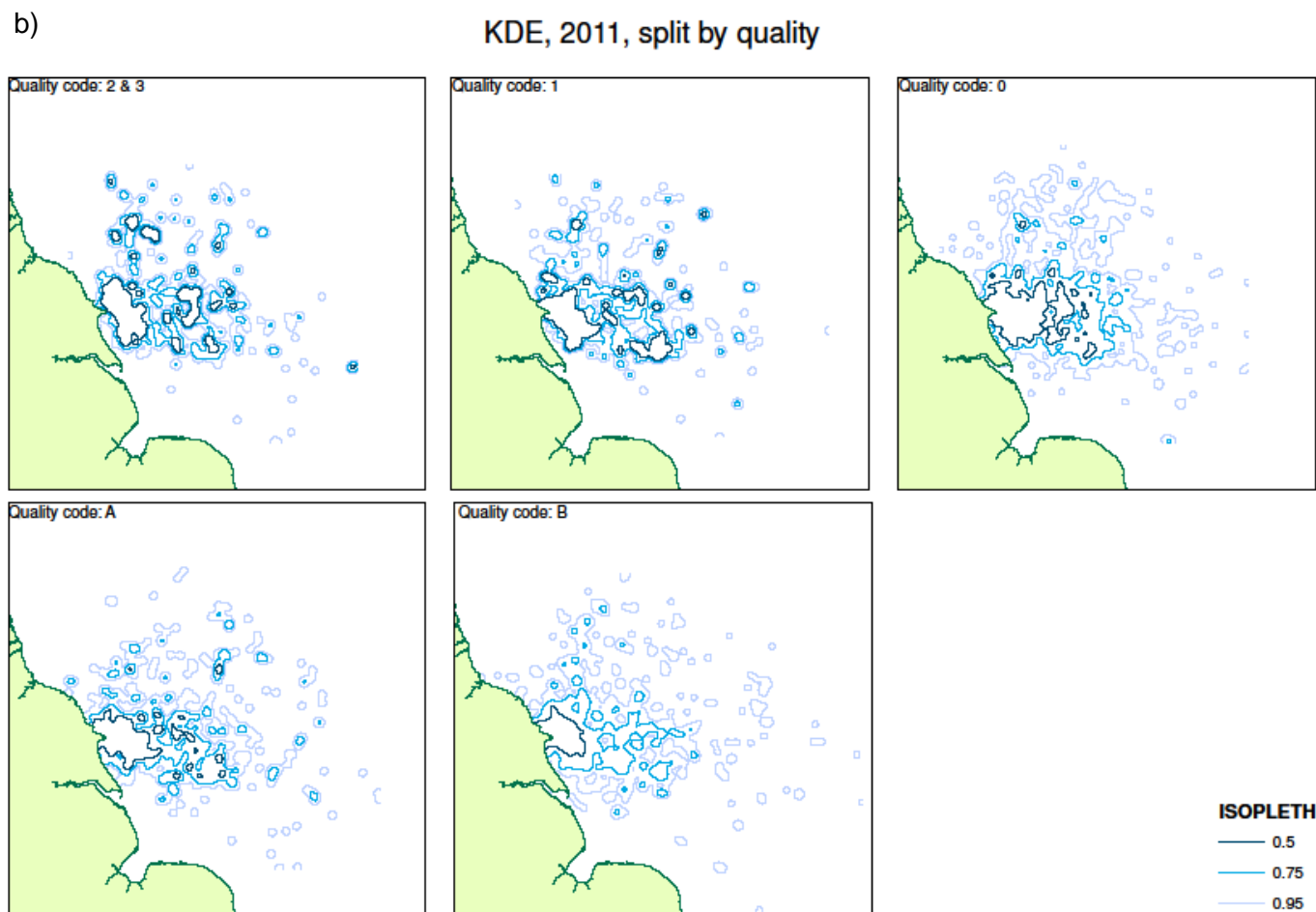
<sup>1</sup>includes Argos Z records

<sup>2</sup>last date recorded at Bempton

**Appendix II:** Comparison of ARGOS location classes for gannets tracked from Bempton Cliffs during 2010-2012 chick-rearing seasons.



**Figure All.1** Kernel Density Estimation for adult gannets tracked from Bempton Cliffs during chick-rearing, comparing different ARGOS location classes, from highest to lowest quality, 3 & 2 combined, 1, 0, A & B, a) 2010, b) 2011, c) 2012.



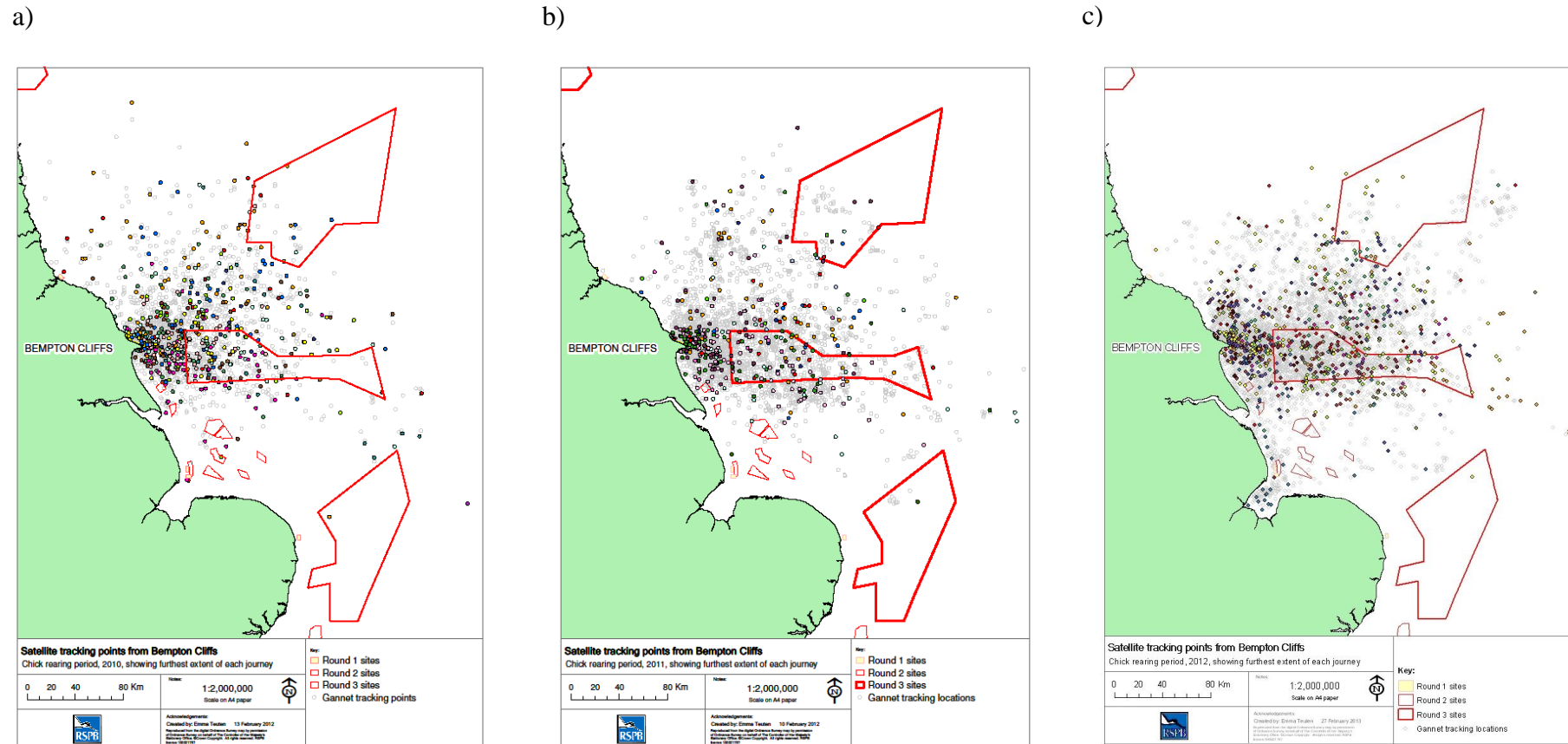
**Figure All.1** Kernel Density Estimation for adult gannets tracked from Bempton Cliffs during chick-rearing, comparing different ARGOS location classes, from highest to lowest quality, 3 & 2 combined, 1, 0, A & B, b) 2011.

c)

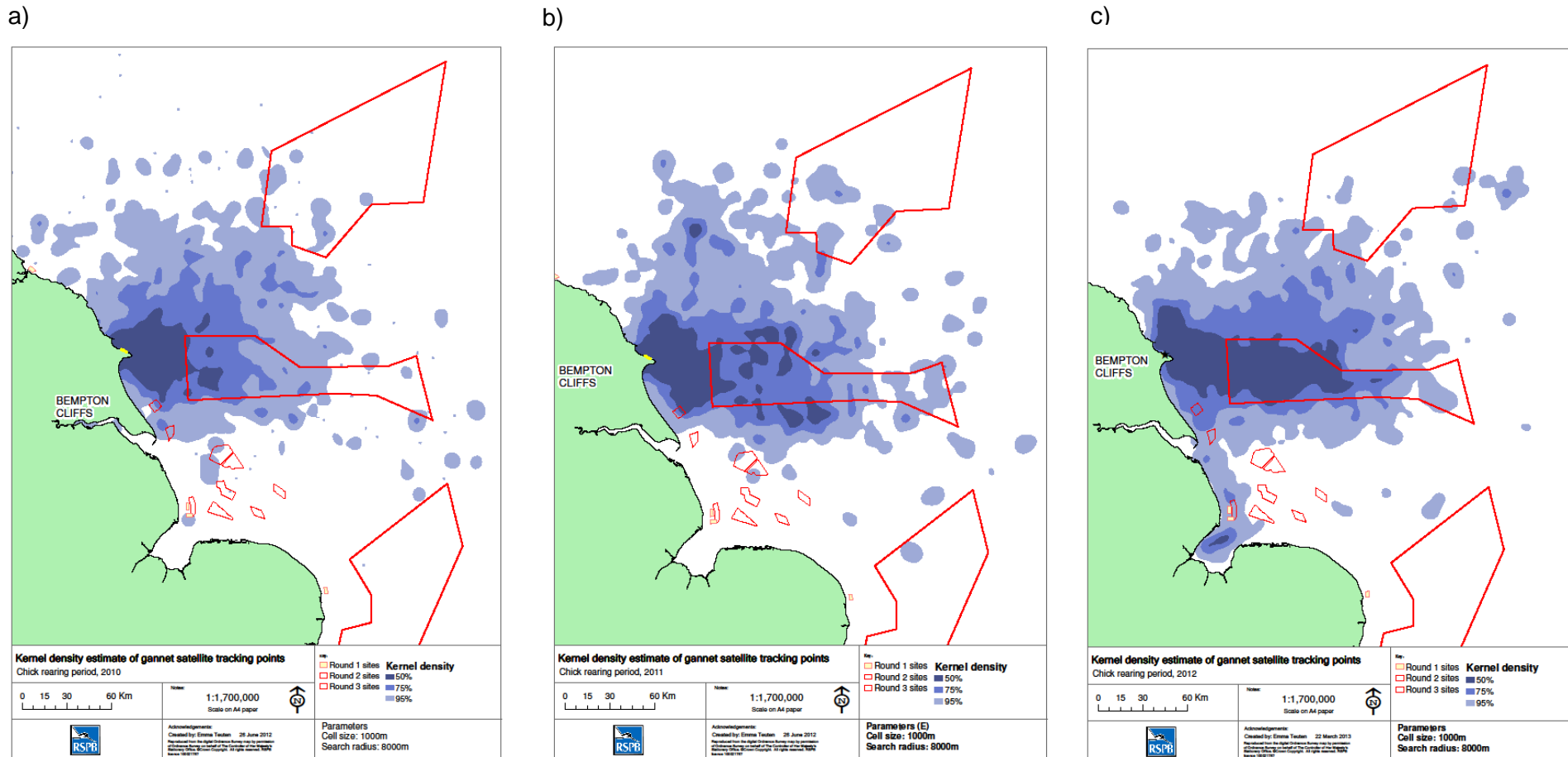
KDE, 2012, split by quality



**Figure AII.1** Kernel Density Estimation for adult gannets tracked from Bempton Cliffs during chick-rearing, comparing different ARGOS location classes, from highest to lowest quality, 3 & 2 combined, 1, 0, A & B, c) 2012.



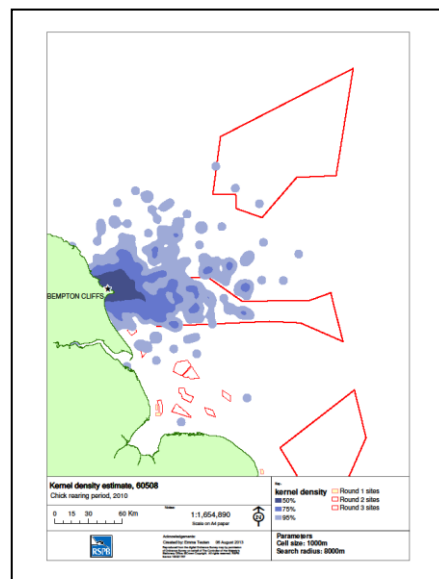
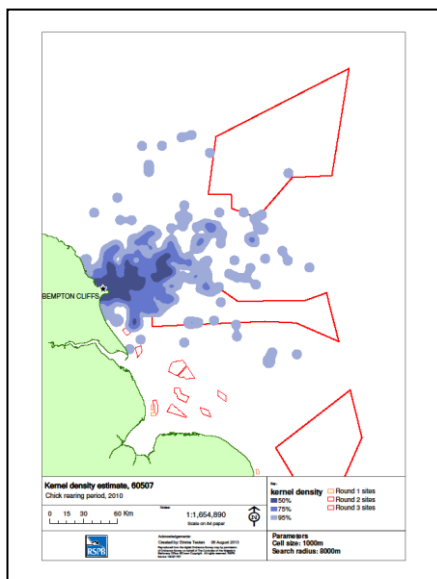
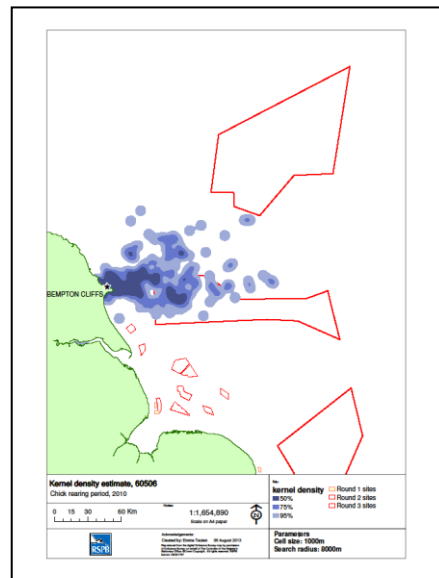
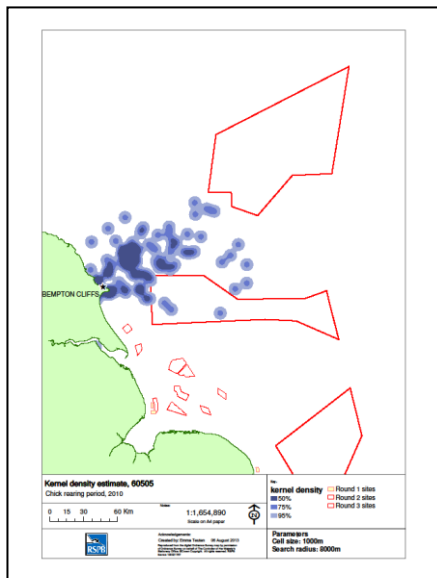
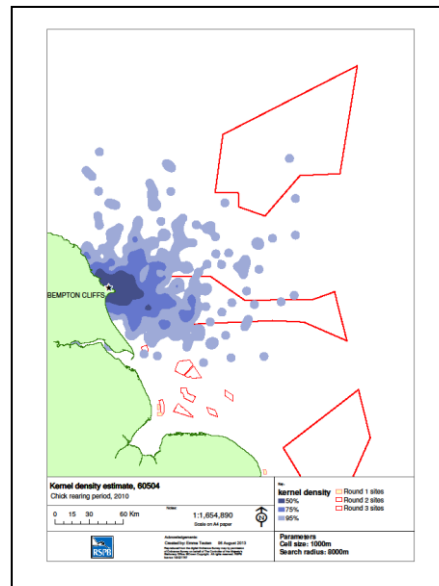
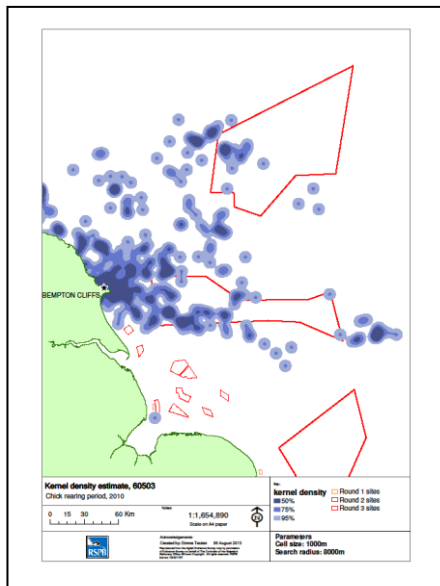
**Figure All.2:** Highlighted flight end points at sea indicating foraging destinations of adult gannets from Bempton Cliffs, during chick-rearing: a) 2010 (4,006 locations,  $n = 14$  birds), b) 2011 (3,565 locations,  $n = 13$  birds), c) 2012 (5,898 locations,  $n = 15$  birds). Different colours signify different individual birds. ARGOS location classes 3, 2, 1, 0, A (see also Figure 4 for equivalent figures including location class B).



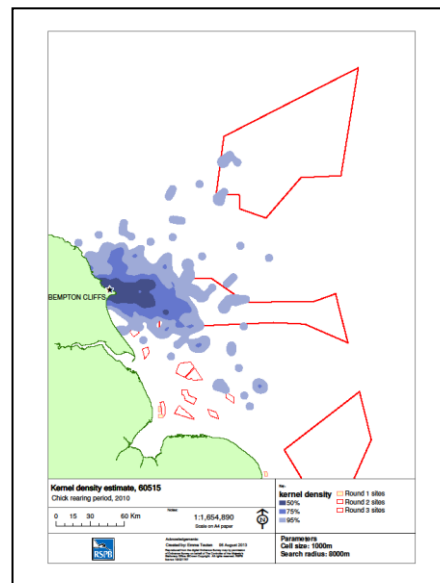
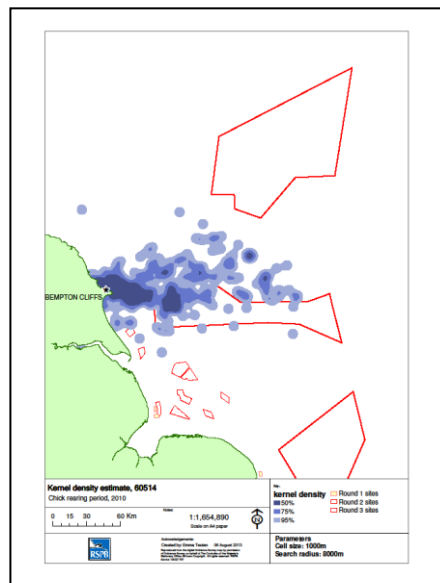
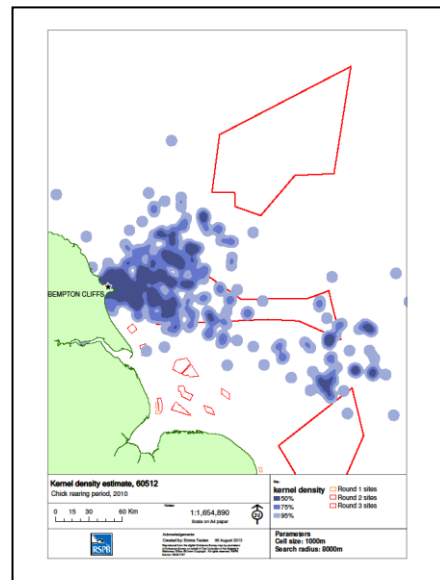
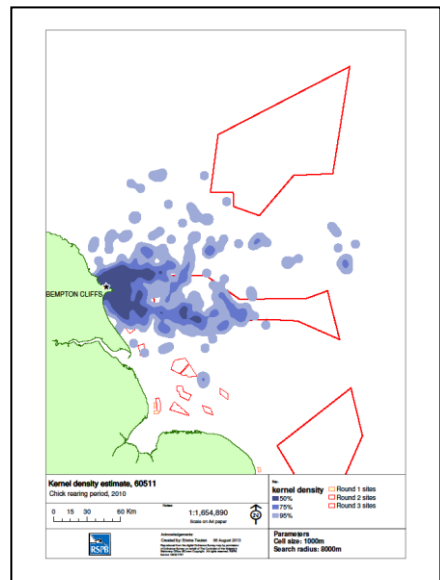
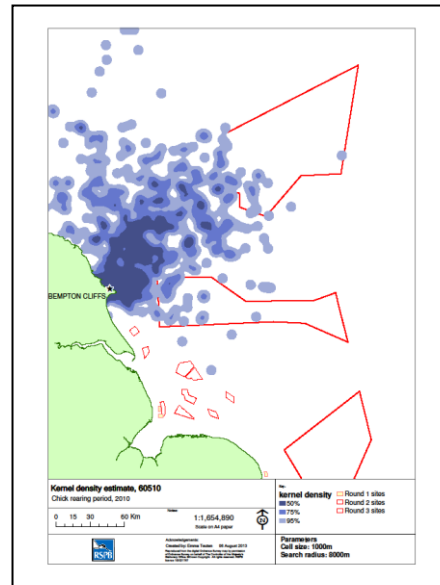
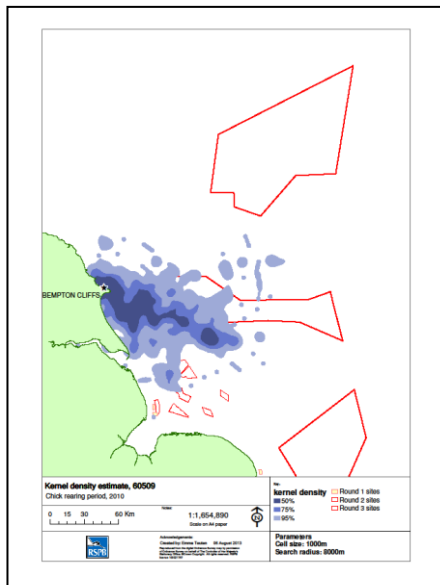
**Figure AII.3:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for adult gannets during chick-rearing seasons in each year: a) 2010 ( $n = 14$ ), b) 2011 ( $n = 13$ ), c) 2012 ( $n = 15$ ), showing the 50%, 75% and 95% density contours. ARGOS location classes 3, 2, 1, 0, A (see also Figure 5 for equivalent figures including location class B).



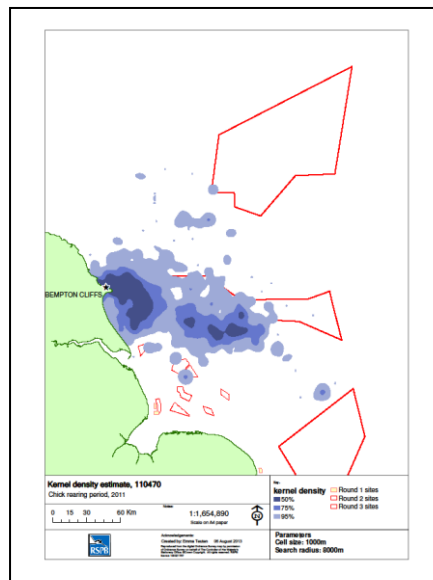
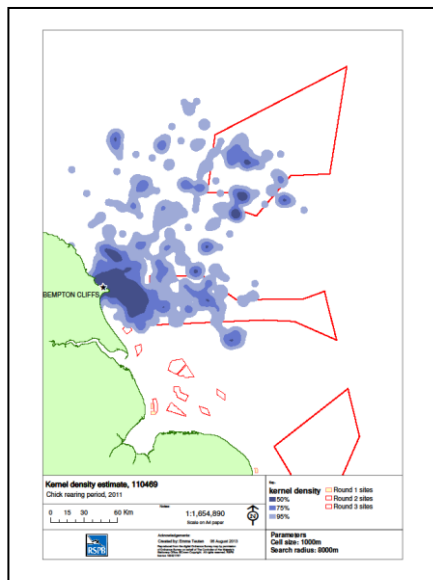
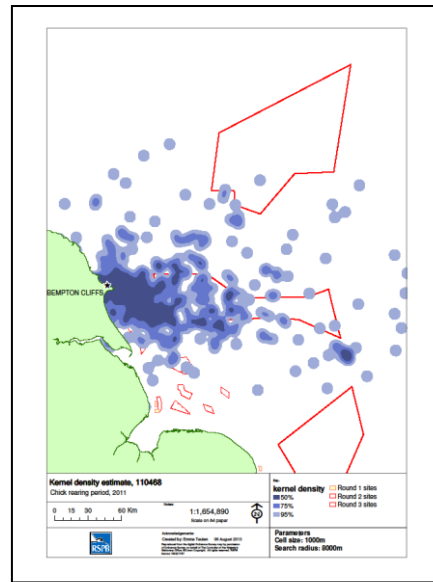
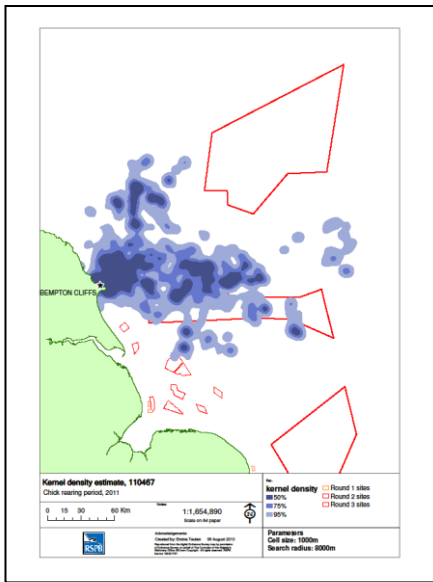
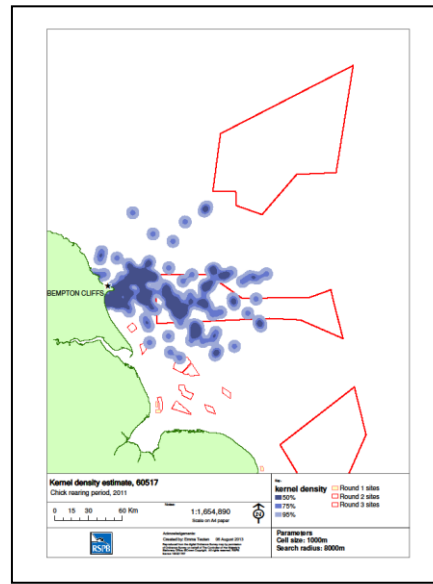
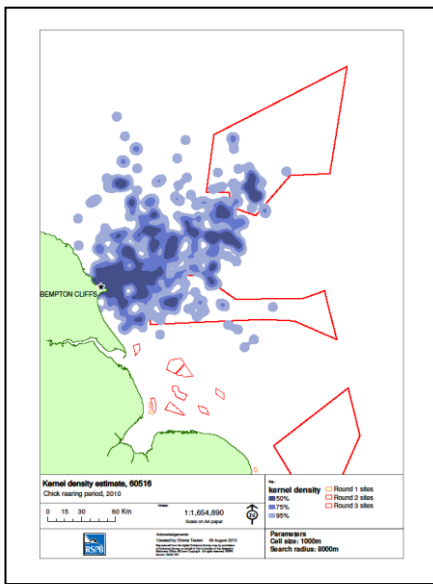
**Appendix III:** Kernel Density Estimation (kernel density tool, ArcGIS Desktop 10) for individual adult gannets from Bempton Cliffs during chick-rearing 2010-2012 (continuous & variable duty cycle tags)



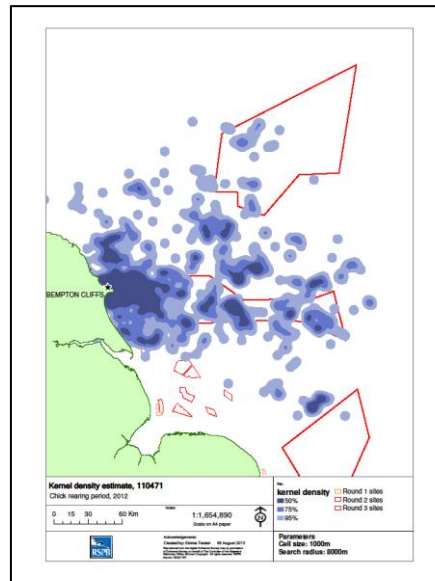
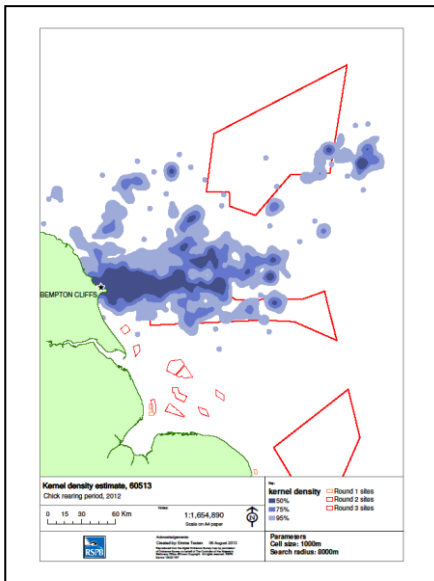
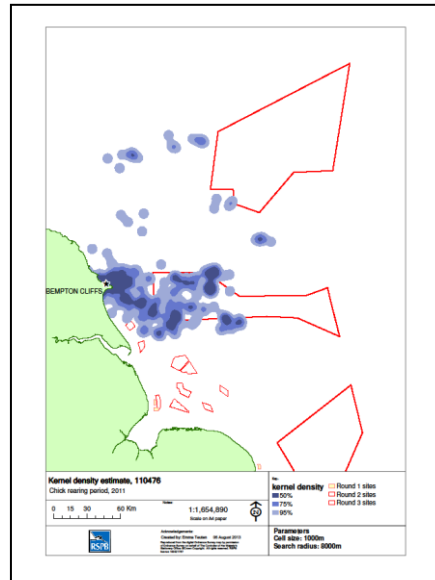
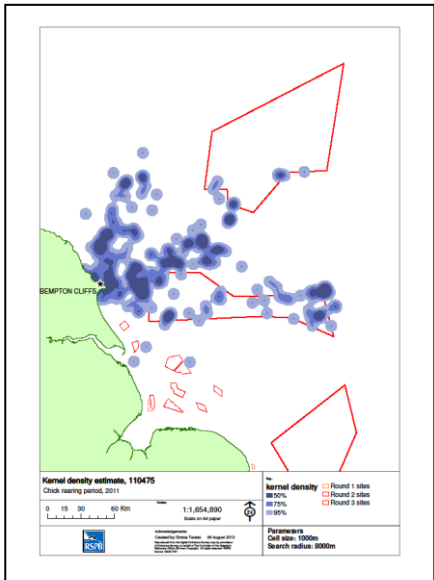
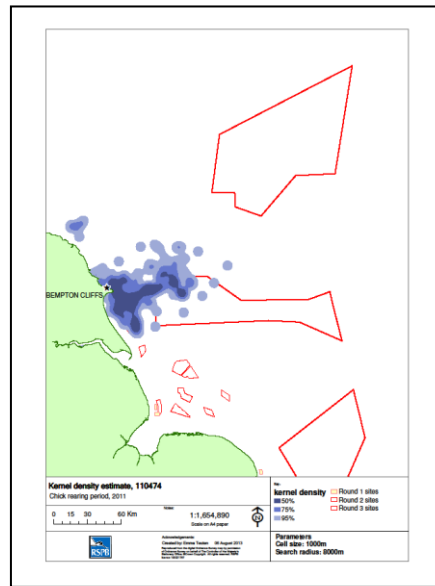
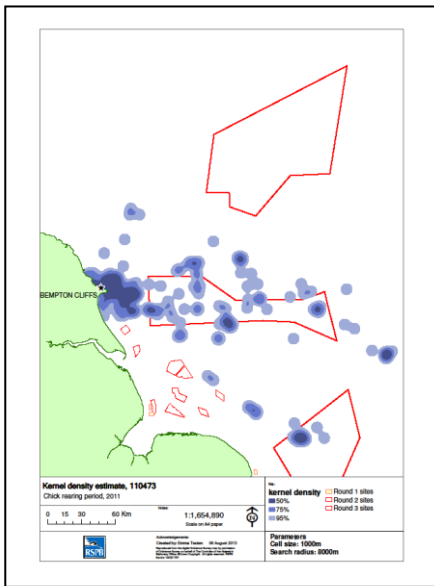
Appendix III continued



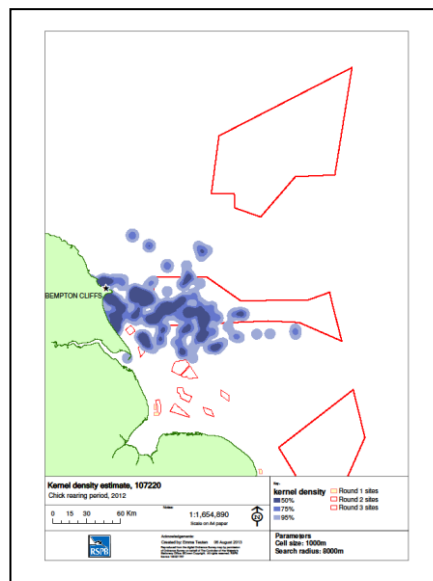
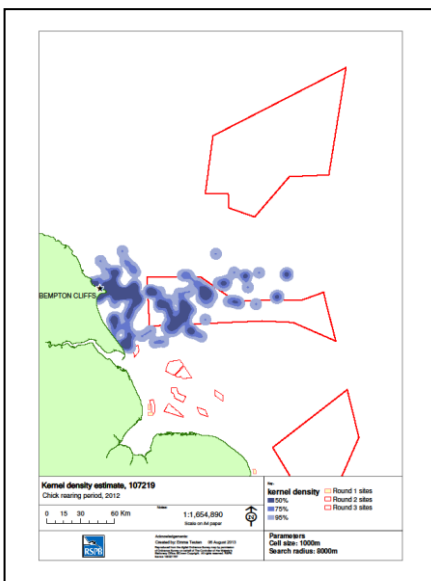
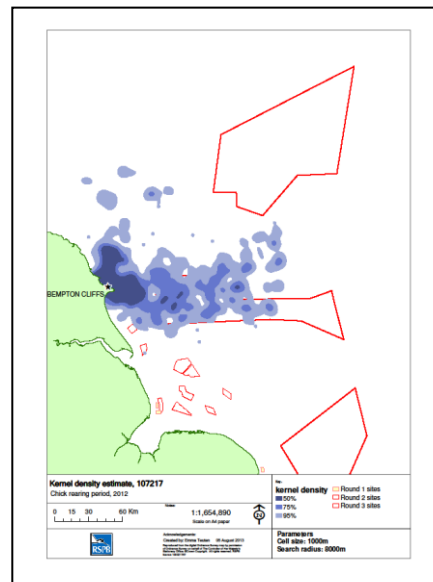
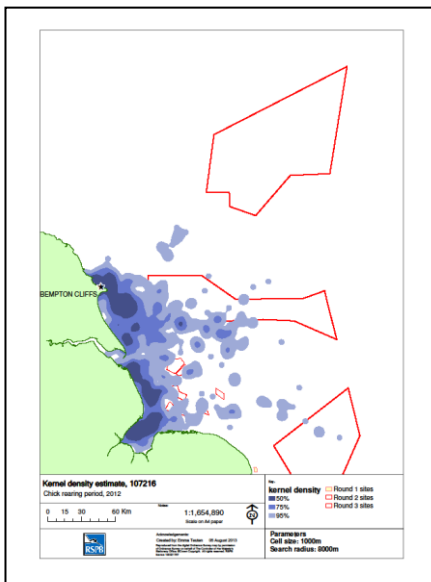
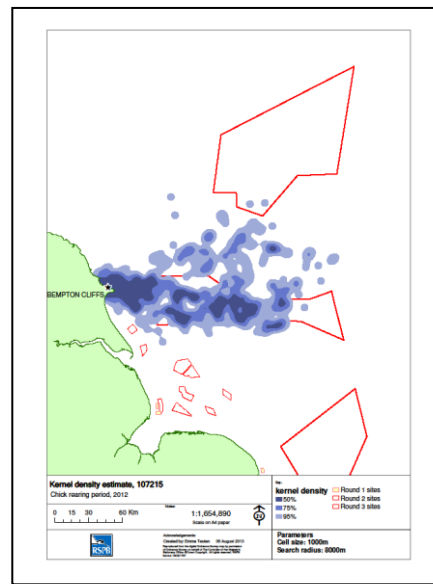
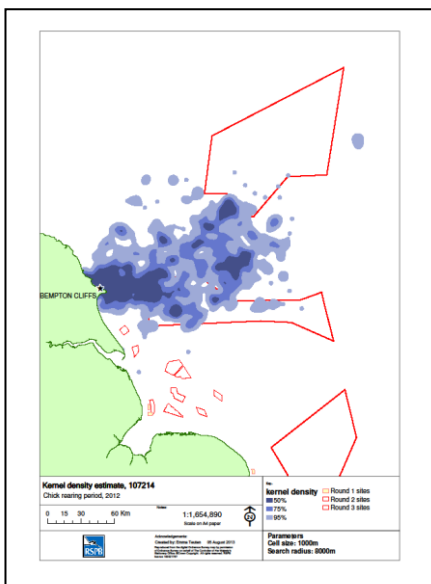
Appendix III continued



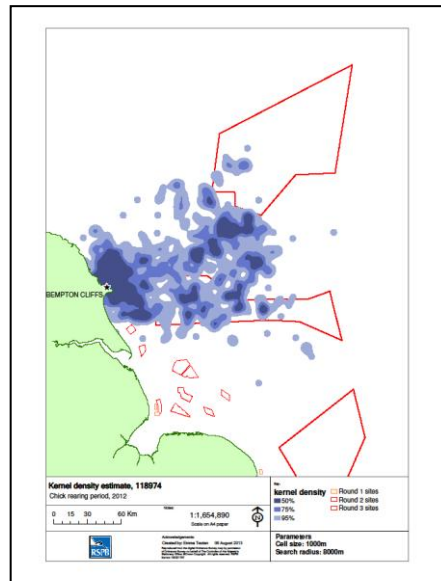
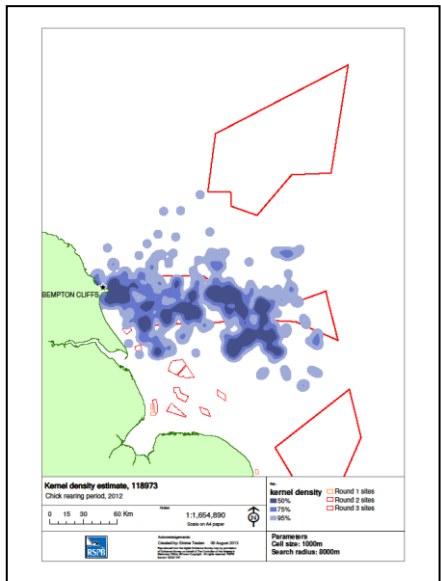
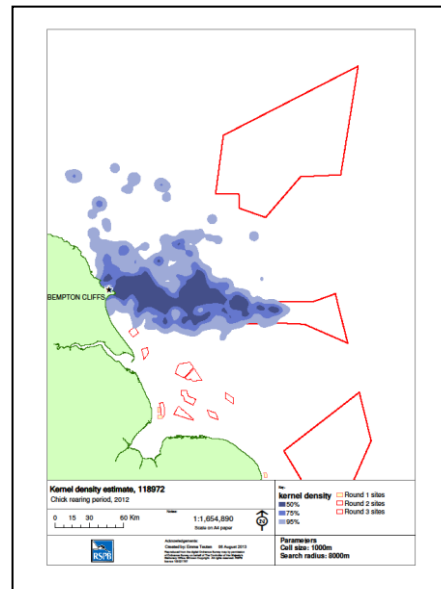
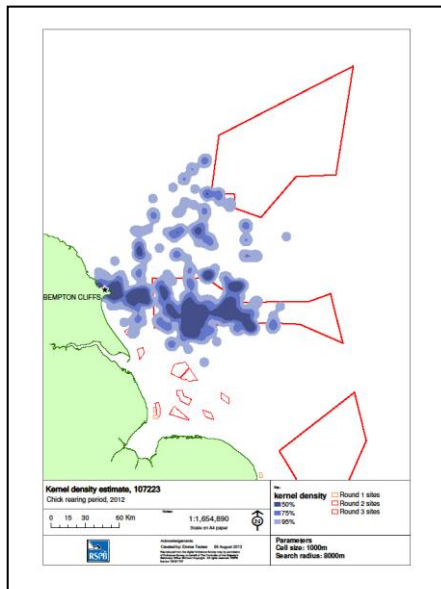
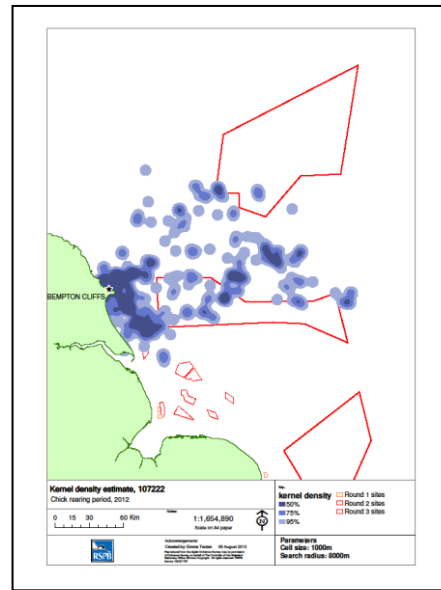
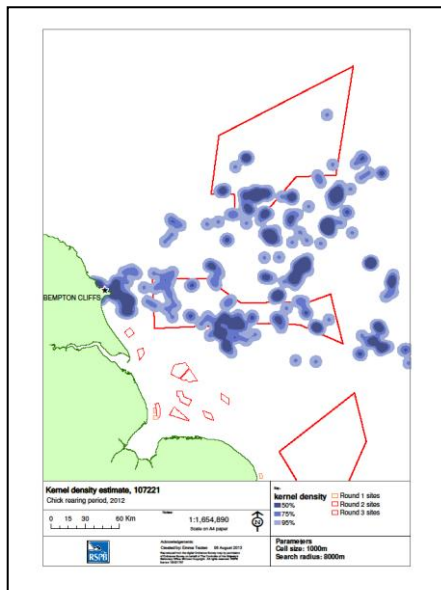
Appendix III continued



Appendix III continued



Appendix III continued

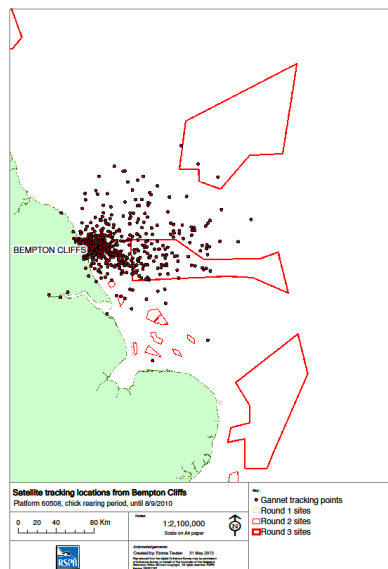
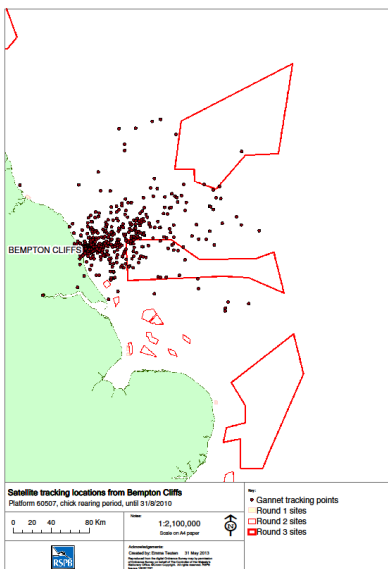
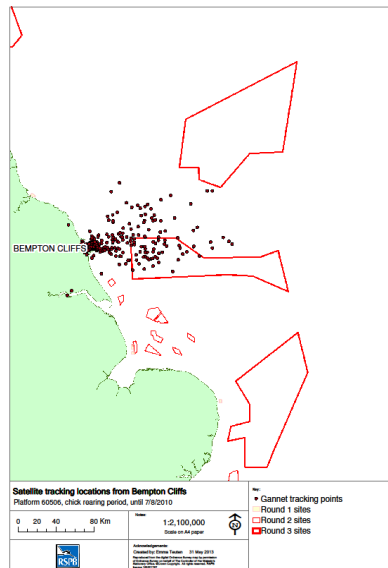
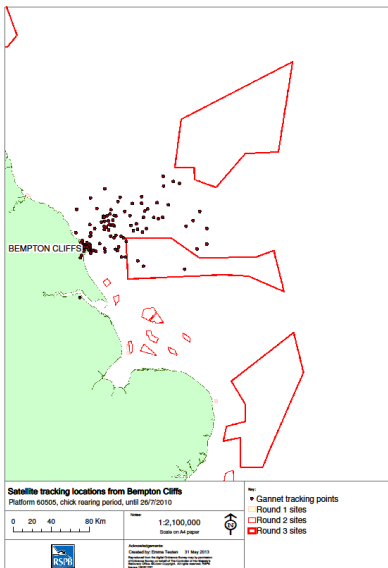
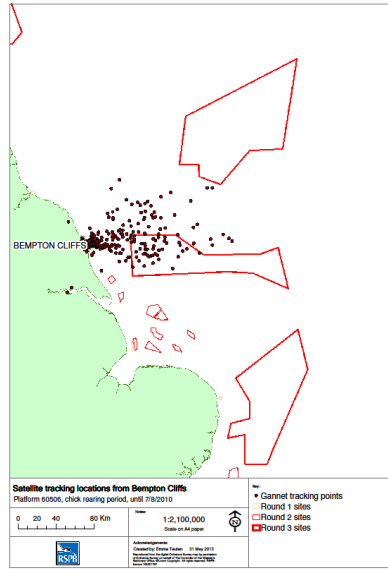
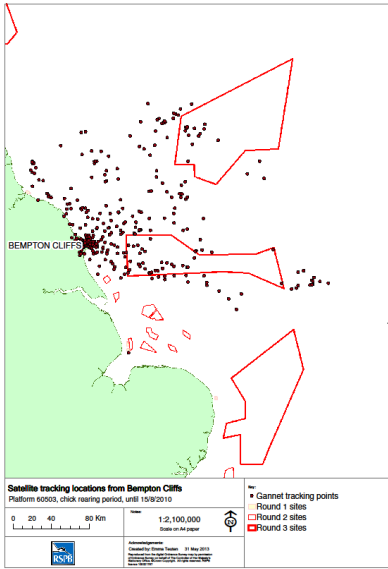


#### **Appendix IV: Tracking locations of individual adult gannets during chick-rearing 2010-2012**

This appendix presents one map for each PTT/ individual adult gannet illustrating recorded locations during chick-rearing, with the one exception of the tag referred to in the main text as yielding only eleven data points. Maps are presented in order of year, starting with 2010, then numerical order of the PTTs used in each year.

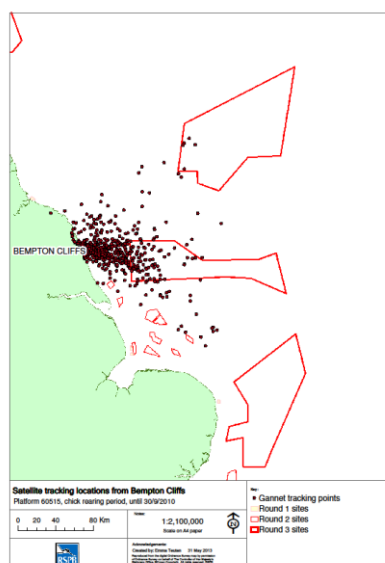
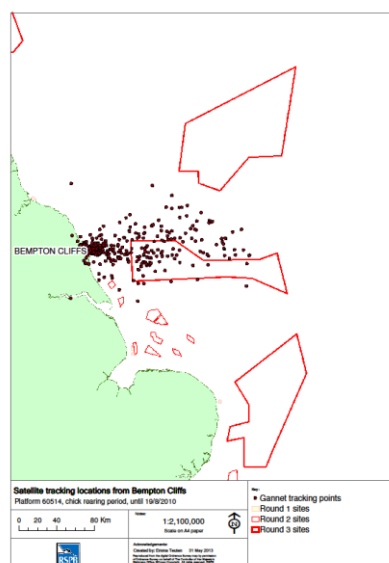
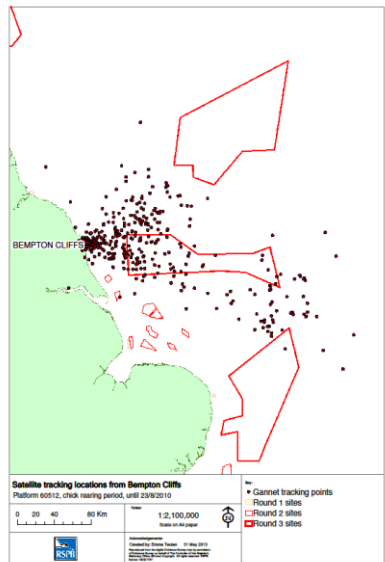
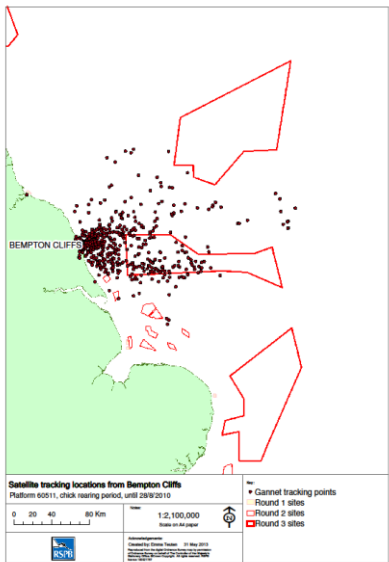
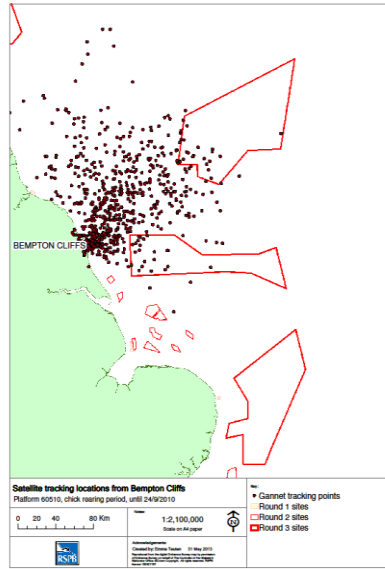
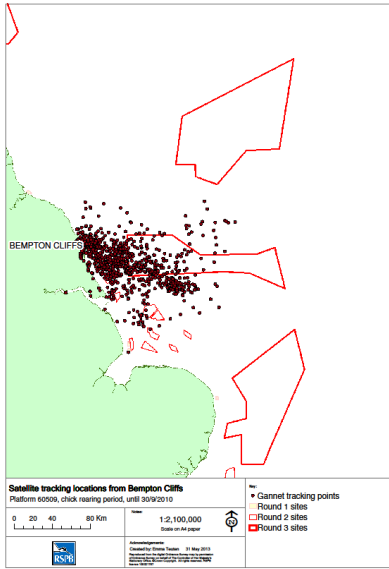
Details of PTT type and duty cycle are presented in Appendix I.

Appendix IV: continued

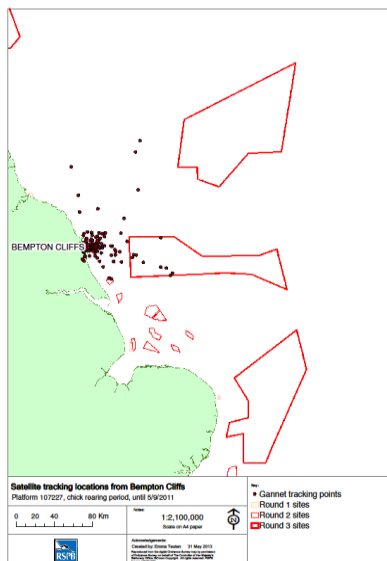
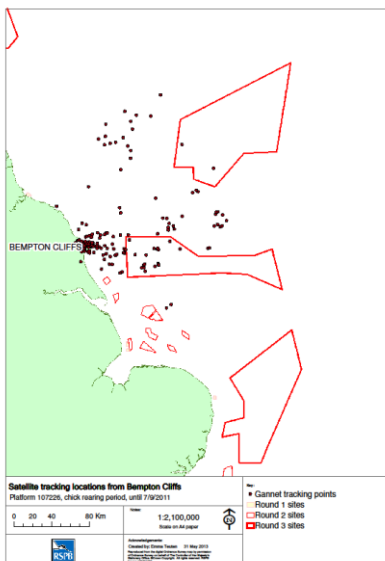
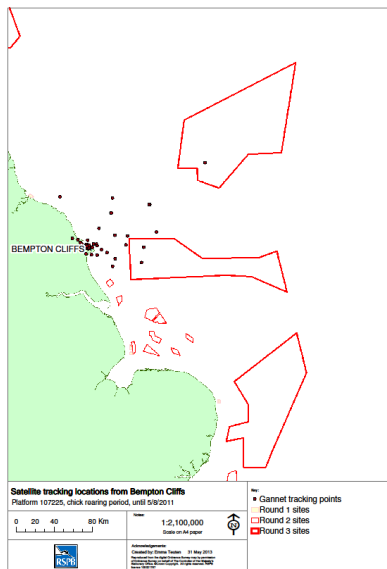
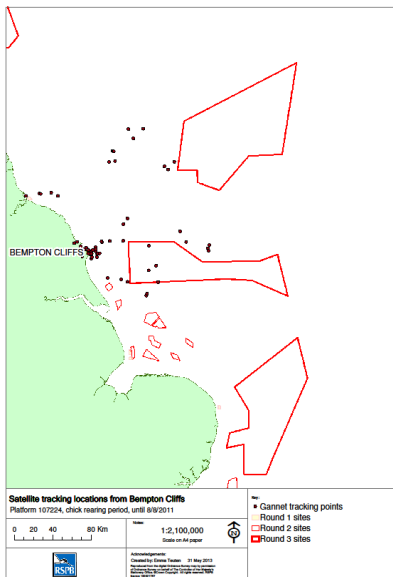
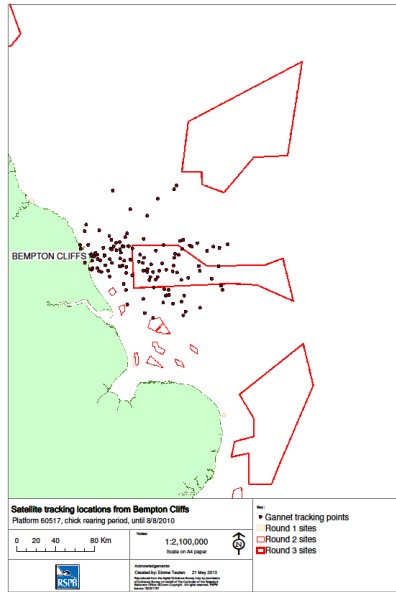
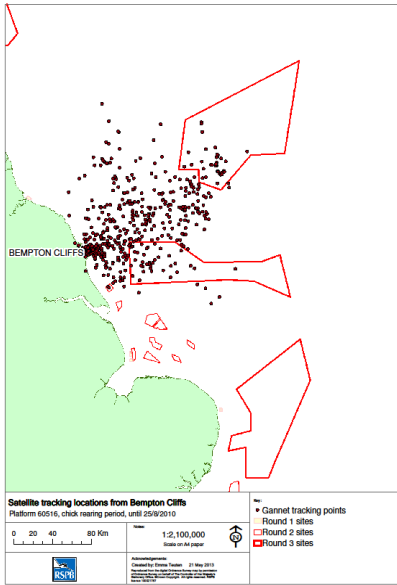




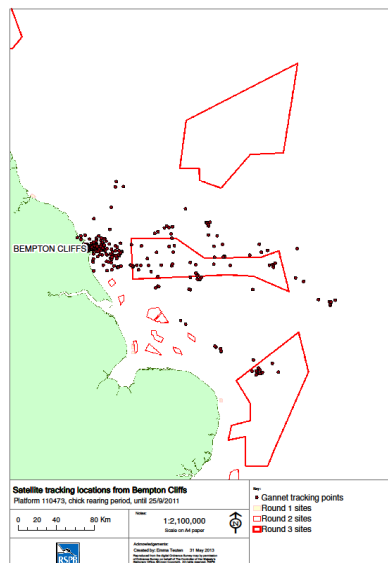
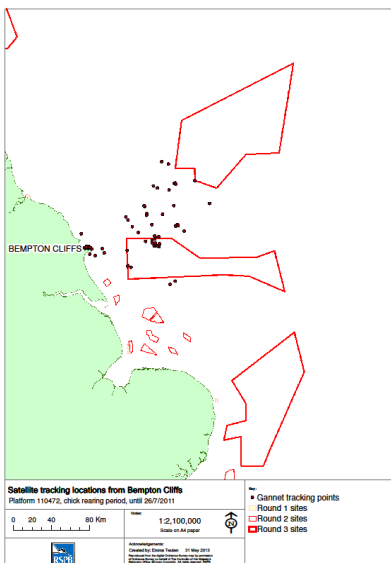
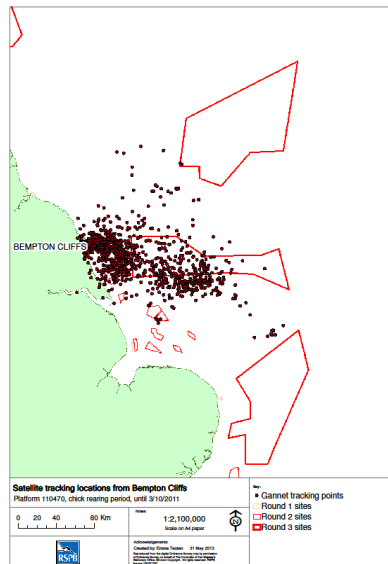
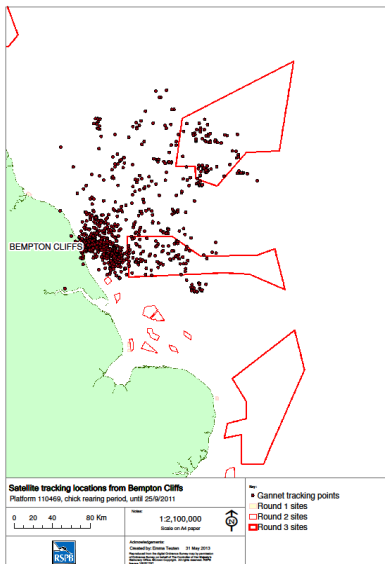
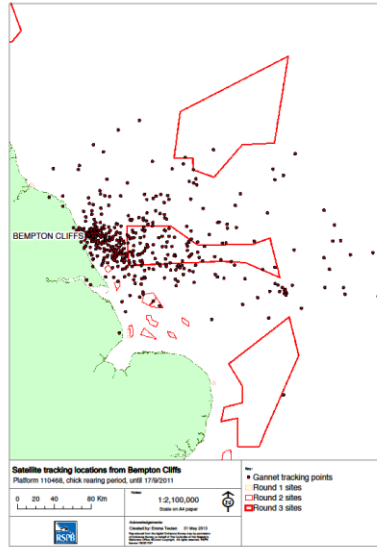
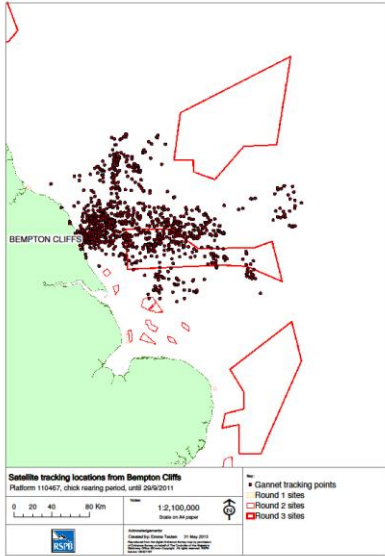
Appendix IV: continued



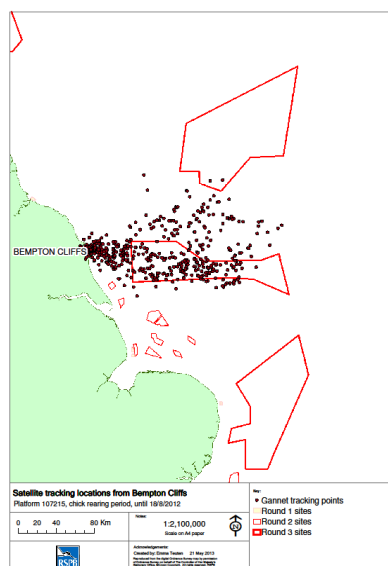
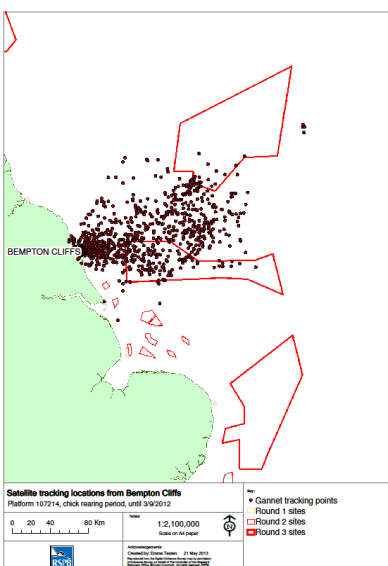
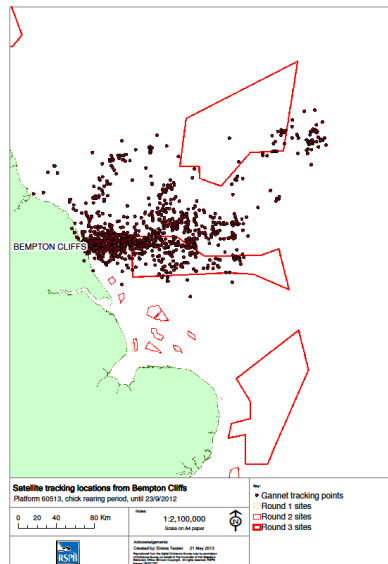
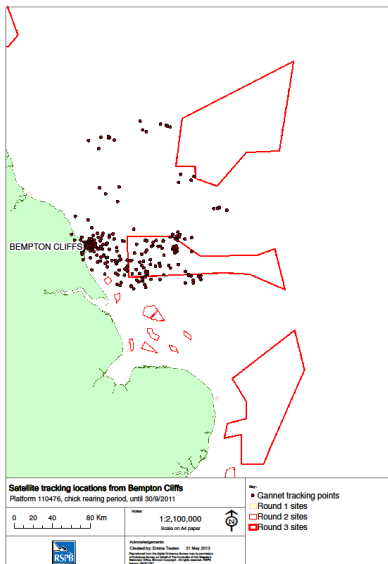
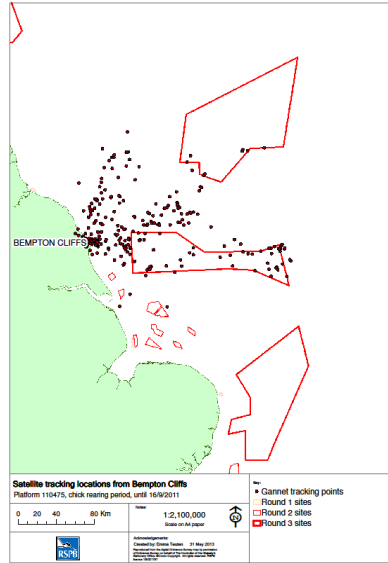
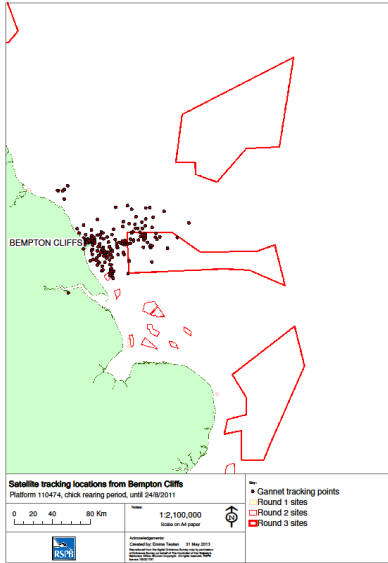
Appendix IV: continued



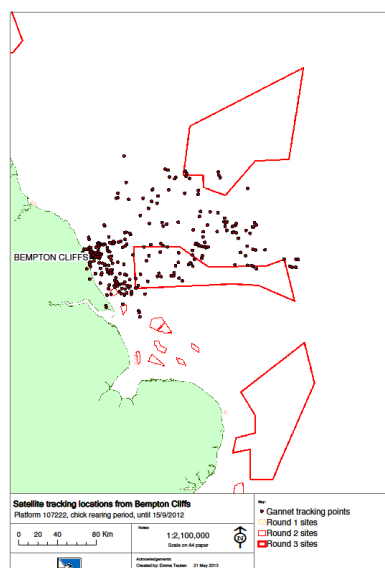
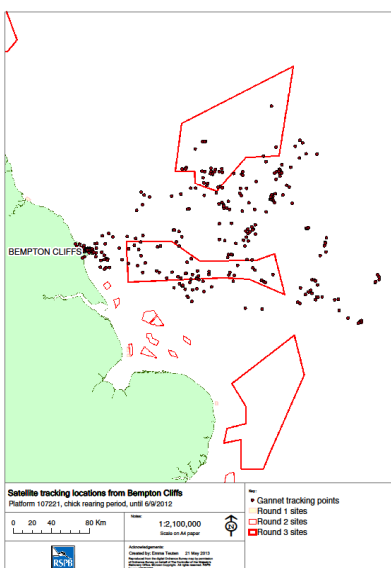
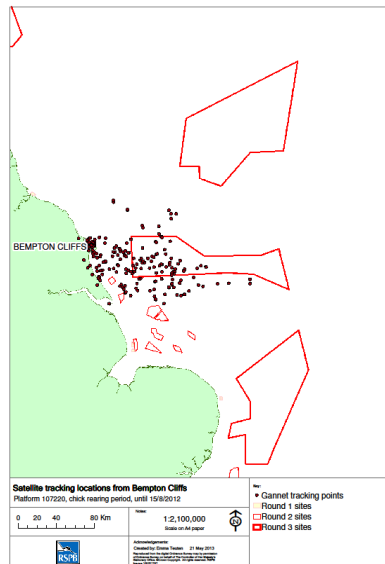
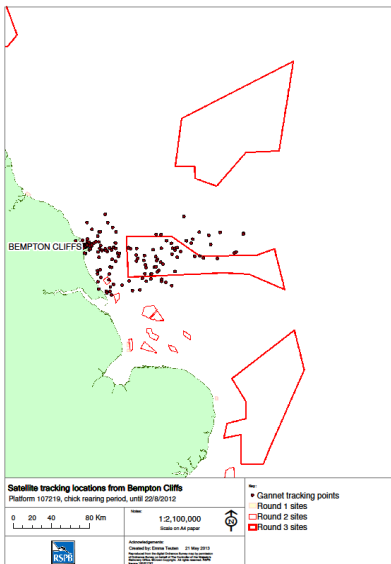
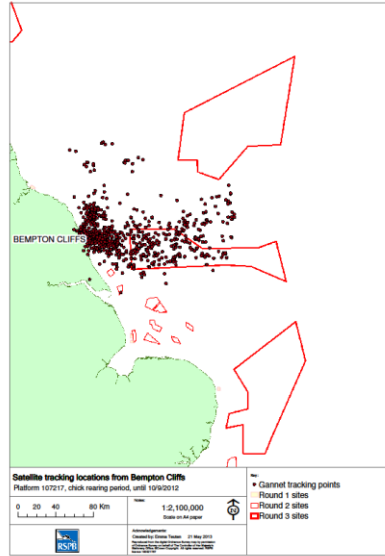
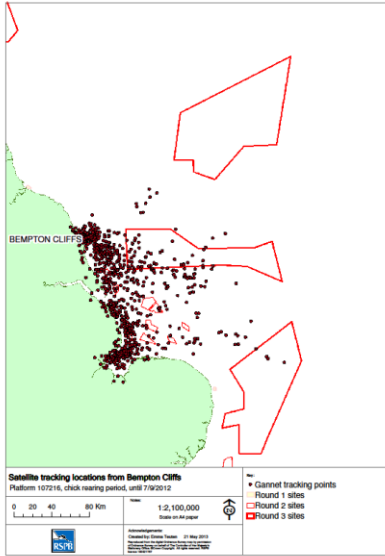
Appendix IV: continued



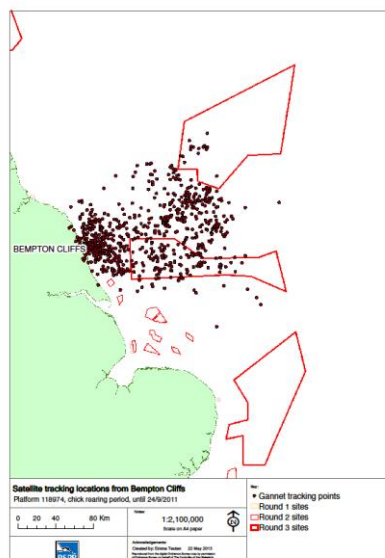
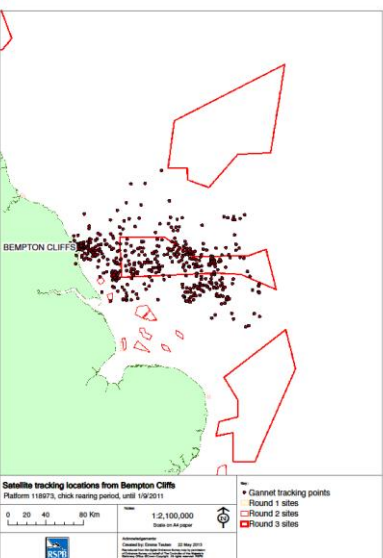
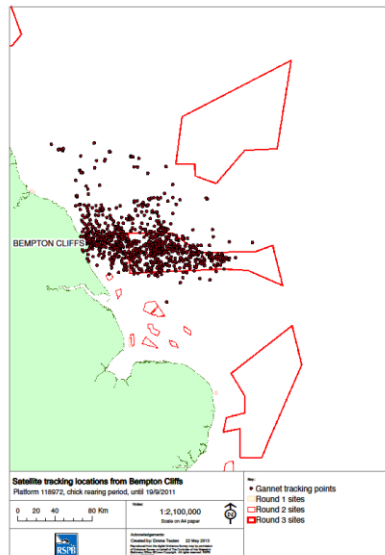
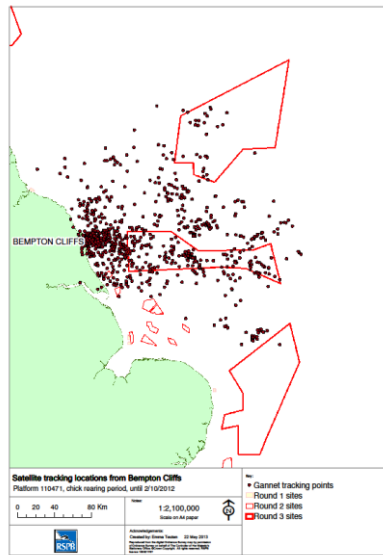
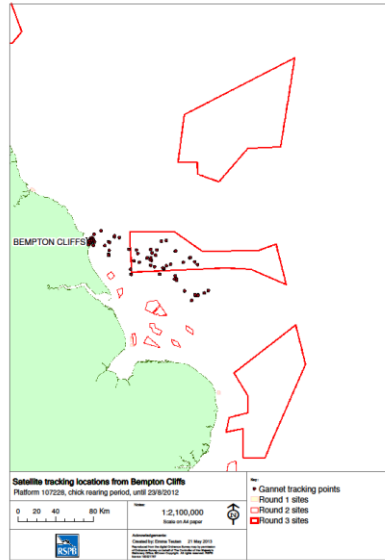
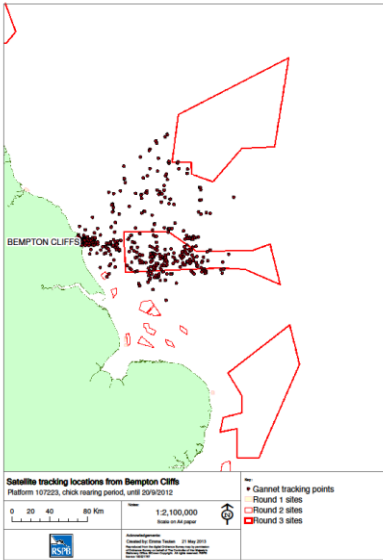
Appendix IV: continued



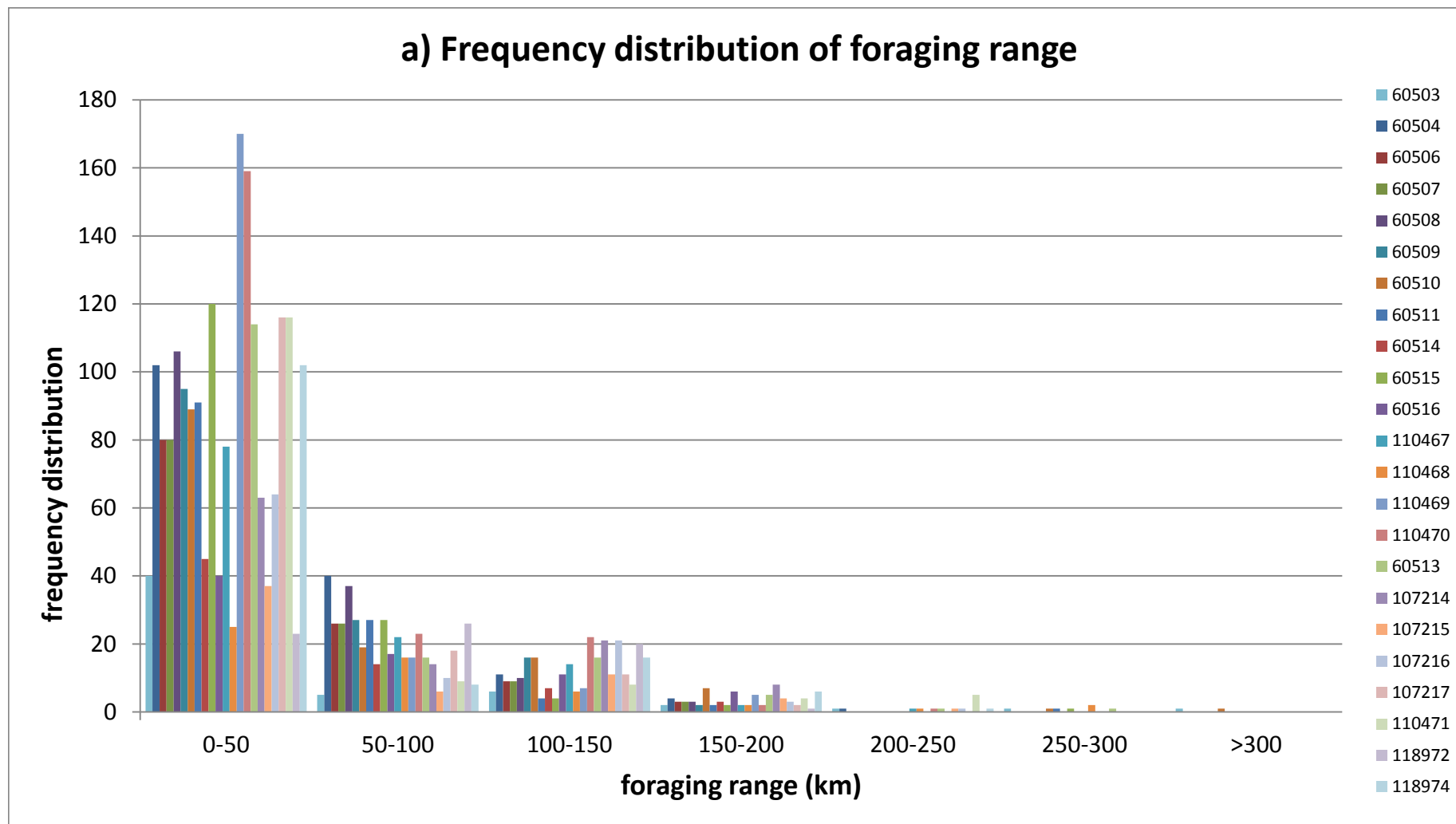
Appendix IV: continued



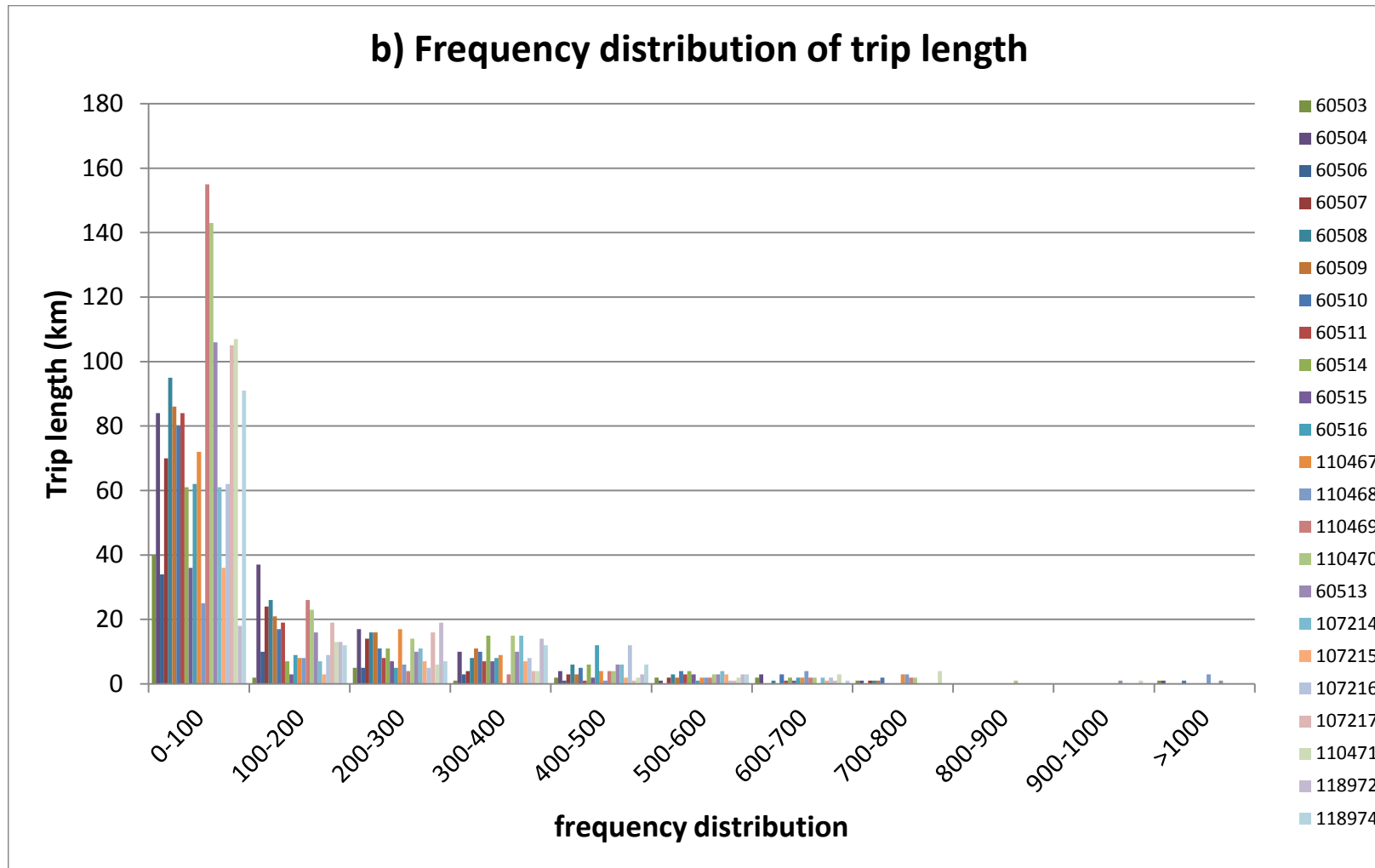
Appendix IV: continued



**Appendix V: Frequency distributions of trip parameters, a) range, b) length, and c) duration for individual adult gannets tracked from Bempton Cliffs during chick-rearing in 2010-2012 (continuous tags).**



Appendix V: continued





Appendix V: continued

