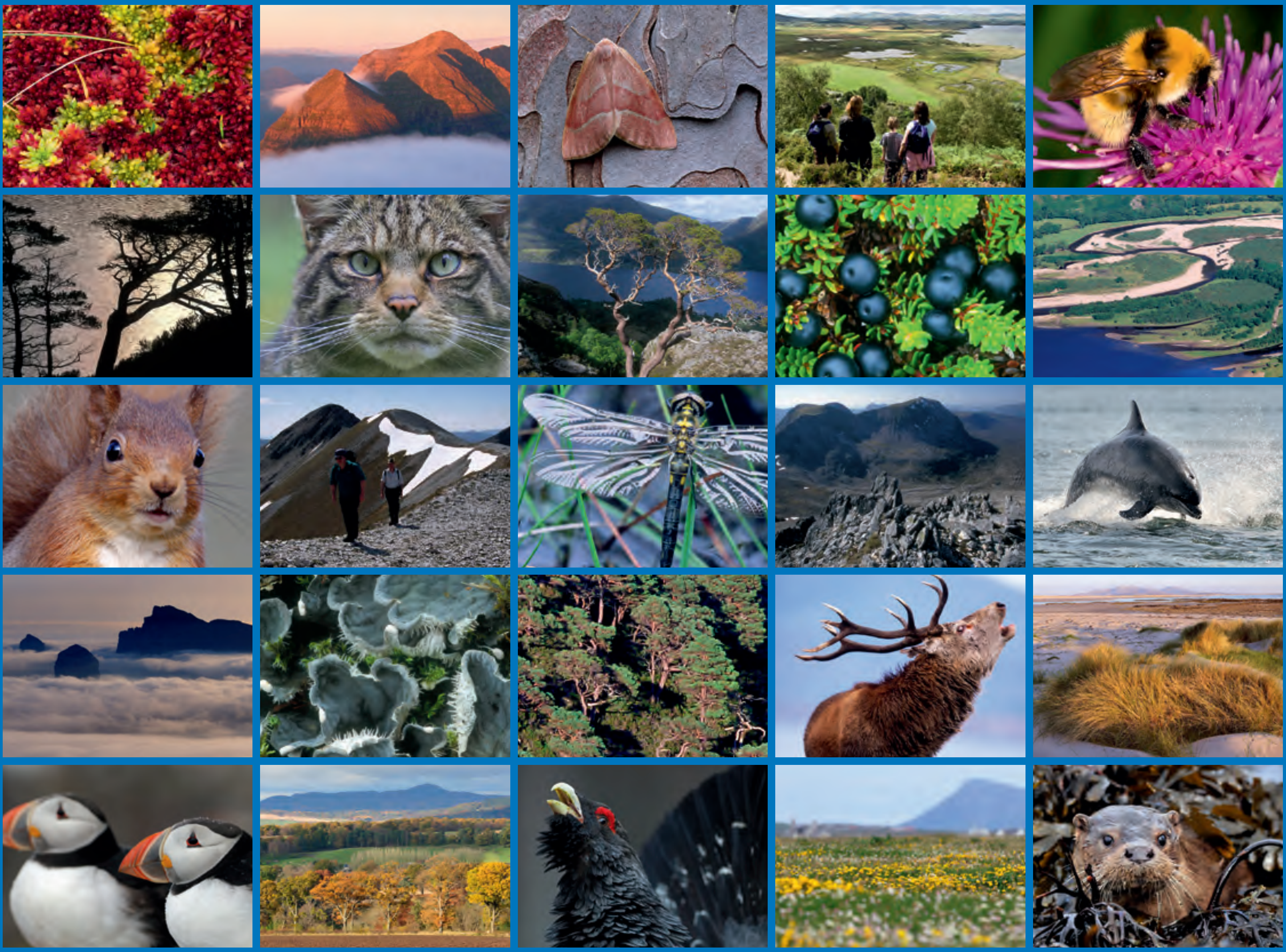
Scottish Natural Heritage
Commissioned Report No. 594

Statistical approaches to aid the identification of Marine Protected Areas for minke whale, Risso's dolphin, white-beaked dolphin and basking shark



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COMMISSIONED REPORT

Commissioned Report No. 594

Statistical approaches to aid the identification of Marine Protected Areas for minke whale, Risso's dolphin, white-beaked dolphin and basking shark

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COMMISSIONED REPORT

Summary

Statistical approaches to aid the identification of Marine Protected Areas for minke whale, Risso's dolphin, white-beaked dolphin and basking shark

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Summary

The 2010 Marine (Scotland) Act makes provision for Nature Conservation Marine Protected Areas (hereafter MPAs). In response to this Marine Scotland established the Scottish MPA Project to select MPAs and develop the Scottish MPA network. Of particular interest here are four megafaunal species that are being used to aid the identification of MPAs in Scottish territorial waters: Risso's dolphin (*Grampus griseus)*, white-beaked dolphin (*Lagenorhynchus albirostris)*, minke whale (*Balaenoptera acutorostrata)* and basking shark (*Cetorhinus maximus*). Areas that support significant aggregations of these species, or that are essential for key life cycle stages may be relevant to consider for designation. The aim of this project was to identify regions of persistent use by each of these species with a view to informing MPA designation.

Here we used a combined data set of marine megafaunal surveys to create a spatially indexed set of adjusted densities. Spatial models were fitted to these data sets for the four species above. These models were then used to make seasonal and annual predictions of relative density over the entire Scottish territorial waters which could inform MPA decision making.

Effort-linked sightings data contained within the Joint Cetacean Protocol (JCP) plus additional data sourced by Scottish Natural Heritage were used to generate estimated densities ($\hat{D}$) per area surveyed (corrected for detection/availability) for minke whale (2000 – 2012), Risso's dolphin (1994 – 2012) and white-beaked dolphin (1994 – 2012). A further relative density per area surveyed index was obtained for basking shark (2000 – 2012). There were up to 23 distinct data sources used for each analysis (25 used in total) with data from at least 172 distinct survey platforms (ships and aircraft) representing up to 180300 km of effort depending on the species considered.

The analyses for each species followed this procedure:

1. Estimates were derived of the probability of detecting a group of animals as a function of covariates affecting detectability measured on all surveys. This detection probability had up to three components: (a) probability of detecting a group given that it was available for detection on the surface and assuming all groups on the survey trackline were seen with certainty; (b) probability of detecting a group on the trackline given it was available for detection ("perception bias"); and (c) probability of a group being available for detection at the surface ("availability bias"). The first component was estimated using available line transect data, modelling detection probability as a function of available covariates such as group size and vessel type. The second component for some vessel types and species was estimated from a limited amount of double-observer line transect data, as well as previous published analyses. The third component was obtained from a limited amount of published data combined with expert opinion.
2. The survey data were divided into short (target approx. 10 km) segments of effort and the observed number of animals per segment was converted into an estimated abundance of animals per segment using the estimated detection probabilities and probability of being at the surface (for the cetacean species only).
3. The following predictor variables were allocated to effort segments for density surface modelling: Depth, Day of Year, Sediment Type, Sea Surface Temperature, a Front Index, a Tidal Energy Index, Chlorophyll concentration and, optionally, position as a 2D smooth.
4. Spatial generalized estimating equations (GEE) models were fitted to the data using methods that allow for modelling around complex topography as well as locally adaptive smoothed responses to predictors. Predictions of relative density were made for all Scottish territorial waters.
5. Uncertainty in the surfaces was generated by means of a bootstrap. Total uncertainty was considered with and without the uncertainty associated with model selection.
6. Persistent areas of relative high density (defined as cells of relative density greater than the mean relative density for that point in time) were identified by considering the summer prediction surface for each year of the data.
7. Uncertainty in the persistence surface was incorporated by means of the bootstrap, resulting in a persistence-certainty score for each 5 km by 5 km cell around the Scottish coast.

Identified areas of interest for minke whale included the areas south and west of the Hebrides, the sea of the Hebrides and the Moray Firth. The single identified contiguous higher than average density area for Risso's dolphin was the region to the north of Lewis/Harris. White-beaked dolphins were widely dispersed in slightly offshore waters. Identified areas for basking shark included the waters of the eastern Sea of the Hebrides and to the west of the Hebrides.

The project also identified several data poor regions notably west of the Hebrides, around the Isle of Arran, the coast of Sutherland and Caithness, Orkney and Shetland.

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1. INTRODUCTION

The 2010 Marine (Scotland) Act makes provision for Nature Conservation Marine Protected Areas (hereafter MPAs). In response to this Marine Scotland established the Scottish MPA Project to select MPAs and develop the Scottish MPA network. The MPA Selection Guidelines (Marine Scotland, 2011) set out the process for identifying MPAs in Scottish waters and include a list of MPA search features (species and habitats of conservation importance for which spatial protection is considered appropriate) that are being used to help drive the selection of MPAs. Three species of cetaceans (minke whale *Balaenoptera acutorostrata*, Risso's dolphin *Grampus griseus*, and white-beaked dolphin *Lagenorhynchus albirostris*) and basking shark *Cetorhinus maximus* are included on the list of MPA search features (Marine Scotland, 2011). The MPA Selection Guidelines suggest that areas which support significant aggregations, or key life cycle stages, of these species may be relevant to consider as MPAs.

Evaluation of cetacean and elasmobranch distribution and habitat assessment of these species has been suggested in the designation of MPAs both in Scotland (e.g. Bailey & Thompson, 2009; Embling *et al.,* 2010) and elsewhere (e.g. Cañadas *et al.,* 2005). Considerable research has been undertaken to identify the habitat preferences of large marine megafauna in Scottish local waters (e.g. Hastie *et al.,* 2003; Canning *et al.,* 2008; Bailey and Thompson, 2009; Marubini *et al.,* 2009; Anderwald *et al.,* 2012) and elsewhere (e.g. Pierce *et al.,* 2010; Azzellino *et al.,* 2012; Becker *et al.,* 2012; Thorne *et al.,* 2012) from visual surveys and other methods. Surveys can lead to estimates of distribution and abundance of large marine megafauna. The exact nature of these estimates depends on the data collected and the analysis methods undertaken. Modelling of abundance by habitat characteristics and density allows predictions to be made into regions of low effort and even into the future (Becker *et al.,* 2012). As a large amount of megafaunal survey effort in Scottish waters has been undertaken, it seemed reasonable to attempt to combine this effort to help identify areas that may be of interest as MPAs for each of the above four species. Thus the aims of this project were to predict the relative densities of the above species, to identify regions of persistent (relative) high densities of each species and if possible to explain the distributions in relation to relevant environmental variables.

To achieve these aims, survey data (1994 – 2012) from a variety of sources were combined into a single, spatially indexed density data set that was then modelled with the intention of predicting density surfaces so areas of persistent higher relative density could be identified to support SNH's advice on MPAs associated with the four species previously mentioned.

If our assumptions are correct, our values represent absolute estimates of density. However, as the emphasis here is not on density estimation *per se* but rather the identification of regions of greater than average abundance, we refer to our estimates throughout as relative densities.

2. METHODS

2.1 Overview of Methods

Here we present a summary of the statistical methods and the general approach used to produce the relative density surfaces, prior to a more detailed description in the later sections. Figure 1 provides a schematic overview of the stages of analysis for a single species. The data under consideration (see below) consisted of spatially and temporally referenced sightings of cetaceans or basking shark, coming from a variety of different survey data sources (Appendix 1). For some of the data sources, each sighting was associated with estimated observed perpendicular distances of the observer to the group of animals seen, allowing estimation of the detection probability. We modelled effort associated sighting data using the number of animals detected in segments of survey effort ("the count method"; see Hedley, 2000; Hedley & Buckland, 2004; Hedley *et al.,* 2004).

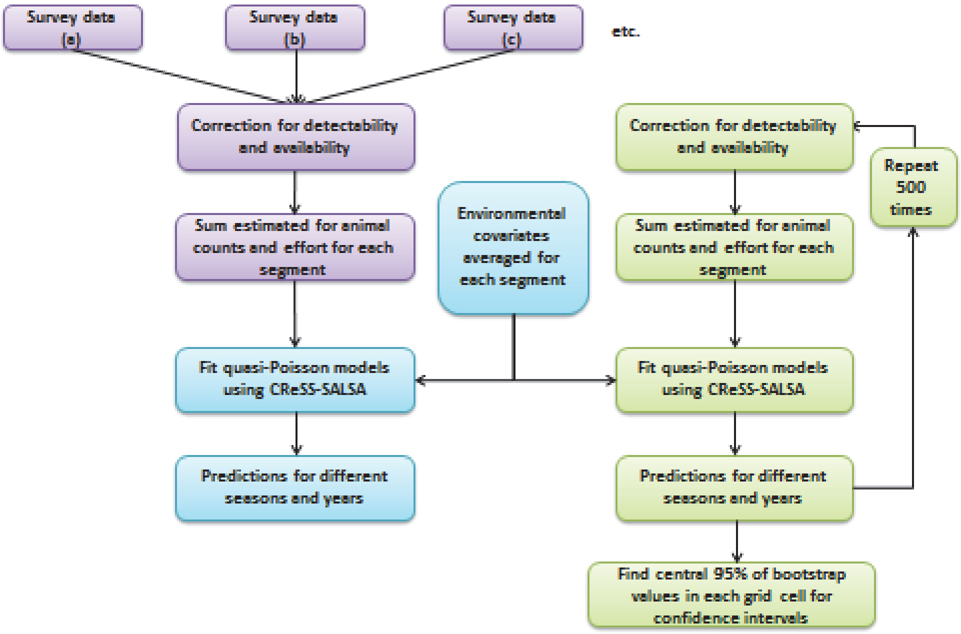

Figure 1. Overview of the methodological procedure used in this study. Purple bubbles indicate the detection probability estimation stage, the blue bubbles are the spatial modelling stage and the green bubbles the uncertainty estimation.

The first stage of the analysis (purple bubbles in Figure 1) consisted of correcting the observed numbers seen both for imperfect detection (not all animals at the surface are seen) and availability at the surface. The second stage of the analysis involved modelling the resultant estimated numbers as a function of space, time and other explanatory variables (blue bubbles in Figure 1). Associated with both of the processes was the estimation of the relevant uncertainty (green bubbles in Figure 1).

The data did not have to come from dedicated line transect surveys, although there had to be systematic observation associated with defined effort, i.e. both location and whether observers were truly observing should be known, as opposed to casual ad-hoc observations when the observers' primary task is something else. It is well established in the psychological literature that objects can easily be missed under such circumstances (e.g. Simons & Chabris, 1999). As detection by observers is imperfect, correction should be made where possible for missed animals. This can be done in part using distance sampling methods (see Buckland *et al.,* 2001, 2004) that can infer detectability by considering the distribution of distances to observed animals. Data without distances can be incorporated into the analysis by assuming that detection probabilities obtained from the distance analysis also apply to the sightings without distances. This is further justification for requiring dedicated survey effort from the surveys that do not include distances.

Detectability was initially estimated assuming detection on the trackline was perfect. If the probability of detection on the trackline, $g(0)$ is actually less than 1 and this can be estimated, or if $g(0)$ actually is 1, then an absolute index of the abundance of animals at the surface can be made (i.e. the actual numbers present at that moment). In this specific context, we considered $g(0)$ as a correction for perception bias only, i.e. it is the probability of detecting an animal on the trackline given it is at the surface, not considering, at this stage, animals that are submerged. For some of the species and surveys considered here, $g(0)$ could be estimated and then applied to the subset of data where $g(0)$ was unknown and assumed not to be one, so abundance of surface animals could indeed be estimated.

Large marine animals are not always available to be detected. Cetaceans unlike basking shark need to come to the surface. Therefore if information about diving times is obtainable, a correction for availability can be made. Here, availability was calculated as a function of surfacing rates of the animals and the transit time of the viewing platform. We caution, however, that knowledge of diving behaviour is very sparse. For larger slow moving vessels, availability was assumed to be one.

For a given survey, effort was divided into segments and the numbers observed, corrected in the case of some species for detectability and availability, were summed for each segment. Data for different surveys were combined at this stage. This created a spatially referenced density or estimated abundance index (in this case the latter) that could then be modelled in the next stage of the analysis. Our primary objective in making the detectability and availability corrections was to put the count data from different data sources onto the same scale so that they could be combined. The best way to do this is to correct as far as possible to absolute density or abundance. However, this required us to assume that animals counted on surveys without distances have the same detectability as those on dedicated line transect surveys; it also required us to make strong assumptions about availability.

The methods used for modelling abundance (Complex Region Spatial Smoother, CReSS, Scott-Hayward *et al.* (2013a) and Spatially Adaptive Local Smoothing Algorithm, SALSA, Walker *et al.* (2011)) accounted for the spatially complex patterns in animal distribution, hugely variable animal counts across the survey area and spatio-temporal autocorrelation. The resultant models were used to interpolate to regions and times without survey data, creating estimated relative density surfaces over a grid of temporally geo-referenced points.

Uncertainty in the modelling process was incorporated using parametric bootstrap techniques (Davison & Hinkley, 1997). Values were simulated from the fitted parameters of the detection functions to create a new simulated density data set, which was then spatially modelled as described above. Values were then simulated from the fitted parameters of the density surface models leading to replicated model prediction surfaces with which percentile confidence intervals could be constructed. There was an additional nonparametric component in that inclusion of sightings without distances was decided by sampling. This two stage process resulted in 500 relative density estimates for each grid cell (given a set of covariates and point in time) and the central 95% of these values were used to define the upper and lower 95% confidence limits in each case (i.e. by identifying the 2.5 and 97.5 percentiles).

2.2 Overview of the Data

2.2.1 Spatial and Temporal Range of the Dependent Data

The region of interest, shown by the coloured area in Figure 2 is the Scottish 12nm limit which extends from the North Sea to the northern boundary of the Irish Sea.

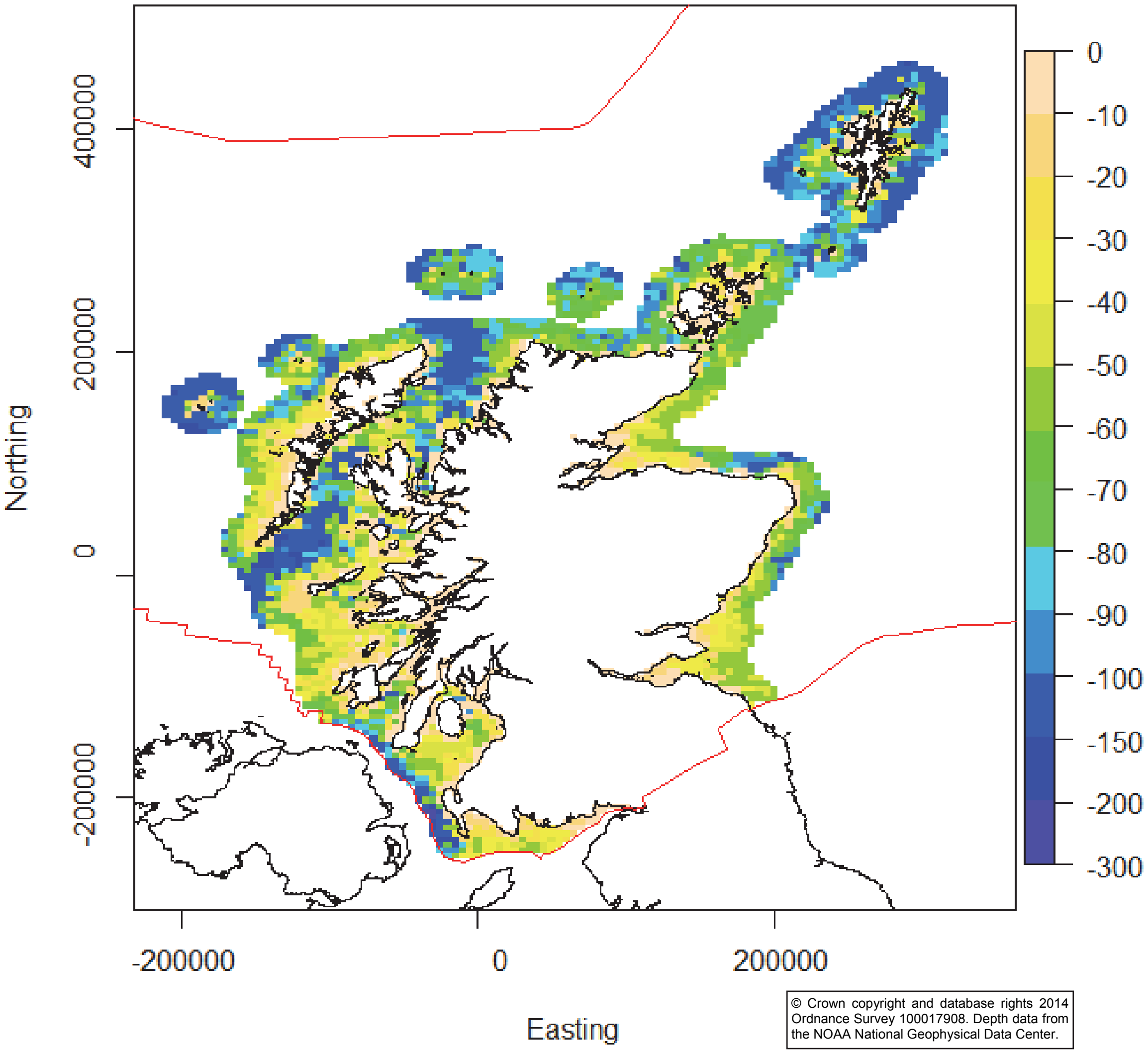

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Figure 2. The area of interest (prediction region). The coloured area (with depth shaded in m) indicates the 12nm Scottish territorial limit and the prediction region for this analysis. The area outlined in red is Scottish waters.

The survey data of interest from the Joint Cetacean Protocol (JCP) and from the additional data sets were from ships and aircraft. All ship and aircraft sightings required effort (i.e. times and locations of observing) to make them usable in the analysis and observers had to have observation as their primary task when on effort. There were 25 distinct datasets available that met these criteria but not all were used in each analysis. These data sets contained data from *at least* 172 vessels (not all vessels are identified by name). Duplicate data were identified and deleted. The individual data sets are described and summarised in Appendix 1. The sightings data could be classified to one of four classes:

a) sightings from a line transect survey, with distances from two observers ("double platform configuration") allowing estimation of *g*(0), the probability of detection on the trackline, for an available pod;

b) sightings with distances from a single observation platform;

c) sightings from count only data collections with no distances;

d) data from aerial imaging surveys where numbers at the surface are, in theory, known without error.

Effort data were checked for anomalous positions and speeds. Data with noticeably erroneous positions that could not be easily corrected (i.e. by reference to adjacent effort) were removed.

To be included in the analysis, segments of effort had to be within the geographic region of interest and within the time period of interest (initially 1994 – 2012). In addition the segments could not be associated with an anomalous speed greater than those actually possible by the participating vessel (based on consultation with the data suppliers and also less than 75 km/h in the case of aeroplanes) and not be based on stationary observations on land or sea. Anomalous speed must be caused by erroneously recorded position or time data. Effort operating at speeds less than 5 km/h for shipboard surveys was also removed as the observation platform should exceed the speed of the observed animals (Hiby, 1986; Buckland *et al.,* 2001, p.200).

The effort and sightings data varied depending on the species under consideration. In the case of minke whale the data consisted of the Scottish 12 nm limit plus a buffer of approximately 10 nm (Figure 3 blue). In the case of Risso's dolphin and basking shark, the effort data came from 12 nm limit plus the 10 nm buffer (as before) plus a southern extension to include the Isle of Man (Figure 3 green). In the case of white-beaked dolphin the data under consideration came from Scottish shelf waters out to 300m depth (Figure 3 red).

Chlorophyll concentration was a potential predictor variable for the modelling of basking sharks and minke whales but this was only available from autumn 2000. Therefore basking shark and minke whale data were only used from this period. Predictions for these species were only made from 2001 onwards. This had an added advantage in that proportion of segments with sightings increases after 2000.

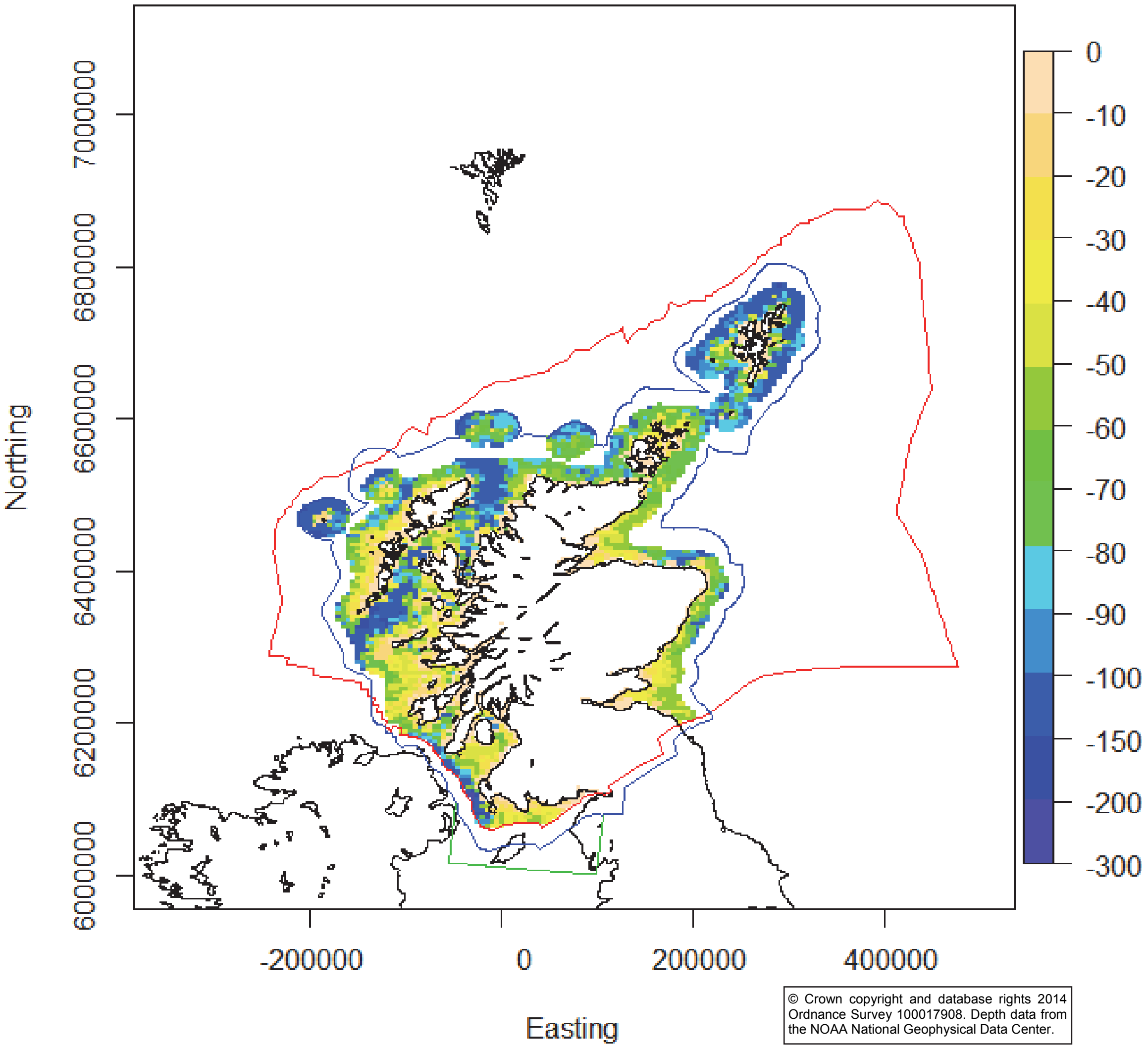

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Figure 3. The area of interest (prediction region) for the analysis and species-specific data input areas. The coloured area (with depth shaded in m) indicates the 12 nm Scottish territorial limit and the final prediction region for this analysis. The red line shows Scottish shelf waters (Scottish waters limited in the west and north by the 300 m contour). This is the input area for white-beaked dolphin data. The area in blue is the 12 nm limit with an additional approximate 10 nm buffer. This is the input area for minke whale. The area in green is an extension of the blue area to include additional data for Risso's dolphin and basking shark from Manx waters.

2.2.2 Predictor Variables

At the spatial modelling stage of the project, animal densities were modelled considering environmental and biological inputs of potential relevance. Only predictors that could be assigned to all the relevant effort and sightings data could be used.

Covariates considered, dependent on species, in the models were *Dayofyear* of survey, *Year* of survey, *Depth*, sediment type (*Sediment*), sandeels index (see below), fronts (*Front*), chlorophyll a (*Chloro*), tidal energy (*TidalEng*) and sea surface temperature (*SST*).

Depth (see Figure 4) for each segment was obtained either from depth data collected on survey itself or from the ETOPO2, 2 minute resolution relief data available from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center[1] (Sandwell & Smith, undated). In the latter case, *Depths* were selected for each segment based on the nearest great circle distance from the segment to a datum in either one of the two depth sources.

SST (a dynamic variable) was obtained from the NOAA Physical Sciences Division High Resolution optimum interpolation (OI) sea surface temperature (SST) analysis[2] of Reynolds & Smith (1995, also Reynolds *et al.,* 2002) available at 0.25 degree and daily resolution since 1981. Figure 5 gives example temperatures for winter and high summer respectively.

Sediment data were obtained from the Joint Nature Conservation Committee (JNCC) led project UK SeaMap 2010[3] (McBreen *et al.,* 2011). Five broad sediment classes were considered (Figure 6).

The sandeel presence index (Figure 7) was obtained from Peter Wright (Marine Scotland, Wright *et al.,* 2000) and consisted of sampled points where sandeels were either present or not present. This was considered to be static. A similar data source, sandeel predicted habitat (Figure 8), from the model of Wright *et al.* (2000) gave a predicted habitat score (0 or 1) at a denser resolution, albeit with a smaller spatial range. Ultimately after review, because of the spatial sparsity of the available indices, sandeel statistics were not considered.

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[1] ETOPO2v2 2006 provided by National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Geophysical Data Center, online at http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html

[2] NOAA_OI_SST_V2 data provided by the National Oceanic and Atmospheric Administration, Earth Systems Research Laboratory, Physical Sciences Division, online at http://www.esrl.noaa.gov/psd/

[3] Sediment data obtained from UK SeaMap webGIS data, available online at http://jncc.defra.gov.uk/ukseamap

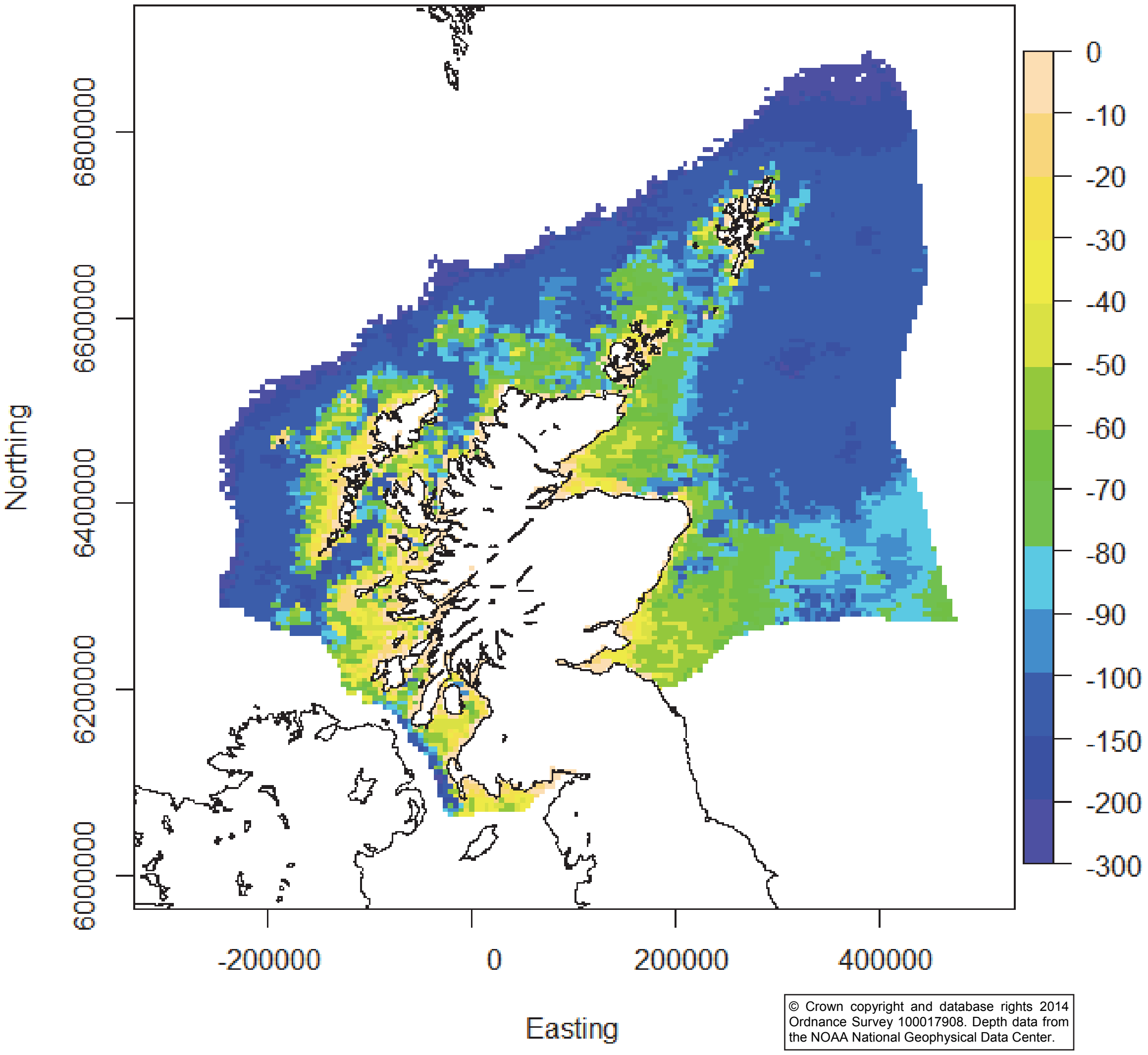

Figure 4. Scottish waters out to 300 m depth, with depths (m) illustrated.

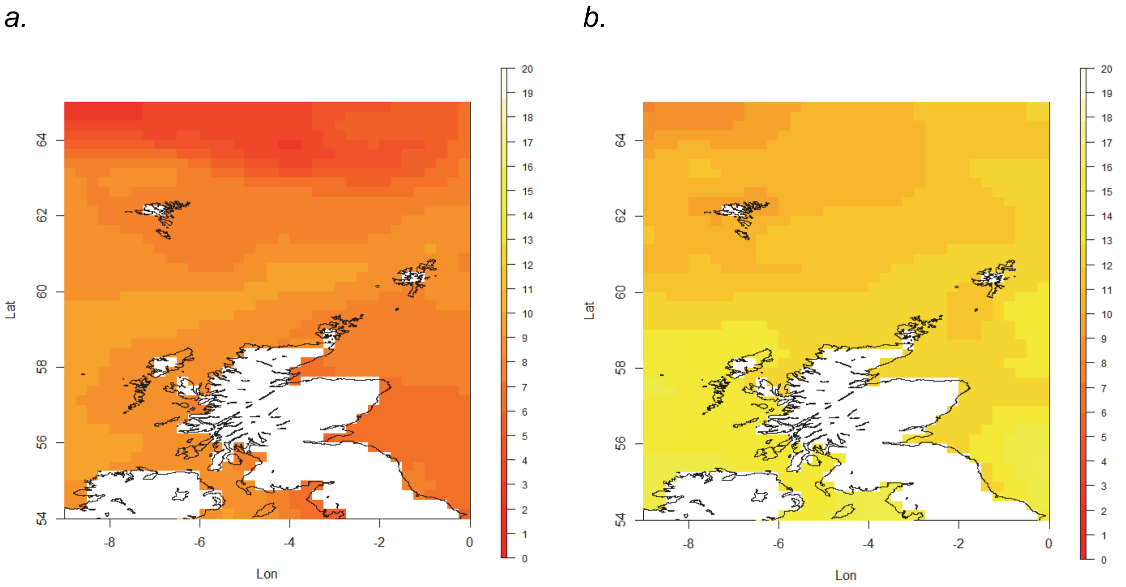

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Figure 5. Example temperatures (°C) from OI SST. a. 1st February 2012. b. 31st August 1994.

An index of thermal fronts (from DEFRA MB0102) was available, derived from earth observation data from the Advanced Very High Resolution Radiometer (AVHRR) (see Miller 2009, Miller *et al.* 2010, for details on the deriving of the fronts). This was a seasonal index varying over the quartiles Dec-Jan-Feb, Mar-Apr-May etc. (Figure 9). Due to the spatial resolution of the source data, this index is unreliable at low levels in proximity to the coast, so the data were supplemented with front data derived from ocean colour, from the MEdium Resolution Imaging Spectrometer (MERIS) (Figure 10) within 7.5 km of the coastline (Miller *et al.,* 2014). This latter index may be influenced by salinity as well as temperature gradients.

Chlorophyll concentration data were obtained from Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Monthly composites of chlorophyll a concentrations were available from the autumn of 2000 to the autumn of 2007 from NERC National Centre for Earth Observation (2010)[4]. For outwith that time period, monthly composites were made from the daily chlorophyll measurements available from NASA[5]. Scotland is not covered from December through February inclusive. An example of a chlorophyll index (Figure 11) is given here. For the period of 2010+, after the end of SeaWiFS data collection, the chlorophyll data were supplemented with data from Aqua MODIS.

Tidal energy[6] was also considered as a predictor variable. This was obtained from the analysis of ABPmer (2010, Figure 12) which was undertaken to inform the JNCC led EU SeaMap project.

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[4] NERC National Centre for Earth Observation (NCEO). Global 10 Year Monthly Climatology and Monthly Composites of Phytoplankton Size Class from SeaWiFS Analyses as part of the NCEO Theme 2 Sub-theme 6. http://www.neodc.rl.ac.uk/browse/neodc/nceo-carbon/data/ST6-ocean_biogeochemistry/Global-PSC-Climatologies/monthly-composites

[5] http://oceancolor.gsfc.nasa.gov/

[6] Derived from EUSeaMap Consortium webGIS data (www.jncc.gov.uk/page-5040) which is made available under the pilot project for the European Marine Observation Data Network (EMODnet), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE).

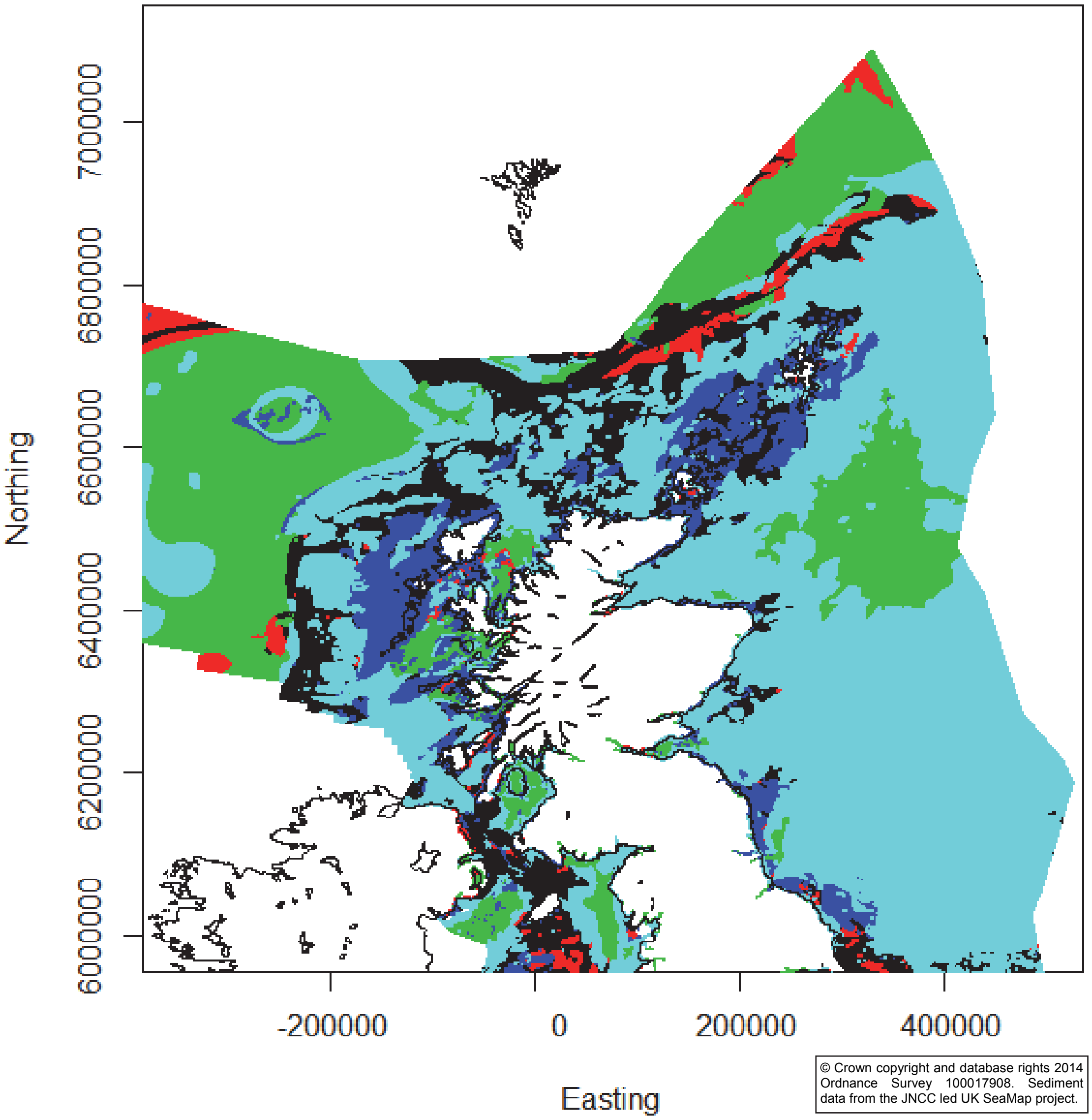

Figure 6. Sediment types from UK SeaMap 2010 (red: mixed sediment; black: coarse sediment; green: mud and sandy mud; blue: rock; & cyan: sand and muddy sand).

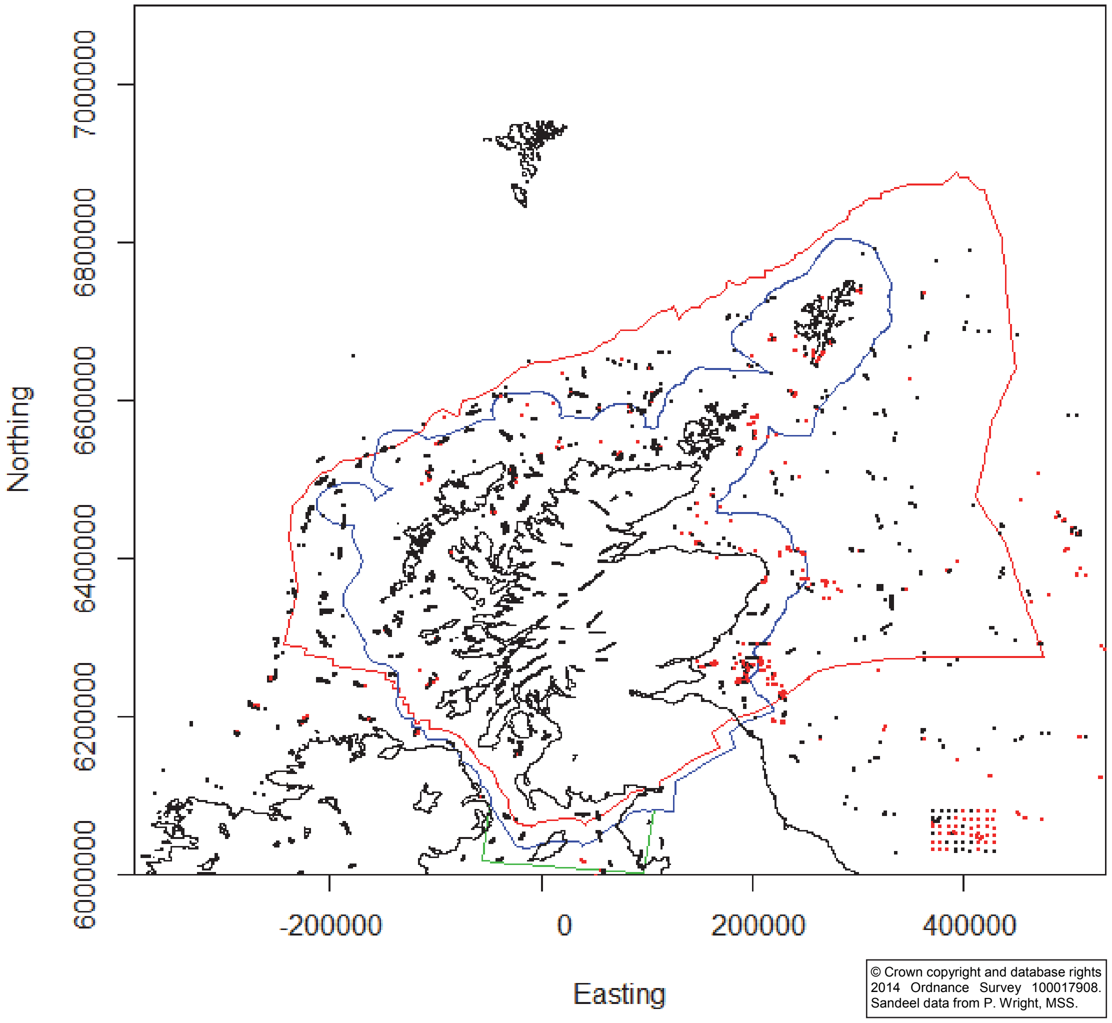

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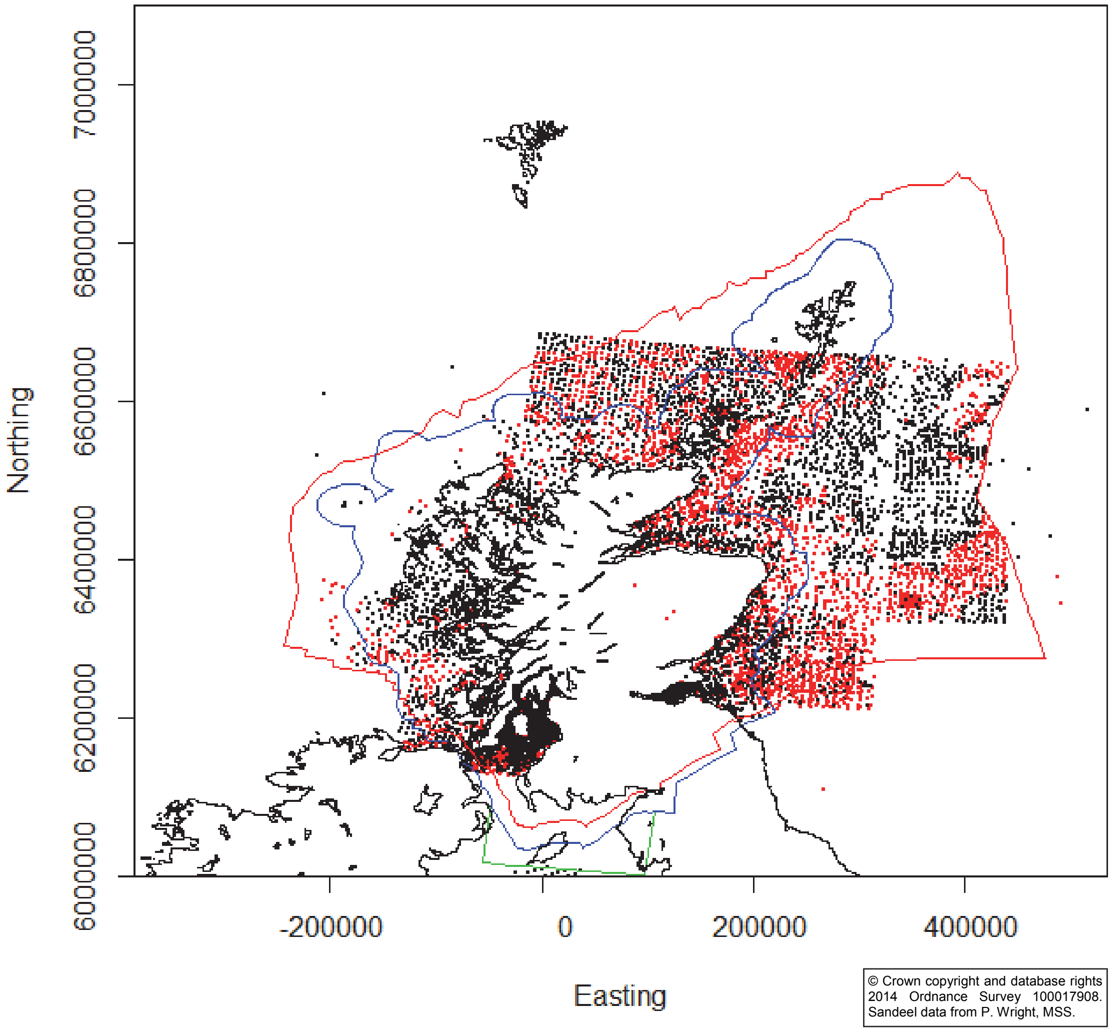
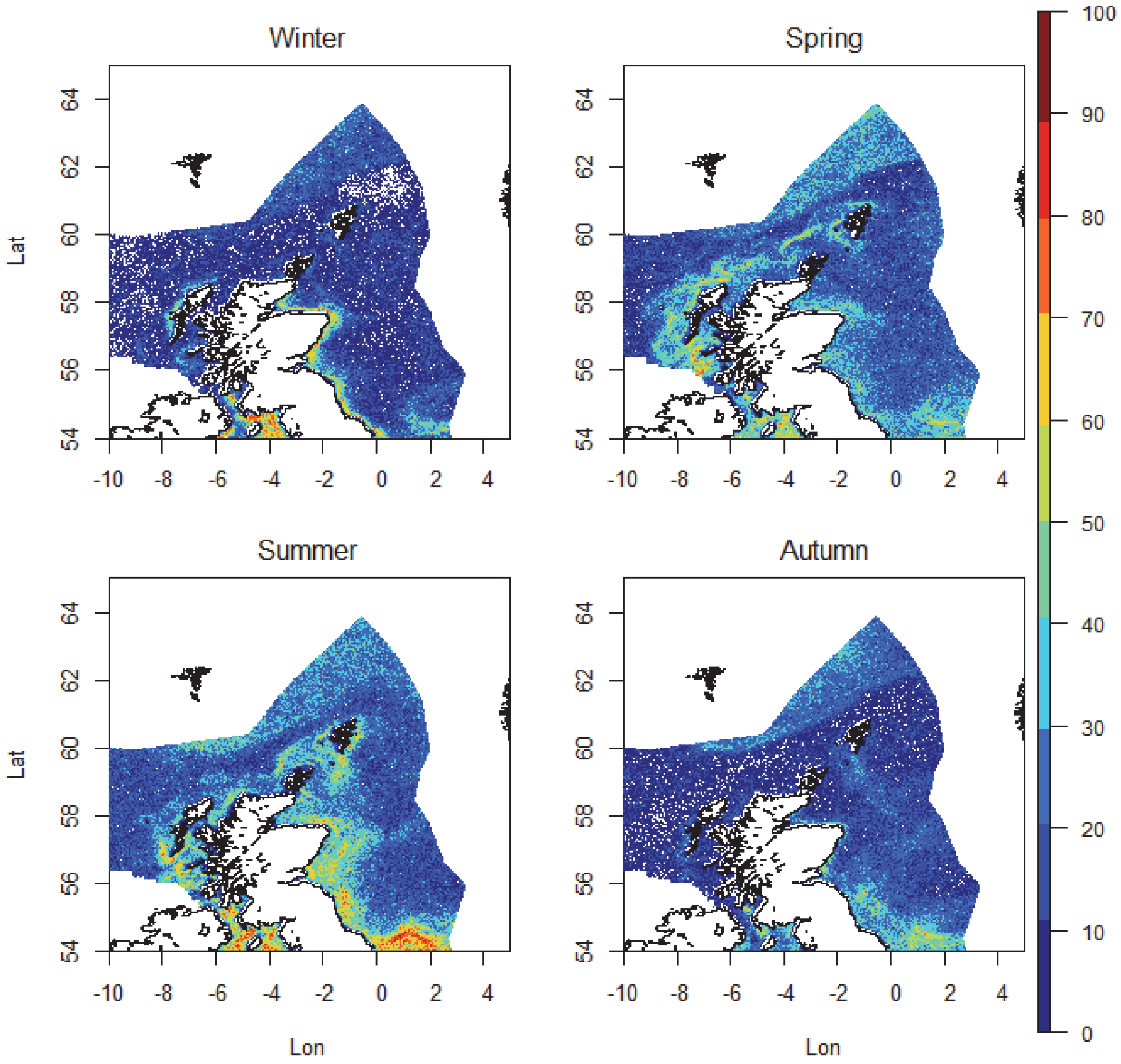
Figure 7. Sandeel presence-absence around the British Isles from Peter Wright, Marine Scotland Science. Points are sampled locations with (red) or without (black) sandeels. The area outlined in red is Scottish shelf waters, limited in the west and north to the 300 m contour, the input area for white-beaked dolphin data. The area in blue is the 12 nm limit with an additional approximate 10 nm buffer. This is the input area for minke whale. The area in green is an extension to the previous area for Risso's dolphin and basking shark with additional data from Manx waters.



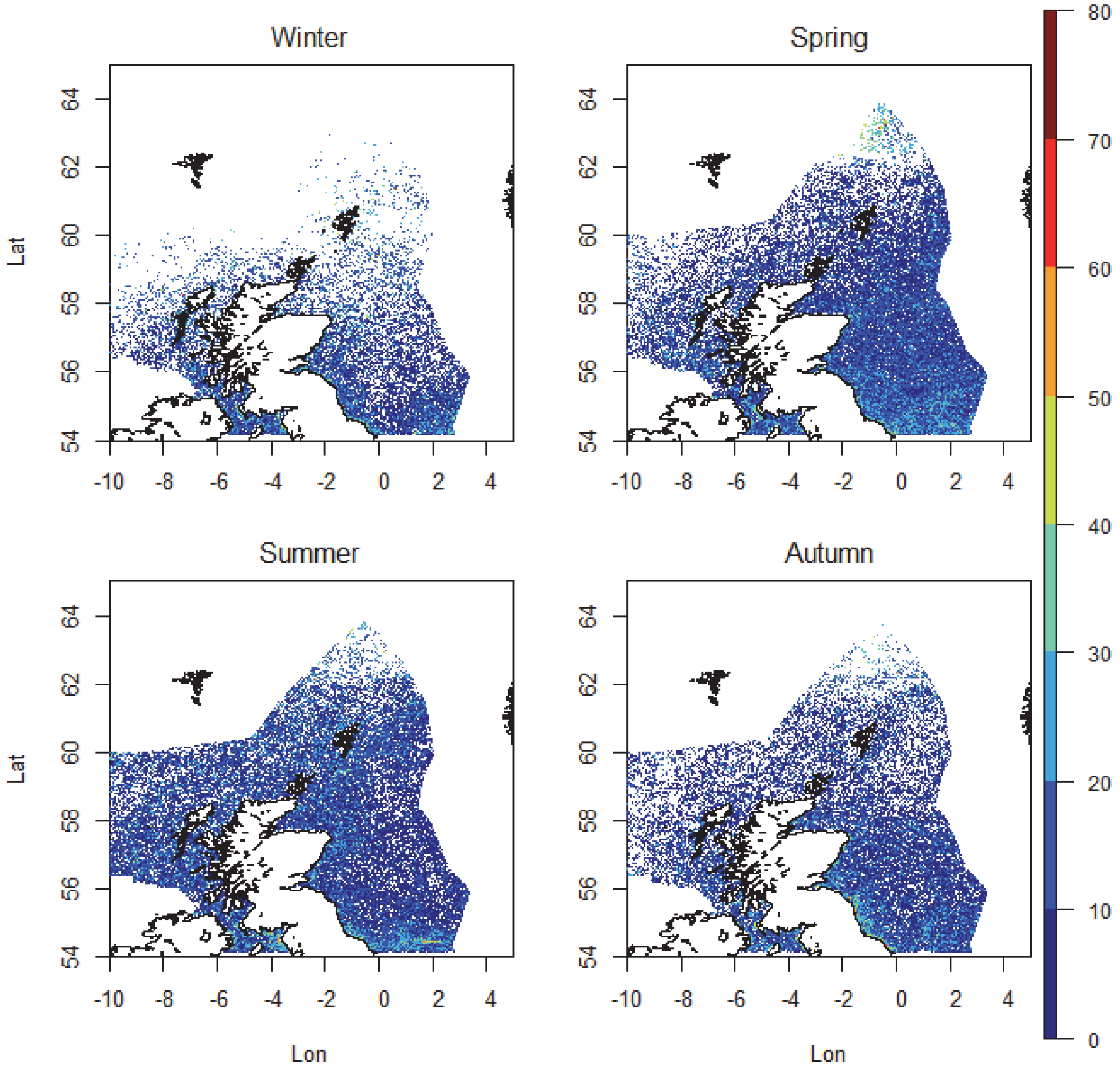
Sandeel data from P. Wright, MSS.

Figure 8. Sandeel preferred habitat around Scotland from Peter Wright, Marine Scotland Science. Points are estimated presences (red) and absences (black) for gridded sampled locations. The area outlined in red is Scottish shelf waters, limited in the west to the 300 m contour, the input area for white-beaked dolphin data. The area in blue is the 12 nm limit with an additional approximate 10 nm buffer. This is the input area for minke whale. The area in green is an extension to the blue area, to include additional data for Risso's dolphin and basking shark from Manx waters.



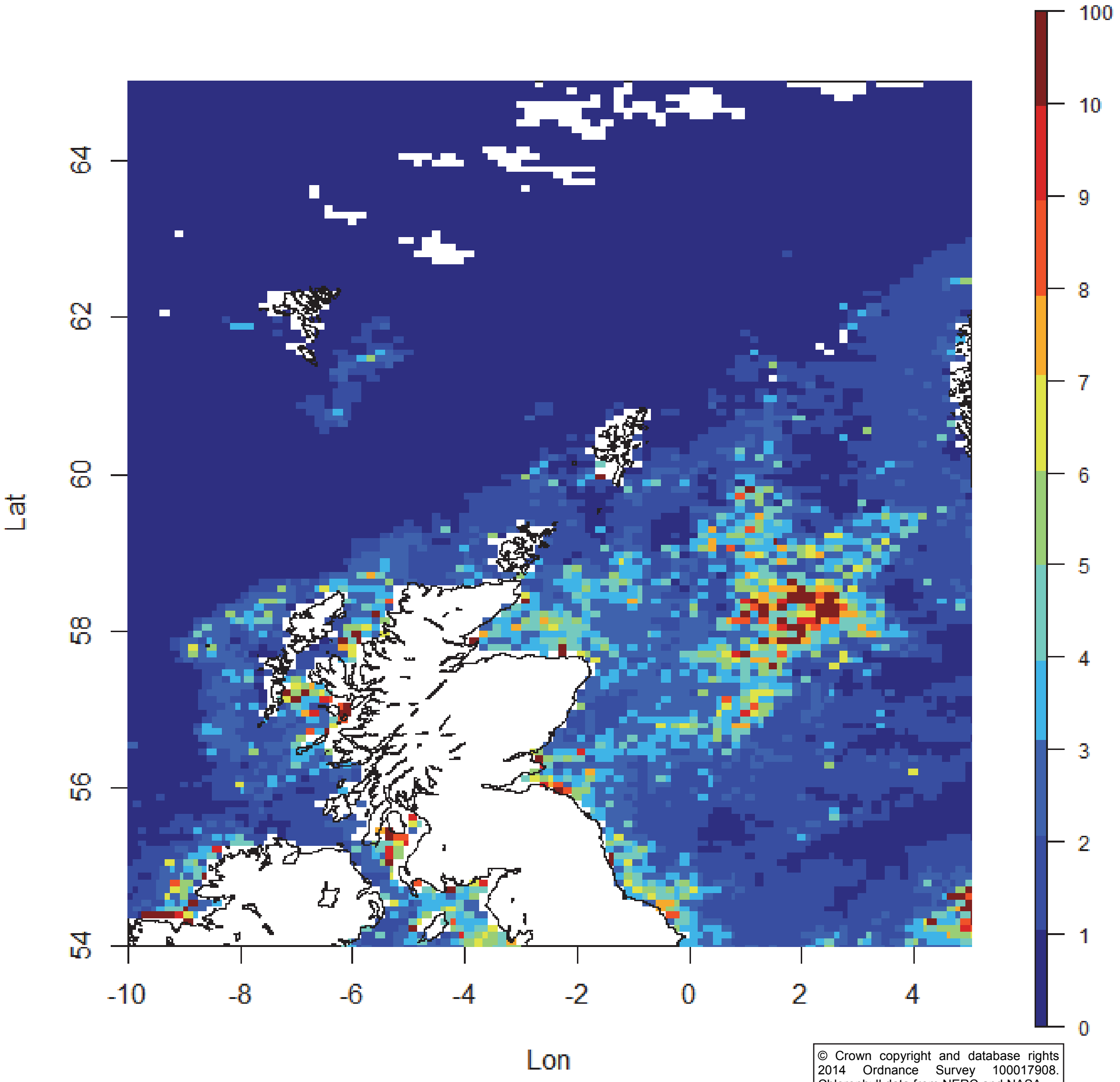
© Crown copyright and database rights 2014 Ordnance Survey 100017908. Fronts data from Defra MB0102 (analysis by PML).

Figure 9. Thermal fronts (% of time that a front is present) based on sea surface temperature, as indicated by the AVHRR. N.B. Winter is December, January and February in this case.



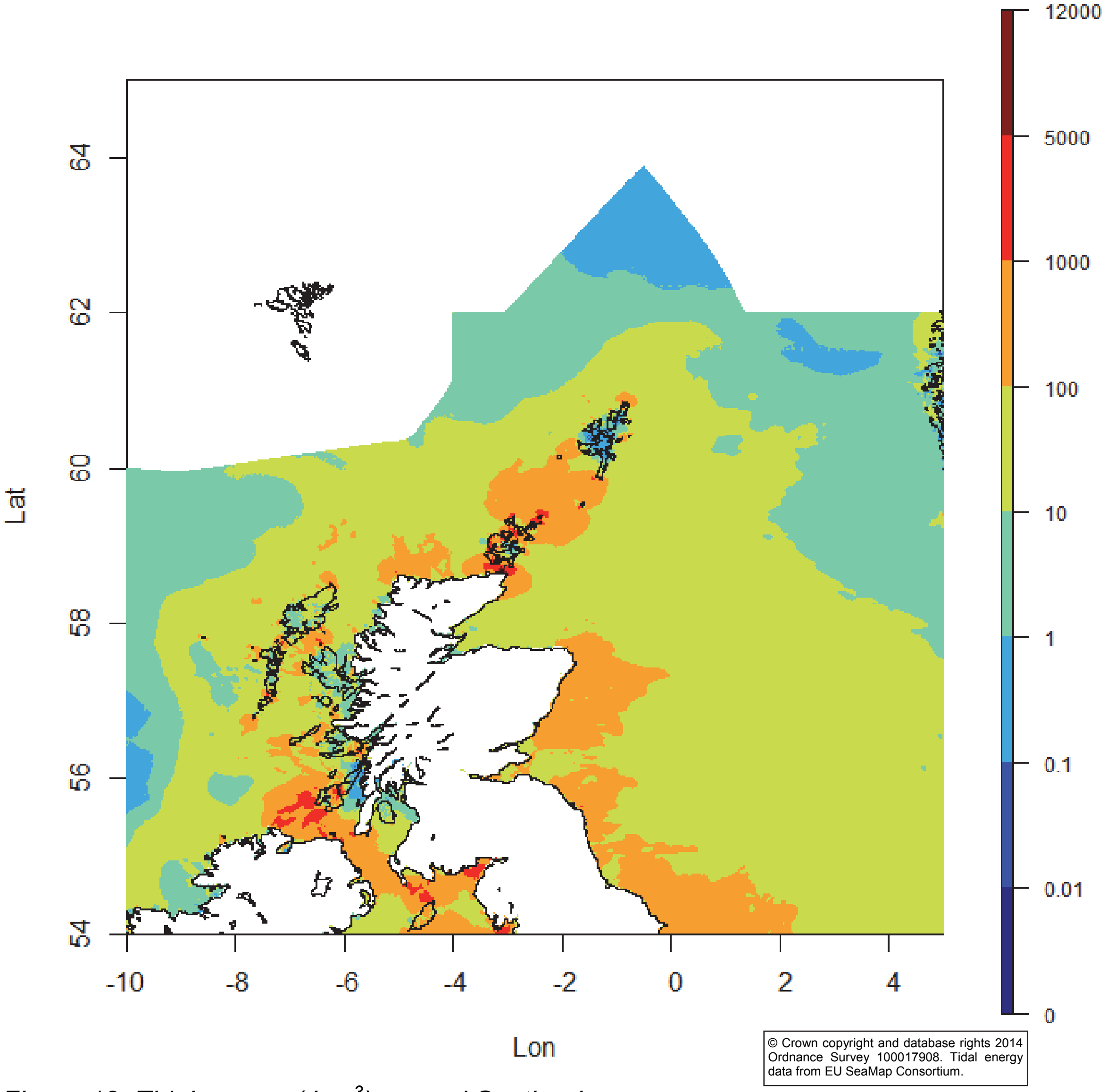
© Crown copyright and database rights 2014 Ordnance Survey 100017908. Fronts data from SNH (analysis by PML).

Figure 10. Front index (% of time that a front is present) based on sea surface colour, as indicated by MERIS. N.B. Winter is December, January and February in this case.



© Crown copyright and database rights 2014 Ordnance Survey 100017908. Chlorophyll data from NERC and NASA.

Figure 11. Monthly composite chlorophyll (mg m^{-3}) April 2007 illustrating the spring plankton bloom.



© Crown copyright and database rights 2014 Ordnance Survey 100017908. Tidal energy data from EU SeaMap Consortium.

Figure 12. Tidal energy (J m^{-3}) around Scotland.

2.2.3 Spatial Data Processing

The spatially referenced survey data (segment midpoints) and environmental data were indexed using latitude and longitude, assumed to be in the WGS1984 geo-coordinate system. For spatial modelling, all of these were projected to a UTM coordinate system (Transverse Mercator projection, false easting 500000.0, false northing 0.0, central meridian 3.0, scale factor 0.9996, latitude of origin 0.0, linear unit metre). Geographic processing took place in *R*.

2.3 Detection Function Modelling

2.3.1 Sightings Classes

Surveys were carried out using a variety of platforms, from rigid inflatables and other small boats to ferries and aeroplanes. A subset of the surveys was conducted under a formal line transect methodology where perpendicular distances of animals seen from the trackline were recorded. Sightings data that had the same truncation distance, type of platform and binning regime were grouped (see below for details) to estimate detection probability. Data were only considered together if they came from the same *survey mode* (i.e. boats as opposed to aeroplanes) with identical truncation with identical binning. Three classes of boat were crudely classified: *littleboats* (observer eye height < 5m above the water level, *bigboats* (observer eye height between 5 and 10 m above water level) and *ferries* (observer eye height > 10 m above the water). This enabled a single platform function (see below) to be fitted to these data with boat class considered as a covariate. Note that *ferries* were not necessarily functionally ferries; they could be large research boats. Also observer eye height was not always available for all platforms so heights, and hence *VesselType* had to be occasionally inferred. Some data classes did not have detection functions fitted because perpendicular distances were not available. We briefly describe the sightings data classes below. The same vessel could be classed differently if observers were located at different heights.

ESAS protocol boat data

ESAS data were collected either by boat or aircraft. Sightings were allocated to one of four distance bins (0 – 50 m, 50 – 100 m, 100 – 200 m, 200 – 300 m) from the track line. The ESAS boat data were combined with the Mainstream RP boat survey data, both of which were collected using the ESAS survey method. Therefore, the data were treated as single platform distance data with initially 300 m truncation. Some data were not binned into distance categories but were coded as only within 300 m. Other data had no distances at all. Fitting a realistic detection function over more than 100 m proved problematic, so the data for these species were right truncated at 100m. Some ESAS surveys, unlike most of the other surveys considered here, are undertaken from one side of the platform only. Effort (see below) was altered to account for this.

University of Aberdeen Aerial Surveys

These continuous distance aerial data were considered combined as single platform data. The data were left truncated at 100 m as inspection of the histogram of the perpendicular distances suggested that sightings close to the plane were missed and right truncated at 400 m.

Wildfowl and Wetlands Trust

The WWT aerial data were treated as distinct from the university aerial surveys because of the unique bins into which the distances were recorded. The data were binned into 3 categories (44 – 163 m, 163 – 282 m, 282 – 426 m). The data were left truncated at 44 m because the region closest to the aeroplane could not be observed.

Other boat data

The remaining boat sightings, from all the other surveys (including SCANS and SCANS-II etc.) were collectively analysed as single platform data although a subset of these data was collected in trial mode (see below) allowing estimation of $g(0)$.

SCANS & SCANS-II aerial surveys

In the case of these data sets, the data were amalgamated and treated as single platform distance data allowing estimation of a detection function where the data were of sufficient magnitude.

Aerial Photo Surveys

In the case of these data, no detection function was fitted and the detection probability was assumed to be one. The width of sea photographed varied within and between surveys.

2.3.2 Fitting Detection Functions

When fitting detection functions, the effects of covariates, other than perpendicular distance, were incorporated into the detection function model ('Multiple Covariate Distance Sampling', MCDS, Marques & Buckland (2004), Marques *et al.* (2007), see also Buckland *et al.* (2001)). The probability of detection becomes a multivariate function, *g*(y,v), representing the probability of detection at perpendicular distance y and covariates v (v = v1,..,vQ where Q is the number of covariates). Using either a hazard-rate (1-exp(-y/σ)-b) or half-normal detection function ($\exp(-y^2/2\sigma^2)$) the covariates were incorporated via the scale term, σ, where for sighting j, σ has the form:

$$\sigma_j = \exp\left(\beta_0 + \sum_{q=1}^{Q}(\beta_q v_{jq})\right)$$

where *b*, β_0 and β_q (q=1,…,Q) are parameters to be estimated (Marques & Buckland, 2004). Separate detection functions were generated for minke whale, dolphin species (i.e. all dolphin species combined, although species was used as a potential covariate in this case, see below) and basking shark.

Potential covariates were Beaufort sea state *SeaState*, cetacean group size *Size,* and *VesselType* in the case of boat surveys. *Survey* (i.e. the survey the data came from) was also considered as a covariate in some analyses. In the case of the collective dolphin detection function, *Species* was also considered as a factor. The number of observers was not considered as an independent variable (and was often not available). Also inter-observer differences in detection could not be considered. On the rare occasions *SeaState* was not available for a given sighting, *SeaState* was taken from adjacent effort. Occasionally *Size* was missing from a sighting in which case a *Size* was taken as the mean of all relevant sightings.

The *R* (R Developmental Core Team 2011) library mrds v.2.0.5. (Laake *et al.,* 2011; Burt *et al.,* in prep.), was used for fitting and selection of detection functions.

2.3.3 Detection Without Distances

For individual detections or surveys without distance measurements, the estimated detection probabilities were obtained from the detection function for the appropriate covariate combination. This assumes that these surveys have the same detection probability, given their covariates, as those with distances. A proportion of sightings with missing distances was discarded at random, this proportion being the same as the proportion of the detections of known distance that were beyond the truncation distance. This is because the detection probability calculated from surveys with distance data are the average probability of detecting an animal group between the trackline and a given truncation distance.

2.4 Adjustments in Addition to Detectability

2.4.1 Perception Bias (g(0))

Some of the boat sightings data (e.g. SCANS & SCANS-II) were collected in trial (or also called Buckland-Turnock) mode (Buckland & Turnock, 1992), with a tracker platform observing at a distance and a primary observer following a normal searching protocol. This allowed estimation of *g*(0) (Laake & Borchers, 2004), the probability of detection on the trackline for *bigboats*. No double platform survey data for *littleboats* within the area of interest was available, so *g*(0)for *littleboats* was calculated based on a survey undertaken in Cardigan Bay in 2008 used in the analysis of the JCP results (see Paxton *et al.,* 2013).

The double platform data, suitably edited, were amalgamated with the remaining single platform boat data to estimate a single platform detection function for the vast majority of reported sightings (see non-ESAS boat section above).

No adjustment for perception bias was made for the aerial surveys.

2.4.2 Availability bias

To standardise among different surveys with different availability biases the proportion of animals available at the surface has to be considered. An index of availability at the surface for each sighting was made by considering the reported proportion of time the animals spend at the surface (see Section 3.2.2). The probability of an individual being available at the surface was given by

$$P(Avail) = \frac{E[s]}{(E[s]+E[d])} + E[d] \times \frac{(1-e^{-\frac{t}{E[d]}})}{(E[s]+E[d])}$$

after Laake *et al.* (1997) where s = surface time, d = dive time and t = window of time during which an animal is within the visual range of an observer. The first half of the right hand side of the equation is the instantaneous probability of a group being at the surface at a single point in time. In addition, the term after the plus sign increases the probability of being at the surface as a function of the time period the group is within the visual range of the observer. As the time period increases, the exponential term tends towards zero so the whole right hand side tends towards 1. The time period that the animal was within the visual range of the observer was normally taken to be the quotient of the maximum observed radial distance and speed. However, in some cases where the maximum radial distance was thought to be unrealistically short or was unavailable, an alternative distance was used based on consultation with a sample of the data providers (i.e. we asked how far forward the observers were looking).

Given individual availability above, group availability (*Group avail*) was calculated as follows

$$P(Group\ avail) = 1-(1-P(Avail))^{Size}$$

where the right hand side represents the probability that at least one member of the group is at the surface assuming no synchrony between individuals within the group (i.e. the group is available at the surface to be detected). The availability correction was not applied to *bigboats* and *ferries* where, as per SCANS and SCANS-II (Hammond *et al.,* 2002; Hammond *et al.,* 2013) we assumed availability was 1 as the availability to observers on these large vessels was assumed to be corrected for by the use of the *g*(0) correction as tracker observers would see animals at such distance that the abilities of primary observers to see the animal would be compromised, not only by perception, but also by availability.

2.5 Density Surface Modelling

2.5.1 Partitioning Data into Segments

The effort data were provided either as waypoints or as segments of transect lines. In the former case, the data were segmented using the waypoints as end points. Segments were then split or amalgamated to achieve final segments of length as close to 10 km as possible. To be amalgamated into a 10 km segment, the existing segments had to be adjacent in space and time and have identical or near similar sea states. Sometimes the target 10 km segment lengths were not achieved. Segments above 15 km in length were split. Ten kilometres was chosen as an appropriate length based on the previous experience of analysing survey data by the authors. Objective criteria for choosing segment lengths are not yet available.

Appendix Table A1.1 gives the realized effort (i.e. effort after removal of unusable effort) for each data set used. The estimated number of individuals in each *i*th covered segment, was estimated via a method similar to the Horvitz-Thompson estimator (Horvitz and Thompson, 1952), i.e.:

$$\hat{N}_{ci} = \sum_{j=1}^{n_i} \frac{s_{ij}}{P_{ij} G_{ij} g_{ij}(0)}, \qquad i = 1, \ldots, T,$$

where, for each segment *i* containing at least one sighting, P_{ij} is the estimated probability of detection (from the line transect analysis) of the *j*th detected pod in the segment, n_i is the number of detected pods in the segment and s_{ij} is the size of the *j*th pod. G_{ij} is the probability of the given pod being available at the surface to be seen, and $g_{ij}(0)$ is the probability of the given pod being detected on the trackline. Sightings were allocated to segments by reference to their time of observation.

$\hat{N}_{ci}$, was modelled with a_i (i.e. the area associated with each segment) as an offset (see below). The resulting estimated density of individuals (corrected where necessary for perception and availability bias) in segment *i*, $\hat{N}_{ci}/a_i$ is hereafter referred to as $\hat{D}_{ci}$ (see Hedley, 2000; Hedley & Buckland, 2004; and Hedley *et al.,* 2004).

The breakdown of sightings by species within each data set and by *Year* and *VesselType* is given in Tables 1, 2 and 3 respectively.

Table 1. Sightings within the truncation distance (see Section 3.2) for each species for each survey. Includes sightings without distances randomly assigned to within truncation distance. A description of each survey dataset is given in Appendix 1.

Data set	**Minke whale**	**Risso's dolphin**	**White-beaked dolphin**	**Basking shark**
CRRU	57	1	0	3
ESAS	14	4	155	0
ESASaircraft	0	0	0	0
Gill	-	20	6	-
HWDT	215	12	57	538
IFAW/Marine Conservation Ltd	0	0	0	0
IWDG				
	1	1	0	0
IWDG Ferry	0	0	0	0
MainstreamRP	1	0	2	0
Manx	3	22	0	36
Marinelife	0	0	0	0
Moray Offshore Renewables (MORL) boat	45	1	8	0
NORCET	60	10	51	-
Orca	1	0	0	1
SCANS	0	4	49	-
SCANS (air)	0	0	0	-
SCANS II	15	2	32	0
SCANS II (air)	4	0	0	4
Sea Energy Renewables Inch Cape boat	22	0	3	0
Speedie	-	-	-	532
SWF	118	75	53	0
University of Aberdeen aerial	2	0	1	0
University of Aberdeen boat	28	0	0	0
University of Aberdeen SAC	8	0	0	0
University of Aberdeen/MORL/HiDef	0	0	0	0
University of Aberdeen/MORL/HiDef/Crown Estate	1	0	0	0
University of Aberdeen ferry	111	5	6	-
WDCS	0	2	0	0
WWT	2	0	48	2
Total	**708**	**159**	**471**	**1116**

Table 2. Sightings within the truncation distance (see Section 3.2) for each species under consideration by year. Includes sightings without distances randomly assigned to within truncation distance.

Data set	Minke whale	Risso's dolphin	White-beaked dolphin	Basking shark
1994	-	19	80	-
1995	-	3	25	-
1996	-	25	20	-
1997	-	37	41	-
1998	-	0	30	-
1999	-	13	7	-
2000	17	2	2	0
2001	73	2	13	0
2002	44	4	9	0
2003	50	4	14	65
2004	53	3	8	91
2005	38	2	44	160
2006	51	8	32	361
2007	23	27	8	72
2008	48	2	12	79
2009	113	1	79	92
2010	58	1	13	132
2011	103	4	28	13
2012	37	2	6	51
Total	**708**	**159**	**471**	**1116**

- *Indicates that data not used.*

Table 3. Sightings within the truncation distance (see Section 3.2) for each vessel type and species under consideration. Includes sightings without distances randomly assigned to within the truncation distance.

Vessel Type	Minke whale	Risso's dolphin	White-beaked dolphin	Basking sharks
Littleboats	239	122	80	635
Bigboats	277	21	242	474
Ferries	183	16	100	1
Planes	9	0	49	6
Total	**708**	**159**	**471**	**1116**

2.5.2 Model Fitting

The data were counts and there were large numbers of zeros, therefore the response data were likely to be more variable than assumed under some model types (i.e. overdispersed). This variability had to be allowed under the selected model. Furthermore, the observations were close together in space/time and these observations were likely to be more similar than observations distant in space/time. Covariate data could explain part of the correlation in the counts. However, it is unlikely that the correlation would be explained in full. The remaining correlation is found in the model residuals and violates a crucial assumption of GLMs/GAMs. Generalised Estimating Equations (GEEs; Hardin & Hilbe, 2002) explicitly permit these patterns in residuals and estimate the dispersion parameter, allowing for overdispersion. Therefore, the GEE framework is fitted to these data. The response data, y_{ijt} are modelled using a quasi-Poisson distribution with mean μ_{ijt}.

$$y_{ijt} \sim quasi\text{-}Poisson(\mu_{ijt})$$

$$\mu_{ijt} = exp(\beta_0 + \beta_1 X1_{ijt} + s1(X2_{ijt}) + s2(XPos_{ijt}, YPos_{ijt}))$$

where y_{ijt} is the estimated count for transect *i,* segment *j* and time point *t. s1* represents a quadratic B-spline smooth of a one dimensional covariate (X2) such as *Depth* and *s2* is a two dimensional smooth of space (with coordinates XPos and YPos). The *b*s are model coefficients for the intercept and linear terms.

To accommodate the potentially patchy numbers of animals across the survey area, the spatial component to the modelling was undertaken using the CReSS method (Complex REgion Spatial Smoother; Scott-Hayward *et al.,* 2013a), with targeted smoothing capabilities using the SALSA method (Spatially Adaptive Local Smoothing Algorithm; Walker *et al*., 2011). While the methods used are spatially adaptive (and thus allow a wide range of surfaces to be accommodated) the method itself does not induce local structure in the data and the models considered were given sufficient scope to adequately describe surfaces with extremely local surface features (e.g. patchy surfaces with locally acting hotspots) and/or global surface features (e.g. flat surfaces or far-reaching trends).

The CReSS smooth implemented here employs geodesic ('as the whale swims') distances to ensure distances across islands or around coastlines more closely reflect cetacean swimming distances. Specifically, the smoothing was carried out using local exponential basis functions ($exp(-d/R^2)$), where d represents pointwise geodesic distance between each observation and each knot location and *R* is the range coefficient (Scott-Hayward *et al.,* 2013a).

The starting point for SALSA-based model selection involves distributing a specified number of knots evenly across the covariate range (or spatial surface) to fill the range/space and adaptively moving these knot locations to areas requiring flexibility. The size of these moves depends on where in the covariate range/spatial surface the largest residuals are located, and if the moves being considered improve the fit statistic of interest (e.g. BIC). While the smooth terms can produce relationships which are nonlinear on the link scale, the smoother-based terms are linear in their parameters which means a GEE fitting framework can be employed to provide coefficients and estimates of precision.

Despite the covariates included in the model, there was compelling evidence for time-based correlation in (Pearson) residuals; a runs test (Mendenhall, 1982) from the final species (uncorrelated) models returned very small p-values ($p << 0.05$) for each species. As a result, a GEE fitting framework was employed using a survey-day-vessel blocking structure and a working independence correlation matrix.

In this case, model residuals pertaining to segments from the same day of survey from the same block (survey-day-vessel) were permitted to be correlated while independence was assumed between blocks (Hardin & Hilbe, 2002). The GEEs allow the estimation of standard errors to be adjusted for the autocorrelation in the 'block' residuals, and to ensure that model standard errors were not based on an inappropriate correlation structure, empirical standard errors were used; these are robust to misspecification of the correlation structure and are based on the observed correlation in the Pearson residuals within blocks.

An 'offset' was also specified to allow for variable search effort across the estimated counts as segments varied in area.

The methods are not known to produce edge effects (Scott-Hayward *et al.,* 2013a,b). In addition the 10 nm buffer further prevents artificial patterns appearing on the edge of predicted density surfaces.

2.5.3 Model selection

An overview of the model selection process is provided in Figure 13. Modelling selection was a two-stage process where the one dimensional (1D) predictor covariates (i.e. *Depth*, *Dayofyear,* etc.) and factors were considered first to produce a best-fit model, then a 2D smooth of position (i.e. a smooth of Easting and Northing) was considered "on top of" the existing model. If this new model provided a better fit (see below), it was kept otherwise the model with 1D predictors only was considered. Further details of the process can be found in Mackenzie *et al.* (2013) and Scott-Hayward *et al.* (2013b,c). The aim was to provide a best fit model rather than an explanatory model that showed the response to habitat variables. The purely spatial variables present in the model (e.g. Easting and Northing) describe the variation without explaining it, and render problematic the interpretation of the response to other variables in the model (e.g. *Depth*). While interpretation of habitat variables is also of interest, the key requirements of the model were description and prediction (Paxton *et al.,* 2014).

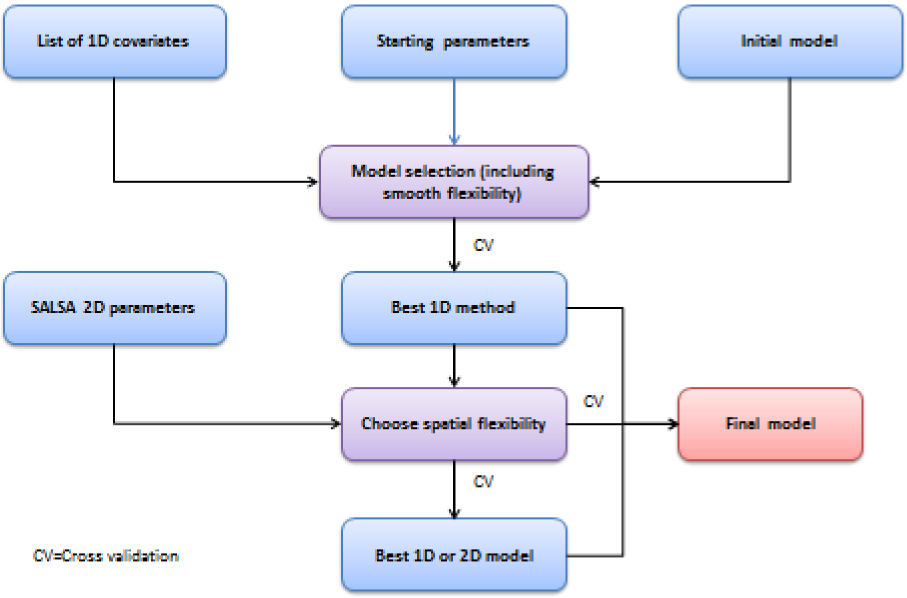


Figure 13. Overview of the model selection process.

The Quasilikelihood under the independence model Information Criterion (QIC_u; Pan 2001) with a Bayesian penalty ($QICb_u$; quasi-likelihood based BIC score) was used for determining the best knot number and location selection using SALSA (with some constraints: *df* = 3-5, 1-3 knots):

$$QICb_u = -2QL + p*log(n)$$

where *QL* is the quasilikelihood, *p* is the number of parameters estimated and *n* is the number of data points.

Five-fold Cross-Validation (CV) was used to choose between models with different covariates.

To ensure any signal between the environmental covariates and the response was not inappropriately allocated to the spatial surface, model selection proceeded by first considering the environmental covariates alone, followed by the addition of a spatial surface.

To combine the covariates into one model, the covariates (*Depth, SST, Front, TidalEng, Dayofyear or Chloro* (in the case of minke whales and basking shark only)) were all added to an initial model with or without the factor variable *Sediment. Dayofyear* and *SST* co-varied together, so two start models were considered with each of these interchangeable variables respectively considered along with the other above predictors. In the case of basking shark, one further factor was considered: whether or not the survey was a dedicated shark survey *SharkSurvey,* as there was evidence that the dedicated basking shark Speedie survey (Appendix 1) saw far more basking shark than other surveys operating in the same area at the same time (Wilcoxon Test W = 49071, n = 105, p = 0.02). Selection for each covariate was employed, using five-fold CV, during which SALSA was used to redistribute the knots, for each term (conditional on an improvement in the quasi-likelihood based BIC score). Each term was tested for inclusion/exclusion and as a linear/smooth term.

For the spatial component and the smooth covariates, SALSA initiates the model selection process by space-filling (Johnson *et al.,* 1990) some specified number of knots from the spatial knot grid/covariate data, and these knot locations are subsequently moved to areas which are poorly fitted by the model as determined by the designated fit criterion (QICb). As a part of the SALSA method for the spatial CReSS component, once knot locations were determined, different range coefficients (*R*) were trialled for each knot and chosen using the same fit criterion. The SALSA algorithm is heuristic and thus does not search the full model space and for this reason, several start points (6, 8, 12, 16 knot models) were considered for the numbers of knots in the spatial surfaces. CV was used to choose between these differing knot models (assuming an improvement in CV score over the model with no spatial component). Further details of the models can be found in Appendix 3.

2.5.4 Prediction

Predictions from the models were made on a 5 by 5 km resolution easting and northing grid covering the coloured area in Figure 2. If the models contained year or season covariates (i.e. *Dayofyear* or *SST* or *Chloro*), the predictions were Year/ DayofYear specific.

Seasons for the purposes of this analysis were assumed to be January, February, March (winter), April, May, June (spring), July, August, September (summer) and October, November, December (autumn). These divisions reflect the annual pattern in sea temperatures around the UK, where the sea is coldest in January, February and March, and warmest during July, August and September. Seasonal predictions (along with confidence intervals) were made for 2005. This year was chosen as it had wide spatial coverage because it was the year of the comprehensive SCANS II survey. The fifteenths of February, May, August and November were taken as representative of winter, spring, summer and autumn respectively. Occasionally the prediction grid had dynamic covariates beyond the range of the original data. If this was the case then those covariates (e.g. *TidalEng*) were set to the maximum observed in the original data thus preventing unreasonable extrapolations. To provide further insights into year on year variation, predictions were also made for 1994 (white-beaked and Risso's dolphin), 2001 (all other species) and 2012 (all species).

2.5.5 Estimation of Uncertainty

The uncertainty in the parameter estimates at both the input stage (i.e. estimating abundances for each segment based on the observed counts) and the modelling stage (i.e. estimating the distribution of these estimates across space and time) was combined using a two-stage parametric bootstrap process (Davison & Hinckley, 1997), with 500 bootstrap re-samples being generated as described below.

The first stage captured uncertainty in the corrected counts ($\hat{D}_c$). For each bootstrap, new estimates of the distance sampling detection probability were generated by sampling from the variance-covariance matrix of the estimated detection function parameters, assuming these parameters followed a multivariate normal distribution. New estimates of $g(0)$ were generated by sampling from a normal distribution with mean and standard deviation taken from the fitted values of $g(0)$. New estimates of availability were generated by sampling the observed surface and/or diving times from a gamma distribution, with mean and standard deviation obtained from reported values in the literature (see Section 3.3.2.); for minke whales, a nonparametric sampling of reported surface frequencies was made as the raw surfacing data were available (see Section 3.3.2) in preference to assuming a distribution. Finally, for surveys that did not contain distance data, the sightings to be omitted were randomly chosen for each bootstrap replicate.

The second stage captured uncertainty in the density surface modelling, and involved re-fitting species-specific models for each of the 500 bootstrap replicates generated from the first stage, and from each of these new GEE-based fits, generating a single parametric bootstrap realisation from the model. A parametric bootstrap replicate was generated from a multivariate normal distribution with variance-covariance matrix estimated using the re-fitted GEE-based model in each case. In cases where the variance-covariance matrices were not symmetric or positive definite (due to numerical optimisation rather than non-convergence) these matrices were coerced to be symmetric and positive definite to allow random generation from each multivariate normal distribution.

This two-stage process resulted in 500 relative density estimates for each grid cell (given a set of covariates and point in time). The central 95% of these values was used to define the upper and lower 95% confidence limits.

Model selection uncertainty was investigated with 200 bootstraps generated as before, but additionally each bootstrap set underwent a full model selection process, so each final bootstrap surface from this procedure incorporated uncertainty in the detection function parameter estimation, whether or not an animal was within the truncation distance (for samples with unknown distances), surface availability, uncertainty in the spatial model parameters and uncertainty in the model itself.

From each bootstrap surface from both bootstrap methods, a total abundance was estimated by multiplying the predicted density and cell area (taking into account intruding land area) so a single coefficient of variation could be estimated to compare bootstraps with and without a model selection component.

2.5.6 Estimating the Effect of Prediction Area on Prediction Accuracy

To evaluate the risk of bias in the predictions of relative density over different areas, accuracy was measured by analysing the change in the mean residuals collected from different sized areas. The method was as follows (see Figure 14):

1. For each size of area of interest (25, 100, 150, 225, 400, 625, 900 & 1225 km^2), 2000 random locations of that size were selected.
2. Within each random location, all available effort segments were identified.
3. For each segment, a simple residual (i.e. a model fitted value less the observed $\tilde{N}_c$) was calculated.
4. These absolute residuals were then averaged across each random sample

The whole process was repeated 5000 times to provide a 95% confidence interval.

Of interest was the width of the 95% confidence interval.

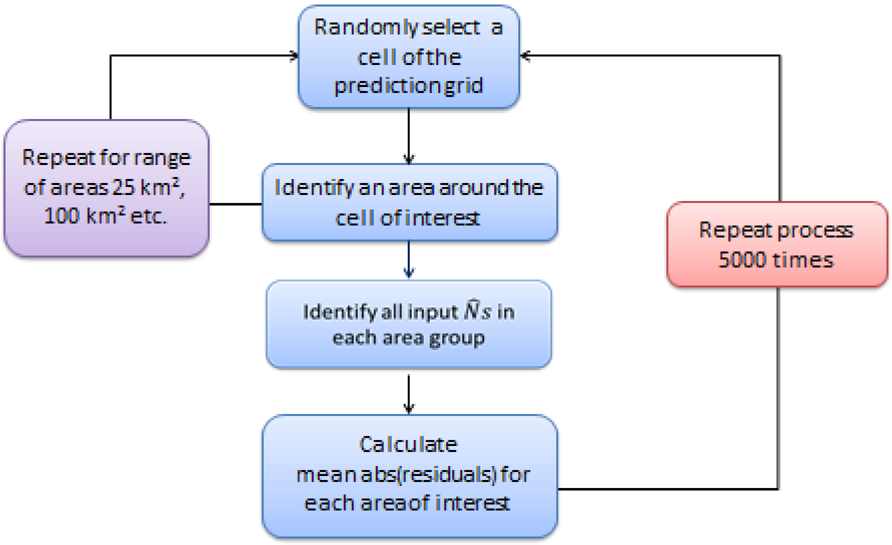


Figure 14. Overview of the prediction accuracy evaluation.

2.6 Investigating Persistence

2.6.1 Testing Persistence

From a conservation perspective, it is interesting to know if regions of relatively high density represent persistent features. As an additional test of the persistence of areas of high density over the course of the sampling period, *Year* was fitted as a covariate with an interaction with position, and fit was assessed by CV score.

In the case of two species (white-beaked dolphins and basking shark) position was not in the final fitted model. In this case, the observed adjusted densities for summer (July, August and September) were compared using the non-parametric surface comparison method of Dette & Neumeyer (2001, see also Wang & Ye, 2010) in the *R* package fANCOVA (Wang, 2010).

Because of the paucity of effort outside of spring and summer, no effort was made to identify areas of seasonal persistence.

2.6.2 Illustrating Persistence

To identify regions of persistent (relatively) high density, prediction surfaces (and their associated bootstraps) were generated for each summer (August 15th) for each species (1994 –2012 for the dolphin species, 2001 – 2012 for minke whale and basking shark). Cells with a predicted relative density higher than the mean predicted relative density for the Scottish territorial waters overall were marked as 1, cells lower than the average marked as 0. Thus a persistence-certainty score could be developed (on a scale of 0 to 6000). Uncertainty was incorporated into this score by repeating the process over 500 bootstrap surfaces for each year. Thus a score of 6000 for a particular cell for a given species would mean that the predicted density was higher than the mean density for every single single bootstrap replicate of each year. A score of zero would mean that the predicted density was consistently less than the mean density for each bootstrap replicate for each year. This persistence-certainty score combines the probability of a cell being of greater than average density in the summer as well as the uncertainty associated with the estimated year-specific density.

3. RESULTS

3.1 Detection Function Results

Estimated detection probabilities and related statistics are given in Table 4. Parameters of the models can be found in Appendix Table A2.1.

Table 4. Estimated detection probabilities for the JCP sightings data.

Species	Survey Analysis (sample size)	Truncation Distance (m)	Detection Probability
Minke whales	Non-ESAS boats (632)	1000	0.323 (SE = 0.038)
	ESAS mode boats (15)	50	1
	University aerial (2)	100 (left truncated)	1
	WWT new binning (2)	382	1
	SCANS-II aerial (14)	150	1
Dolphins (from Risso's area)	Non-ESAS boats (500)	800	0.392(SE=0.037)
	ESAS mode boats (101)	100	0.523 (SE = 0.050)
	University aerial (21)	300 (left truncated)	0.621 (SE = 0.132)
	WWT new binning (19)	382	0.507(SE=0.109)
	SCANS aerial combined (60)	180	0.494 (SE=0.051)
Dolphins (from white-beaked dolphin area)	Non-ESAS boats (567)	800	0.399(SE=0.034)
	ESAS mode boats (180)	100	0.468 (SE = 0.032)
	WWT new binning (50)	382	0.555(SE=0.074)
Basking sharks	Non-ESAS boats (575)	800	0.384 (SE=0.030)
	ESAS mode boats (11)	125	1
	WWT new binning (2)	238	1
	SCANS aerial combined (2)	100	1

3.1.1 Minke whale

Over 600 (n = 632) sightings were made by non-ESAS boats to generate the single platform half normal detection function (goodness of fit: $\chi2 = 1.16$, df = 2, P = 0.558, Figure 15) with a truncation distance of 1000 m. The inclusion of *VesselType* lowered the AIC but the order of the *VesselType*'s influence on detection was counter intuitive (i.e. small boats had better detectability than ferries) so this model was not considered. Twenty-one whale groups were seen by ESAS boats within the range 0 – 100m but the standard error on any estimated detection probability from the detection function were large, so a strip transect was assumed with an estimated half-width of 50m (i.e. detection probability = 1 within 50 m, 0 thereafter). In the case of the university aerial surveys, only two minke whales were seen so no detection function could be fitted. In the case of WWT aerial surveys there were just two sightings so the data were assumed to come from a strip with a half-width of 382m. The second SCANS aerial survey saw a total of 14 minke whales. The data were assumed to come from a strip with a half-width of 150 m.

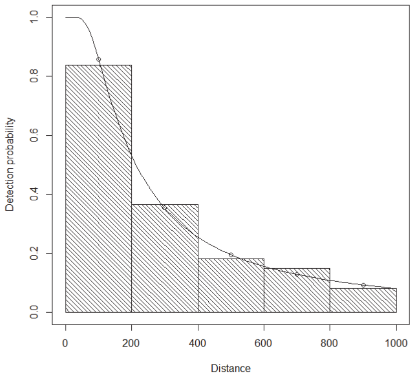


Figure 15. Detection functions for minke whales: non-ESAS boat sightings.

3.1.2 Dolphins

The spatial area for Risso's dolphins differed from that for white-beaked dolphins so two model selection procedures were undertaken for each data type, if the numbers of observations differed.

Figure 16 gives the detection functions for the single platform data from the spatio-temporal area for Risso's dolphins. There were 500 non-ESAS boat sightings over the range 0 – 800 m. The detection function with the lowest AIC was hazard rate with *SeaState* as an additional variable (no goodness of fit test possible, Figure 16a). *VesselType* also lowered the AIC but the effect was counter-intuitive, *bigboats* were associated with a higher detection probability than either *ferries* or *littleboats*. Interestingly dolphin *Species* had no effect. In the case of the ESAS boat surveys, there were 101 sightings of Risso's dolphin groups within the truncation distance of 100 m. The best fit detection function was half-normal with the additional covariate of *VesselType* (no goodness of fit test possible, Figure 16b). The university aerial surveys saw 21 groups of Risso's dolphins. The best fit detection function was a half-normal distance only model (goodness of fit: $\chi^2 = 0.15$, df = 1, $P = 0.694$, Figure 16c). In the case of the WWT new binning arrangements (n = 19), the best fit model was a hazard rate with no covariates (goodness of fit: $\chi^2 = 0.280$, df = 1, $P = 0.597$, Figure 16d). In the case of the SCANS-II aerial data, a half-normal detection function with no additional covariates was fitted over the range 0 – 300m to 60 sightings (goodness of fit: $\chi^2 = 5.61$, df = 6, $P = 0.468$, Figure 16e).

In the case of the data from the white-beaked dolphin spatio-temporal area, there were 567 non-ESAS boat sightings over the range 0 – 800 m. The detection function with the lowest AIC was hazard rate with *SeaState* as before, as an additional variable (no goodness of fit test possible, Figure 17a). Interestingly dolphin *Species* had no effect. In the case of the ESAS boat surveys, there were 180 sightings of dolphin groups within the truncation distance of 100 m. The best fit detection function was half-normal with no additional covariates (no goodness of fit test possible, Figure 17b). The university aerial data were the same as before. In the case of the WWT new binning arrangements (n = 50), the best fit model was half normal with no covariates (no goodness of fit test possible, Figure 17c). The SCANS aerial data were the same as before.

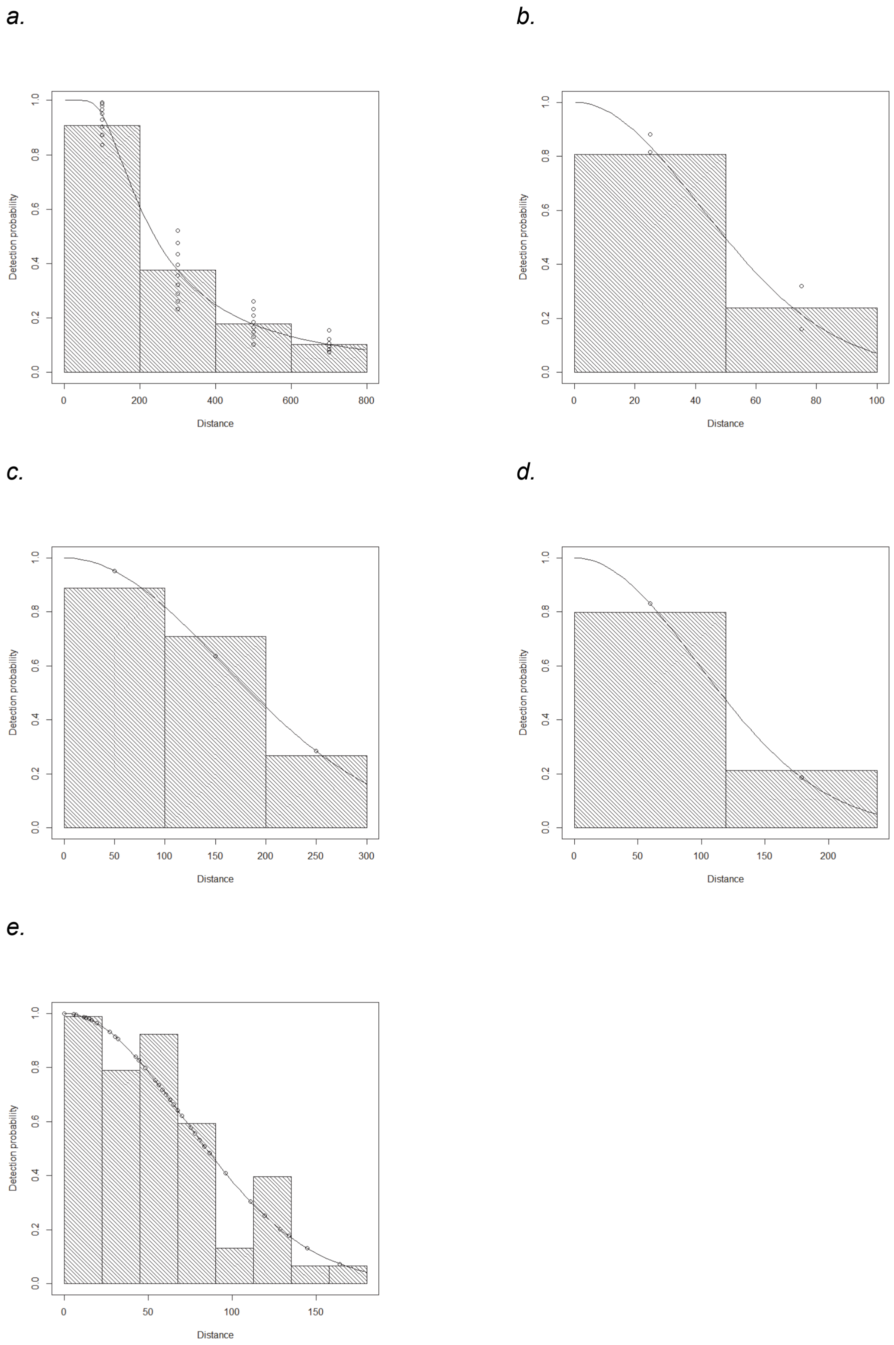


Figure 16. Detection functions for dolphins (Risso's dolphin area) for a. non-ESAS boat sightings, b. ESAS mode boat sightings, c. University of Aberdeen aerial sightings, d. WWT aeroplane sightings with the new binning and e) SCANS-II aerial sightings.

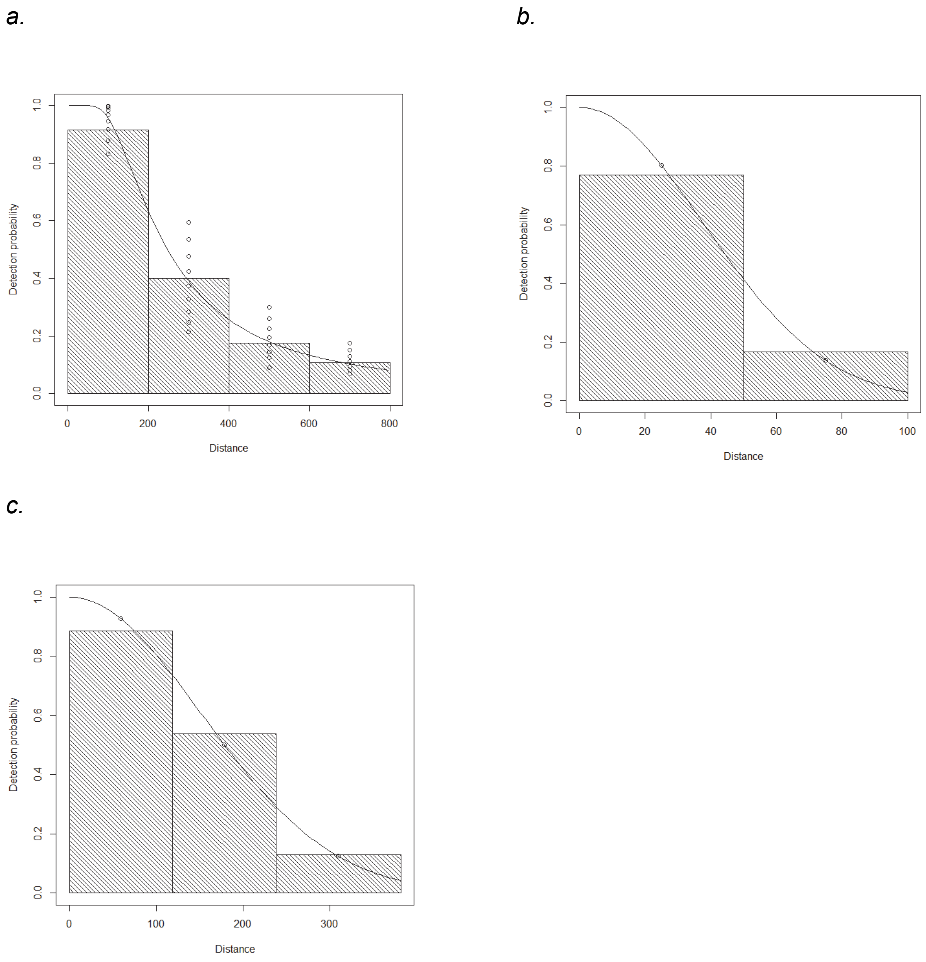


Figure 17. Detection functions for dolphins (white-beaked dolphin area) for a. non-ESAS boat sightings, b. ESAS mode boat sightings, c. WWT aeroplane sightings with the new binning.

3.1.3 Basking Shark

There were 575 non-ESAS boat sightings over the range 0 – 800 m. The detection function with the lowest AIC was half normal with *Seastate* and group size as additional variables (no goodness of fit test possible, Figure 18). Based on a single sighting from ESAS surveys, perfect detectability for basking sharks was assumed to a distance of 125m. The University of Aberdeen aerial survey saw no basking sharks. In the case of the WWT aerial surveys, there were just two basking shark sightings so a strip transect was assumed to 200 m. In the case of the SCANS and SCANS-II aerial data, they saw one basking shark each. So a strip transect was assumed of half-width 100m

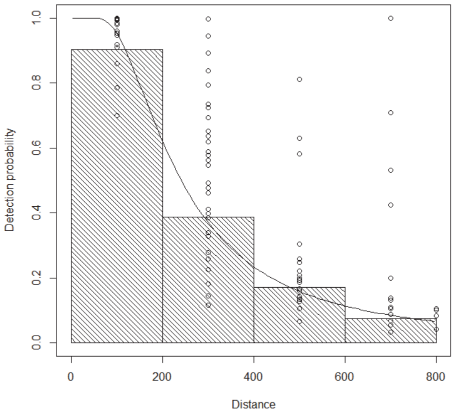


Figure 18. Detection functions for basking shark for non-ESAS boat sightings

3.2 Adjustments to Detectability

3.2.1 Detection on the Trackline (g(0))

Minke whales

No *g*(0) for *littleboats* was available so *g*(0) for *littleboats* was assumed to be the same as the estimate for *bigboats* taken from the analysis of the double platform SCANS/SCANS-II surveys. In the latter case there were 15 encounters of which a mere 8 were trials (i.e. seen by the tracker observers), and of these, 2 were seen by the primary observers. The estimate of *g*(0) was 0.255 (SE = 0.164) from the mark-recapture component of the conditional detection function (goodness of fit: $\chi^2 < 0.01$, df = 3, $P \sim 1$).

No adjustments for aerial *g*(0) were made.

Dolphins

The bigboat *g*(0) estimate was 0.555 (SE = 0.096) from 27 trials with 15 duplicate sightings (goodness of fit: $\chi^2 = 2.60$, df = 5, $P = 0.761$).

No adjustments for aerial *g*(0) were made.

Basking shark

No data on trackline detectability were available so no correction for perception bias could be made. Availability at the surface is not really a meaningful concept for basking shark because they are not obligate air breathers. Therefore no adjustment for availability bias was made either.

General comments

The estimates of perception bias were, unsurprisingly because of the data overlap, comparable with the published figures for the individual surveys. For example, *g*(0) estimates from SCANS-II boat surveys (Hammond *et al.* 2013) were comparable to the figures found here: minke whale SCANS-II 0.55 (CI: 0.23 - 0.86), dolphins: SCANS-II (common dolphin only): 0.57 (CI: 0.40 - 0.74)).

3.2.2 Availability at the surface

The sources for species availability at the surface are summarised in Table 5. Dolphin species not fully represented in Table 5 (Risso's dolphins and white-beaked dolphins), were assumed to have the same characteristics as the other species, although dive times are likely to be longer for Risso's dolphin than the other dolphin species considered here (Wells *et al.,* 2009; P. Evans, *pers. comm.*). Final group availability was unique to a particular sighting, dependent on vessel speed and the presumed window of opportunity (see Section 2.4.2): minke whale between 0.04 and 1.00; Risso's dolphin between 0.06 and 1.0 and white-beaked dolphin between 0.06 and 1.0. Table 6 shows the *potential* alterations made to each data set and Table 7 shows the effect of the availability corrected on the mean $\hat{N}$ for each survey.

Table 5. Mean surface and dive times of target species' individuals.

Species	**Mean surface time (mins)**	**Mean dive time (mins)**
Minke whale	0.067 (Anderwald, 2009)	1.311
	0.044 (Gunnlaugsson, 1989)	(from Joyce *et al.,* 1989)
	0.053 (Joyce *et al.*, 1989 off Svalbard)	
Risso's dolphin	0.058 (Evans, P., pers. comm)	
White-beaked dolphin	0.058 (Evans, P., pers. comm)	0.517 (Rasmussen, pers. comm.)

Table 6. Potential perception (P) and availability (A) bias corrections made to detection probabilities by cetacean species (if species was present) and survey.

Data set	Minke whale	Risso's dolphin	White-beaked dolphin
CRRU	*P, A*	*P, A*	*P, A*
ESAS	*P*	some *P* only, *A*	some *P* only, *A*
ESAS aircraft	*A*	*A*	*A*
Gill	-	*P, A*	*P, A*
HWDT	*P, A*	*P, A*	*P, A*
IFAW	*P,A*	*P, A*	*P, A*
IWDG	*P*	*P*	*P*
IWDG Ferry	*P*	*P*	*P*
MainstreamRP	*P, A*	*P, A*	*P, A*
MANX	*P, A*	*P, A*	*P, A*
Marinelife	*P, A*	*P, A*	*P, A*
Moray Offshore Renewables (MORL) boat	*P*	*P*	*P*
NORCET	*P*	*P*	*P*
Orca	*P*	*P*	*P*
SCANS	*P*	*P*	*P*
SCANS (air)	*A*	*A*	*A*
SCANS II	*P*	*P*	*P*
SCANS II (air)	*A*	*A*	*A*
Sea Energy Renewables Inch Cape boat	*P*	*P*	*P*
SWF	*P, A*	*P, A*	*A*
University of Aberdeen aerial	*A*	*A*	*A*
University of Aberdeen boat	*P, A*	*P, A*	*P, A*
University of Aberdeen ferry	*P, A*	*P, A*	*P, A*
University of AberdeenSAC	*P, A*	*P, A*	*P, A*
University of Aberdeen/MORL/HiDef	*A*	*A*	*A*
University of Aberdeen/MORL/HiDef/Crown Estate	*A*	*A*	*A*
University of Aberdeen ferry	*P*	*P*	*P*
WDC	*P, A*	*P, A*	*P, A*
WWT	*A*	*A*	*A*

Table 7. Mean $\hat{D}$ per segment with and without an availability correction. Red indicates a change in mean value.

Survey	**Minke whale**		**Risso's dolphin**		**White-beaked dolphin**	
	Without correction	With correction	Without correction	With correction	Without correction	With correction
CRRU	0.209	0.790	0.009	0.012	0	0
ESAS	0.054	0.054	0.006	0.006	0.181	0.181
ESASaircraft	-	0	0	0	0	0
Gill	-	-	1.809	1.885	0.194	0.218
HWDT	0.059	0.156	0.004	0.005	0.175	0.183
IFAW		-	-	-	0	0
IWDG	0.002	0.002	0.001	0.001	0	0
IWDG Ferry	0	0	0	0	0	0
MainstreamRP	<0.001	<0.001	0	0	0.003	0.001
Manx	-	-	0.176	0.267	0	0
Marinelife	0	0	0	0	0	0
Moray Offshore Renewables boat	0.052	0.052	<0.001	<0.001	0.008	0.008
NORCET	0.013	0.013	0.003	0.003	0.033	0.033
Orca	0.023	0.041	0	0	0	0
SCANS	-	-	0.020	0.020	0.079	0.125
SCANS (air)	-	-	0	0	0	0
SCANS II	0.124	0.124	0.006	0.006	0.079	0.079
SCANS II (air)	0.005	0.073	0	0	0	0
Sea energy renewables Inch Cape boat	0.076	0.076	0	0	0.024	0.024
SWF	0.180	0.227	0.063	0.063	0.025	0.054
UOA aerial	<0.001	0.003	0	0	0.002	0.003
UAO boat	0.124	0.124	0	0	0	0
UOA ferry	0.035	0.035	0.003	0.003	0.003	0.003
University of Aberdeen SAC	0.037	0.320	0	0	0	0
UOA/MORL/HiDef	0	0	0	0	0	0
UOA/MORL/HiDef/Crown Estate	0.015	0.380	0	0	0	0
WDC	0	0	0.071	0.117	0	0
WWT	<0.001	0.004	0	0	0.021	0.145

3.3 Realized Effort

Realized survey effort by vessel type for white-beaked dolphins is given in Figure 19, while Figures 20 and 21 give the quantity of realized survey effort per 5 × 5 km cell over the region of interest by year and by season respectively. There is confounding of location and survey vessel type, with ferries traversing the same region repeatedly and aerial effort primarily in coastal regions. There is greater effort in more recent years and, unsurprisingly, during the summer. There is relatively little effort in the western and north-western approaches. In more recent years survey effort has been concentrated in regions of potential offshore development interest (e.g. later images in Figure 20).

The annual and seasonal breakdown of effort frequency since 1994 is given in Figure 22.

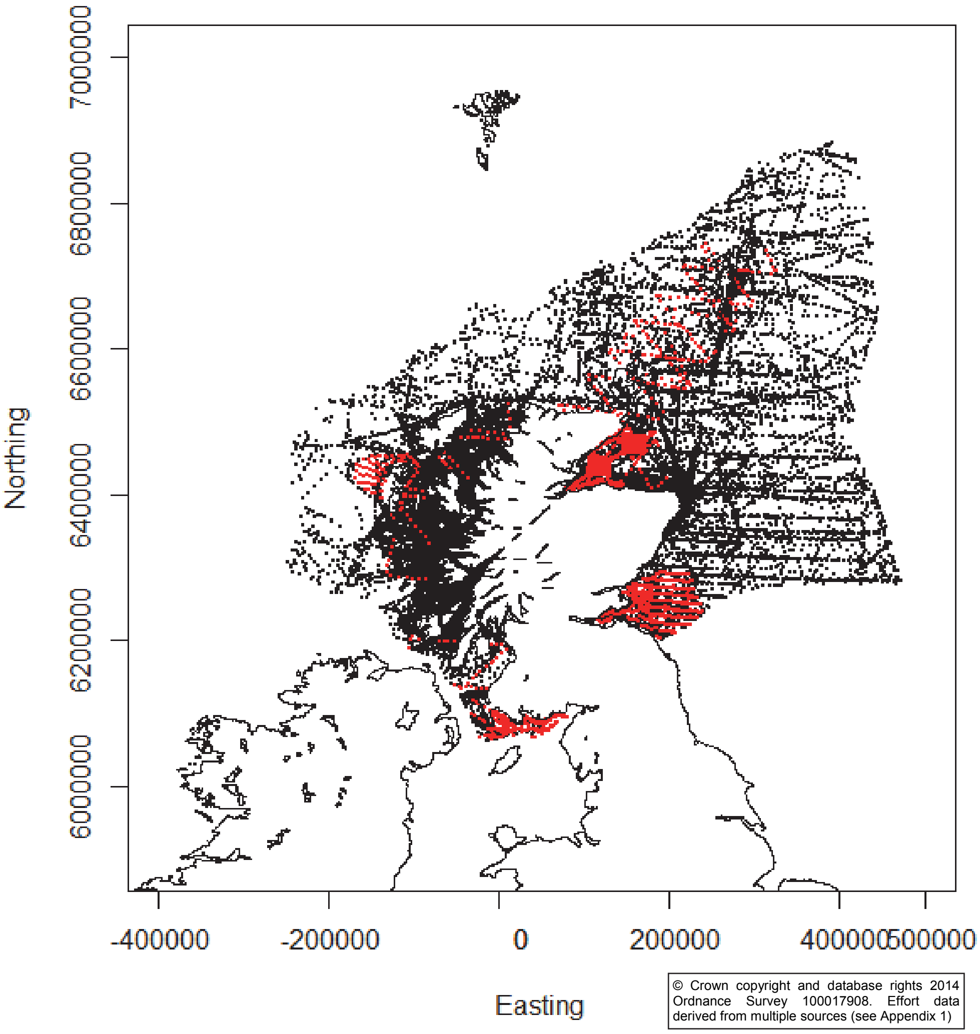


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Figure 19. Realized effort for white-beaked dolphin by platform type. Each point represents the midpoint of a segment of effort from the period 1994 – 2012: black is boat effort and red is aeroplane effort. White-beaked dolphin effort is illustrated as the data input area for this species had the greatest extent and includes all the effort for the other species, except around the Isle of Man.

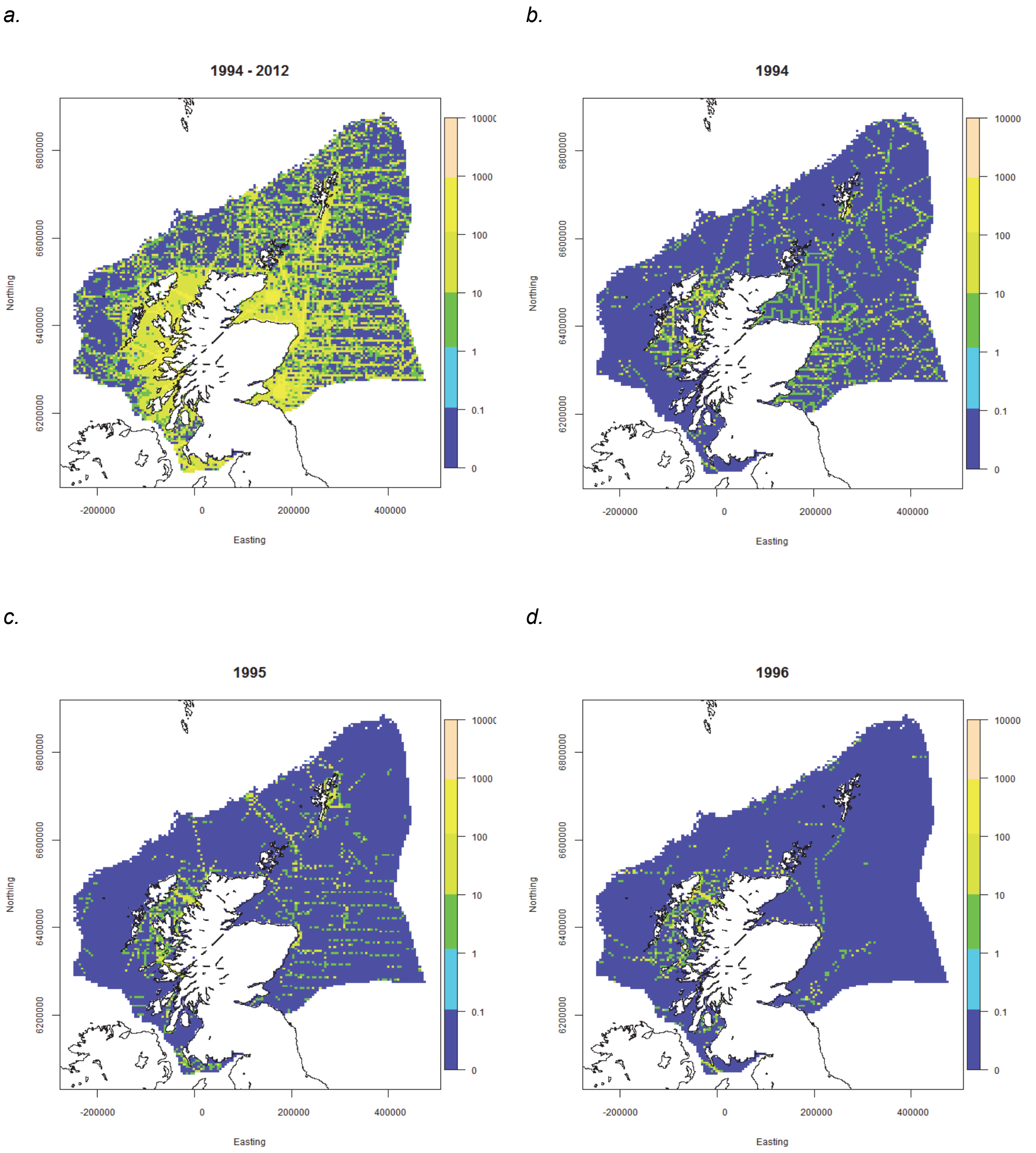

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Figure 20. Realized effort over the white-beaked dolphin data input area: a. all years 1994 - 2012, b. 1994, c. 1995, and d. 1996. Colours represent effort as distance travelled (km) per grid cell over the appropriate period in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

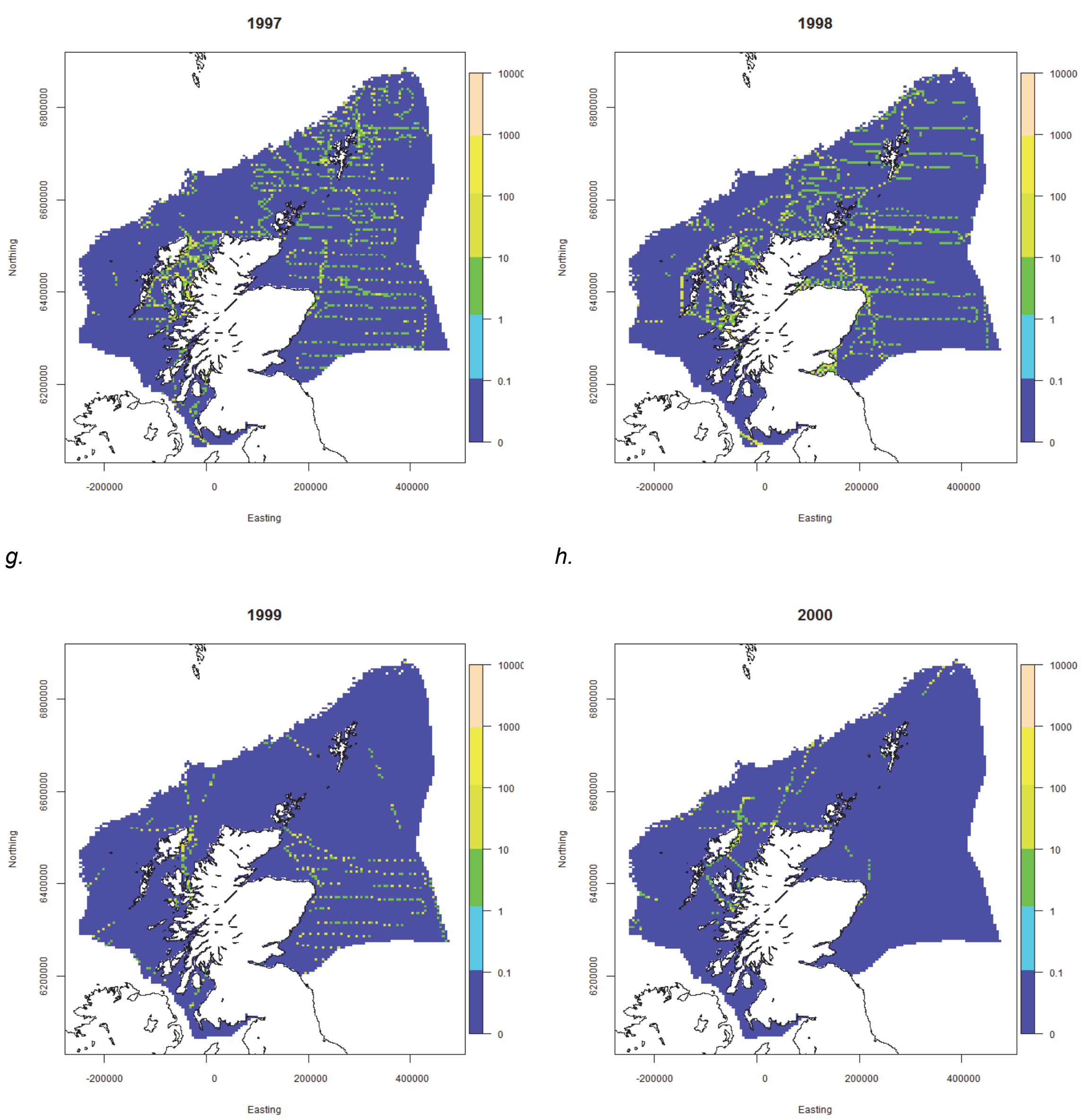
e. f. g. h.

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Figure 20 continued. Realized effort over the white-beaked dolphin data input area: e. 1997, f. 1998, g. 1999, and h. 2000. Colours represent effort as distance travelled (km) per grid cell over the appropriate period in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

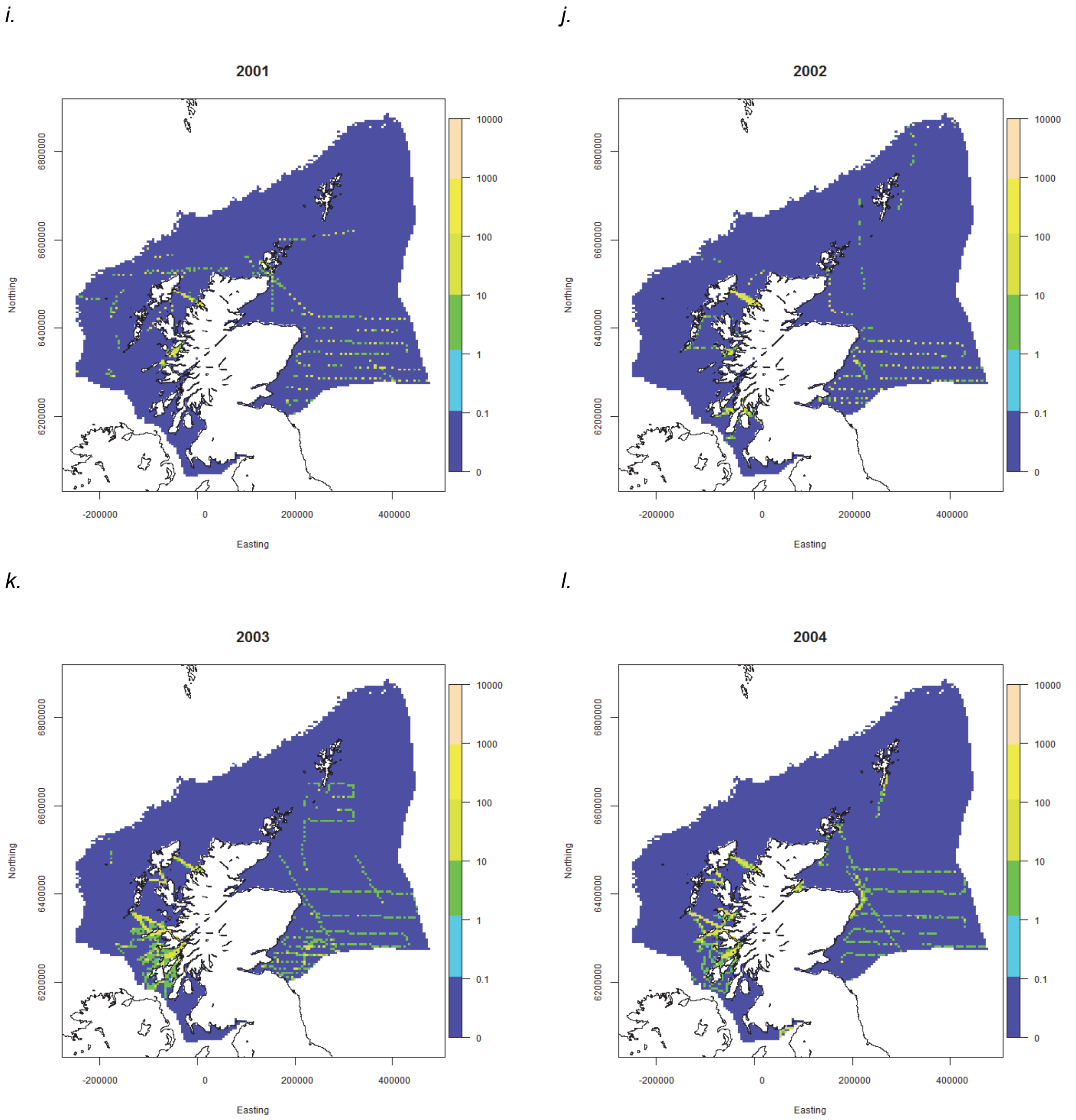

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Figure 20 continued. Realized effort over the white-beaked dolphin data input area: i. 2001, j. 2002, k. 2003, and l. 2004. Colours represent effort as distance travelled (km) per grid cell over the appropriate period in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

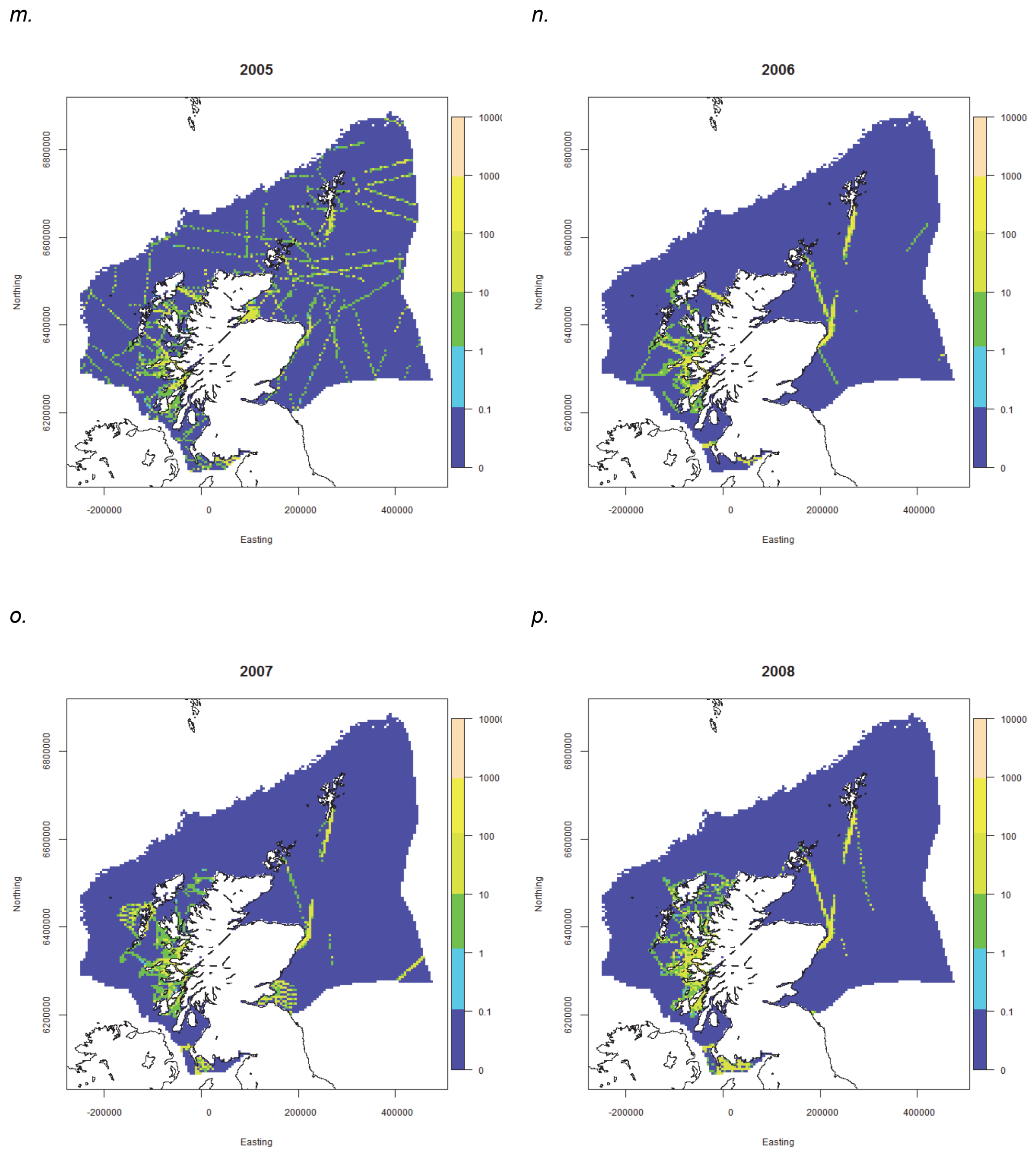

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Figure 20 continued. Realized effort over the white-beaked dolphin data input area: m. 2005, n. 2006, o. 2007, and p. 2008. Colours represent effort as distance travelled (km) per grid cell over the appropriate period in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

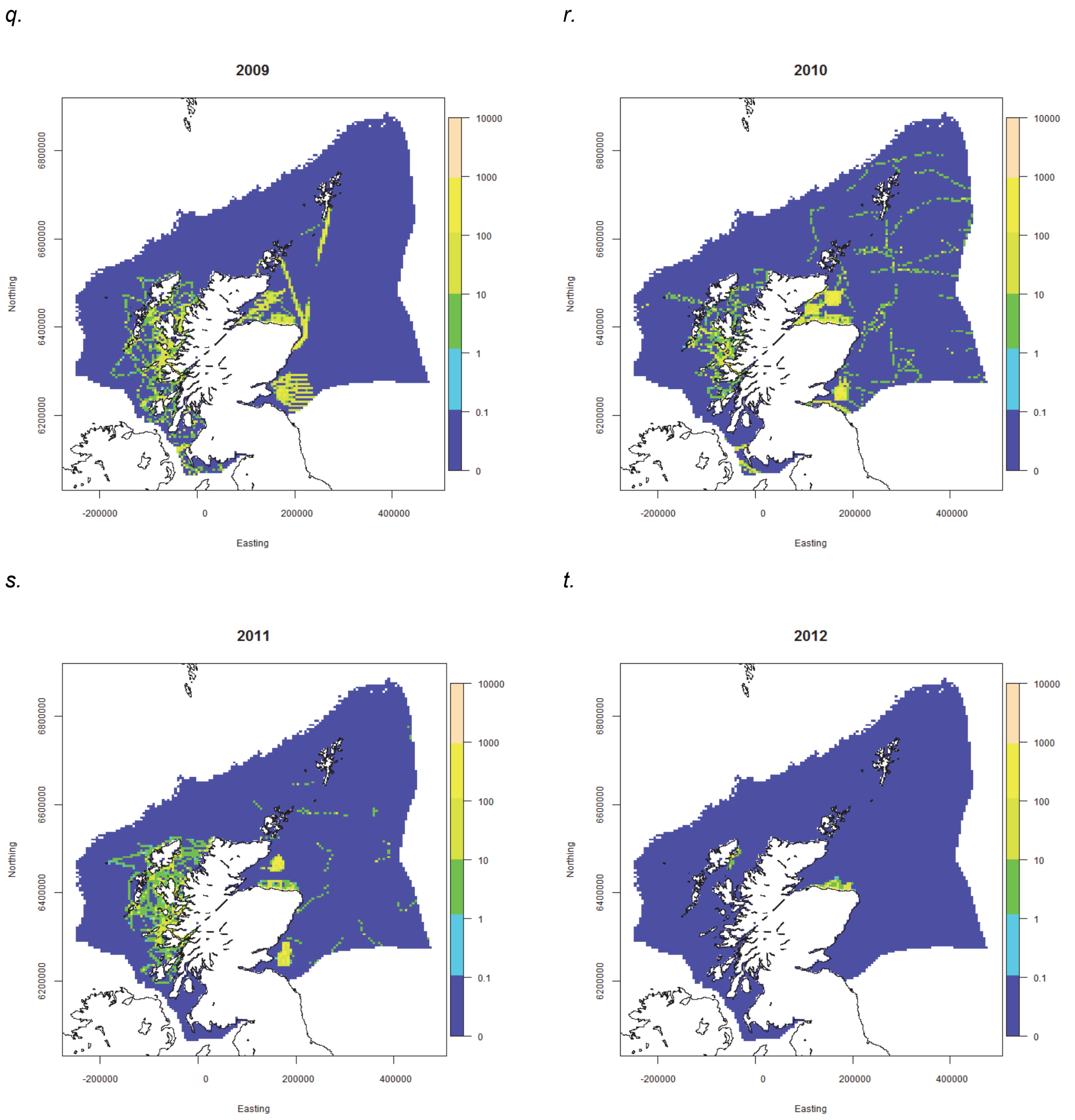

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Figure 20 continued. Realized effort over the white-beaked dolphin data input area: q. 2009, r. 2010, s. 2011, and t. 2012. Colours represent effort as distance travelled (km) per grid cell over the appropriate period in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

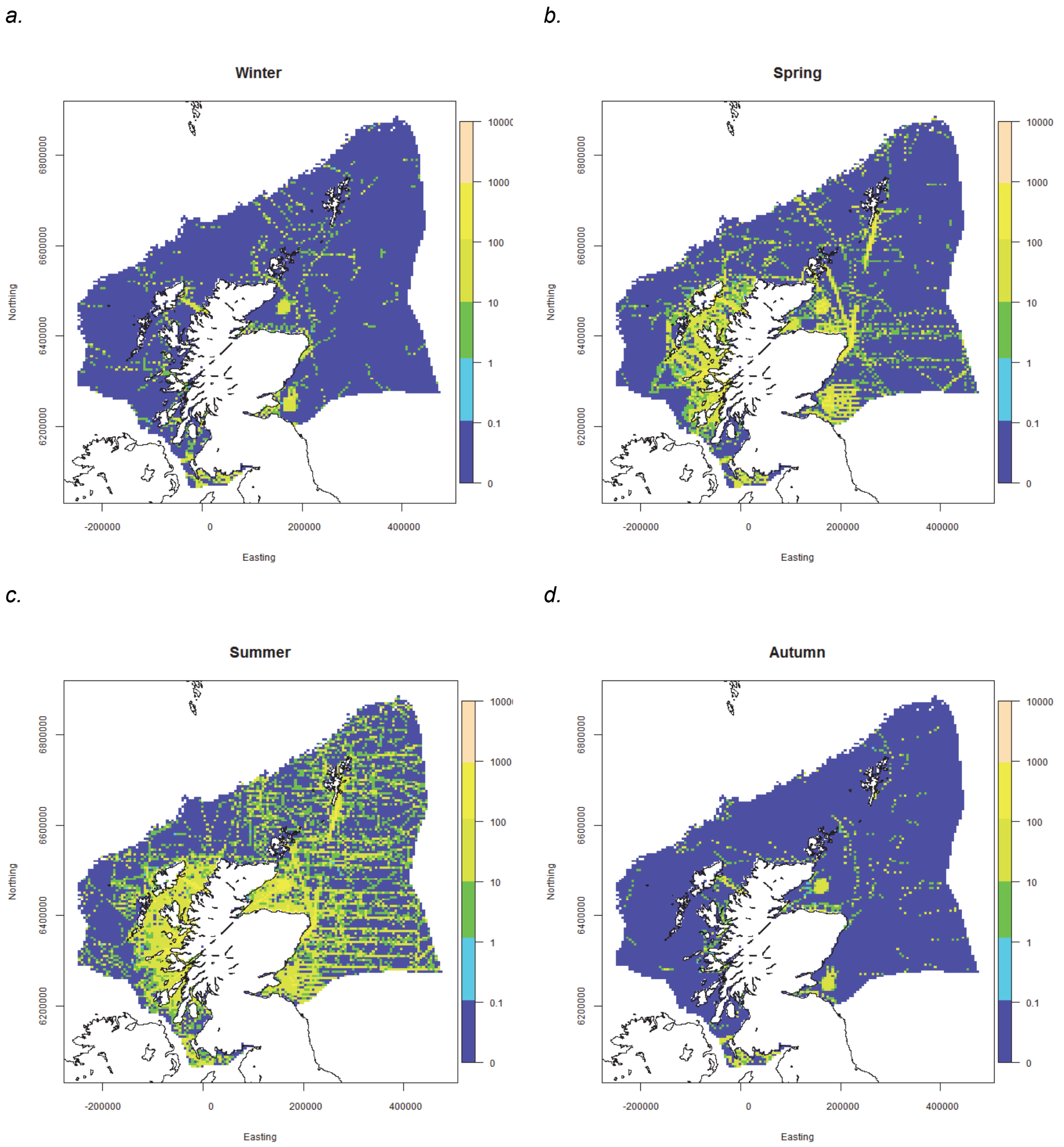

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Figure 21. Realized effort over the white-beaked dolphin data input area. a. Winter (Jan. – Mar.), b. Spring (Apr. – Jun.), c. Summer (Jul. – Sep.) and d. Autumn (Oct. – Dec.). Colours represent effort as distance travelled (km) per grid cell over the relevant season 1994 - 2012 in conditions of sea state 4 or less (with the addition of some aerial effort at sea state 6 or less). Each cell is 5 by 5 km.

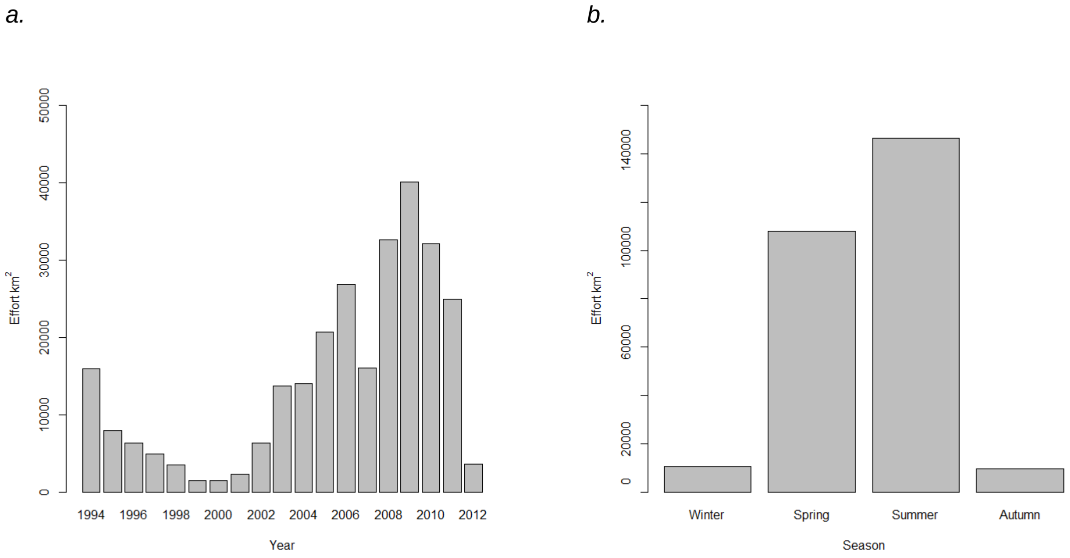

Figure 22. Aspects of the effort in the white-beaked dolphin data input area. a. Realized effort by year across all surveys, b. Realized effort by season across all surveys (areas of segments km^2).

3.4 Spatial Modelling

Table 8 gives the summarised details of the models fitted for each species. In each case the initial considered variables and final chosen variables are given along with two measures of model fit. Note that these are models for prediction and should not be interpreted as a definitive statement of the potential influence of a given explanatory variable because the response to a variable is conditional on the presence of other variables in the model. The individual results for each species are discussed below. In each case adjusted, observed densities ($\widehat{D}$) over the entire range of the data are shown along with seasonal and some annual predictions with the related confidence surfaces. It should be noted that there are few data available for winter and autumn in every case, so the models draw on information from other times of the year. The models also interpolate spatially into regions of low effort.

The upper bound of the coloured scale in the relative density plots (Figures 23 to 28, 32 to 39, 43 to 50, & 54 to 59) reflects the highest observed adjusted density or the upper bound of the 97.5% confidence surface. Note that the highest relative density class may not actually be visible as the number of cells of that density class may be very small. Care should be taken in the interpretation of the density plots. The following points should be considered.

a) The $\widehat{D}$ surface (top left hand side) provides a summary of the relevant input data for the prediction both in terms of adjusted observed densities but also shows where there was actually effort (albeit not necessarily from the year in question) in that season. Predictions in regions of low effort should be treated with caution.

b) The point estimate surfaces (top right hand side) should be considered along with the estimated uncertainty surfaces (bottom row). Of particular interest is the lower bound and whether that is substantially more than zero in the region of interest as this is robust evidence of high relative density in the region.

c) Single predictions over very small areas are generally more likely to be biased than predictions over larger areas. So isolated small regions should be treated with caution.

d) Summer is the most effort rich season so it is perhaps conservative to base conclusions primarily on this season, although of course there could be seasonal changes in distribution.

For example in Figure 24 for minke whale (spring), the predicted high density region to the south of Arran and the band south-west of the Outer Hebrides is not supported by any spring effort and is associated with great uncertainty. However, in the summer (Figure 25) there is some (limited) effort to the south-west of the Hebrides and animals are seen in non-negligible quantities. The predicted hot spot to the south of Arran is supported by two locations where minke whales were seen, but it is a very small area and so the predictions may be inaccurate (see Section 2.5.6 and Figure 29). In spring and summer the lower bound in these regions is often greater than 0.1 animals km^{-2}. Also in both seasons, the predicted regions of high density north of Aberdeenshire and in the Sea of the Hebrides are supported by effort, but the lower bound confidence surface in summer suggests that the predicted density may not necessarily be that high north of Aberdeenshire, except for a few cells.

The persistence-certainty plots (Figures 30, 41, 52 & 61) also provide information on areas of persistent higher densities reflecting both persistence in time and the uncertainty in the predictions and hence provide a summary of all the available information with the caveat that they identify areas of merely higher than average density rather than high density *per se*.

For example the persistence-certainty plot for minke whale (Figure 30) suggests animals were found consistently at higher than average density in the four regions previously mentioned. Therefore it seems reasonable to conclude that with the existing data, a region of relatively high summer minke whale density is well supported for a small area of the Sea of the Hebrides (predicted densities high and persistent, lower bound of confidence above 0.1 animals km^{-2} in a region well supported by summer effort), whereas the regions north of Aberdeenshire (high predicted persistent density, some effort but low lower confidence bound) and south of Arran and south-west of the southern Outer Hebrides (high and persistent predicted density but a lack of effort) should be regarded as less well supported but perhaps worthy of further investigation. Note that a high persistence-certainty score only suggests a cell was persistently above average in density, not necessarily a persistent “very high” density, however that term might be defined.

Table 8. Initial and final models for each species

Species	**Temporal Range**	**Initial Candidate Variables**	**Final Model**	**Concordance correlation**	**Marginal R^2**
Minke whale N = 43306	March-November 2000 – 2012	*Sediment, Depth, Year, Front, Tidal Energy, SST* & Chloro*	*Depth, Year, Front, TidalEng, SST, Chloro & Position*	0.08	0.04
Risso's dolphin N = 52191	All seasons 1994 – 2012	*Sediment, Depth, Year, Front, Tidal Energy & SST**	*Sediment , Depth, Year, Front, SST & Position*	0.12	0.08
White-beaked dolphin N = 55056	All seasons 1994 – 2012	*Sediment, Depth, Year, Front, Tidal Energy & Dayofyear***	*Sediment, Depth, Year, TidalEng & Dayofyear* [a]	0.02	0.01
Basking shark N = 33896	May – November 2000 – 2012	*Sediment, SharkSurvey, Depth, Year, Front, TidalEnergy, SST* & Chloro**	*Sediment, SharkSurvey, Depth, Year, Front, TidalEng & SST*	0.12	0.07

**Dayofyear also considered as substitutes for SST. **SST also considered as substitutes for Dayofyear. [a]2D smooth with workable bootstraps could not be fitted.*

3.4.1 Minke whale

The adjusted observed densities ($\hat{D}$) from all of the available data (spring - autumn) are given in Figure 23. Observed seasonal densities along with predictions and confidence intervals for spring, summer and autumn 2005, are given in Figures 24 to 28. Predicted surfaces for summer of 2001 and 2012 are also provided. The selected model is given in Table 8.

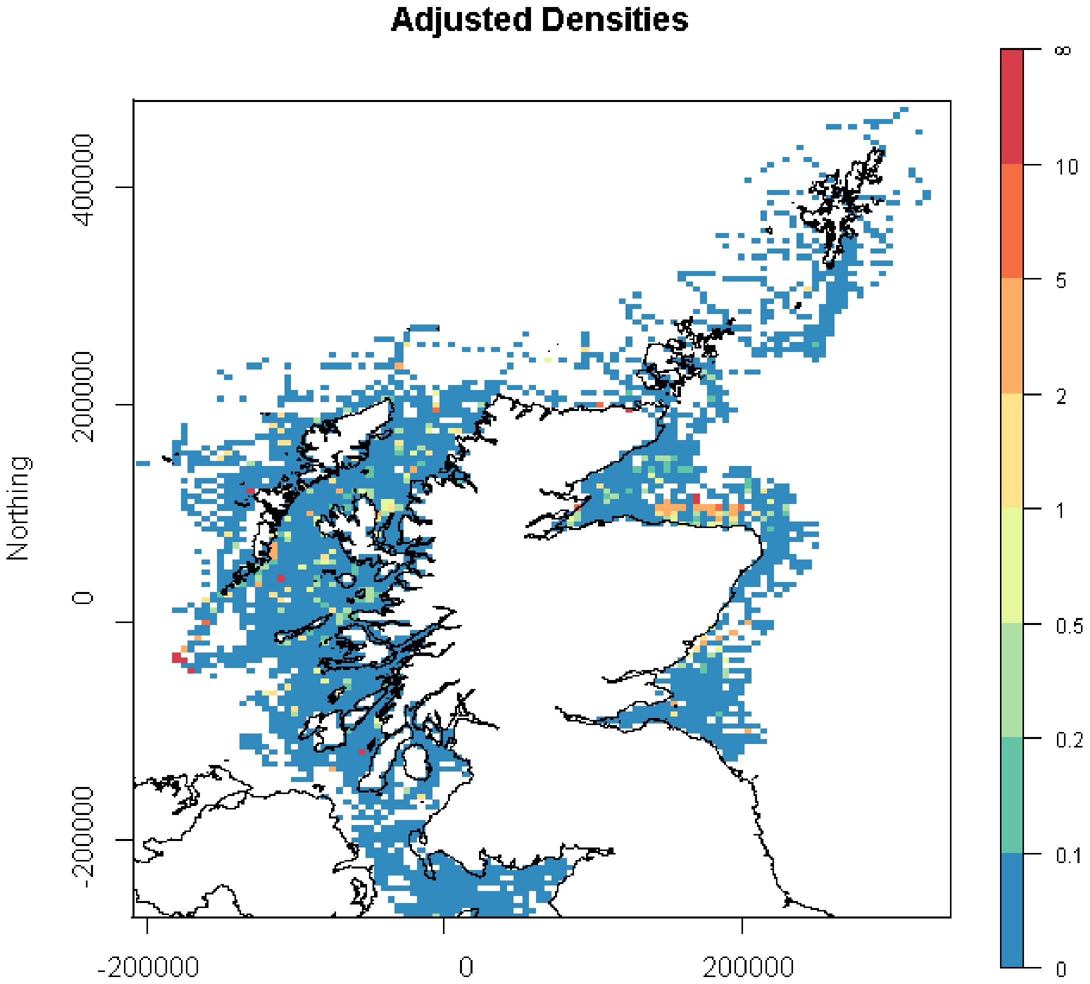

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Figure 23. Observed adjusted relative densities ($\hat{D}$) of minke whale 2000 – 2012 All seasons. Colours indicate animals km^{-2}. Each cell is 5 by 5 km.

A model equivalent to the final selected model but with a position year interaction was associated with a higher CV score suggesting patterns in distribution, not described by the other predictors, were consistent across years.

The coefficient of variation of the abundance estimate derived from the bootstrap, not including model selection uncertainty, (n = 500) was quite high at 0.79. The coefficient of variation associated with the bootstrap incorporating model selection uncertainty (n = 105) was an extremely high 4.27. One cell of the surface was not included as it was consistently associated with huge predictions because of a unique covariate combination which would have inflated the coefficient of variation.

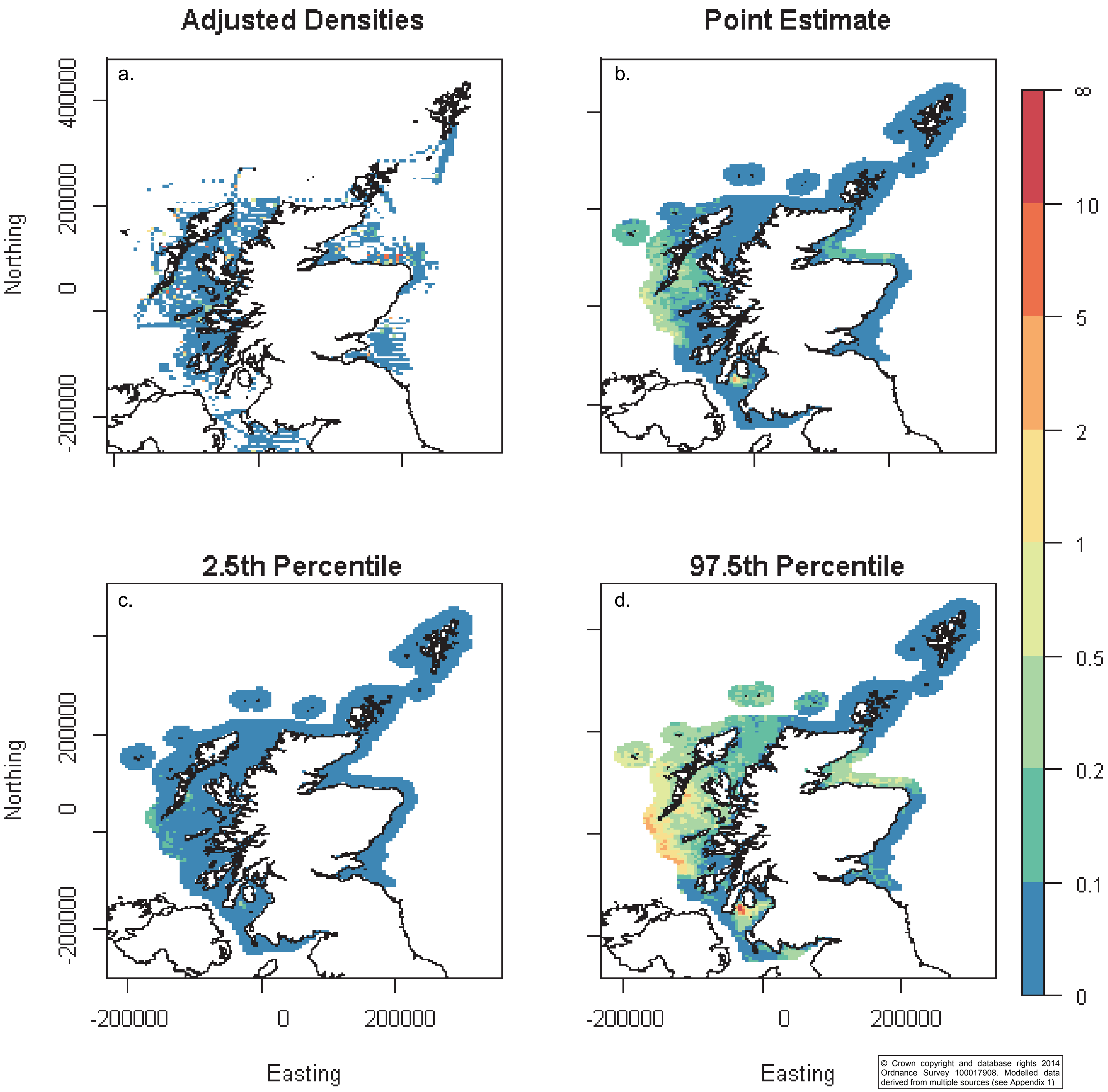

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Figure 24. Minke whale, spring 2005: a. Observed adjusted spring (2000 - 2012) densities ($\hat{D}$) of minke whale b. Estimated density surfaces for minke whale on May 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

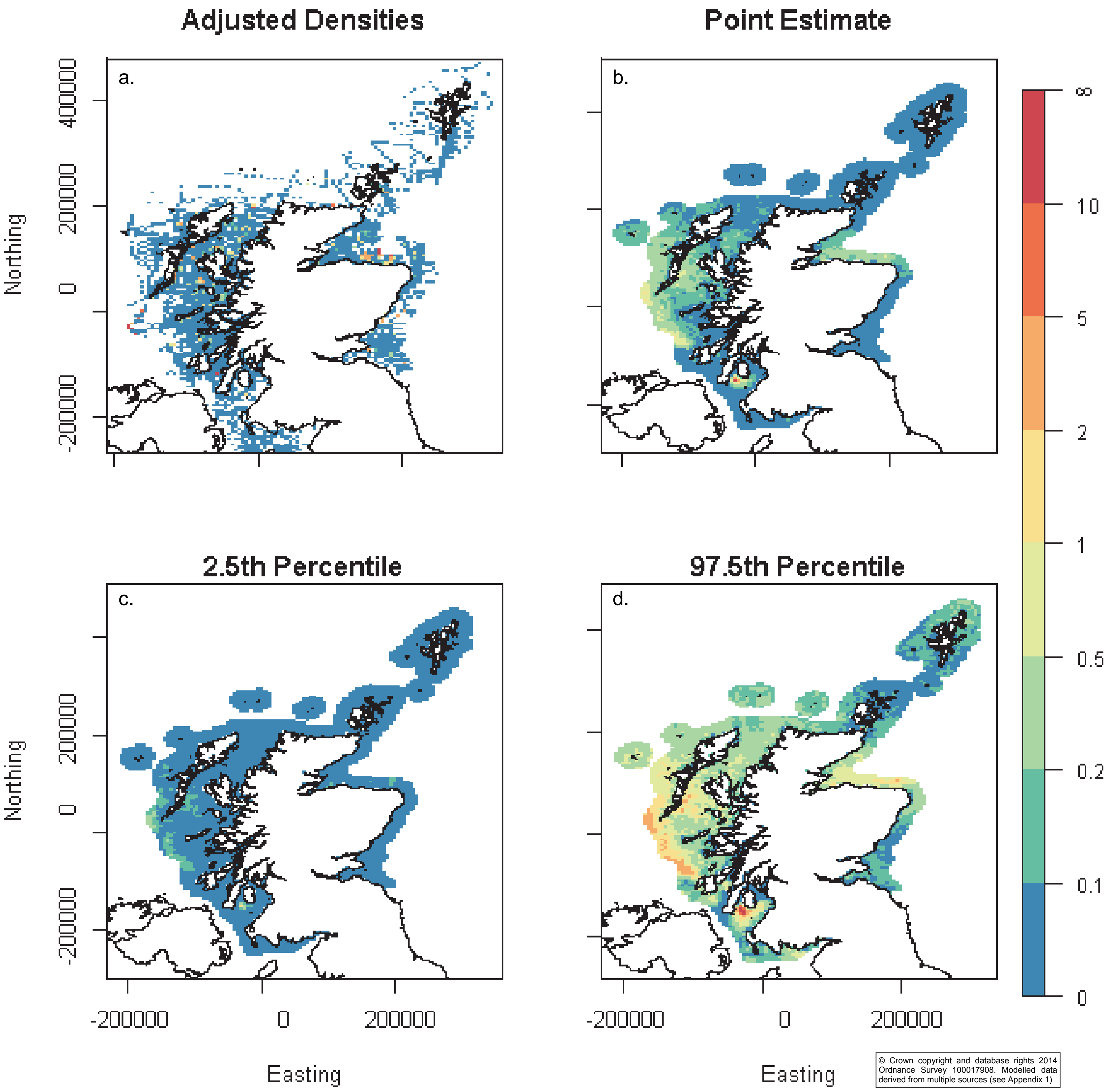

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Figure 25. Minke whale, summer 2005: a. Observed adjusted summer (2000 – 2012) densities ($\hat{D}$) of minke whale. b. Estimated density surfaces for minke whale on August 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

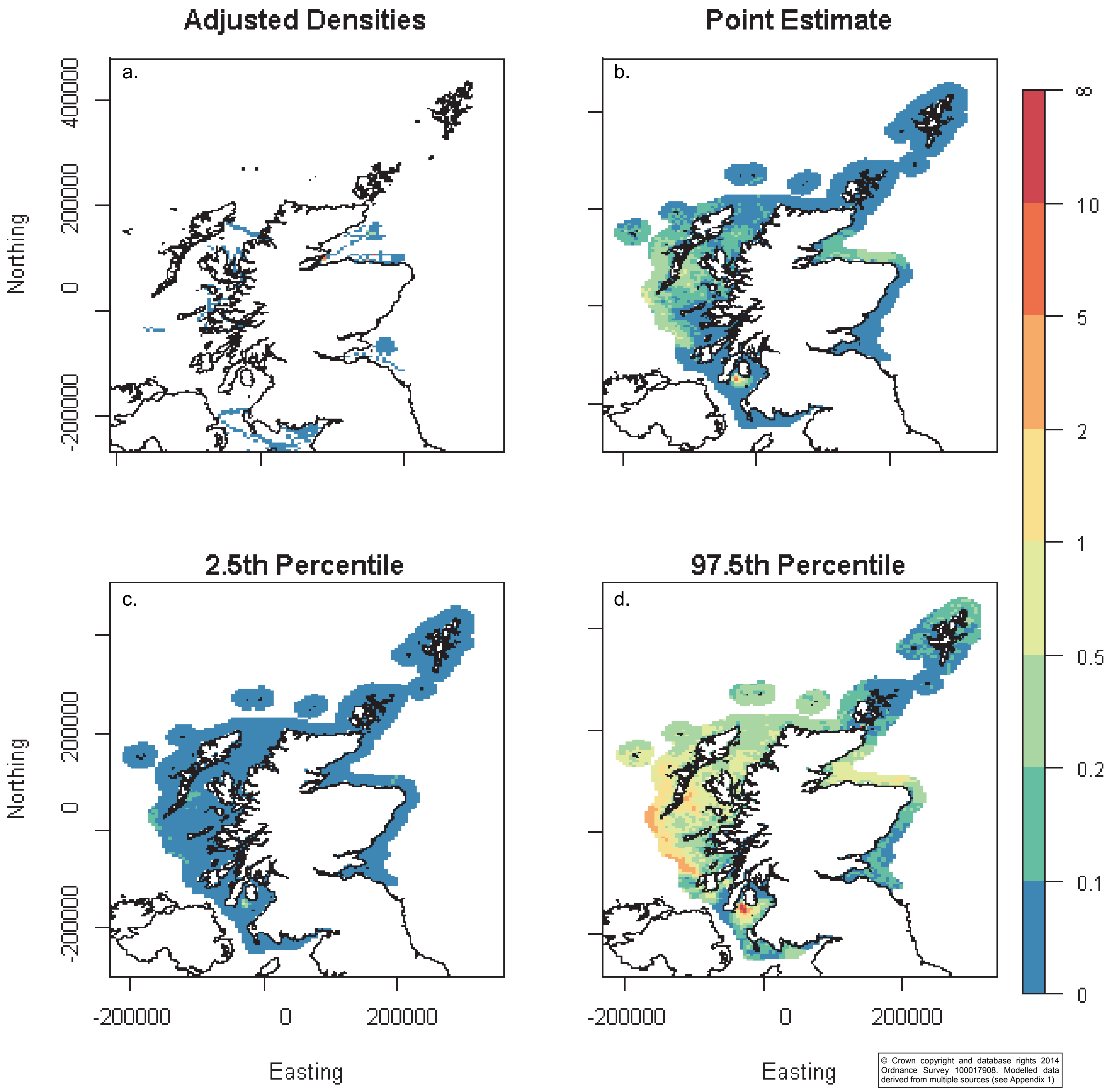

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Figure 26. Minke whale, autumn 2005: a. Observed adjusted autumn (2001 - 2012) densities ($\hat{D}$) of minke whale. b. Estimated density surfaces for minke whale on November 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

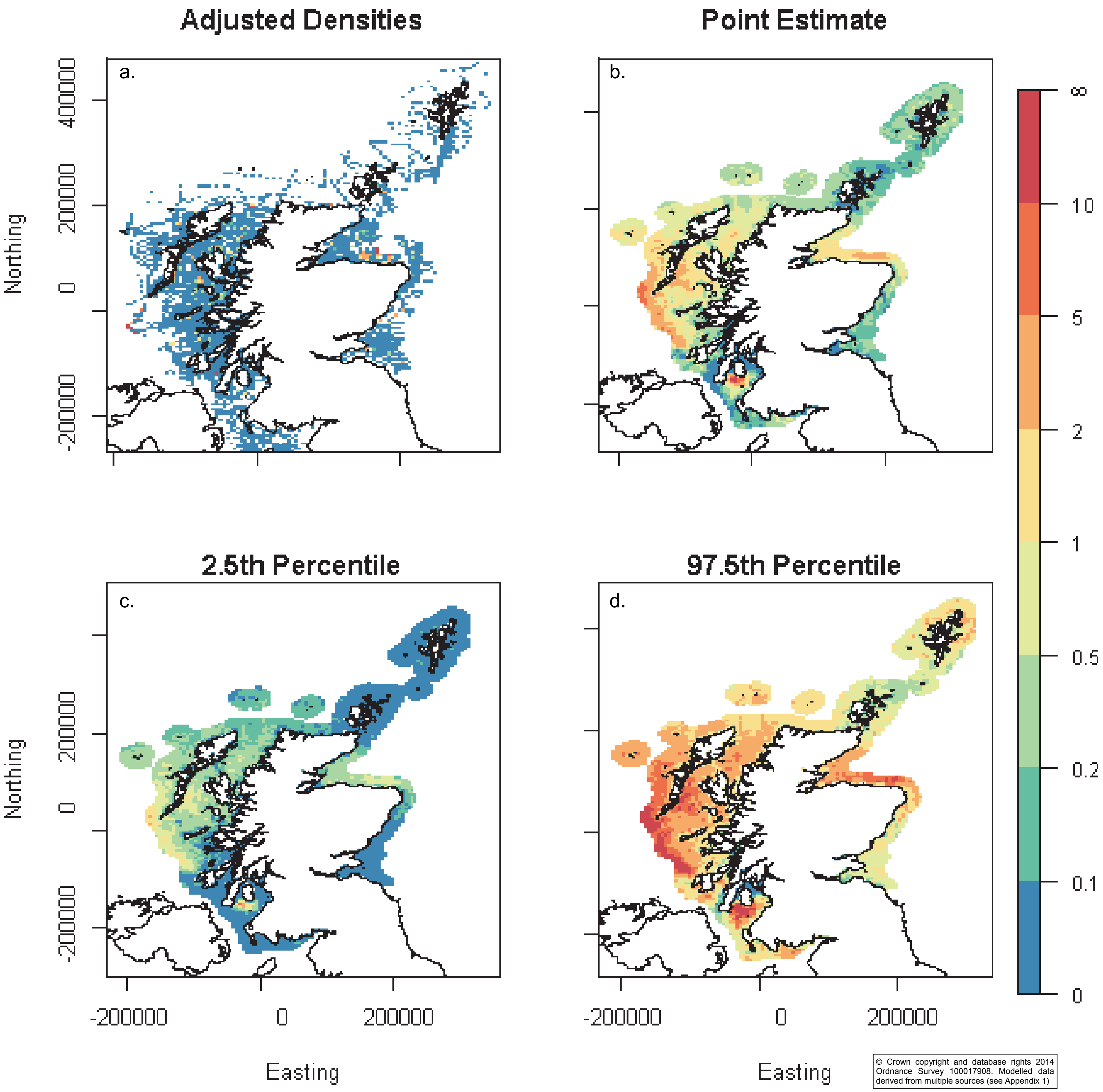

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Figure 27. Minke whale, summer 2001: a. Observed adjusted summer (2000 – 2012) densities ($\hat{D}$) of minke whale. b. Estimated density surfaces for minke whale on August 15th 2001. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

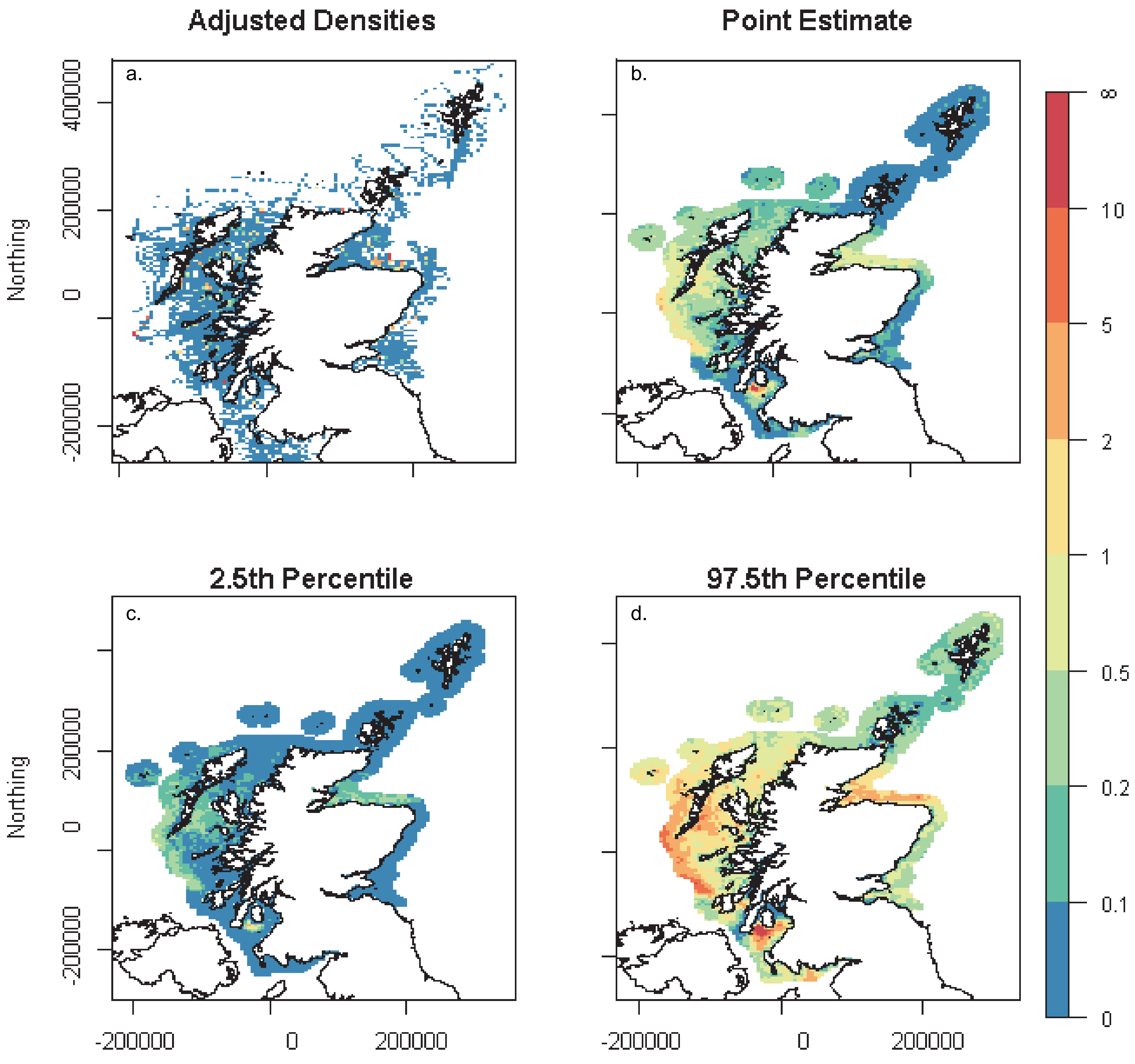

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Figure 28. Minke whale, summer 2012: a. Observed adjusted summer (2000 – 2012) densities ($\hat{D}$) of minke whale. b. Estimated density surfaces for minke whale on August 15th 2012. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

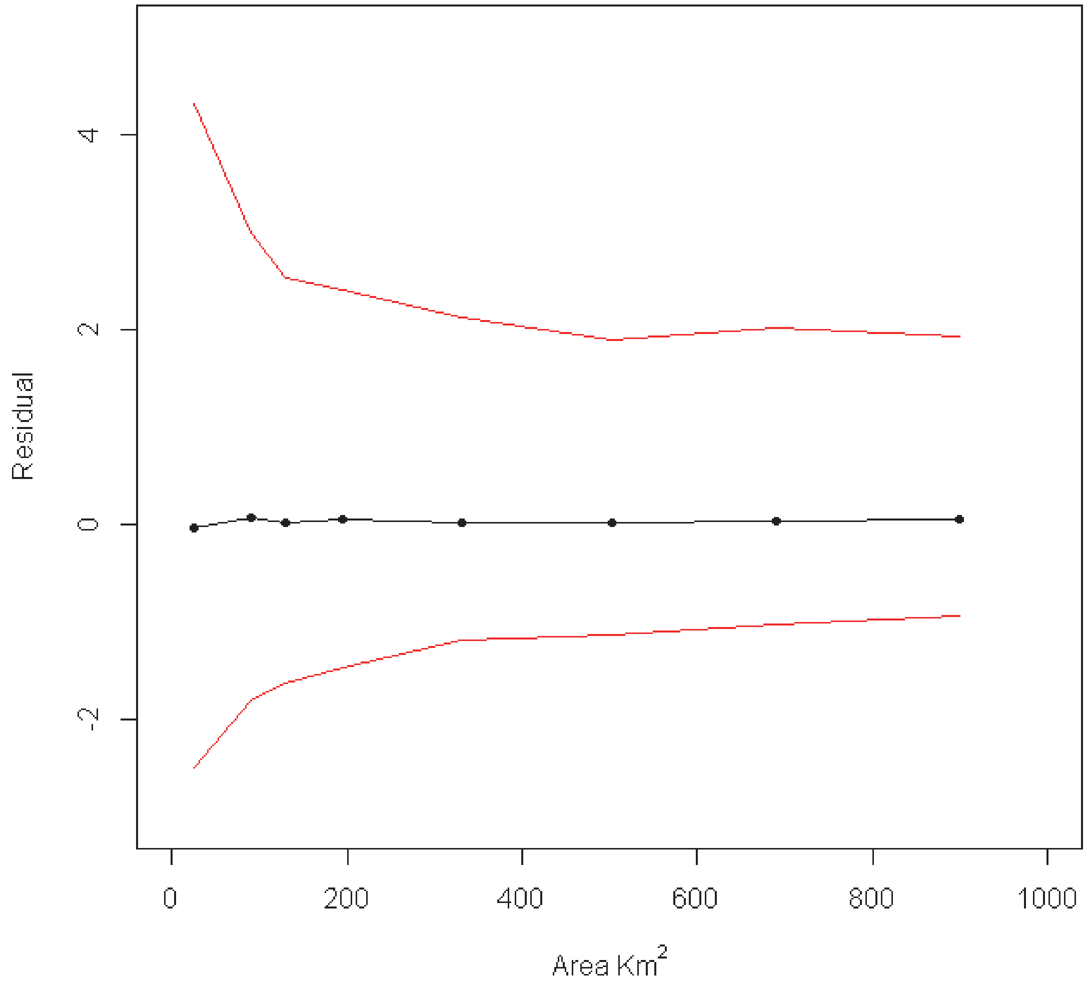

Figure 29. Residuals of minke whale density as a function of area. Black line and points: mean value, red lines: lower and upper 95% confidence bounds.

Figures 24 – 28 suggests that the areas to the south of Arran, south-west of the Hebrides, the Sea of the Hebrides and north of Aberdeenshire are regions of higher density for this species (see discussion in Section 3.4).

Figure 29 gives the results of investigation of bias in the predictions. Because the localities were randomly located, the actual realized area was sometimes less than the target area (as some selected areas overlapped the edges of the prediction region or on land). The realized areas were approximately 25, 90, 129, 195, 331, 503, 689, 899 km^2. Unsurprisingly overall uncertainty in the residuals, decreased with larger areas as more residuals were associated with a greater considered area. Therefore a single prediction from a larger area would be less likely to be biased than a prediction made over a smaller area.

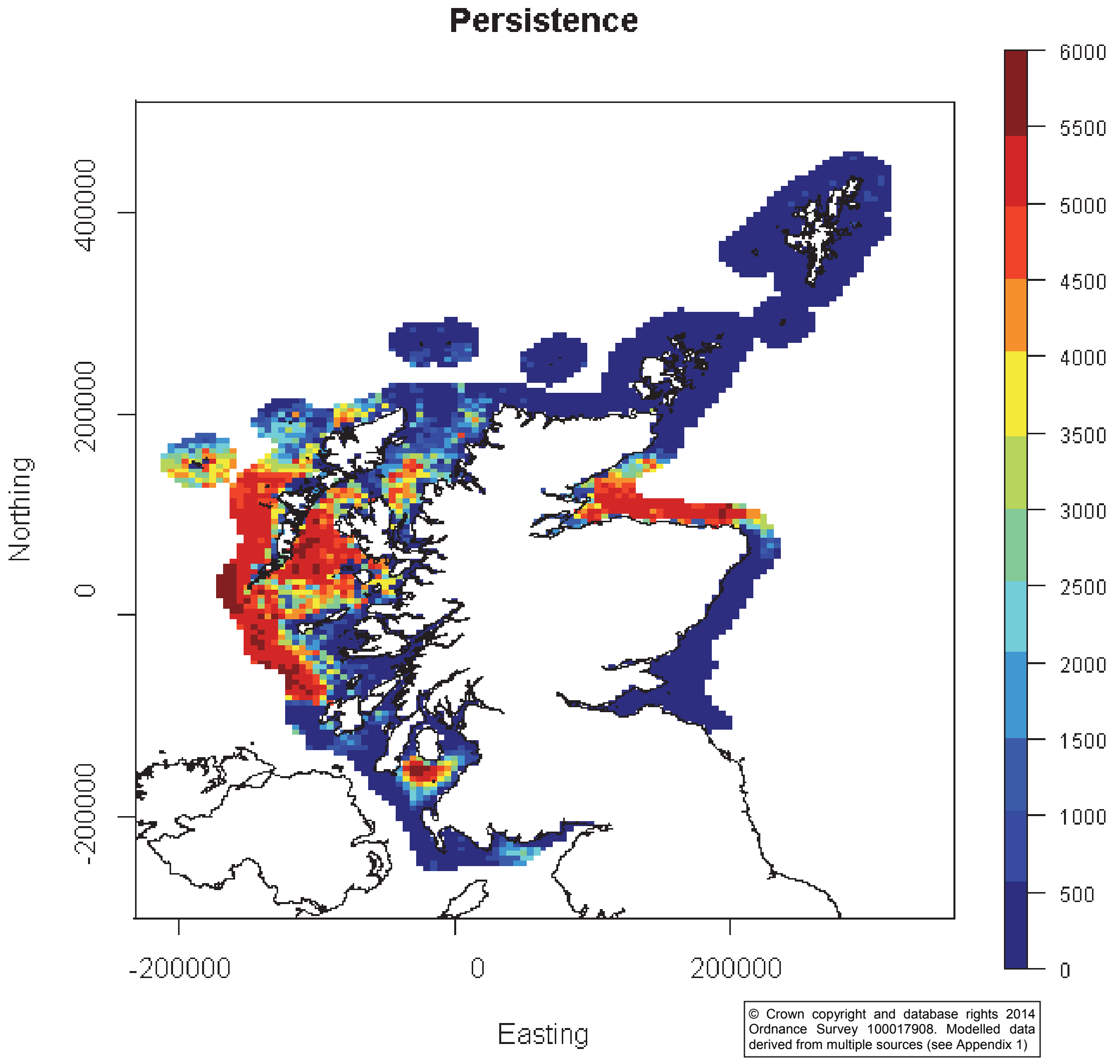

Figure 30. Index of predicted minke whale persistence-certainty summers 2001 – 2012. Colours indicate persistence of above mean density on a score 0 to 6000. Each cell is 5 by 5 km.

Figure 30 suggested surprisingly high persistence-certainty scores in regions of low effort (e.g. to the west of the Hebrides). To investigate this further the variance in cell predictions across years was plotted against effort in the cell to confirm there really was a correlation of effort and uncertainty (Figure 31). There was a weak inverse correlation (-0.035) of effort and prediction cell variance (df= 3599, P=0.036), indicating variation is highest in regions of low effort as one might expect. So it appears that the high predicted density is a persistent prediction of the environmental covariates in that region, given the response to those predictors in the rest of the data set. Note that the high persistence score only suggests persistent above average density rather than persistent high density.

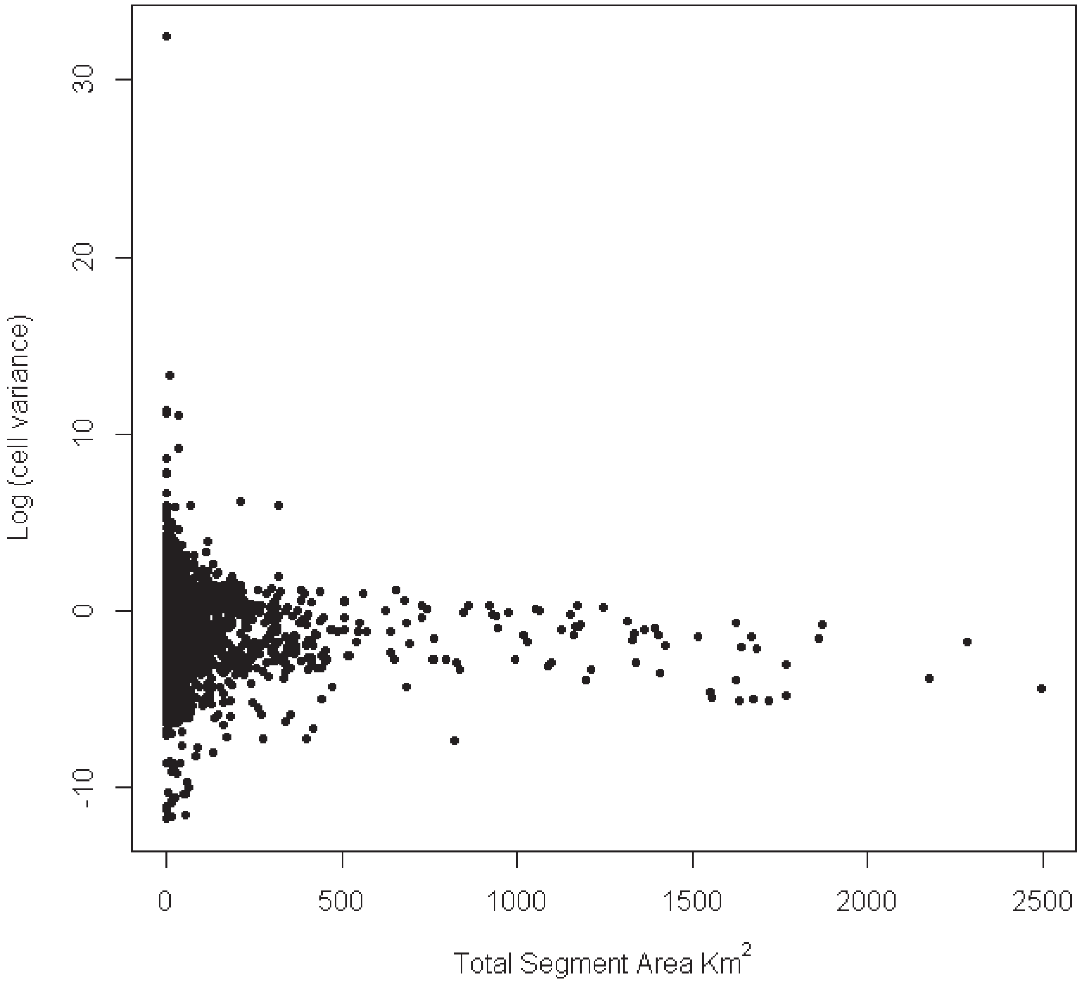

Figure 31. Prediction cell variance and per cell effort (measured as area) for minke whale.

3.4.2 Risso's dolphin

The adjusted observed densities ($\hat{D}$) for each season (across all years, Figure 32) along with predictions and confidence intervals for winter, spring, summer and autumn 2005 and summers 1994, 2001 and 2012 are given in Figures 33 to 39. The selected model is given in Table 8. The confidence intervals incorporated uncertainty in the detection function, estimated perpendicular distances and uncertainty in the spatial model.

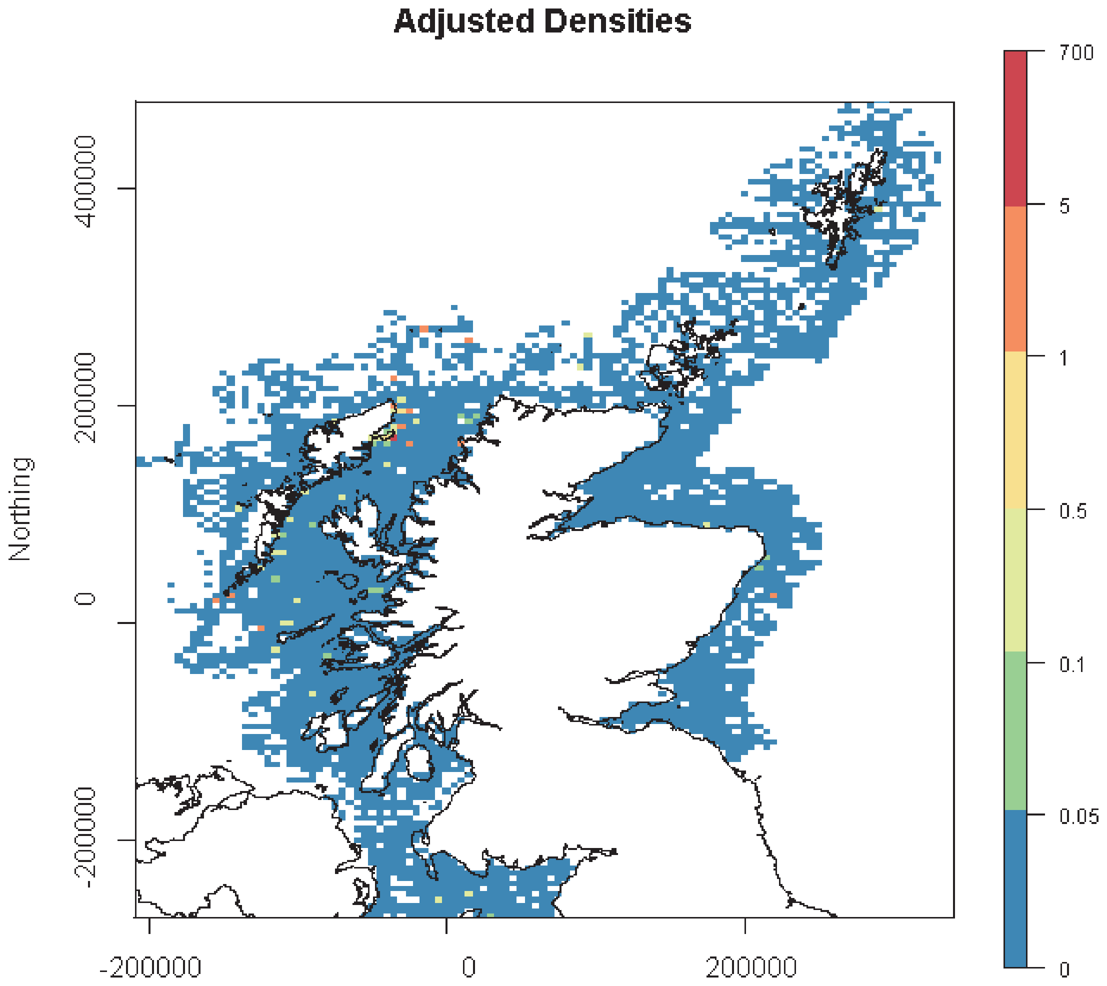

Figure 32. Observed adjusted densities of Risso's dolphin 1994 – 2012 All seasons. Colours indicate animals km^{-2}. Each cell is 5 by 5 km.

A model equivalent to the final selected model but with a position year interaction was associated with a higher CV score suggesting patterns in distribution, not described by the other predictors, were consistent across years.

The coefficient of variation of abundance derived from the bootstrap, not including model selection uncertainty, (n = 500) was a large 2.57. The coefficient of variation associated with the bootstrap incorporating model selection uncertainty (n = 100, final n = 97) was a considerable 11.13. Three model selection bootstraps were removed because they were associated with abundances >10^8.

Only the region to the north of Lewis and Harris stands out as having anything other than negligible density (Figures 33 – 39), but even then the estimated relative densities can be very low with the lower bound confidence surface in some years scarcely different from zero.

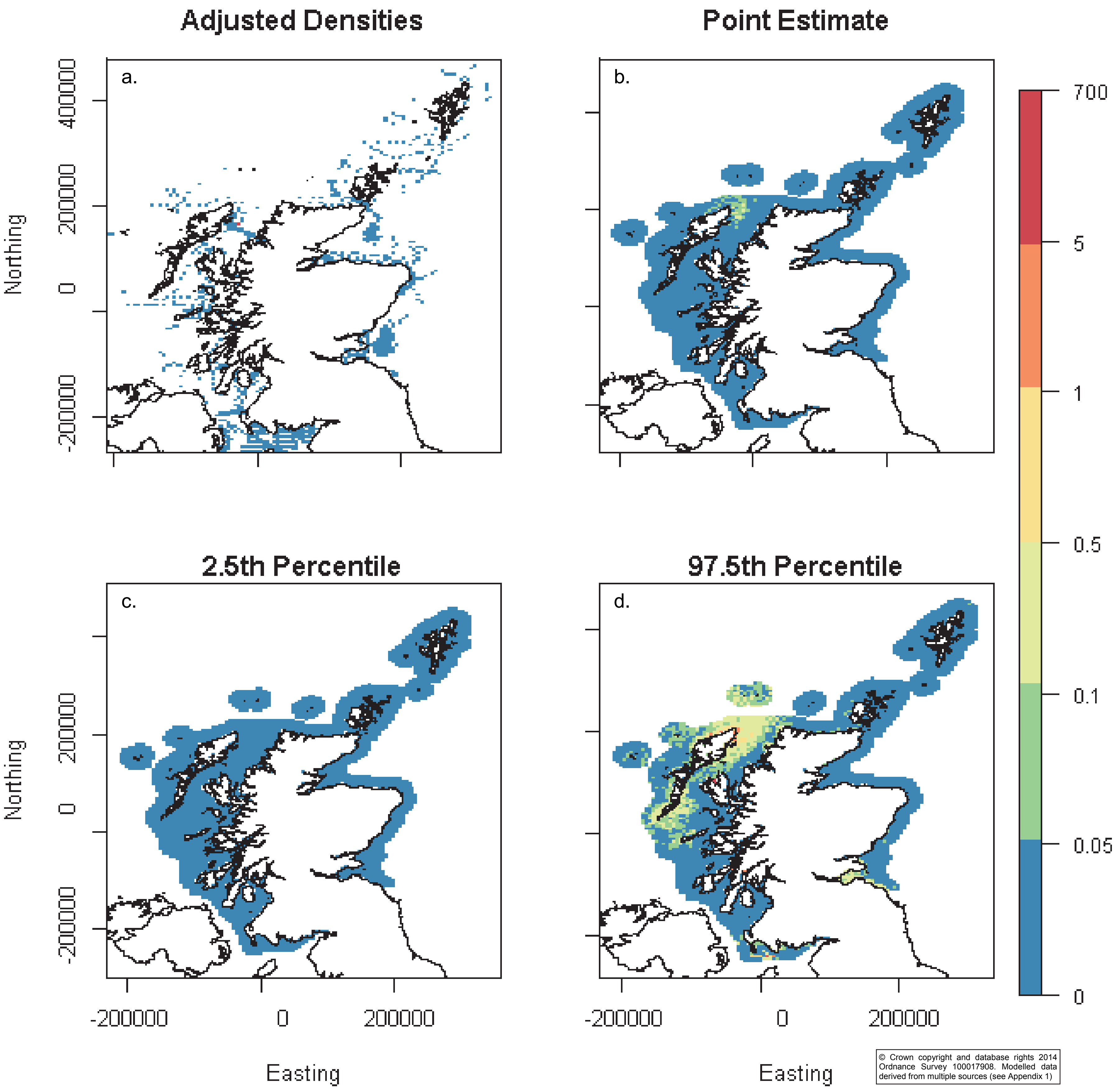

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Figure 33. Risso's dolphin, winter 2005: a. Observed adjusted winter (1994 – 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on February 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

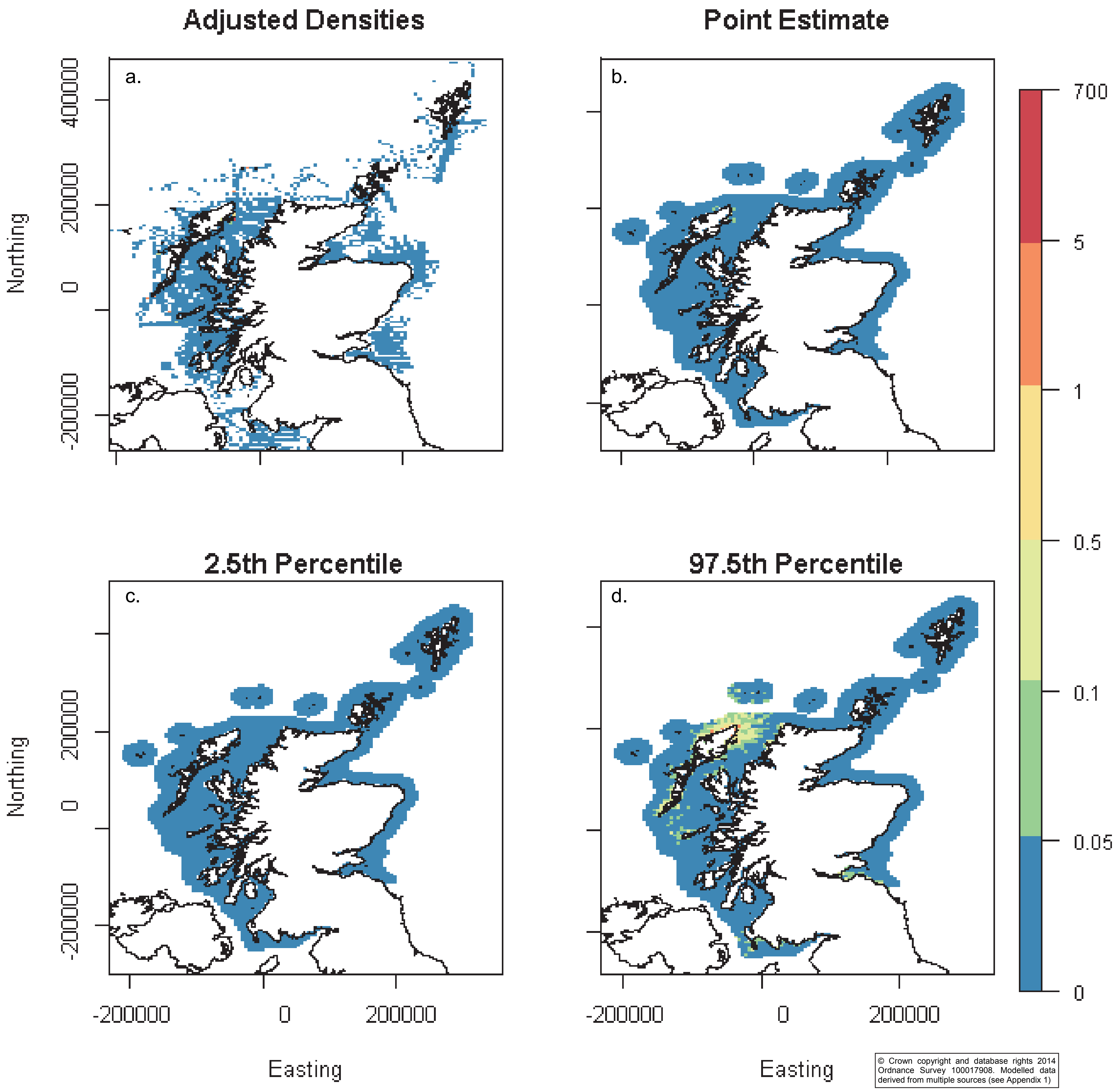

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Figure 34. Risso's dolphin, spring 2005: a. Observed adjusted spring (1994 - 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on May 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

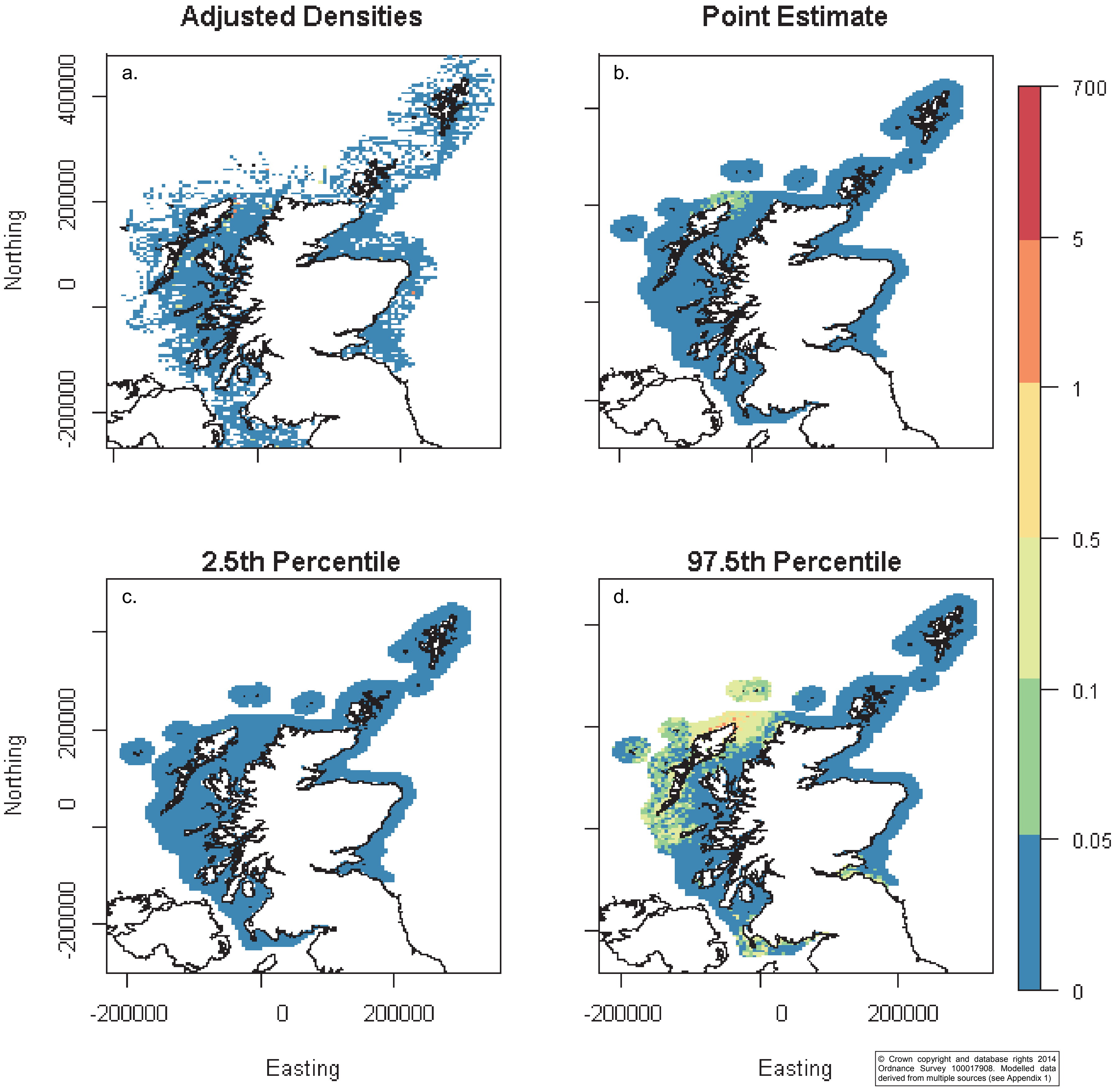

Figure 35. Risso's dolphin, summer 2005: a. Observed adjusted summer (1994 - 2012) densities ($\bar{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on August 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

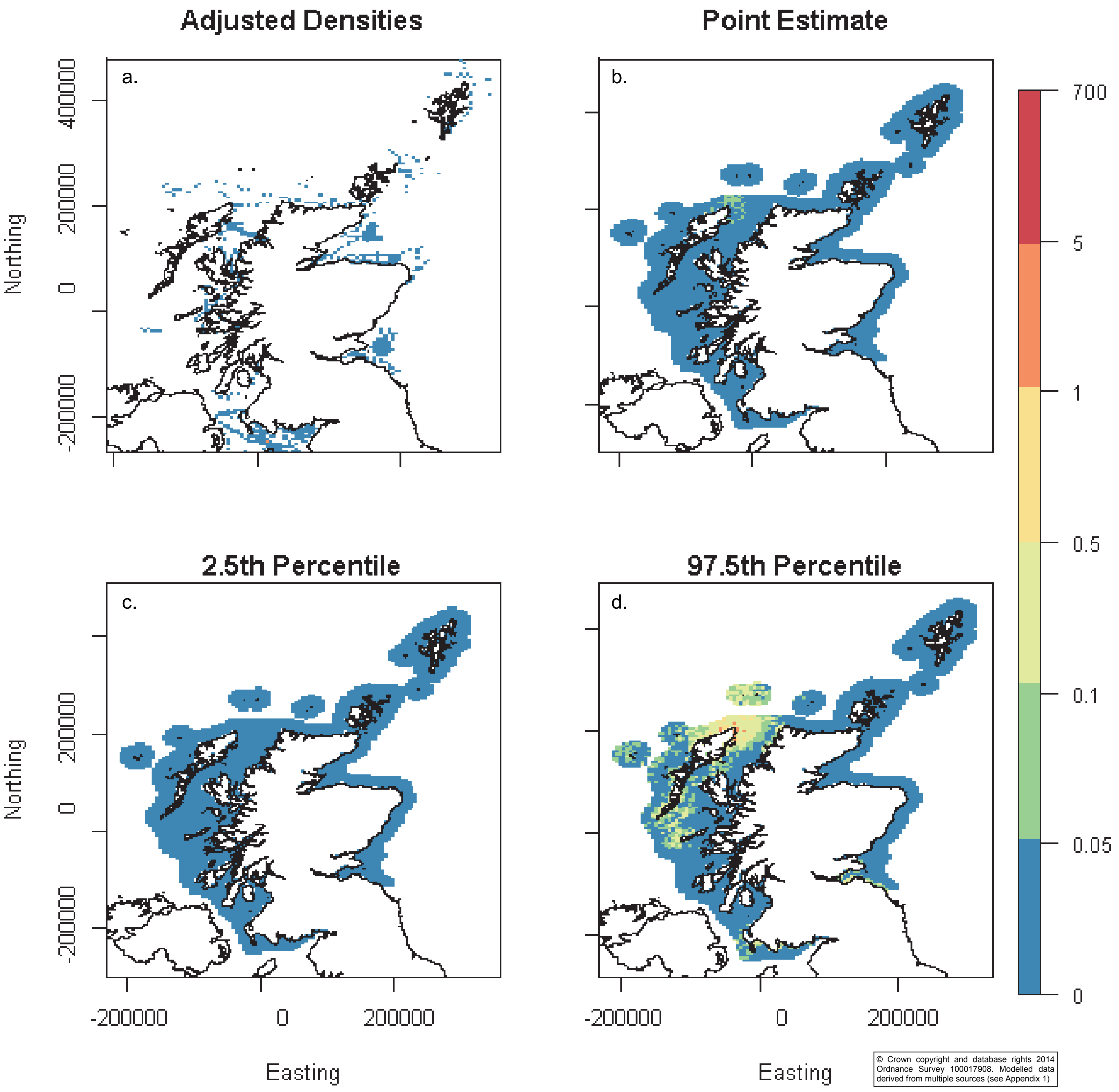

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Figure 36. Risso's dolphin, autumn 2005: a. Observed adjusted autumn (1994 - 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on November 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

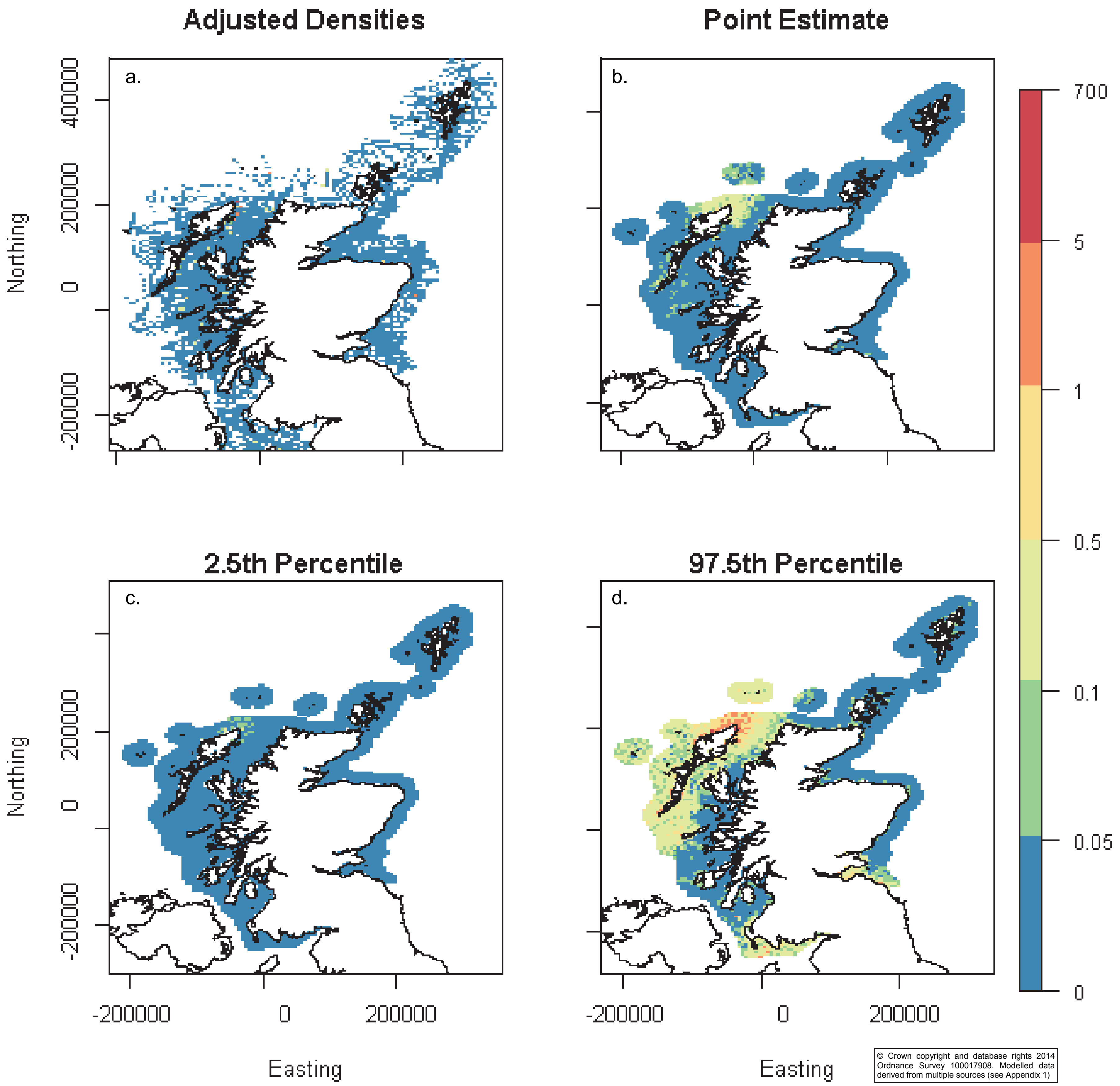

Figure 37. Risso's dolphin, summer 1994: a. Observed adjusted summer (1994 - 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on August 15th 1994. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

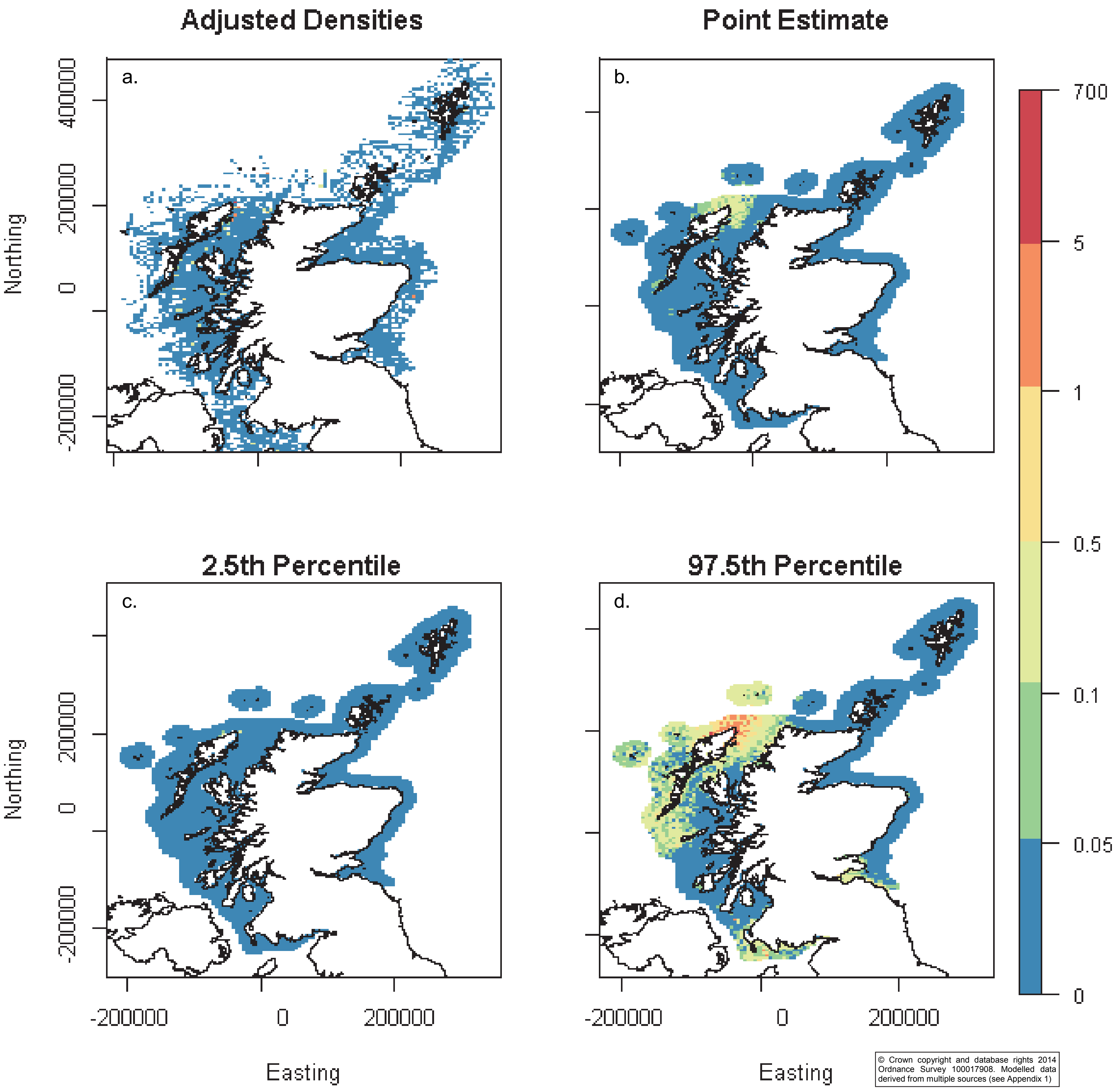

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Figure 38. Risso's dolphin, summer 2001: a. Observed adjusted summer (1994 - 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on August 15th 2001. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

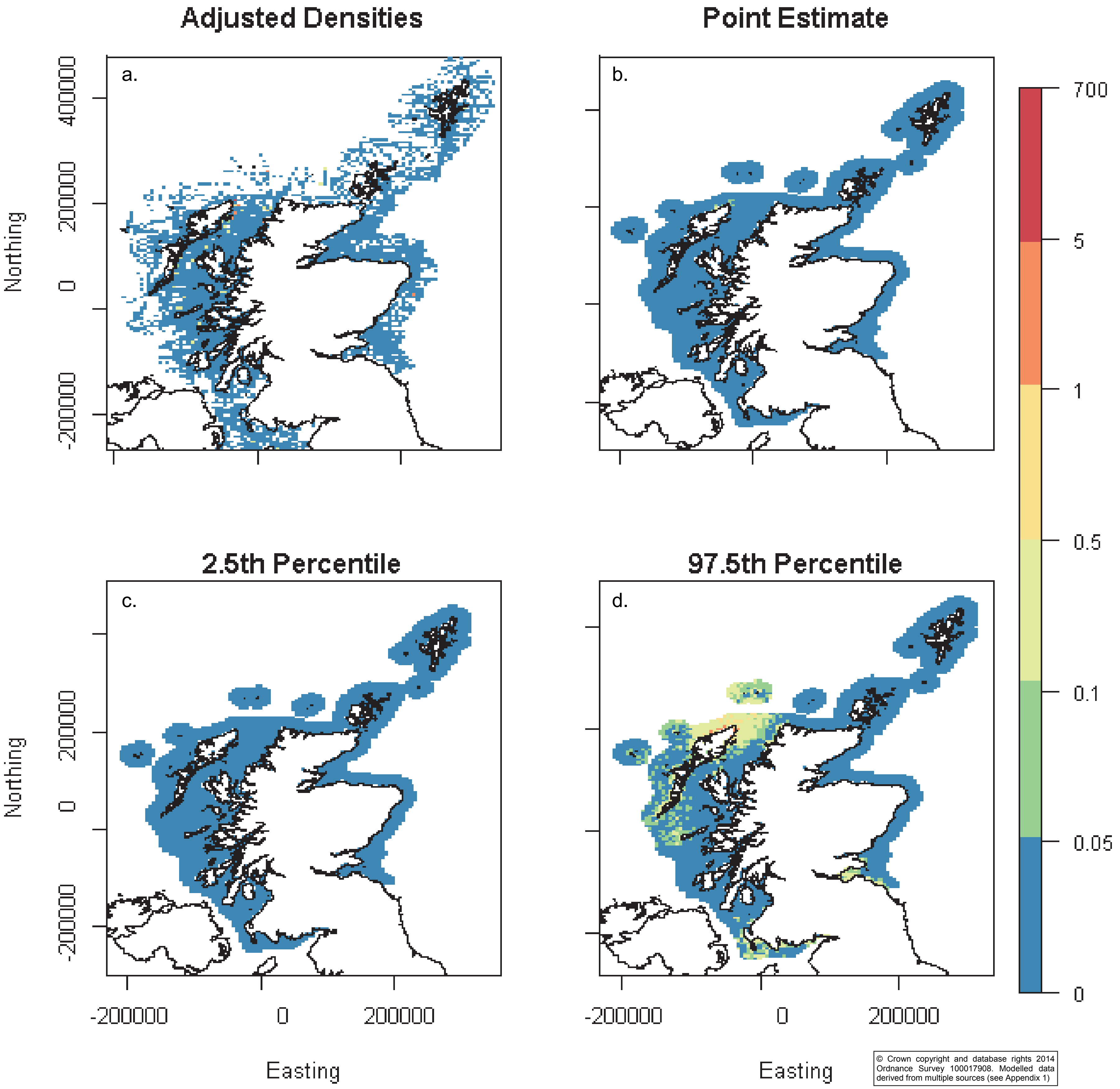

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Figure 39. Risso's dolphin, summer 2012: a. Observed adjusted summer (1994 - 2012) densities ($\hat{D}$) of Risso's dolphin. b. Estimated density surfaces for Risso's dolphin on August 15th 2012. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

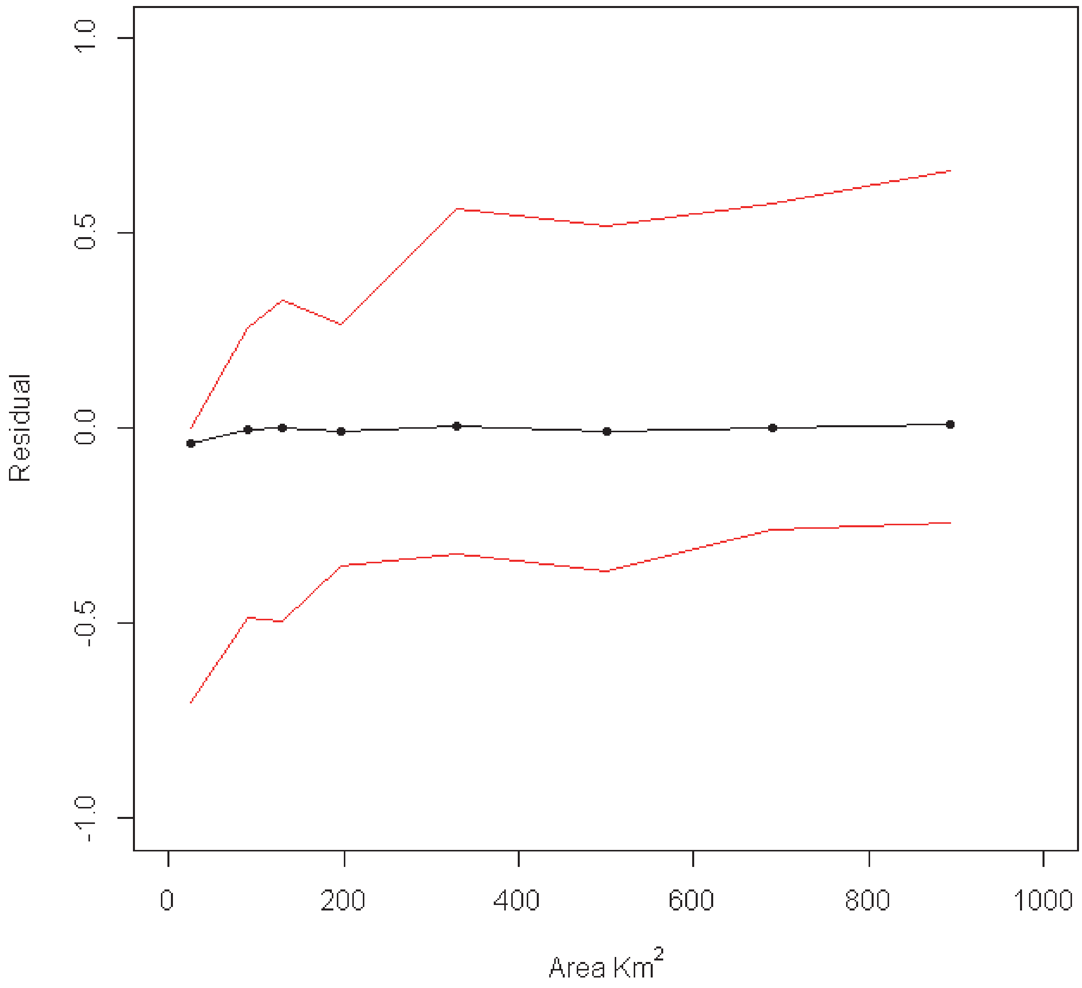

Figure 40. Residuals of Risso's dolphin relative density as a function of area. Black line and points: mean values, red lines: lower and upper 95% confidence bounds.

Figure 40 gives the results of investigation of bias in the predictions. Because the localities were randomly located, the actual realized area was sometimes less than the target area (as some selected areas overlapped the edges of the prediction region or on land). The realized areas were approximately 25, 90, 129, 196, 330, 500, 690, 893 km^2. There was no systematic pattern in the distribution of the residuals other than over small areas the distribution was highly skewed.

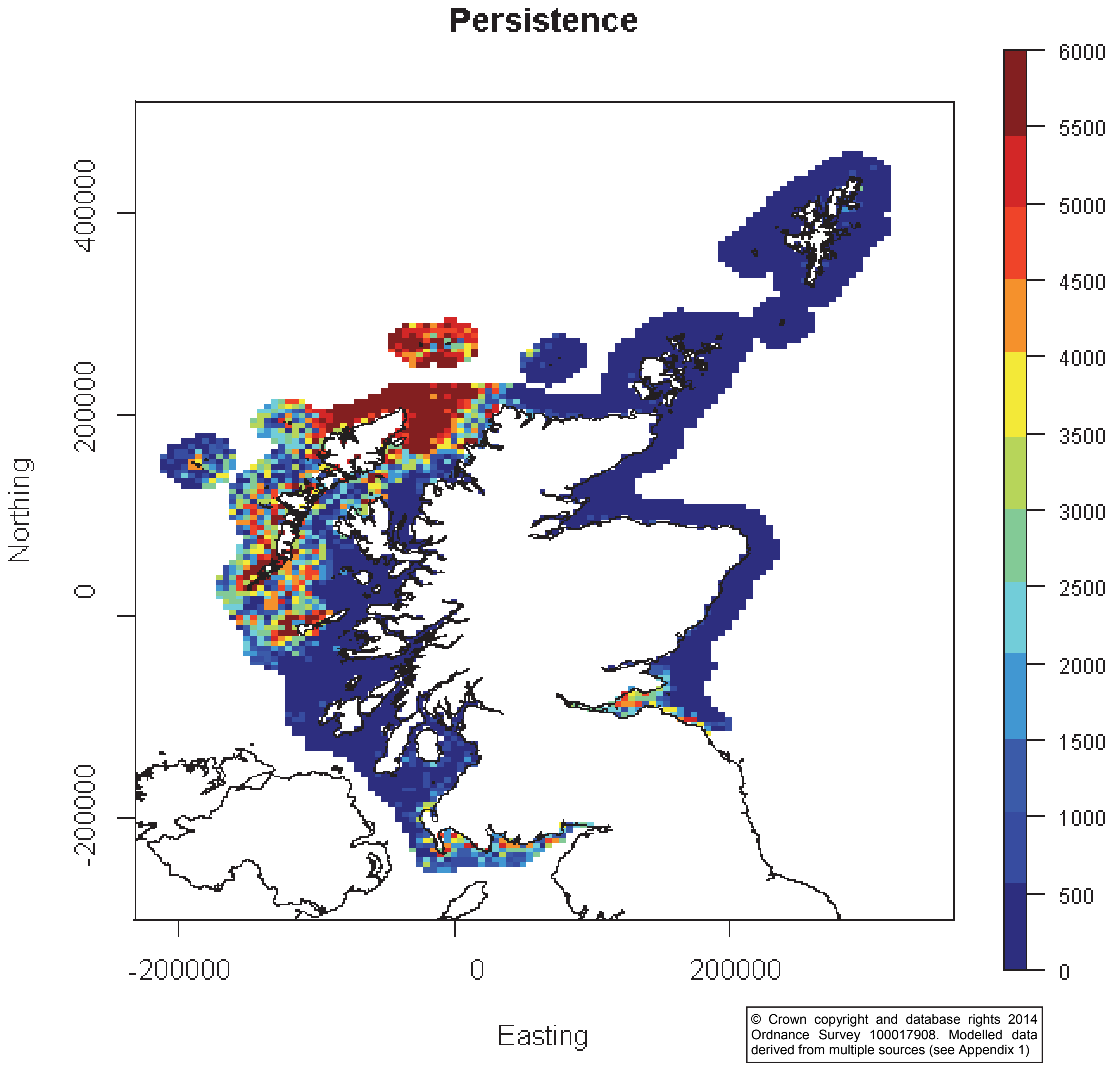

Figure 41. Index of predicted Risso's dolphin persistence-certainty summers 1994 – 2012. Colours indicate persistence of above mean density on a score 0 to 6000. Each cell is 5 by 5 km.

Because of the lower densities, a number of smaller regions exhibit persistent higher than average densities (Figure 41) but the largest contiguous region is the area north of Lewis and Harris.

Figure 41 suggested high persistence-certainty scores in regions of moderately low effort (i.e. north of Lewis, figure 32). To investigate this further the variance in cell predictions across years was plotted against effort in the cell to confirm there really was a correlation of effort and uncertainty (Figure 42). There was an inverse correlation (-0.110) of effort and prediction cell variance (df= 3599, P<0.001).

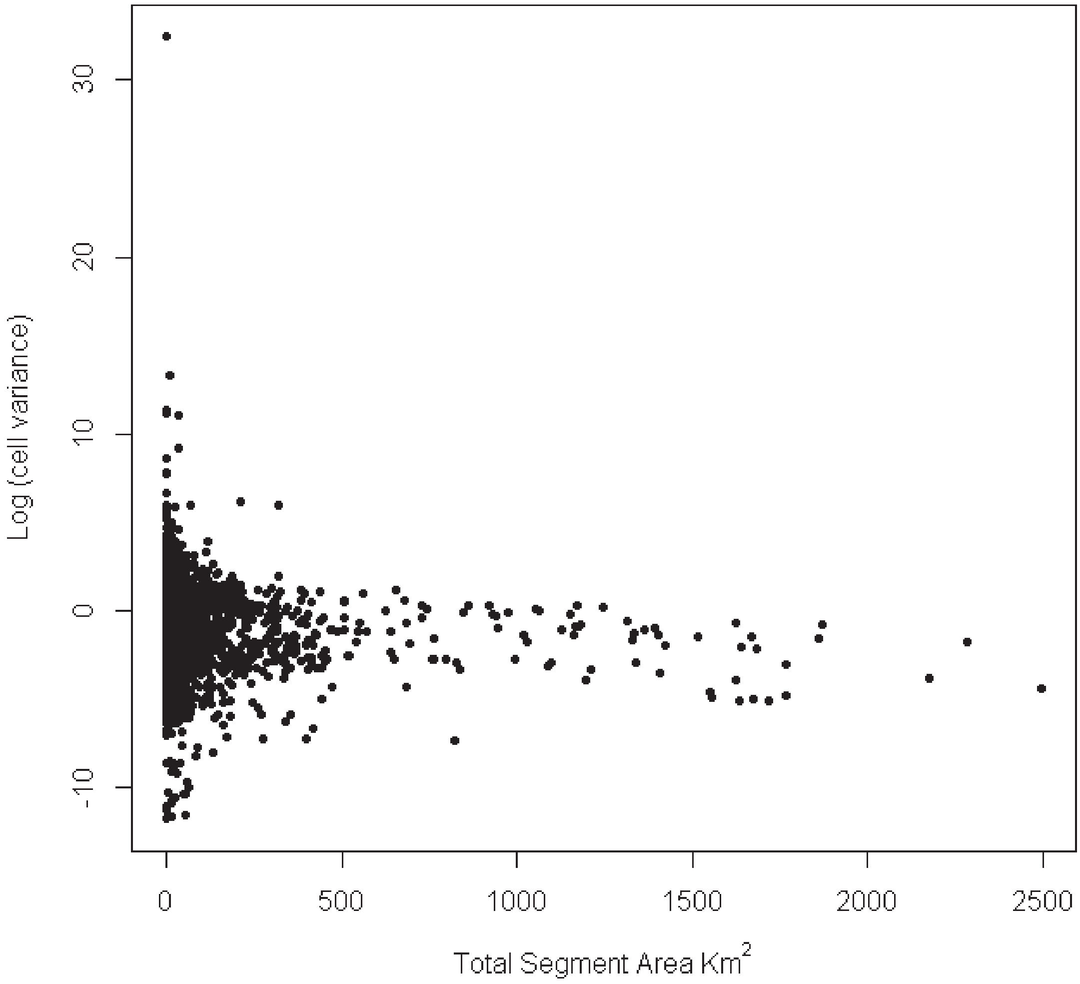

Figure 42. Prediction cell variance and per cell effort (measured as area) for Risso's dolphin

3.4.3 White-beaked dolphin

The adjusted observed densities ($\hat{D}$) for each season (across all years, Figure 43) along with predictions and confidence intervals for winter, spring, summer and autumn 2005, are given in Figures 44 to 47. Prediction surfaces for the summers of 1994, 2001 and 2012 are given in figures 48 to 50. The selected (1D smooth only model) model is given in Table 8. The confidence intervals incorporated uncertainty in the detection function, estimated perpendicular distances and uncertainty in the spatial model.

Because a model with a 2D smooth of position generated unreasonable bootstraps and so was not considered, the Dette & Neumeyer (2001) test was used to crudely investigate the similarity of $\hat{D}$ as a surface across years. There was no significant difference between the summer distribution of densities across years ($T < 0.05$, $P = 1$, see also Figures 45, 48 – 50) implying that there are no significant differences in predictions across summers.

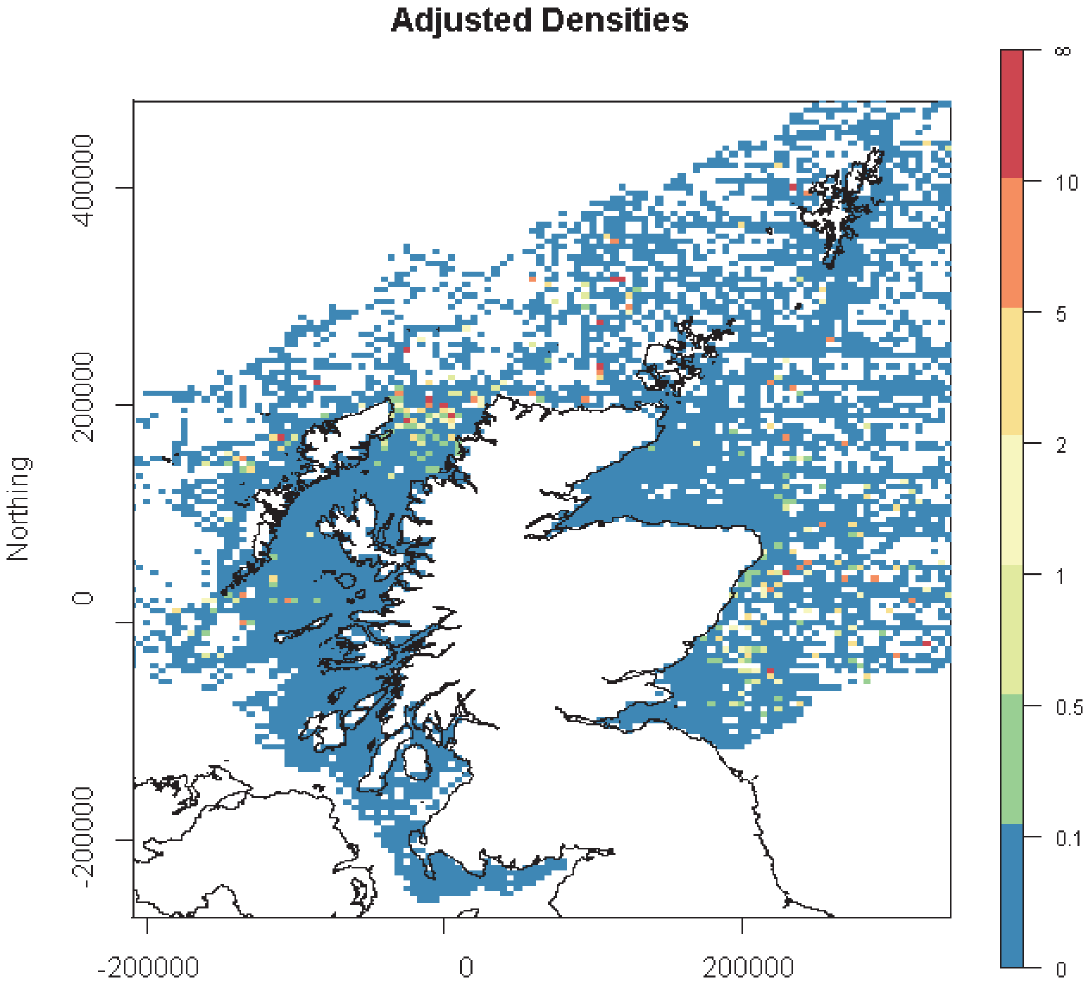

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Figure 43. Observed adjusted white-beaked dolphin densities 1994 – 2012 All seasons. Colours indicate animals km^{-2}. Each cell is 5 by 5 km.

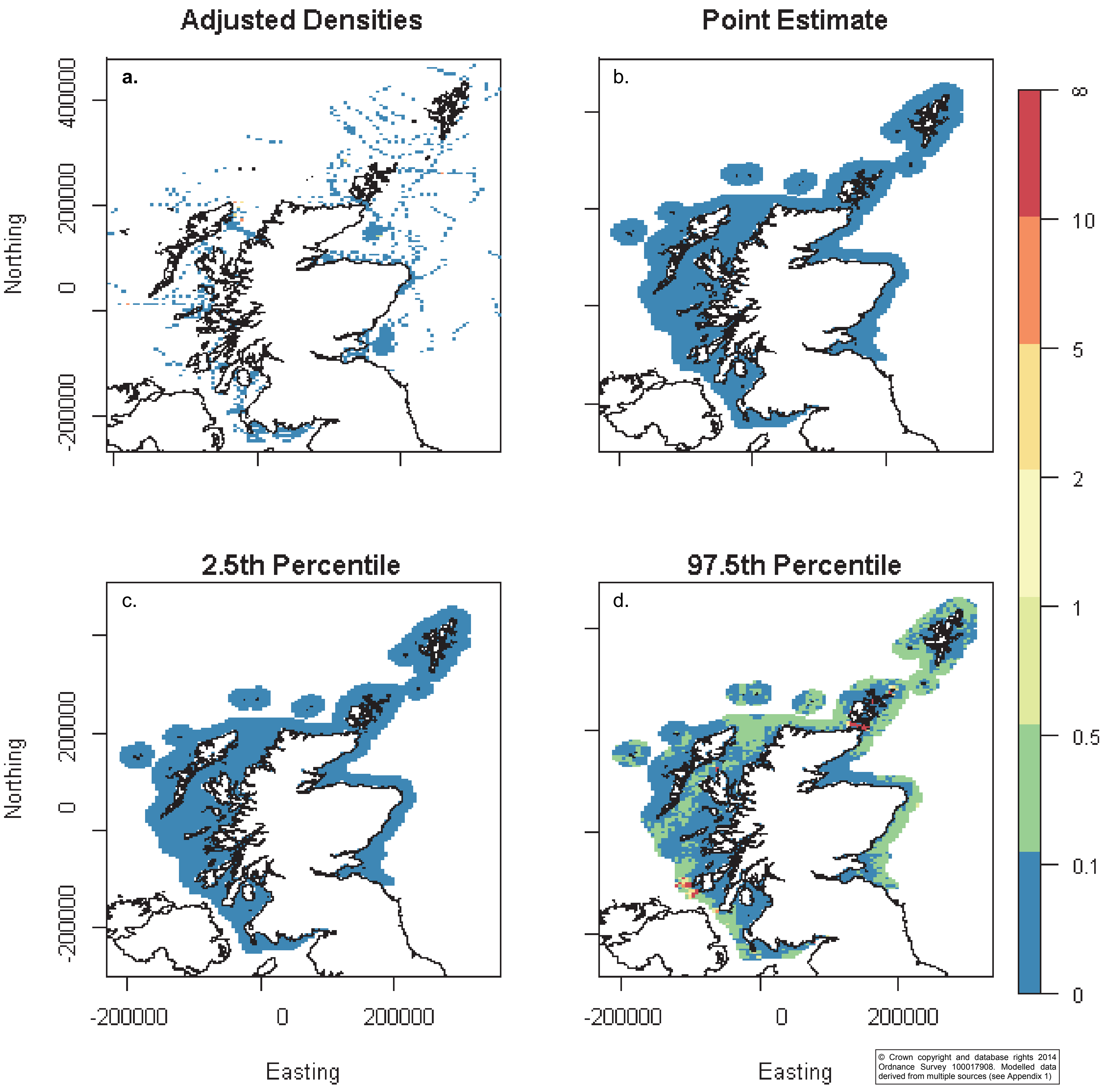

Figure 44. White-beaked dolphin, winter 2005: a. Observed adjusted winter (2001 – 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on February 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

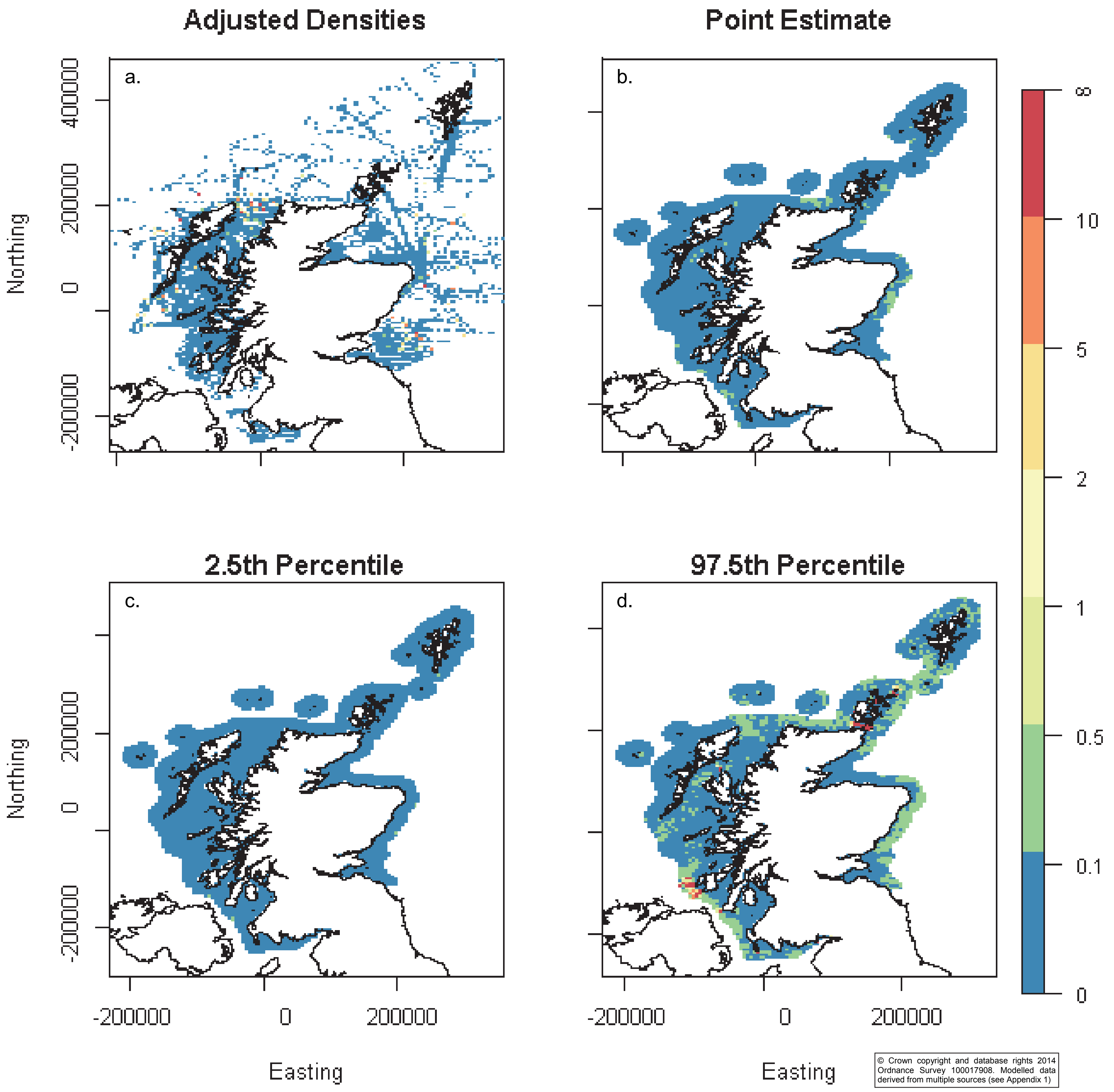

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Figure 45. White-beaked dolphin, spring 2005: a. Observed adjusted spring (1994 – 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on May 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

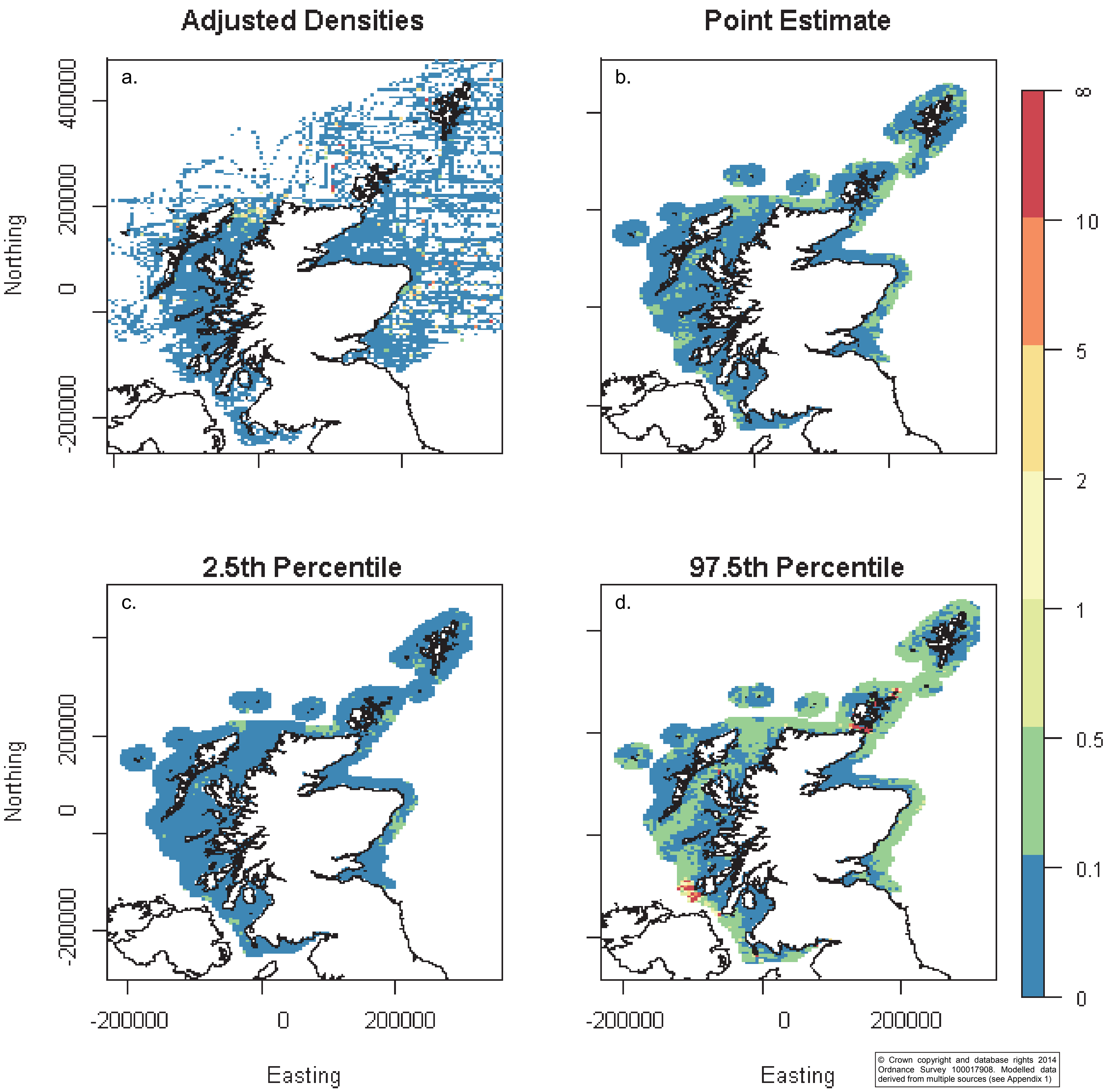

Figure 46. White-beaked dolphin, summer 2005: a. Observed adjusted summer (1994 - 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on August 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

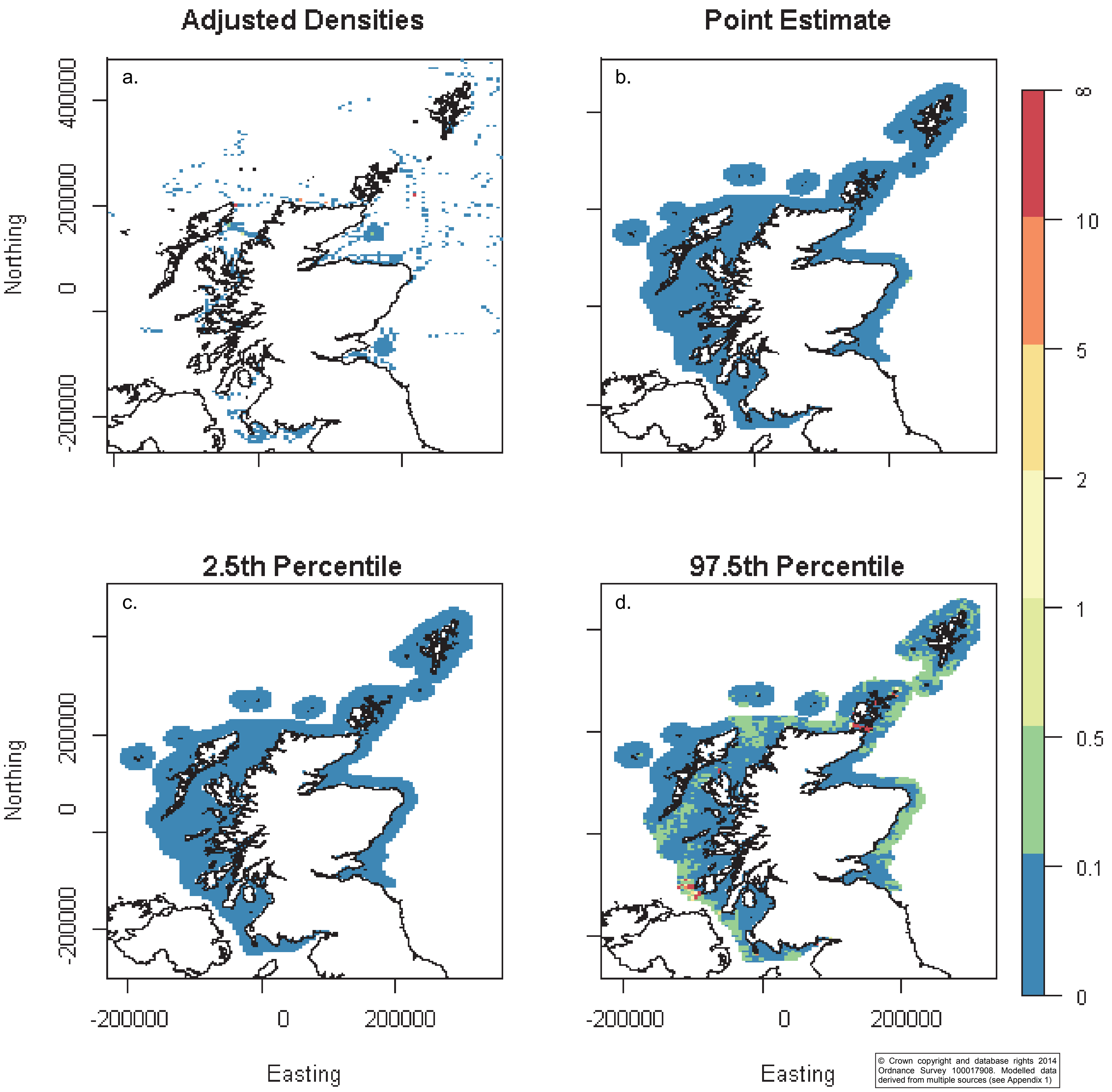

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Figure 47. White-beaked dolphin, autumn 2005: a. Observed adjusted autumn (1994 - 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on September 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

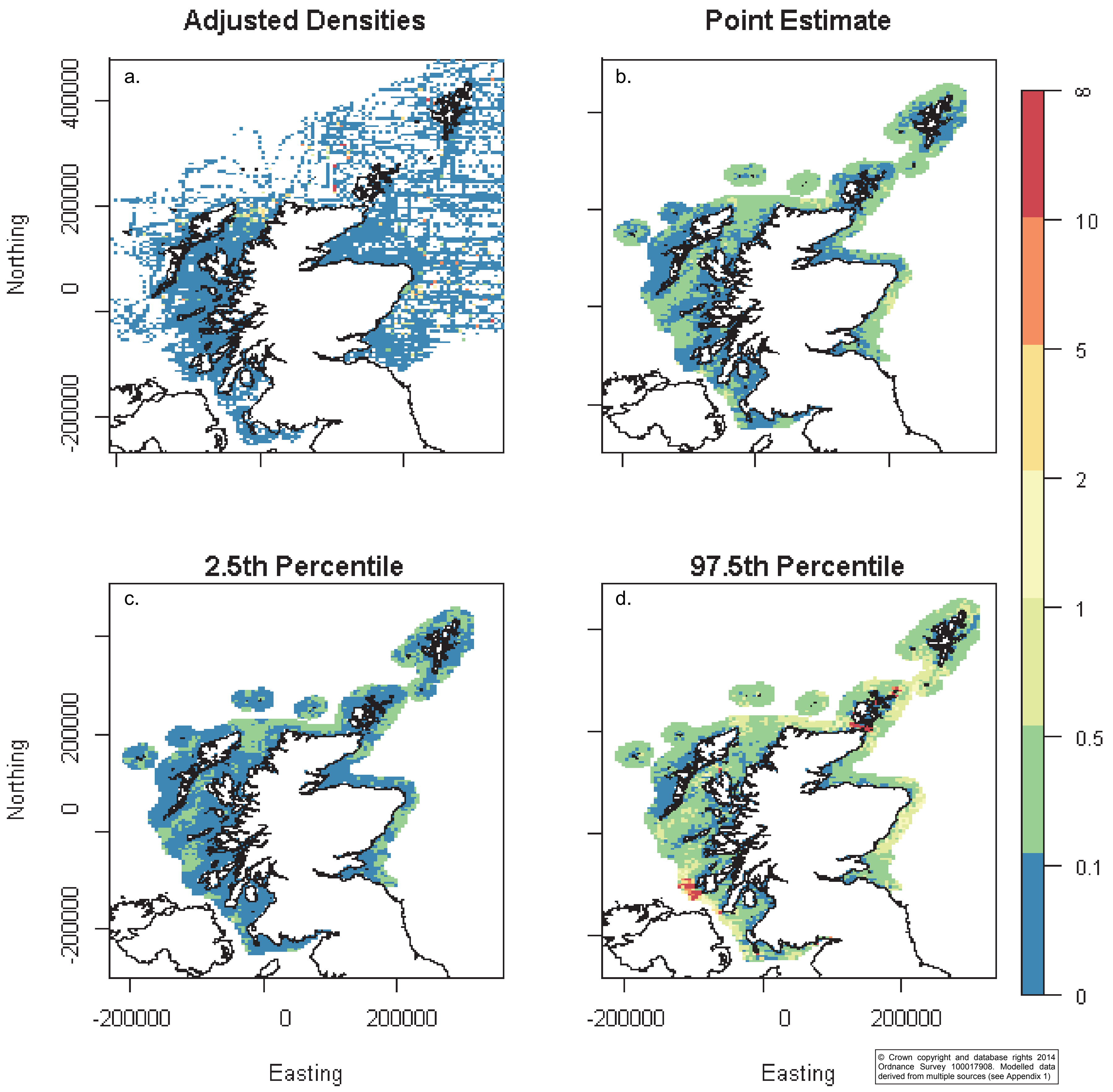

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Figure 48. White-beaked dolphin, summer 1994: a. Observed adjusted summer (1994 - 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on August 15th 1994. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

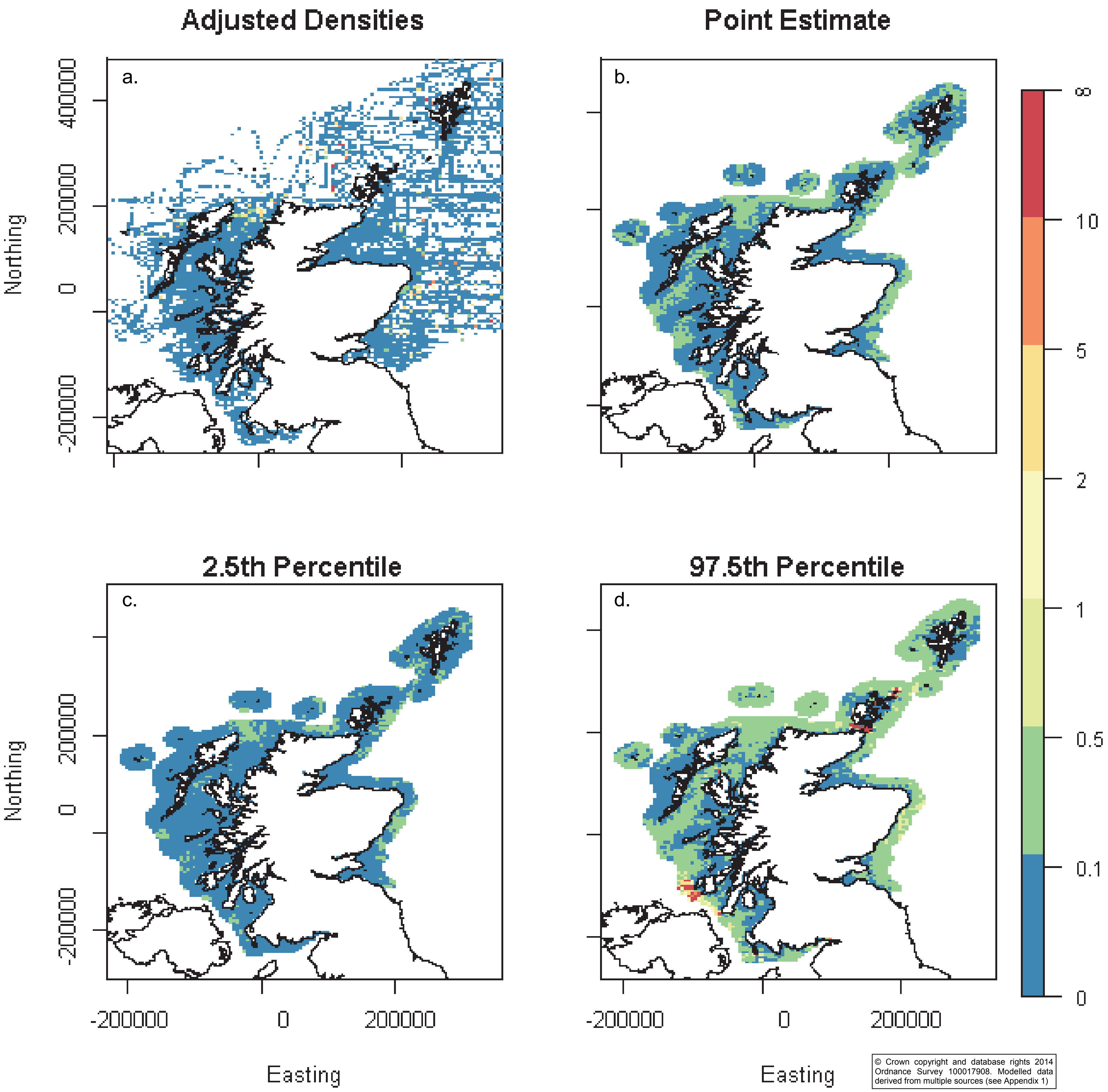

Figure 49. White-beaked dolphin, summer 2001: a. Observed adjusted summer (1994 – 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on August 15th 2001. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

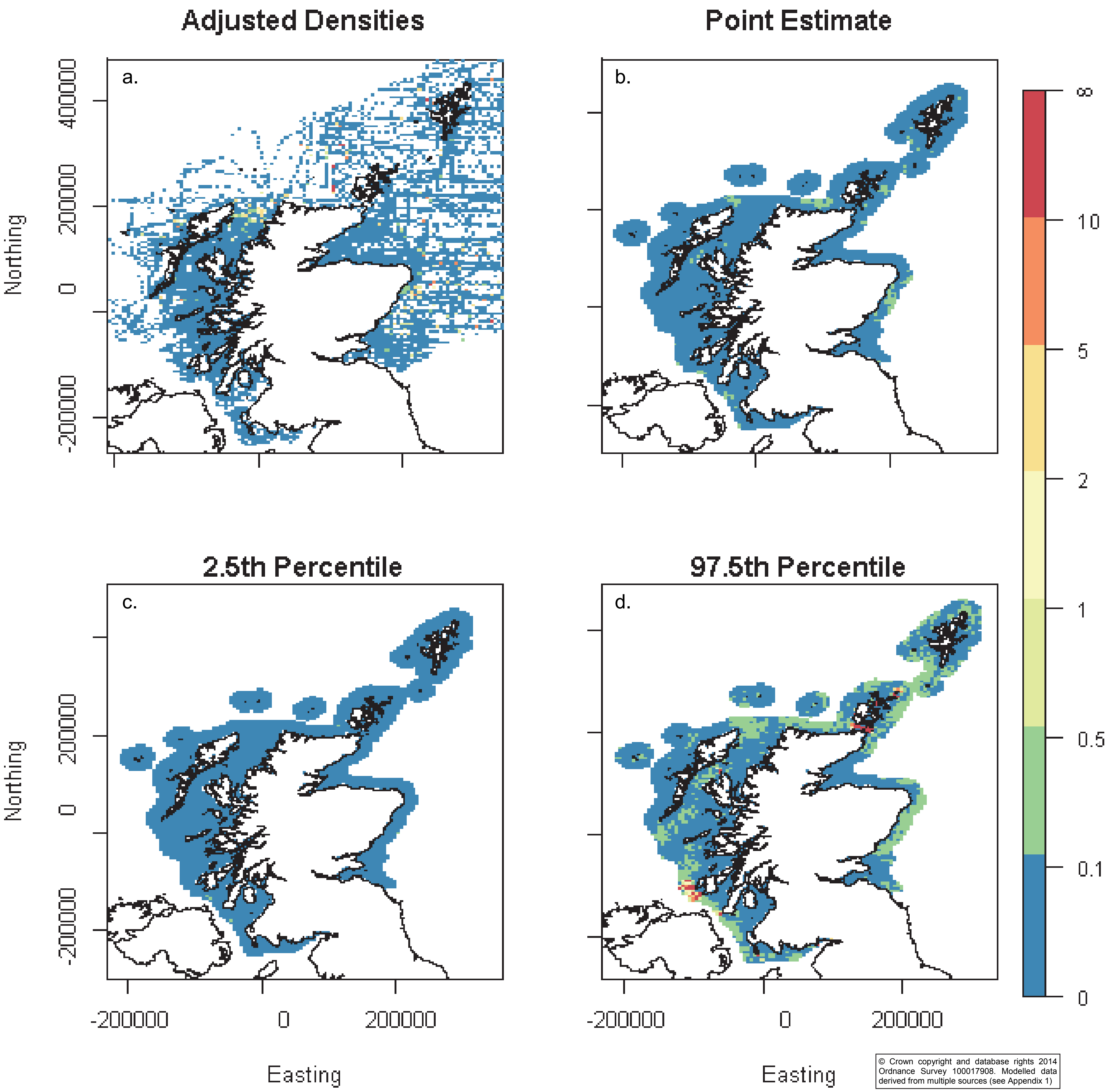

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Figure 50. White-beaked dolphin, summer 2012: a. Observed adjusted summer (1994 – 2012) densities ($\hat{D}$) of white-beaked dolphin. b. Estimated density surfaces for white-beaked dolphin on August 15th 2012. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

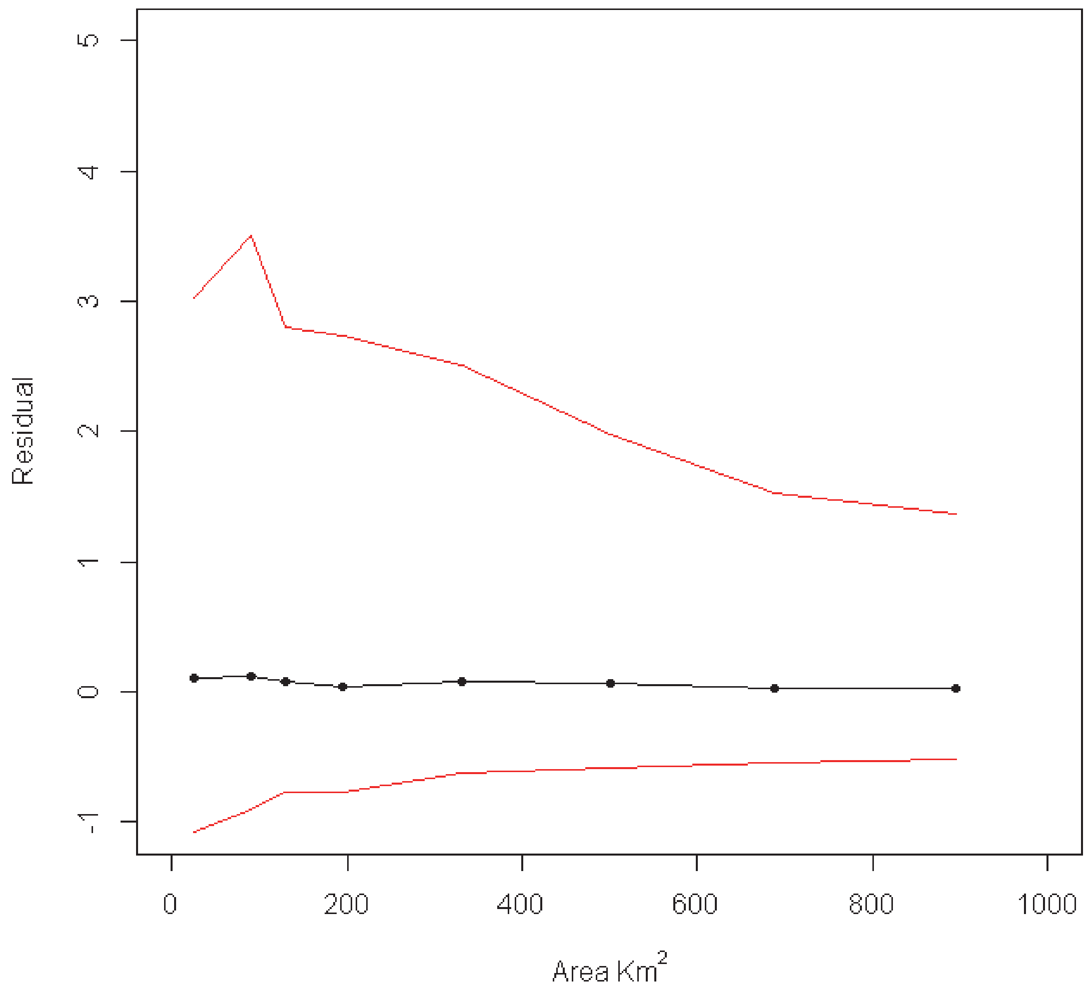

Figure 51. Residuals of white-beaked dolphin relative density as a function of area. Black line and points: mean values, red lines: lower and upper 95% confidence bounds (based on 1500 bootstraps).

The coefficient of variation associated with the abundance estimate derived from the bootstrap not including model selection uncertainty (initial n = 500, final n = 485) was a high 2.46. The coefficient of variation associated with the bootstrap incorporating model selection uncertainty (initial n = 130, final n = 56) was two orders of magnitude larger even with bootstraps with total abundance estimates of greater than 10^7 removed prior to the coefficient of variation calculation.

This species shows a great deal of dispersion, with observed animals occupying multiple deeper regions of the Scottish territorial waters except the region south-west of the Hebrides (Figures 43-50). Figure 51 gives the results of investigation of bias in the predictions. Because the localities were randomly located, the actual realized area was sometimes less than the target area (as some selected areas overlapped the edges of the prediction region or on land). The realized areas were approximately 25, 89, 129, 197, 329, 494, 695, 896 km^2. A single region of less than 200 km^2 is liable to be more biased than a region of greater than 200 km^2.

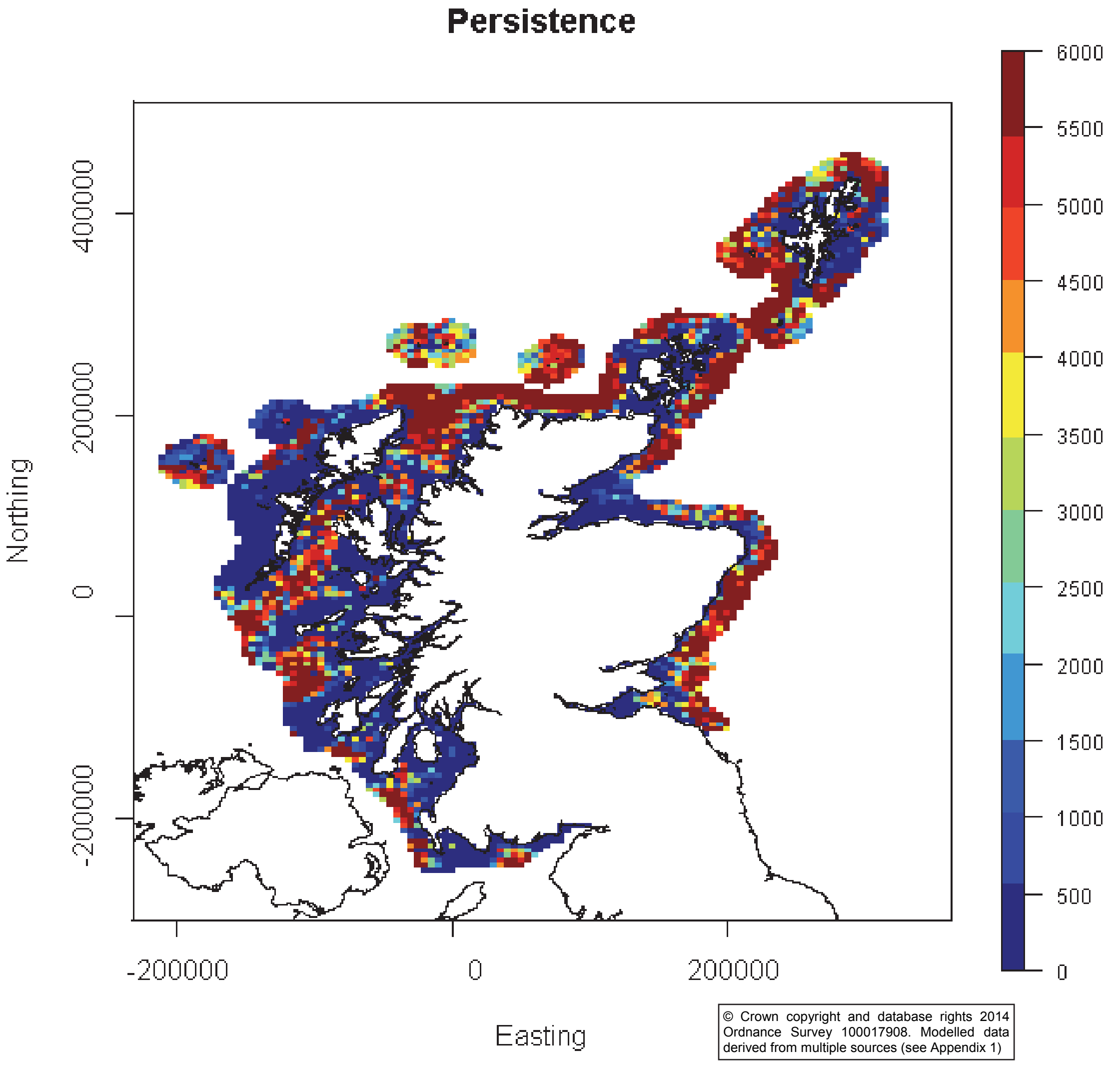

Figure 52. Index of predicted white-beaked dolphin persistence-certainty summers 1994 – 2012. Colours indicate persistence of above mean density on a score 0 to 6000. Each cell is 5 by 5 km.

The persistence-certainty surface (Figure 52) reflects this trend with approximately half of all Scottish waters with an above average density but many of these regions are quite small. Some of these (e.g. north of Lewis and Harris, east of Aberdeenshire and north of Sutherland/Caithness) seem to be persistent and are in a region of high effort and the lower bound confidence surface suggests animals are present at non-negligible densities. Because of the dispersion, the persistence-certainty map is not really that informative with much of the region of interest showing persistence.

Figure 52 suggested high persistence-certainty scores in regions of low effort. To investigate this further the variance in cell predictions across years was plotted against effort in the cell to confirm there really was a correlation of effort and uncertainty (Figure 53). Whilst there was negative correlation (-0.032) of effort and prediction cell variance, it was not significant (df= 3598, P=0.055). Possibly predictions for cells in regions of low effort drew upon data from surrounding areas.

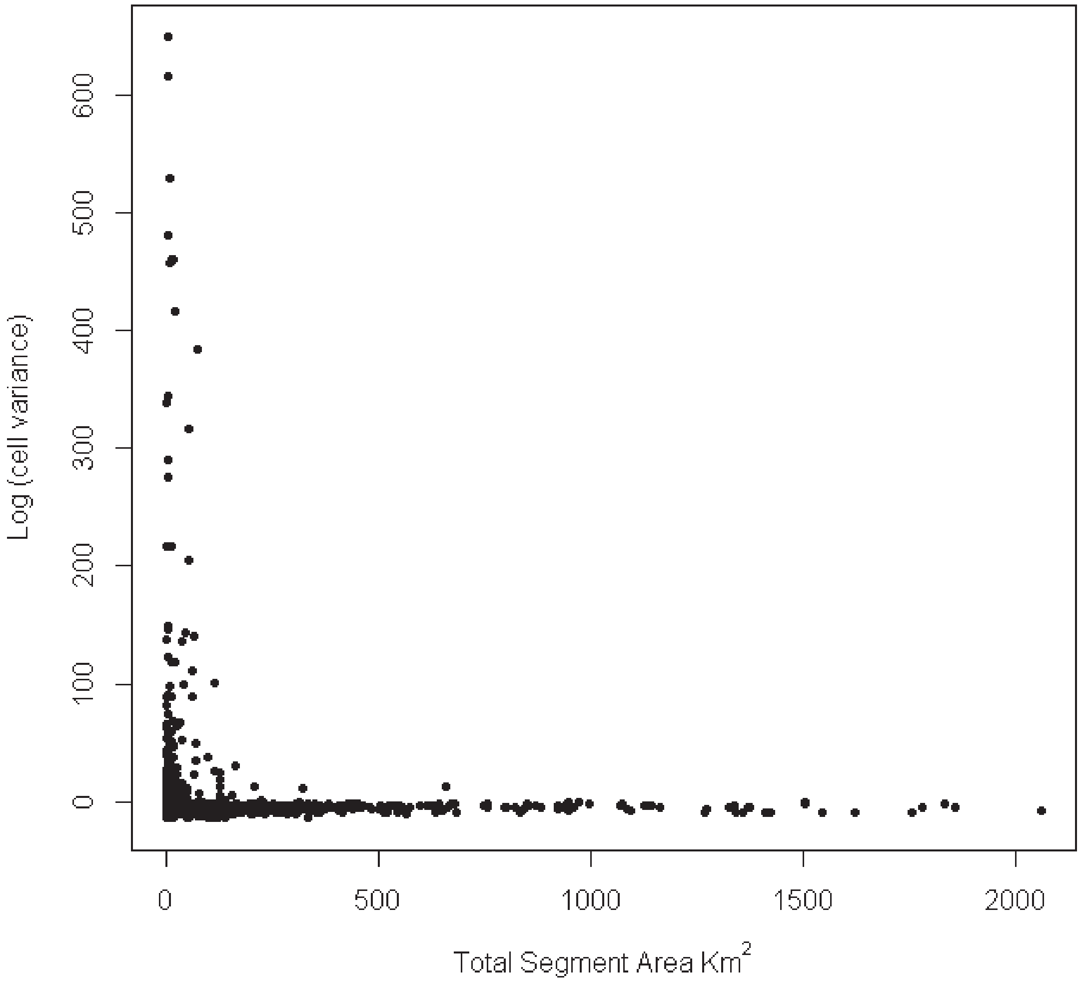

Figure 53. Prediction cell variance and per cell effort (measured as area) for white-beaked dolphin.

3.4.4 Basking shark

The adjusted observed relative surface densities ($\hat{D}$) for basking shark for each season (across all years, Figure 54) along with predictions and confidence intervals for spring, summer and autumn 2005, are given in Figures 55 to 57. Figures 58 and 59 give predictions for the summer of 2001 and 2012. The selected model is given in Table 8. The confidence intervals incorporated uncertainty in the detection function, estimated perpendicular distances (when not present in the data) and uncertainty in the spatial model.

Because a 2D smooth of position was not selected, the Dette & Neumeyer (2001) test was used (with 1000 bootstraps) to investigate the similarity of $\hat{D}$ as a surface across years. There was evidence of a difference between the summer distribution of densities across years (T = 0.33, P = <0.001). Presumably this difference was generated by the dynamic variables in the model.

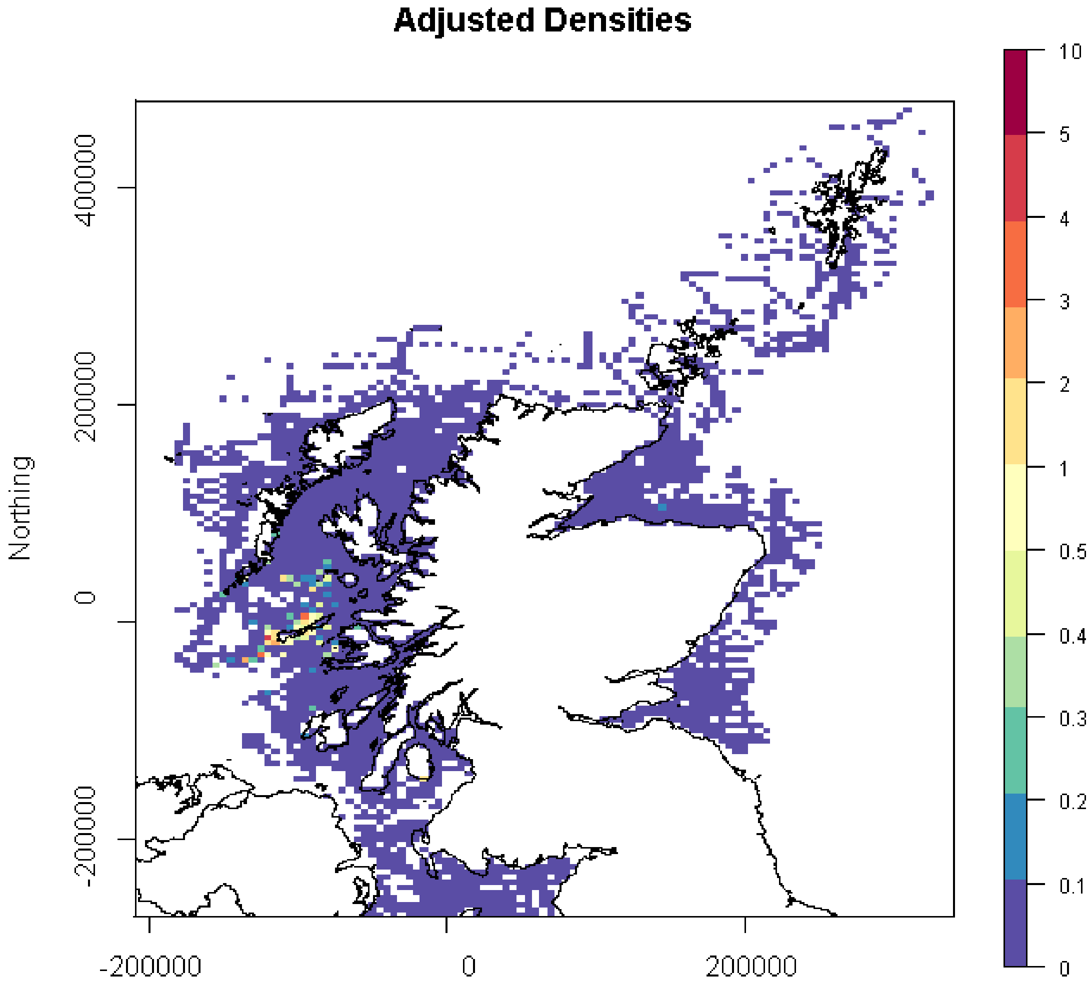

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Figure 54. Observed adjusted densities of basking shark 2000 – 2012. All seasons. Colours indicate relative surface animals km^{-2}. Each cell is 5 by 5 km.

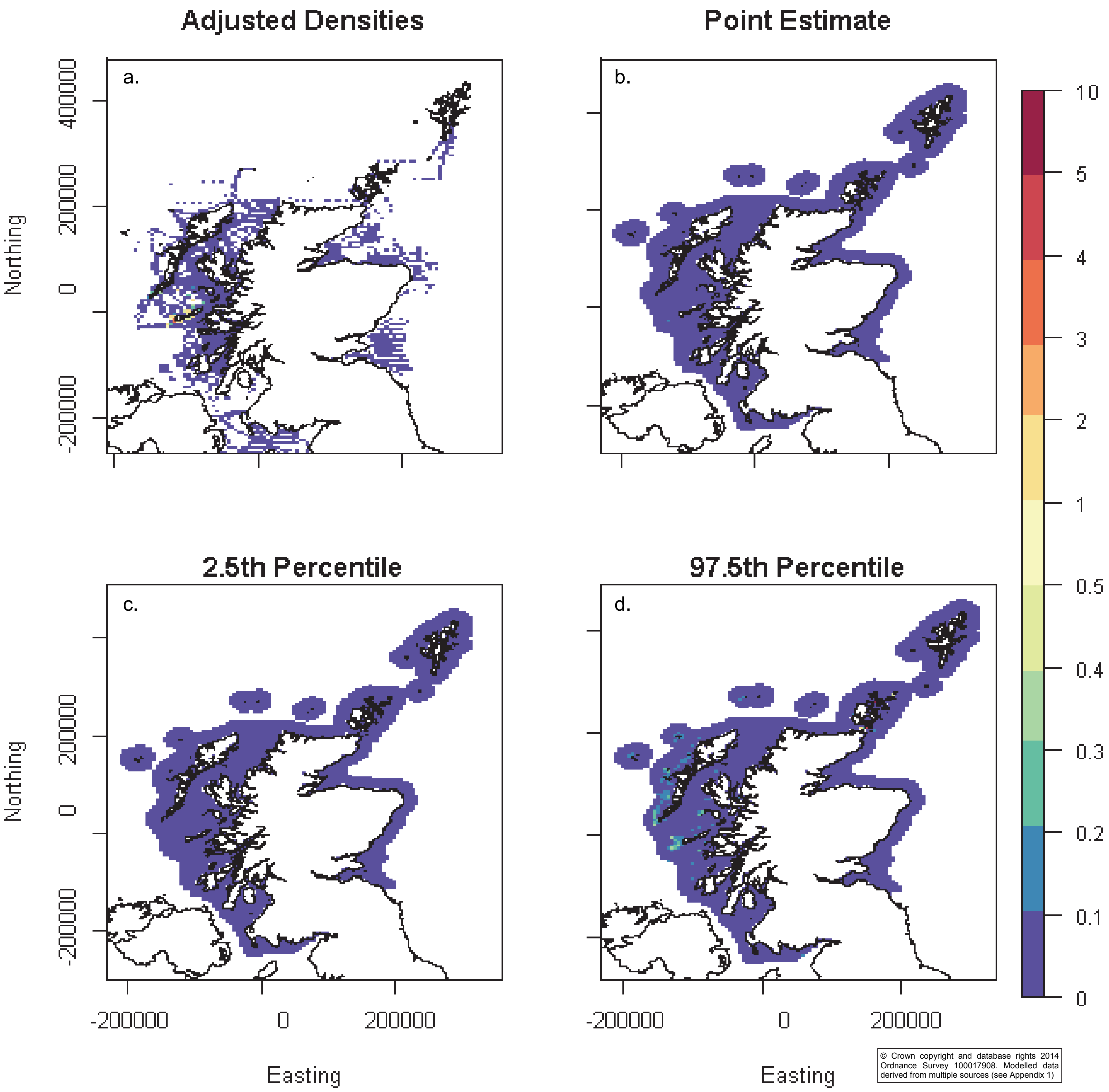

Figure 55. Basking shark, spring 2005: a. Observed adjusted spring (2000 – 2012) densities ($\hat{D}$) of basking shark. b. Estimated density surfaces for basking shark on May 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

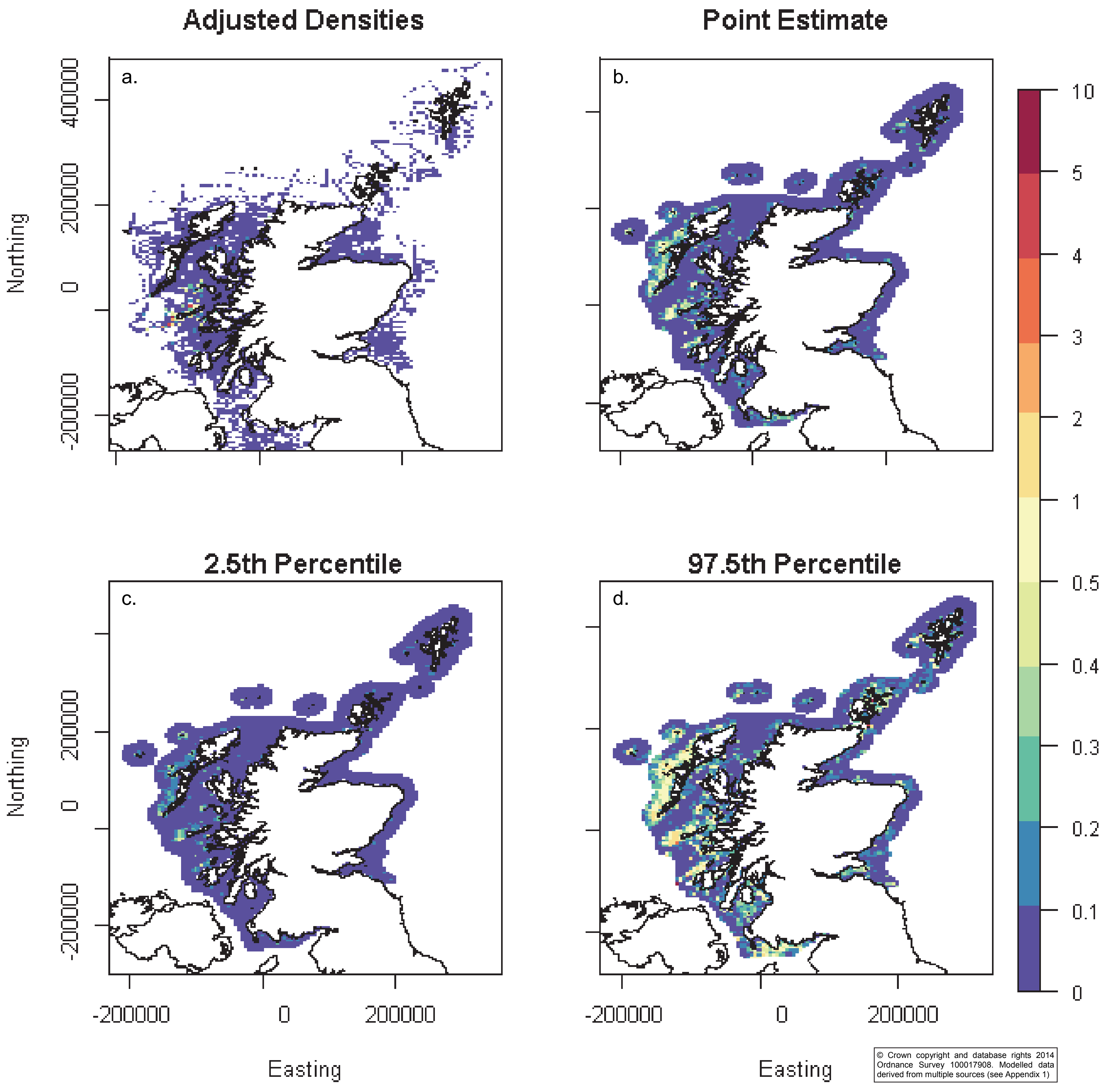

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Figure 56. Basking shark, summer 2005: a. Observed adjusted summer (2000 - 2012) densities ($\hat{D}$) of basking shark. b. Estimated density surfaces for basking shark on August 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

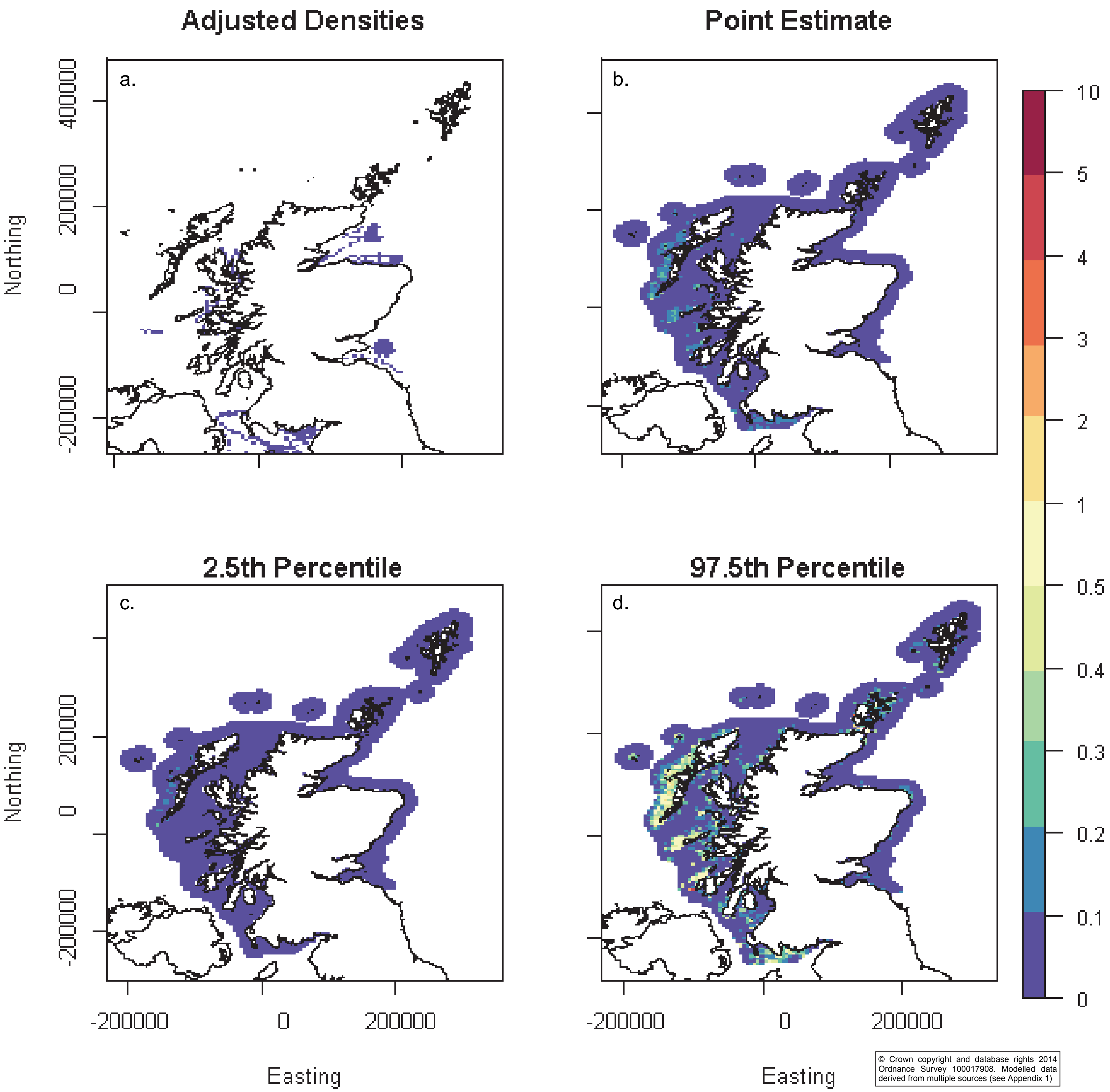

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Figure 57. Basking shark, autumn 2005: a. Observed adjusted autumn (2000 - 2012) densities ($\hat{D}$) of basking shark. b. Estimated density surfaces for basking shark on September 15th 2005. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

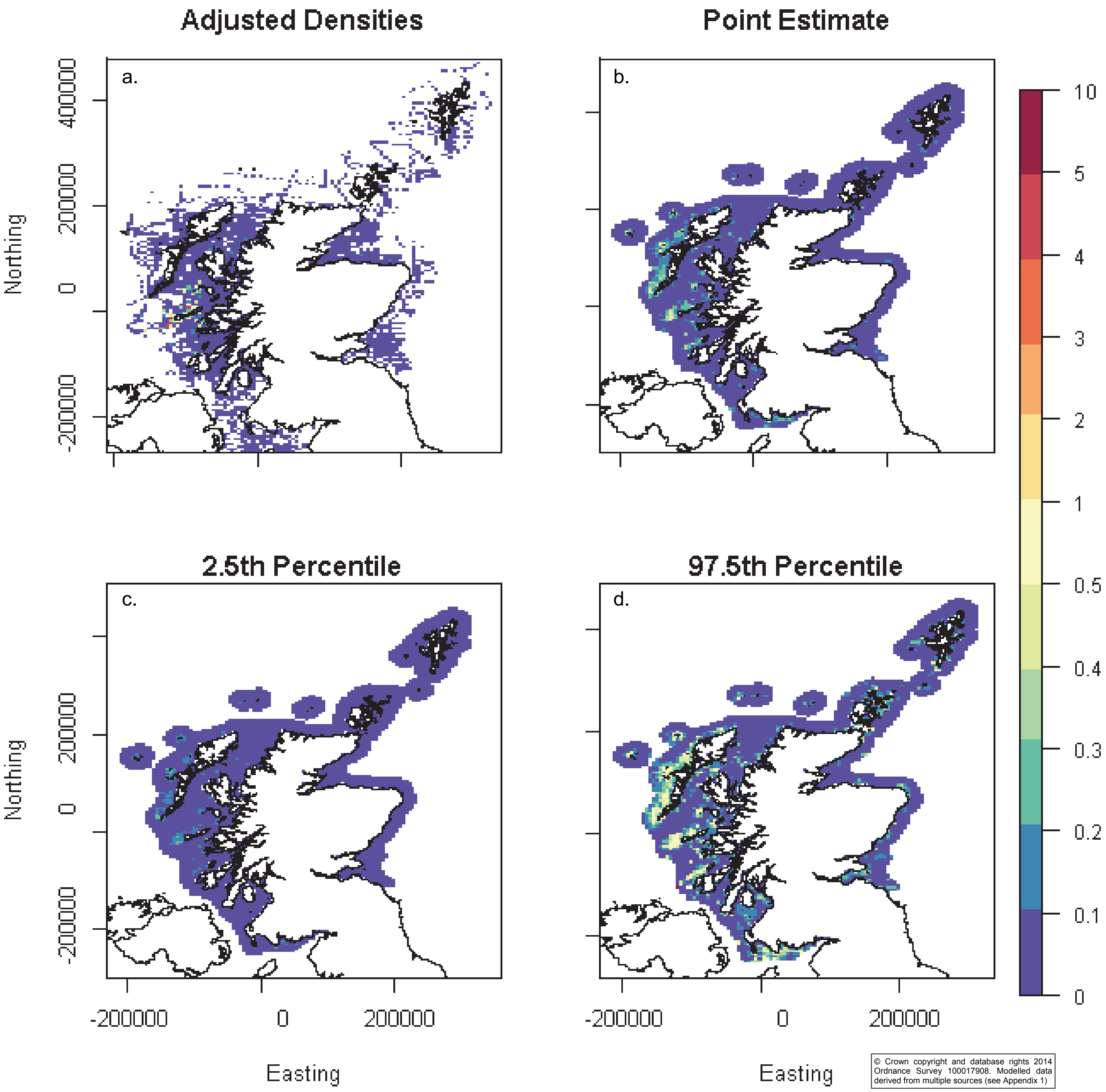

Figure 58. Basking shark, summer 2001: a. Observed adjusted summer (2000 - 2012) densities ($\hat{D}$) of basking shark. b. Estimated density surfaces for basking shark on August 15th 2001. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

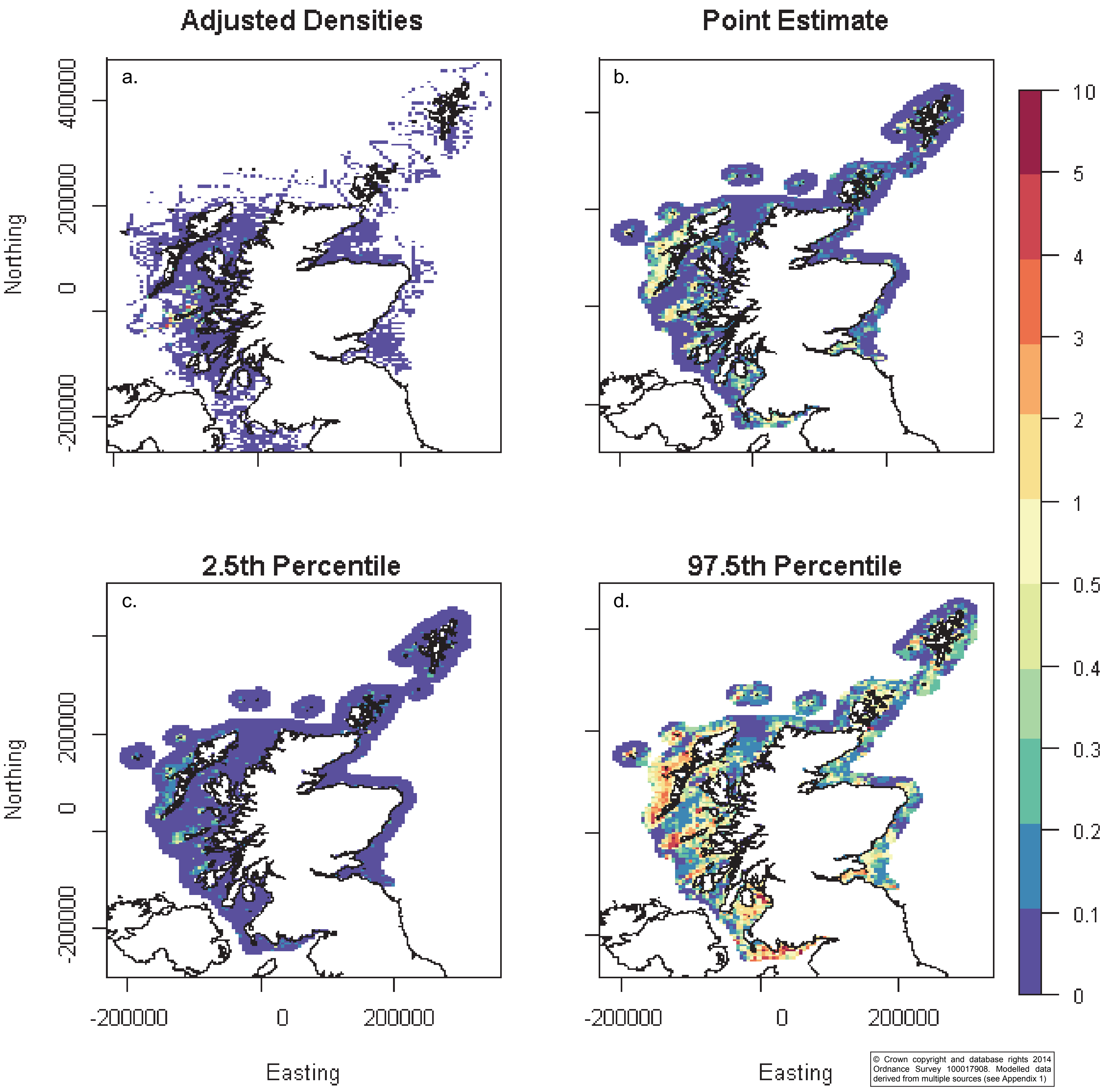

Figure 59. Basking shark, summer 2012: a. Observed adjusted summer (2000 - 2012) densities ($\hat{D}$) of basking shark. b. Estimated density surfaces for basking shark on August 15th 2012. c. & d. Estimated lower and upper bound confidence surfaces. Colours indicate animals km^{-2}. Each cell is 5 by 5 km. (see Section 3.4 for how to interpret this image).

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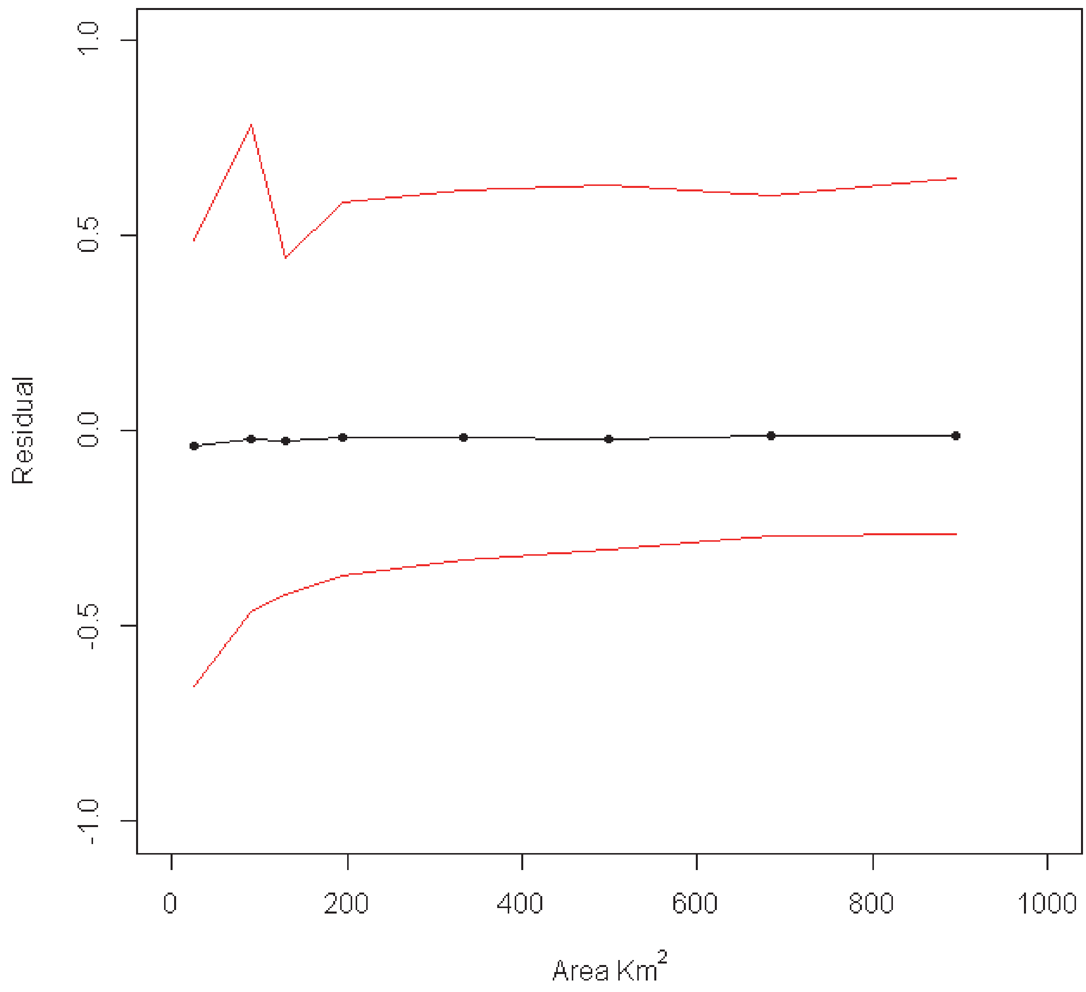

Figure 60. Residuals of basking shark relative surface density as a function of area. Black line and points: mean values, red lines: lower and upper 95% confidence bounds.

The coefficient of variation of the abundance estimate derived from the bootstrap, not including model selection uncertainty, (initial n = 500) was 2.57. The coefficient of variation associated with the bootstrap incorporating model selection uncertainty (initial n = 147, final n = 55) was a huge 25. One cell of the surface was not included as it was consistently associated with huge predictions because of a unique covariate combination. Bootstraps where the model selection process chose a 2D smooth of position model were associated with unrealistically high abundance estimates ($>10^8$) and were omitted from the analysis, so these results should be looked on as a best case scenario.

Figure 60 gives the results of investigation of bias in the predictions. Because the localities were randomly located, the actual realized area was sometimes less than the target area (as some selected areas overlapped the edges of the prediction region or on land). The realized areas were approximately 25, 90, 129, 195, 333, 499, 685, 896 km^2. Unsurprisingly, overall uncertainty in the residuals decreased with larger areas, as more data were associated with a greater considered area. This implied that a prediction of a single region of 150 km^2 or more, would be less likely to be biased than a prediction from a smaller area.

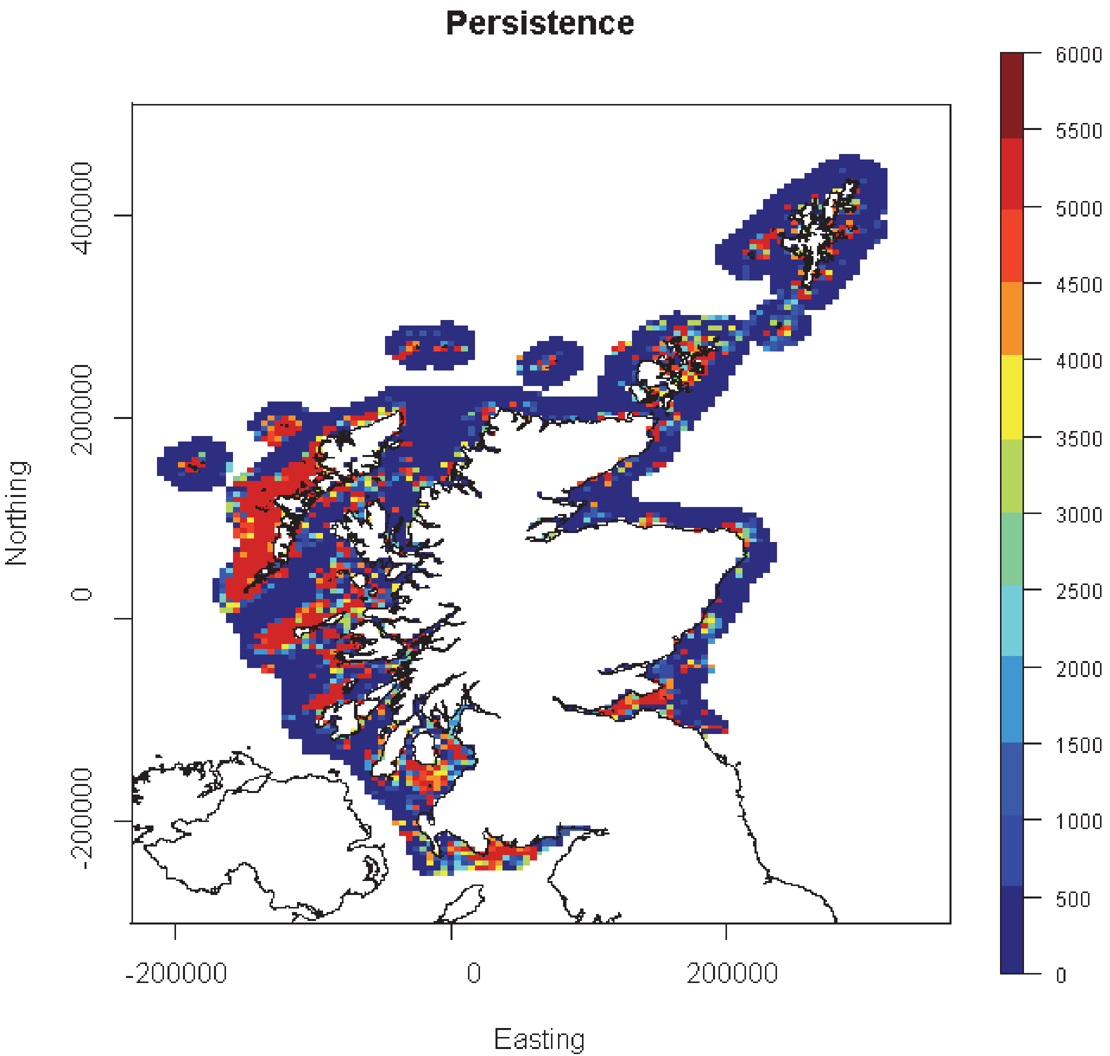

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Figure 61. Index of predicted basking shark surface persistence-certainty summers 2001 – 2012. Colours indicate persistence of above mean density on a score 0 to 6000. Each cell is 5 by 5 km.

Basking sharks are scarcely present in spring but are present by summer (July, August, September). In summer, contiguous high densities were predicted to the west of Tiree and west of Islay (supported by effort and observation) and west of the Outer Hebrides. All of these contiguous regions are persistently predicted to have higher than average densities (brown-red regions in Figure 61) and in most years are distinguishable in the lower bound confidence surface. Less distinguishable in the lower bound confidence surface are the Scottish waters of the Solway Firth, which are persistently predicted as having higher than average density. The Firth of Forth whilst exhibiting persistence is not really associated with high predicted basking shark density, except in 2012.

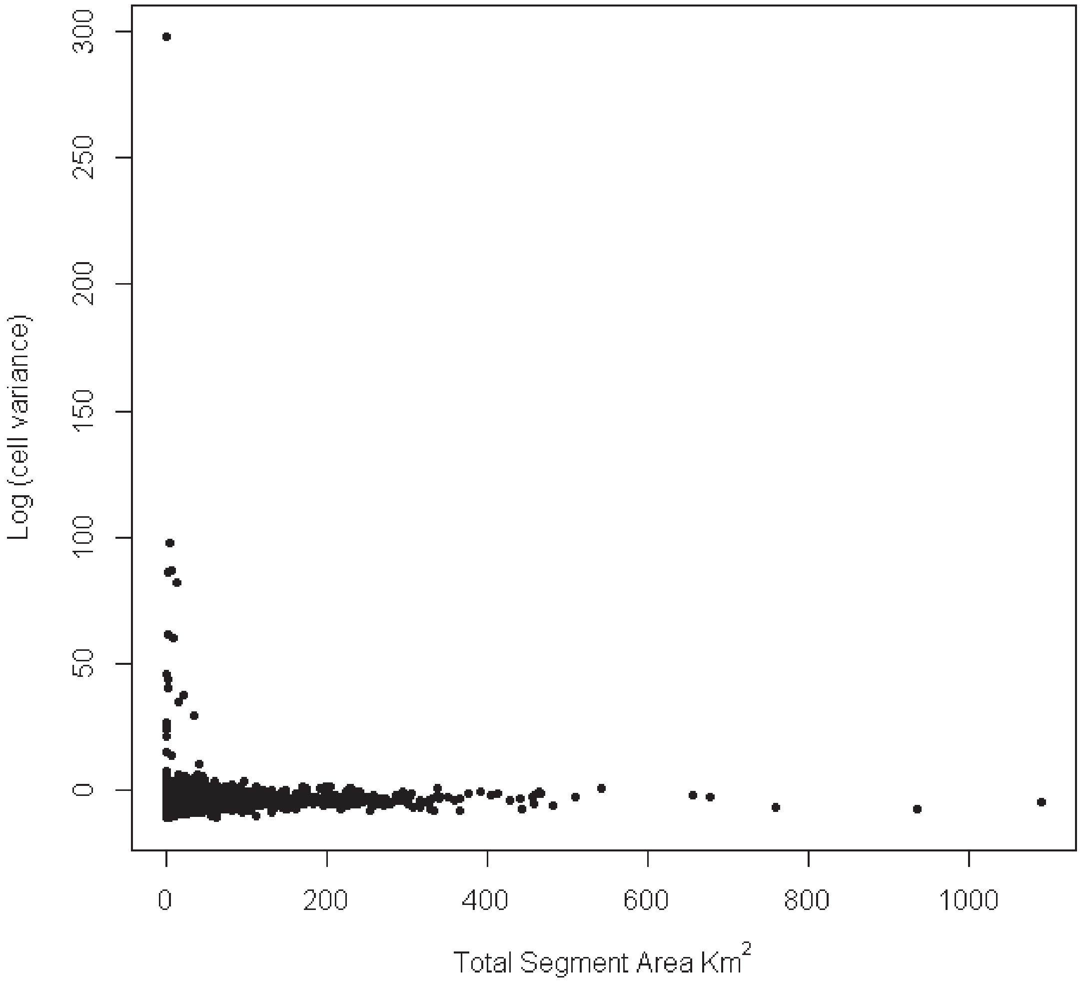

Figure 62. Prediction cell variance and per cell effort (measured as segment area) for basking shark.

Figure 60 suggested surprisingly high persistence-certainty scores in a region of low effort (west of the Hebrides). To investigate this further, the variance in cell predictions across years was plotted against effort in the cell to confirm there really was a correlation of effort and uncertainty (Figure 62). Surprisingly there was no evidence of an inverse correlation of effort and prediction cell variance (r = 0.02 , df= 3599, P=0.345) so caution should be exercised in interpretation of high persistence-certainty scores in the region to the west of the Hebrides, which is not strongly supported by effort.

4. DISCUSSION

4.1 Effort Coverage

Effort coverage varies considerably (Figures 19 – 22) both spatially and temporally with much more effort since 2000. There has also been a shift in the distribution of effort, with much more recent survey effort concentrated in regions of developer interest (cf. later images in Figure 20).

Winter (Jan. - Mar.) and autumn (Oct. - Dec.) have meagre coverage away from the ferry routes compared to summer (Figure 20), compromising the ability to make accurate and precise estimates of abundance for this time period. There is relatively little effort in the northern North Sea and the east coast.

Only survey data or systematically collected data were used from the available data. There are data defined as "casual watches", etc., in the available datasets, and data from boats where the height of the observer above sea level was not known or not recorded. These data are not used in the analyses. Nevertheless, there remains an important distinction in the surveys used: some are formal surveys designed for megafaunal abundance (either relative or absolute) estimation, while others are opportunistic placement of observers on board available vessels. The surveys themselves may have different target groups and this may lead to different detectabilities. For example, more basking sharks were seen on a dedicated basking shark survey compared to a contemporaneous cetacean survey in the same locality (see Section 2.5.3). This effect was controlled for in the spatial modelling. Some surveys did not have marine megafauna as the target group (e.g. ESAS, WWT aerial surveys), so it is possible this could cause under recording. It is possible that platform of opportunity data, based solely in areas of high cetacean abundance could bias the results; although the models should be robust to this if nearby effort was unbiased in terms of expected cetacean density. Also, much of the platform of opportunity data are ferry based, so are from set routes without regard to presumed megafaunal densities.

4.2 Interpretation of Surfaces

All maps are abstractions of a reality or of a dataset, that out of necessity distort truth (Monmonier, 1996), although hopefully this is undertaken in a way that does not bias the viewer. In this case, absolute truth, the actual or even relative number of animals present when the surveys were undertaken, is not known. The observed adjusted densities are a reflection of that truth, which if the assumptions are correct, are unbiased although locally imprecise. The predicted density surface plots represent the observed, adjusted densities, with additional interpolation into times and places where there was no effort. This is especially the case for the density surfaces for winter and autumn. The models explained only a small proportion of the total variation observed in the densities (Table 8) and the estimated coefficients of variation even in the cases without model selection uncertainty are large. The point estimate surfaces should be considered in the light of Section 3.4. Some regions can be associated with a high degree of uncertainty, either where there is a low amount of effort or because the uncertainty in this quasi-Poisson-derived model is correlated with the local point estimate. Also the illustrated pattern in the density surfaces is sensitive to the choice of scales used in coloration; more structure would be revealed if more divisions closer to zero were considered. Of special interest in an MPA consideration, is the lower bound confidence surface rather than the upper bound, as structure in this plot suggest features that are robust even with high model uncertainty. Preliminary analysis suggests that model selection uncertainty contributes massively to total uncertainty, so the utility of the predicted surfaces should be considered in the light of this.

The models could account for changing distributions of densities of animals within years both by the presence of dynamic variables (i.e. *Chloro* and *SST*) and, in models with position, by the presence of a position-year interaction. Even so, the lack of a position-year interaction should not necessarily mean the distribution of animals is static over the duration of the data set. Partial regression plots (i.e. plots of the responses to the predictors given the presence of other predictors in the model) are not given here as they are not of interest in the context of MPAs, where the marginal response (i.e. the direct relationship) between a predictor and abundance is more of interest (i.e. the response of basking shark density directly to depth, rather than the response of density to depth given position is in the model as well). Furthermore, covariates have been included in models not because their coefficients are statistically significant from zero (p-value analysis), but because they make more robust predictions (improvement in CV score).

The persistence-certainty plots indicate summer persistence year on year and also incorporate uncertainty in the model predictions (but not model selection uncertainty). As regions of greater than average density (for each bootstrap replicate) are identified, a large proportion of Scottish territorial waters can be identified as being of interest. This is especially the case for the more dispersed species. A low persistence-certainty score could reflect uncertainty about a region of importance to the animal rather than an actual low density of animals but we see the aim here as evidence-based identification of regions of conservation interest *given the existing data* and also identification of regions of little knowledge. If an area has little effort and a low persistence-certainty score than that would be a case for further investigation rather than protection unless an extreme precautionary principle was being applied. Used in conjunction with the effort maps, the observed adjusted densities and the predictions, the persistence-certainty scores do inform which areas are likely to be of MPA interest.

4.2.1 Minke whale

The minke whale is the most abundant and widespread of baleen whales in British waters, occurring in greatest numbers in northern Britain and in summer; there is limited evidence for a general movement out of coastal waters during winter, although at least some are present year-round (see Appendix 4 for details). The dataset records minke whale on the east, north and west coasts of Scotland especially off the Hebrides, the Outer Moray Firth and off the coast of Angus. The fitted model (applied to the years since 2000) predicts animals in the Moray Firth and off the Hebrides and also with some uncertainty, in the regions to the west and south-west of the Outer Hebrides and to the south of the Isle of Arran where there is little effort. These regions are also represented in the lower 2.5% surface and show evidence of persistency year on year. Minke whales are seen in the Pentland Firth and off the Northern Isles (see Appendix 4) but these are regions of low effort and so are not represented here. There was no evidence of an interaction of space and time but the presence of the dynamic variables *SST* and *Chloro* in the model suggest that surfaces will fluctuate year on year.

4.2.2 Risso's dolphin

The Risso's dolphin is a small cetacean species visiting British waters, recorded mainly in summer, with a patchy distribution although showing fidelity to several of those patches. It is commonest in north-west Scotland although in the last decade has been recorded increasingly within the northern North Sea (see Appendix 4 for details). The dataset records Risso's dolphins primarily off the Outer Hebrides (especially the north and east of the Isle of Lewis) and Aberdeenshire in Scottish territorial waters. The fitted model mainly predicts higher relative densities of Risso's dolphin off the Outer Hebrides, especially Lewis. The region of high density around Lewis is still prominent in the 2.5% surface and this region is associated with a persistent higher than average density. There was no evidence of a space-time interaction but the presence of the dynamic variable SST suggests that there will be a measure of redistribution of animals from year to year, even though there is a more general region of persistent high density

4.2.3 White-beaked dolphin

The white-beaked dolphin is restricted globally to the North Atlantic, and the British Isles hold a significant proportion of the population. It is widely distributed in the North Sea and around Scotland, but rare in the Irish Sea and Channel (see Appendix 4). Numbers in coastal waters are highest during summer. The dataset records white-beaked dolphins primarily offshore and with a dispersed distribution in the North Sea and to the north of Britain. The fitted model mainly predicts animals in the northern part of the Minch and off Angus and eastern Aberdeenshire. These regions of high density are still prominent in the 2.5% surface. There is great uncertainty in the predictions to the south of Islay and west of the Mull of Kintyre. There was no evidence that the distribution of this species varies year on year probably because no dynamic variables that varied year on year were retained in the model. There was no persistent concentration of animals in this dispersed species and a wide area was identified as having persistently higher than mean densities

4.2.4 Basking shark

The basking shark has a circumglobal distribution and around Scotland is particularly recorded on the west coast during summer (see Appendix 5). The dataset records basking shark primarily in the Sea of the Hebrides and to the north of Aberdeenshire in Scottish territorial waters. The model unsurprisingly predicts regions of high density in the Sea of the Hebrides but also to the west of the Outer Hebrides and Solway Firth, albeit with some uncertainty in these data sparse regions. This model was associated with much more explained variation, due to the presence of the *SharkSurvey* factor suggesting that the detection/recording of basking sharks on non-dedicated shark surveys is very low. There was evidence that the distribution of sharks significantly alters year on year. In the future, data on surface availability will be available (Witt, pers. comm.) that may allow estimation of absolute numbers.

4.3 Conclusions & Future Work

1. Consideration of observed densities and predicted densities allows identification of regions of higher density persistence for the marine megafaunal species of interest. However, the predicted densities for each area should be considered along with their associated uncertainty, persistence and the available survey effort associated with the locality.
2. Identified contiguous, higher than average density areas for minke whale included the areas south and west of the Hebrides, the Sea of the Hebrides and the Moray Firth.
3. The single identified contiguous higher than average density area for Risso’s dolphin was the region to the north and east of Lewis/Harris.
4. White-beaked dolphins were widely dispersed in slightly offshore waters. The northern part of the Minch and off Angus and eastern Aberdeenshire are large contiguous areas of persistent higher than average density.
5. Identified contiguous higher than average density areas for basking shark included the waters of the eastern Sea of the Hebrides and to the west of the Hebrides.
6. These areas of predicted higher density could be considered by SNH against the MPA Selection Guidelines, alongside other contextual information (e.g. on species ecology and behaviour), to inform their advice on whether they should be considered for designation as Nature Conservation MPAs.

7. The outputs of this project also expose gaps in our knowledge i.e. the density surfaces indicate:
   a) where there has been a lack of effort in time (both seasonally and annually) i.e. autumn and winter. Of course in the case of basking shark they are not at the surface in the winter (Parker & Boeseman, 1954); and
   b) where there has been a lack of effort in space (i.e. the west of the Hebrides, around Arran, the region immediately north of Caithness and Sutherland, and Orkney and Shetland.
8. Future work may improve modelling techniques allowing more precise density estimates and the existing database may be augmented with further data.

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APPENDIX 1: DESCRIPTION OF THE DATASETS AND INCLUSION CRITERIA

This appendix describes the data sets in detail and should be read in conjunction with Section 2.1. There were 25 usable distinct data sources comprising several hundred distinct surveys in space and time but not all were used in each analysis. Figure A1.1 describes each dataset. Some datasets overlapped with each other. Duplicate data were identified and deleted.

Table A1.1 summarizes the total annual search effort for each of the datasets. Only search effort collected within depths of less than 300m and in Beaufort sea states less than 4 was included (with the exception of some aerial surveys where sea state was stated only to be less than a figure greater than 4). Table A1.2 summarizes search effort by vessel type. Data were collected from both sides of the vessel or plane unless otherwise stated.

Figure A1.1. Realized survey effort (i.e. as used in the spatial models) for each data source. Each point represents the centre of a segment of effort. (For SCANS and SCANS II, aerial effort is shown in red, boat effort in black). a. CRRU, b ESAS surveys, c. Gill, d. HWDT, e. IWDG, f. MainstreamRP, e. Manx Whale and Dolphin Trust, f. Marinelife g. Manx, h. Marinelife, i. MORL boat, j. NORCET k. ORCA, l. SCANS. m. SCANS II, n. SeaEnergy Renewables Inchcape, o. SWF p. Speedie basking shark, q. University of Aberdeen aerial, r. University of Aberdeen boat, s. University of Aberdeen platform of opportunity surveys, t. University of Aberdeen SAC surveys, u. University of Aberdeen/MORL/HiDef/The Crown Estates, v. University of Aberdeen/MORL/HiDef, w. WDC survey. v. WWT surveys.

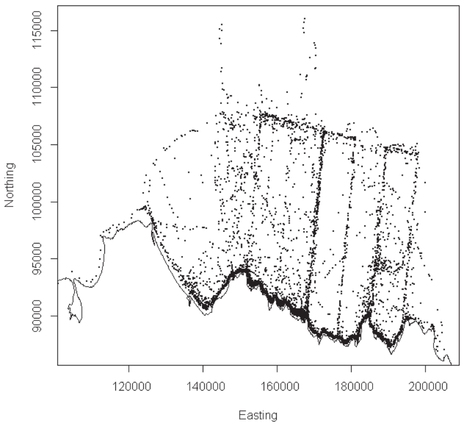
Survey name and description	Realised survey effort
Cetacean Research and Rescue Unit Surveys These little boat surveys were undertaken off the coast of Banffshire from 2009 – 2012 (Figure A1.1a)	*a.* 

Figure A1.1 cont.

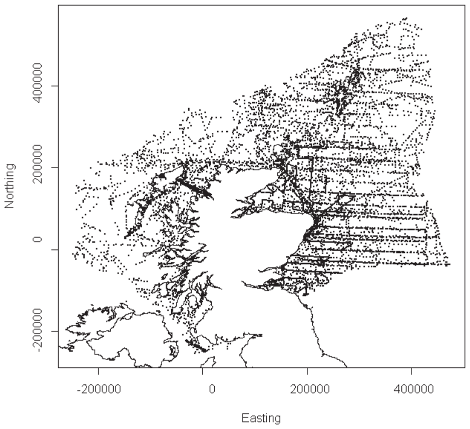
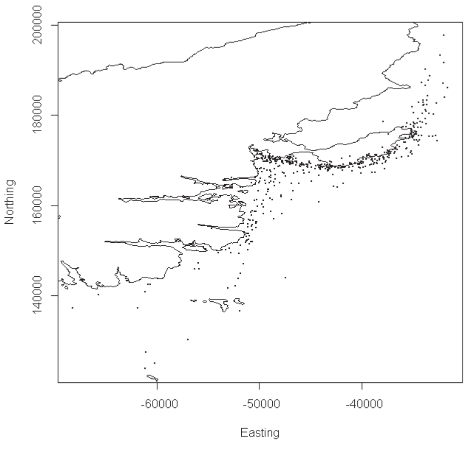
Survey name and description	**Realised survey effort**
European Seabirds at Sea (ESAS) shipboard surveys These surveys date back to 1979 but only data from 1994 onwards have been utilised here. Numerous *littleboats, bigboats* and *ferries* were used on these surveys from 1994 to 2010 (Figure A1.1b) with seabirds being the target group particularly in the 1980s and 1990s, although cetaceans were also recorded. Details of the early surveys can be found in Stone *et al.* (1995). Perpendicular distances were generally collected in distance intervals although sometimes sightings were just known to be within a 300 m horizontal distance with the exact distance not known. ESAS North Sea harbour porpoise sightings were previously analysed by Winship (2008); however, data analysed here were not treated as per that analysis in a number of respects. Winship's (2008) altering speed criteria (< 50 km/h) for identifying periods of non-effort was not implemented and vessel type was included in the analysis (see below). However, like Winship (2008), effort associated with surface speeds in excess of that possible for boat based surveys was excluded. Banded distances for these surveys were assumed to be initially observed perpendicular distances although for ESAS, this is not necessarily the case (Northridge *et al.,* 1995a,b).	*b.* 
Gill Survey for Risso's dolphin This survey was undertaken in 1996 targeting Risso's dolphin (Figure A1.1c) in association with SWF but other species were recorded.	*c.* 

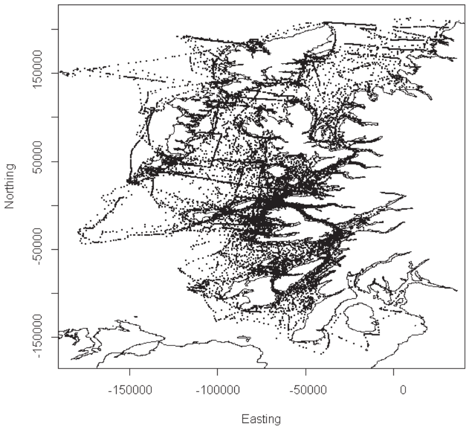
Figure A1.1 cont.

Survey name and description **Realised survey effort**

Hebridean Whale and Dolphin Trust (HWDT) surveys

These eight surveys took place between 2003 and 2012 using a *littleboat* around the Hebrides and north-east coast of Scotland (Figure A1.1d). Exact perpendicular distances were available for each sighting.

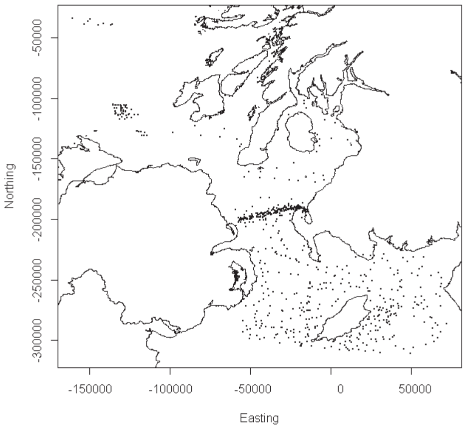
d.



Irish Whale & Dolphin Group (IWDG) surveys

A variety of *bigboat* size survey vessels have been used to collect these data for the years 2003 to 2009 (Figure A1.1e). Additionally six *ferries* have been used to collect data for the years 2001 to 2010. Exact perpendicular distances were available for each sighting.

e.



Mainstream Renewable Power (Neart na Gaoithe)

Boat surveys undertaken in 2009 and 2010 off the coast of Fife (Figure A1.1f). Distances were mostly available. This one-sided survey was treated as two-sided here.

f.

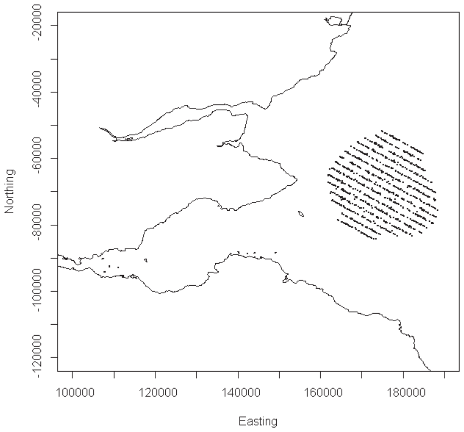


Figure A1.1 cont.

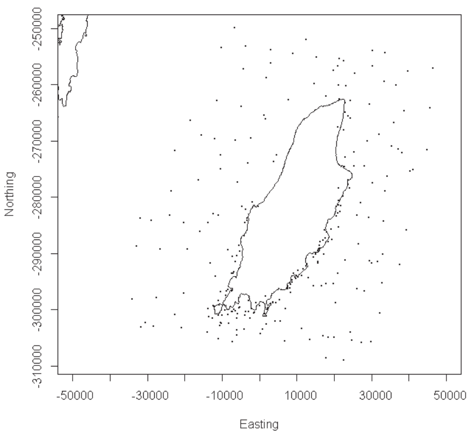
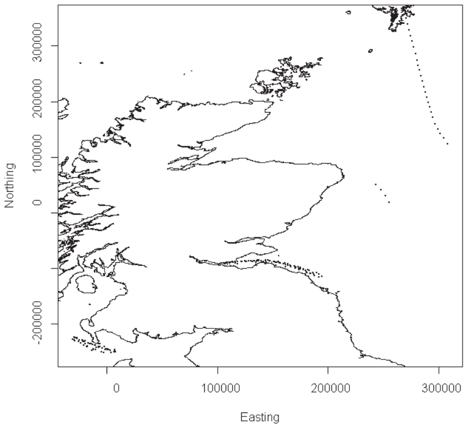
Survey name and description	**Realised survey effort**
Manx Whale and Dolphin Trust survey This survey was conducted around the Isle of Man in 2008 (Figure A1.1g) by the Manx Whale and Dolphin Trust. A *littleboat* was used and perpendicular distances were available for all sightings.	*g.* 
Marine Conservation Research Ltd/International Fund for Animal Welfare (IFAW) A boat survey undertaken over the continental slope of the western approaches in 2010, perpendicular distances were available. Only a very small amount of effort was available on the continental shelf (not shown).	
MARINElife/BDRP surveys Ferries were used to collect data from 2008 to 2010 (Figure A1.1h). Exact perpendicular distances were available for all sightings.	*h.* 

Figure A1.1 cont.

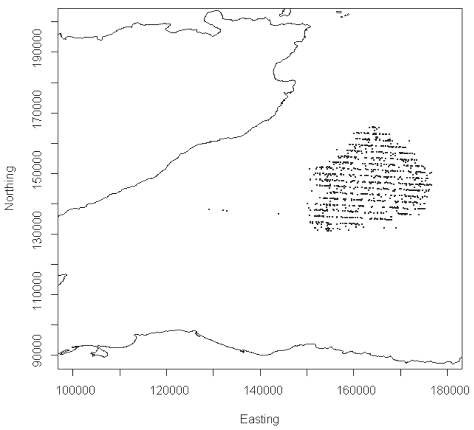
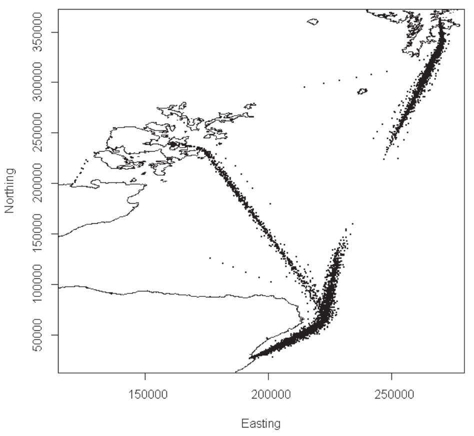
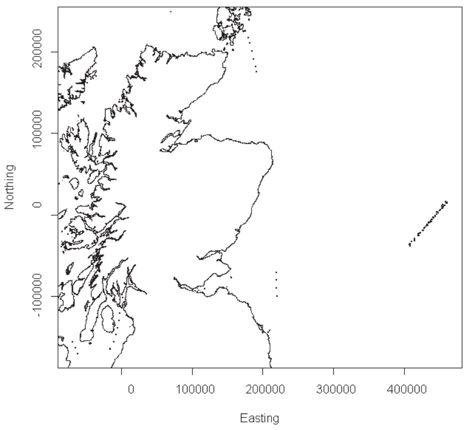
Survey name and description	Realised survey effort
Moray Offshore Renewables Ltd (MORL) boat surveys Surveys undertaken in the Outer Moray Firth in 2010 (Figure A1.1i). Distances were available.	*i.* 
Northern North Sea Cetacean ferry (NORCET) surveys Platform of opportunity surveys undertaken from ferries going to and from Aberdeen (Figure A1.1k). Data were available from 2004 to 2009. These surveys had an asymmetrical survey method with observations 90° to the left and 45° to the right of the bow. Only cetacean data were considered.	*j.* 
ORCA and Company of Whales (CoW) surveys Surveys were conducted in 2009 and 2010 from various ferry routes (Figure A1.1j). Exact perpendicular distances were available for all sightings.	*k.* 

Figure A1.1 cont.

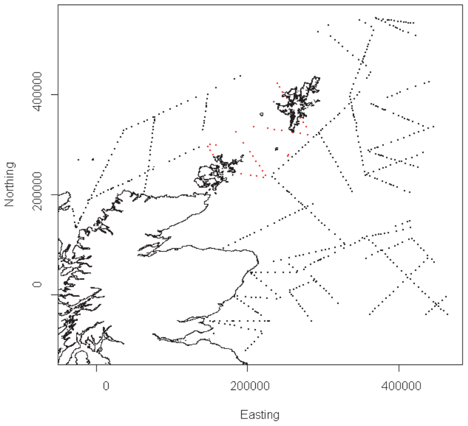
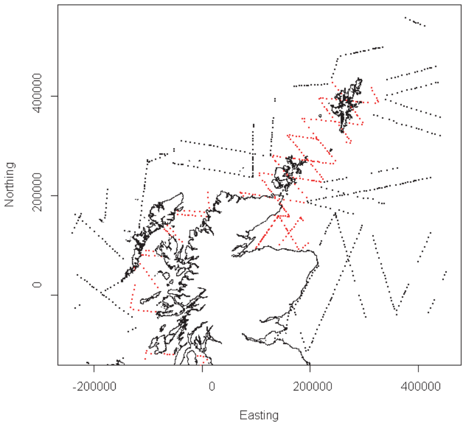
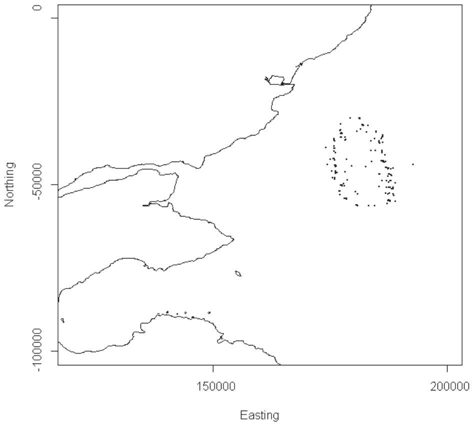
Survey name and description	**Realised survey effort**
SCANS This survey was conducted in 1994 (Hammond *et al.* 2002) using *bigboats* (Figure A1.1l, black) with additional aerial coastal surveys (Figure A1.1l, red). The majority of search effort was conducted in double platform mode and exact perpendicular distances were available for each sighting.	*l.* 
SCANS-II This survey was conducted in 2005 using *bigboats* (Figure A1.1m, black) with additional aerial coast surveys (Figure A1.1m, red). The majority of search effort was conducted in double platform mode and exact perpendicular distances were available for each sighting. The data are described in detail in SCANS-II (2008).	*m.* 
Sea Energy Renewables (now EDP Renewables and Repsol Nuevas Energias UK) Inch Cape survey A boat survey undertaken off Angus in 2010 (Figure A1.1n). Perpendicular distances were not available.	*n.* 

Figure A1.1 cont.

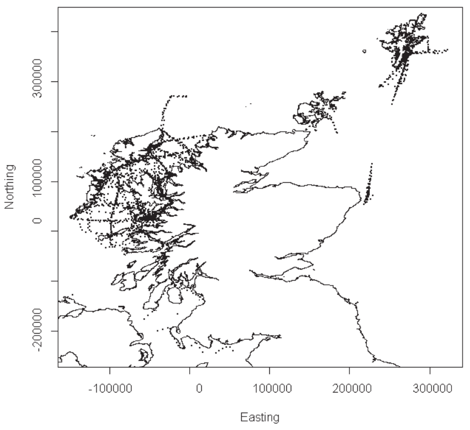
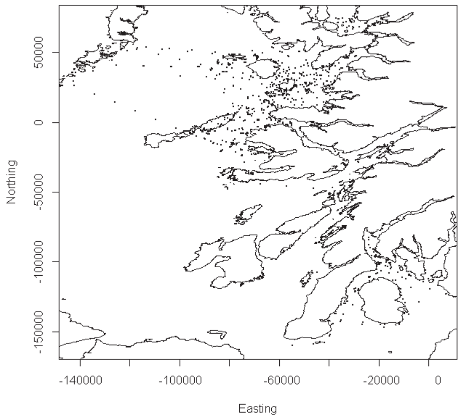
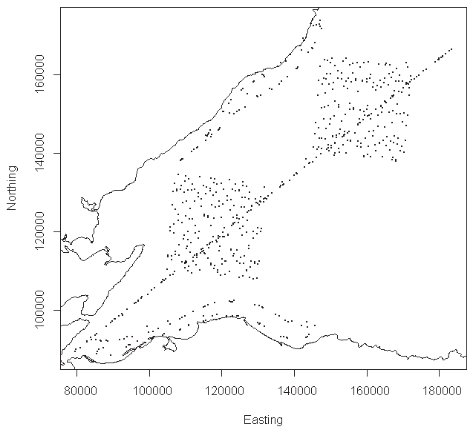
Survey name and description	**Realised survey effort**
Sea Watch Foundation (SWF) surveys Surveys conducted from 1994 to 2007 around the British Isles (Figure A1.1o). Earlier surveys have been excluded from this analysis. Both big and *littleboats* were used. The Irish Sea data are described in detail in Baines & Evans (2009, 2012). A *littleboat* was used in this survey conducted in 2008 around Cardigan Bay and the North Wales coast. Exact perpendicular distances were available for most sighting and some data were collected in double platform mode.	*o* 
Speedie Basking Shark Surveys These surveys, for basking shark only, took place on the east coast of Scotland from 2003 – 2006 (Figure A1.1p).	*p.* 
University of Aberdeen aerial surveys These were aerial visual surveys conducted in 2010 in the Moray Firth (Figure A1.1q). Distances were available. There were also aerial photo surveys in the same area (see below).	*q.* 

Figure A1.1 cont.

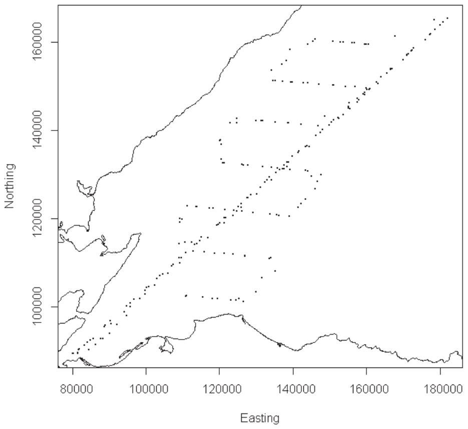
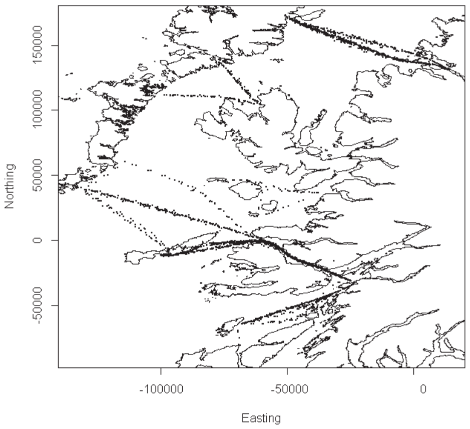
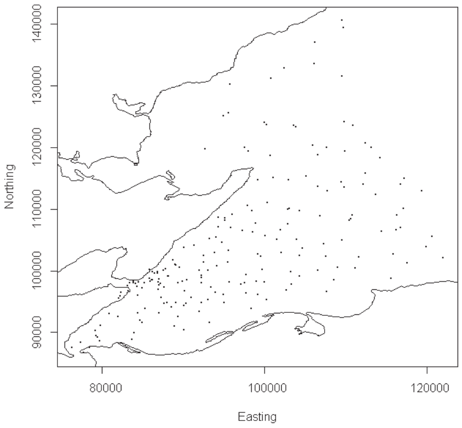
Survey name and description	**Realised survey effort**
University of Aberdeen boat survey A *bigboat* survey undertaken in the Moray Firth in 2009 (Figure A1.1r). Distances were available.	*r.* 
University of Aberdeen platform of opportunity surveys These data were collected from 2001 to 2006 on 36 ferry routes to, from and around the Hebrides (Figure A1.1s). Exact perpendicular distances (as opposed to distances in interval intervals) were available for each sighting. Only cetacean data were used from this survey.	*s.* 
University of Aberdeen SAC Survey A *littleboat* survey undertaken in the inner Moray Firth in 2004 and 2005 (Figure A1.1t). Distances were available.	*t.* 

Figure A1.1 cont.

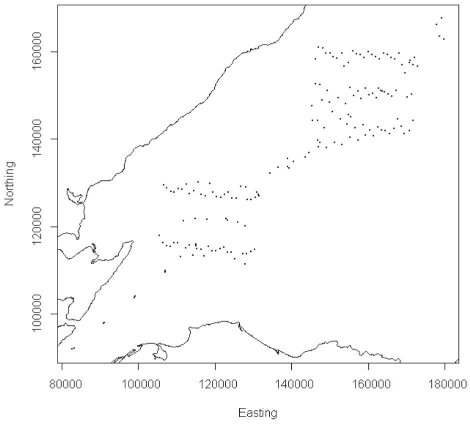
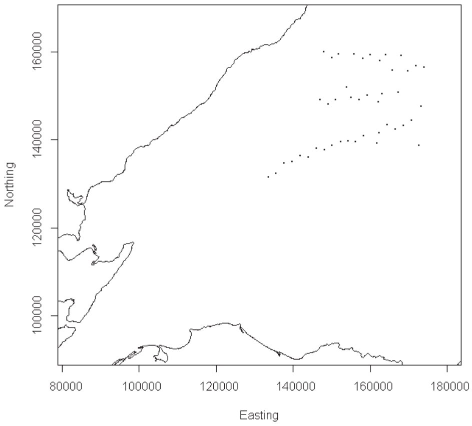
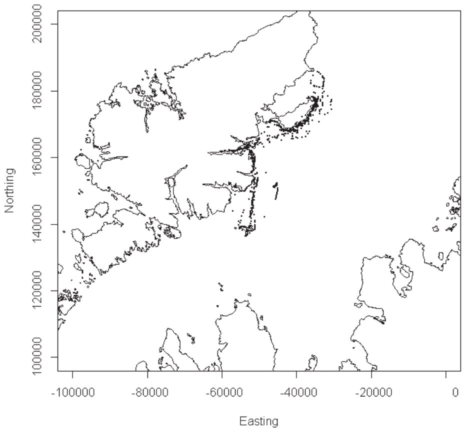
Survey name and description	Realised survey effort
University of Aberdeen/MORL/HiDef/The Crown Estates An aerial survey undertaken in the Moray Firth in 2010 (Figure A1.1u). Distances were available.	*u.* 
University of Aberdeen/MORL/HiDef An aerial survey undertaken in the Moray Firth in 2009 (Figure A1.1v). Distances were available.	*v.* 
Whale and Dolphin Conservation Surveys undertaken off Lewis in 2011 & 2012 (Figure A1.1w).	*w.* 

Figure A1.1 cont.

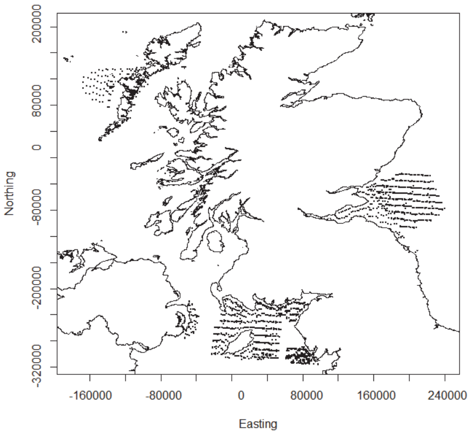
Survey name and description	Realised survey effort
Wildfowl and Wetlands Trust (WWT) surveys WWT conducted aerial surveys from 2001 to 2009 (Figure A1.1x) targeting seabirds but also recording other species. Perpendicular distances were recorded in three or four distance intervals. Some of these data are described in WWT Consulting (2009). Showing effort for both white-beaked dolphin and basking sharks/Risso's dolphins.	*x.* 

Table A1.1. Realized annual search effort (km) for each dataset assumed for a white beaked dolphin analysis, apart from for Manx Whale and Dolphin Trust and Speedie data where a basking shark analysis was assumed.

Dataset	***VesselType***	***1994***	***1995***	***1996***	***1997***	***1998***	***1999***	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***	***2009***	***2010***	***2011***	***2012***	***Data source Total***
CRRU	Littleboats	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2435	1819	1575	1814	**7643**
Gill	Littleboats	0	0	1759	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1759**
ESAS	Littleboats, bigboats & Ferries	8460	8397	3688	9120	10150	3131	1330	2558	2165	3236	1627	1451	171	61	0	0	3043	869	0	**59457**
HWDT	Bigboat	0	0	0	0	0	0	0	0	0	1418	1066	1534	3446	3426	6432	6509	4204	5933	4443	**38411**
IFAW	Littleboat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	**27**
IWDG	Bigboat & Ferry	0	0	0	0	0	0	0	0	0	64	10	0	498	341	697	1097	445	0	0	**3152**
Mainstream	Ferry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	632	3527	2301	0	**6460**
Manx Whale and Dolphin Trust	Littleboat	0	0	0	0	0	0	0	0	0	0	0	0	0	1748	0	0	0	0	0	**1748**
Marinelife	Ferry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	300	71	1239	0	0	**1610**
MORL boat	Bigboat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3112	3563	0	**6675**
NORCET	Ferry	0	0	0	0	0	0	0	0	0	0	795	234	7677	4448	12178	9034	0	0	0	**34366**
ORCA	Ferry	0	0	0	0	0	0	0	0	0	0	0	0	72	478	0	67	209	0	0	**826**
SCANS	Bigboat & Aeroplane	4297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4297**
SCANS-II	Bigboat & Aeroplane	0	0	0	0	0	0	0	0	0	0	0	6201	0	0	0	0	0	0	0	**6201**
Sea Energy Renewables	Bigboat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	203	1610	0	**1813**
Speedie		0	0	0	0	0	0	0	0	0	1400	1449	1509	3261	0	0	0	0	0	0	**7619**
SWF	Bigboat, littleboat & ferry	4857	3876	1763	1935	891	541	729	963	1041	9	244	1021	568	34	0	0	0	0	0	**18472**
UOA aerial	Aeroplane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4675	0	0	**4675**
UOA boat	Boat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1450	0	0	0	**1450**
UOA ferry	Ferry	0	0	0	0	0	0	0	136	2606	6637	5999	4308	4160	0	0	0	0	0	0	**23846**
UOA SAC Survey	Littleboat	0	0	0	0	0	0	0	0	0	0	266	1054	0	0	0	0	0	0	0	**1320**
UOA MORL/HIDEF/The Crown Estates	Aeroplane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1708	0	0	**1708**
UOA MORL/HIDEF	Aeroplane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	437	0	0	0	**437**
WDC	Littleboat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	479	431	**910**
WWT	Aeroplane	0	0	0	0	0	0	0	0	0	0	362	945	664	2589	1602	7786	0	0	0	**13948**
Year total		**17614**	**12273**	**7210**	**11055**	**11041**	**3672**	**2059**	**3657**	**5812**	**12764**	**11818**	**18257**	**20517**	**13125**	**21209**	**29518**	**24211**	**16330**	**6688**	**248830**

Table A1.2. Effort (km) by vessel type by year (for white-beaked dolphin data set).

	Bigboat	Ferry	Littleboat	Aeroplane	Total
1994	7930	4220	5150	318	17618
1995	4829	3820	3655	0	12304
1996	584	3115	3521	0	7220
1997	3138	5981	1935	0	11054
1998	5215	4935	891	0	11041
1999	2782	349	541	0	3672
2000	674	656	729	0	2059
2001	1713	1006	803	0	3522
2002	1969	354	926	0	3249
2003	4579	139	9	0	4727
2004	2852	94	266	362	3574
2005	6300	1224	1054	3631	12209
2006	3773	982	0	664	5419
2007	3491	853	20	2589	6953
2008	6621	809	0	1602	9032
2009	9171	656	2435	8223	20485
2010	11291	4692	1846	6383	24212
2011	7475	869	7999	0	16343
2012	0	0	5583	0	5583
Total	**84387**	**34754**	**37363**	**23772**	**180276**

A1 references

See main reference list on page 91.

APPENDIX 2: PARAMETERS OF DETECTION FUNCTIONS

Readers should refer to Section 3.2 for a graphical display of the functions. Details of the parameters of the detection function models are given in table A2.1 for completeness.

Table A2.1. Parameters of the fitted detection functions.

Species	**Data type**	**Model Type**	**Parameters Source**	**Estimate (SE)**
Minke whale	Non-ESAS boats	HR	Scale	
			coefficient	5.094 (0.239)
			Shape	
			coefficient	0.308 (0.130)
Dolphin (Risso's)	Non-ESAS boats	HR	Scale	
			Intercept	5.527 (0.202)
			SeaState	-0.146 (0.084)
			Shape	
			Intercept	0.558 (0.148)
	ESAS boats	HN	Scale	
			Intercept	3.669 (1.597)
			VesselType=Ferry	0.253 (0.119)
	University aerial	HN	Scale	
			Intercept	5.060 (0.288)
	SCANS aerial	HN	Scale	
			Intercept	4.273 (0.113)
	WWT (new binning) aerial	HN	Scale	
			Intercept	4.579 (0.240)
Dolphin (white-beaked)	Non-ESAS boats	HR	Scale	
			Intercept	5.647 (0.168)
			SeaState	-0.181 (0.075)
			Shape	
			Intercept	0.599 (0.134)
	ESAS boats	HN	Scale	
			Intercept	3.629 (0.073)
	WWT (new binning) aerial	HN	Scale	
			Intercept	5.022 (0.134)
Basking shark	Non-ESAS boats	HR	Scale	
			Intercept	5.536 (0.131)
			SeaState	-0.234 (0.069)
			size	
			Shape	
			Intercept	0.732 (0.128)

APPENDIX 3: DETAILS OF THE SPATIAL MODELS

Here we provide additional details of the spatial models used.

Table A3.1. Table of 1D parameters.

Covariate	**Starting Knots for quadratic B-spline**	**Min Knots**	**Max Knots**	**Gap**
Depth	1 at mean	1	4	5 metres
Year	1 at mean	1	4	1
Chloro	1 at mean	1	4	0.2
Front	1 at mean	1	4	2
TidalEng	1 at mean	1	4	5 Joules m^{-3}
SST	1 at mean	1	4	1 degrees C

Table A3.2. Parameters for spatial component.

Starting knots	6, 8, 12, 16
Min Knots	4
Max knots	20
Min gap	1 km
No of Range parameters	8 (using defaults from MRSea)

APPENDIX 4: BIOLOGICAL BACKGROUND FOR CETACEANS (PETER EVANS, UNIVERSITY OF BANGOR & SEA WATCH FOUNDATION)

A4.1. Minke whale *Balaenoptera acutorostrata*

A4.1.1 Status & Distribution

The minke whale is the commonest baleen whale both in the North Atlantic and around the British Isles. It occurs in small numbers along the Atlantic seaboard of Europe mainly from Norway south to France, as well as in the North Sea, although abundance is greatest in the north (Hammond *et al*., 2002, 2013; Evans *et al*., 2003; Reid *et al*., 2003; Anderwald *et al*., 2008). The species is widely distributed in British and Irish waters, with numbers greatest off the west coast of Scotland, around the Hebrides, in the Pentland Firth, Moray Firth, and Firth of Forth (Evans, 1996, 1997b, c, d, e; Evans *et al*., 2003; Reid *et al*., 2003; Macleod *et al*., 2004; Robinson *et al*., 2009; Evans & Baines, 2010; Anderwald *et al*., 2010, 2012; Hammond *et al*., 2013). In some of those localities, aggregations of up to 20 individuals have been recorded in summer (in one instance in the Pentland Firth, 30 individuals were estimated to occur around Gills Bay at any one time – Evans & Baines, 2010). The species occurs commonly in the northern and central North Sea as far south as Yorkshire, but is rare in the southernmost North Sea and eastern half of the English Channel; in the western English Channel, it is evenly distributed but in low numbers to the continental shelf edge, being largely absent from the deeper parts of the Bay of Biscay (Evans *et al*., 2003; Reid *et al*., 2003; Anderwald *et al*., 2008).

There is some indication of a shift in summer distribution in recent years. During the 1980s-90s, minke whales were more abundant off the west coast of Scotland and in the Hebrides than they appear to be currently (Evans *et al*., 2003; Anderwald *et al*., 2012; Sea Watch, unpublished data), the areas with greatest abundance now being in the west central North Sea (Hammond *et al*., 2013). Seasonal and inter-year variation in abundance has been linked to temporal variation in oceanographic conditions and prey availability (Tetley *et al*., 2008; Anderwald *et al*., 2012).

A4.1.2 Abundance & Trends

The only published population estimates for minke whales in UK waters are from the SCANS & CODA surveys. In July 1994, a survey (SCANS) of the N Sea, English Channel and Celtic Sea estimated 8,445 individuals (CV=0.24; 95% C.I. 5,000-13,500) (Hammond *et al*., 2002).

A more extensive line transect survey (SCANS II) over the NW European continental shelf in July 2005 gave an overall estimate of 18,958 (CV=0.35) (including 13,734 for the equivalent area as 1994, with a CV of 0.41) (Hammond *et al*., 2013). And the offshore CODA survey in July 2007 yielded a population estimate of 6,765 (95% CI 1,300-34,200; CV=0.99) (CODA, 2009). This latter estimate has very wide confidence intervals and was uncorrected for animals missed along the track-line, and is therefore negatively biased.

A population estimate for the entire north-eastern North Atlantic (based upon data from 2002-2007) gave 81,000 individuals with a further 40,000 in the Central North Atlantic (IWC website: www.iwcoffice.org, accessed 5 Dec 2013). Previously, the stock seasonally inhabiting the Norwegian and Barents Seas was estimated at 86,700 individuals (95% C.I. 61,000-117,000) (Schweder *et al*., 1997).

Population changes in the north-east Atlantic remain uncertain. Effort-related sightings surveys suggest that the species has generally increased in UK shelf waters between the 1980s and the present (Evans 1992; Boran *et al*., 1999; Evans *et al.,* 2003; Paxton *et al*., 2013), although for the equivalent area surveyed in 1994 and 2005, whereas an increase was noted, it was not statistically significant (Hammond *et al.*, 2013).

A4.1.3 Habitat

Although widely distributed in all the major oceans of the world from tropical to polar seas, minke whales are most abundant in relatively cool waters and on the continental shelf (in depths of 200 m or less) (Anderwald *et al.*, 2008). The species can be found very close to land, sometimes entering estuaries, bays or inlets, and usually feeding around banks and in areas of upwelling or strong currents around headlands and small islands, primarily during summer (Anderwald *et al.*, 2008).

A4.1.4 Annual Cycle

The species appears to be a mainly summer visitor to the British Isles, with few sightings in winter, although this may partly be due to low effort at that period (Anderwald & Evans, 2007). In the North-east Atlantic, births are mainly around December, probably in temperate offshore waters, but possibly extending to the subtropics (Anderwald *et al.*, 2008).

Usually seen singly or in pairs, minkes sometimes aggregate into larger groups of around 10-20 (exceptionally 30) individuals when feeding (Evans *et al.*, 2003; Reid *et al.*, 2003). In Scottish waters, peak numbers of sightings and of individuals occur in June to September, with August or September tending to be the peak months (Evans *et al.*, 2003; Reid *et al.*, 2003; Robinson *et al.*, 2009; Evans & Baines, 2010; Anderwald *et al.*, 2010, 2012). However, the species is present year-round, although in apparently small numbers, between November and April (Anderwald & Evans, 2007).

A4.1.5 Diet & Ecology

The minke whale is the most catholic feeder of all the rorquals. In the Northern Hemisphere, the species takes more fish (sandeels, herring, sprat, cod, capelin, haddock, saithe and whiting) than the other baleen whales, although euphausiids and pteropods are also taken, especially in higher latitudes (Haug *et al.,* 1995, 2002; Nordøy *et al.,* 1995; Neve, 2000; Sigurjónsson *et al.,* 2000; Olsen & Holst, 2001; Born *et al.,* 2003; Pierce *et al.,* 2004; Windsland *et al.*, 2007; Anderwald *et al.*, 2012).

In Scottish waters (mainly east coast), examination of the stomach contents of ten minke whales found only fish, with sandeels forming 66% by number and 62% by weight (standardised for incomplete sampling) (Pierce *et al.*, 2004). Clupeids (herring and sprat) formed the next most important category, accounting for 33% by number and 32% by weight of the diet. The estimated size of sandeels eaten ranged from 6cm to 15cm, and the majority of sprats were 10-13cm in length. Other species found in the stomachs included mackerel, Norway pout and/or poor cod, and gobies. On the west coast of Scotland, in late summer, minke whales were observed feeding on bait balls comprising mainly sprat (but also including herring), whilst during early summer, their distribution suggested an association with sandeel grounds (MacLeod *et al.*, 2004; Anderwald, 2009; Anderwald *et al.*, 2012).

A4.2. Risso's dolphin *Grampus griseus*

A4.2.1 Status & Distribution

The Risso's dolphin is widely but patchily distributed in tropical and temperate seas of both hemispheres (Reeves *et al.*, 1999). It occurs in small numbers along the Atlantic European seaboard from the Northern Isles south to the Iberian Peninsula and east into the Mediterranean Sea, favouring continental slope waters (Evans *et al.*, 2003; Reid *et al.*, 2003; Evans, 2008).

The major populations in northern European waters occur in the Hebrides particularly around the Eye Peninsula, Isle of Lewis (Evans, 1997e; Atkinson *et al*., 1997, 1998; Evans *et al*., 2003) but the species is regular also in Shetland & Orkney (Evans, 1997a, b; Evans *et al*., 1997; Evans & Baines, 2010), and the Irish Sea (Baines & Evans, 2012), as well as in South-west Ireland. It is rare in the North Sea and all but the western end of the English Channel. Elsewhere, it is present in NW France, the southern Bay of Biscay, around the Iberian Peninsula, and in the Mediterranean Sea (Evans *et al*., 2003; Reid *et al*., 2003).

A4.2.2 Abundance & Trends

In the western North Atlantic, a population estimate of 20,479 (CV=0.59) exists for waters off eastern USA and 1,589 in the northern Gulf of Mexico (Waring *et al*., 2011). No population estimates exist for any region in the eastern North Atlantic. A study in the North Minch, Scotland, identified at least 142 individuals (Atkinson *et al*., 1997, 1998). There are no obvious population trends for the species in British waters; numbers visiting coastal waters can vary a great deal between years. However, in recent years the species has been seen increasingly along the north-east and east coasts of Scotland (Evans, 1996, 1997c; Evans & Baines, 2010; Sea Watch unpublished data).

A4.2.3 Habitat

Risso's dolphins show a preference for warm waters (ranging from 7.5-28°C, but mainly at 5-20°C, and rarely below 10°C), generally favouring continental slope waters (Evans, 2008). In the eastern Pacific, the species typically occurs seaward of the 180 m depth contour, and is seen in coastal areas only where the continental shelf is relatively close to shore (Leatherwood *et al*., 1980; Kruse, 1989). In those areas, the depth averaged 1,000 m. Steep sections along the edge of the continental shelf are also identified as high-use areas in eastern USA and the Gulf of Mexico (Hain *et al*., 1981; Kenney & Winn, 1986, 1987; Baumgartner, 1997). By contrast, over the continental shelf around the British Isles, the species is seen mainly over slopes of 50-100 m depth (Evans, 2008).

A4.2.4 Annual Cycle

The species is mainly a summer and autumn visitor, with the highest sightings rates in the period July to September. Risso's dolphins breed in the region, and young have been observed wherever groups have been sighted. Calves may be born in most months of the year, although calving seems to peak between March and July (Evans *et al*., 2003; Evans, 2008). An examination of 51 stranded animals in the NW Mediterranean indicated calving to be between the end of winter and early summer (Raduán *et al*., 2007), although the number of calves there peaks in July, whilst the proportion of adults to calves largely remains the same throughout the year (Gaspari, 2004). It is possible that calves are born in most months of the year (CETAP, 1982).

In the Minches, peak numbers of sightings and individuals occur between August and September, and when corrected for effort, peak sightings rates are between August and October, and individual rates between August and September (Evans *et al*., 2003). The species has been recorded in most months of the year although only rarely reported between November and April (Evans *et al*., 2003; Evans, 2008).

A4.2.5 Diet & Ecology

Risso's dolphins are largely cephalopod feeders, taking particularly octopus *Eledone cirrhosa,* cuttlefish *Sepia officinalis* and various squid *Todarodes sagittatus, Loligo forbesi* and *L. vulgaris, Gonatus* spp., *Histioteuthis reversa* and *H. bonnellii, Ancistroteuthis lichtensteinii, Sepiola oweniana* and members of the family Cranchiidae. They will also occasionally take small fish (e.g. cod *Gadus morhua*) (Eggleton, 1905; Tsutsumi, *et al.,* 1961; Clarke & Pascoe, 1985; Desportes, 1985; Clarke, 1986; Zonfrillo, *et al.,* 1988; Bello &

Pulcini, 1989; Podestà & Meotti, 1991; Bello, 1992; Carlini, *et al.*, 1992; Wurtz, *et al.,* 1992; Cockcroft *et al.*, 1993; Atkinson, *et al.*, 1998; Santos *et al.*, 1994, 1995, 1996; Raga *et al.*, 2006; Bloch *et al.*, 2012).

Risso's dolphins form small to medium-sized pods of 2–50 animals (most commonly 6–12 in UK coastal waters) (Evans *et al.*, 2003; Evans, 2008), although they may be seen singly or in some parts of the world, in groups of several hundreds or even thousands (Kruse *et al.*, 1999).

A4.3 White-beaked dolphin (*Lagenorhynchus albirostris*)

A4.3.1 Status & Distribution

The white-beaked dolphin is restricted to temperate and sub-polar seas of the North Atlantic. It occurs over a large part of the northern European continental shelf, its distribution extending northwards to northern Norway, Iceland, the Greenland Sea and central west Greenland (Reeves *et al.,* 1999; Evans & Smeenk, 2008).

The species is common in British and Irish waters, and is found most abundantly in the central and northern North Sea across to north-west Scotland, although it also occurs less commonly in the southern North Sea, and occasionally in western and southern Ireland, St George's Channel, English Channel, and northern Bay of Biscay (Evans *et al.*, 2003; Reid *et al.*, 2003; Evans & Smeenk, 2008). The species is uncommon within the Moray Firth (Evans *et al.*, 2003; Reid *et al.*, 2003; Robinson *et al.*, 2007) but is regular off the east Grampian coast (Weir & Stockin, 2001; Weir *et al.*, 2007; Anderwald *et al.*, 2010).

In recent years, the species may be exhibiting a shift northwards. During the SCANS II survey in July 2005, only one sighting of white-beaked dolphins was made south of 55°N. A similar reduction in sightings in northern Britain was observed in the Sea Watch database, comparing sightings during the 1980s with those since then (Evans, 1990, 1992; Northridge *et al.,* 1995a; Evans *et al.*, 1997, 2003). A decrease in strandings in northern Britain has also occurred over the same period (Canning *et al.*, 2008). Possible causes for a range shift include a response to changing prey distributions resulting from warming sea surface temperatures, or a more direct thermal response (MacLeod, 2009; Evans *et al.,* 2010).

A4.3.2 Abundance & Trends

From line transect surveys in July 1994 (Hammond *et al.*, 2002), a population estimate of 7,856 white-beaked dolphins (CV=0.30; 95% CI 4,032-13,301) was made for the North Sea and Channel. An abundance estimate of 11,760 (95% CI 5,867-18,528) dolphins was obtained when all *Lagenorhynchus* (i.e. white-beaked and Atlantic white-sided dolphins) sightings were combined (including those whose specific identity was not known). The most recent (July 2005) population estimate, covering European continental shelf seas from South-west Norway, south to Atlantic Portugal, gave an estimate of 16,536 (CV=0.30), with the majority in inshore waters of west Scotland and in the northern North Sea (Hammond *et al.*, 2013).

Elsewhere, Kovacs *et al.* (2009) report an abundance estimate of 60,000-70,000 in the Barents Sea although it is not clear how that estimate was derived. There are also populations of white-beaked dolphins around Iceland and in the Greenland Sea (Salo, 2004; Cecchetti, 2006; Magnusdottir, 2006), as well as off the coast of West Greenland (Hansen, 2010). No abundance estimates have been made for these entire regions but from aerial surveys in SW Greenland during 2007, NAMMCO (2012) reported an abundance estimate of 11,800 (95% CI 7,562-18,416). Given the restricted North Atlantic distribution of this species, the population inhabiting British waters has some global significance.

No clear trends have been identified for the species overall in the north-east Atlantic region. No significant difference in abundance estimates was observed between the two SCANS surveys given the high CVs around those estimates. The abundance estimate for the North Sea (including Shetland & Orkney) and English Channel was 10,666 (CV=0.38; 95% CI 9,200-29,600) compared with the 7,856 referred to above in the equivalent area in 1994 (Hammond *et al.*, 2002, 2013).

In the Grampian region, where there has been some sustained monitoring, local trends in sighting rates and number of individuals per unit effort indicate strong peaks in 2000 and again in 2004, for both vessel-based and land-based surveys (Anderwald *et al.*, 2010). Before 1999, the species was recorded only occasionally, whereas both overall sightings and sighting rates have declined since 2004 (Weir & Stockin, 2001; Anderwald *et al.*, 2010). On the other hand, more generally in UK waters, although there may be range shifts, abundance appears to have remained stable or increased slightly (Evans *et al.*, 2003; Paxton *et al.*, 2013), And in the southern North Sea, strandings on the Dutch and Belgian coasts have increased sharply since the late 1970s, whilst sightings in this region have fluctuated with no obvious trend (Camphuysen & Peet, 2006).

A4.3.3 Habitat

White-beaked dolphins in northern Europe occur mainly in waters of 50-100 m depth, and almost entirely within the 200 m isobath (Evans & Smeenk, 2008), although in the Barents Sea and off west Greenland, it occurs in deeper waters (Skern-Mauritzen *et al.*, 2009; Hansen, 2010; Fall, 2011**)**. Off West Greenland, for example, the species occurs regularly in much deeper waters (GAMs showed a preference for depths of c. 900m – Hansen, 2010). In the Barents Sea, a GAMM of white-beaked dolphin habitat preferences found abundance to increase with depth at least to 300m – Fall, 2011). Whereas around the British Isles the species has been recorded predominantly over the continental shelf, there are many sightings in deeper waters in the Faroe-Shetland Channel (Evans *et al.*, 2003).

A4.3.4 Annual Cycle

In the northern North Sea, white-beaked dolphins typically occur mainly offshore and in late summer between May and October (particularly between July and September); these are also the peak months for sighting rates and individual rates when corrected for effort (Northridge *et al.*, 1995; Evans *et al.*, 2003; Reid *et al.*, 2003; Anderwald *et al.*, 2010). It is rarely reported between November and April.

A4.3.5 Diet & Ecology

White-beaked dolphins feed upon mackerel, herring, cod, poor-cod, sandeels, bib, whiting, haddock, and hake, as well as squid, octopus, and benthic crustaceans (Canning *et al.*, 2008; Evans & Smeenk, 2008). The species breeds mainly between May and August, although some births may occur also in September and October (Evans & Smeenk, 2008).

A4 references

See main reference list on page 91.

APPENDIX 5: BIOLOGICAL BACKGROUND FOR BASKING SHARK (PHILIP DOHERTY & MATTHEW WITT, UNIVERSITY OF EXETER)

A5.1 Basking shark

A5.1.1 Status & distribution

The basking shark is the world's second largest fish species (Compagno, 2001) with a circumglobal distribution (Valeiras *et al.*, 2001; Francis and Duffy, 2002). In the Northern Hemisphere, they are present in the north-east Atlantic from Iceland, Norway and as far north as the Barents Sea, extending southwards into the Mediterranean Sea, as well as from the north-west Atlantic and through the North Pacific. In the Southern Hemisphere, they are also found in both the Pacific and Atlantic, from Australia and New Zealand to South America and the Western Cape and South Africa (Compagno, 2001). In coastal seas they are typically found near the surface in cold to warm-temperate water and in deep water below the thermocline in tropical and equatorial regions (Skomal *et al.*, 2009). These sharks have demonstrated the ability to undertake extensive oceanic basin migrations (Gore *et al.,* 2008; Skomal *et al.,* 2009).

The basking shark is listed by the International Union for the Conservation of Nature (IUCN) Red list as 'Vulnerable' globally, but 'Endangered' in the north-east Atlantic due to population depletion from historical exploitation (Fowler, 2005). The species is listed in Appendix II of the Convention on International Trade of Endangered Species (CITES, 2010), and Appendices I and II of the Convention on Migratory Species (CMS, 2009). Within the UK, these sharks are protected under the Wildlife & Countryside Act (1981) and more recently in Scotland by the Nature Conservation Act (2004). Under European legislation, it is prohibited for basking sharks to be fished for, retained on board, or landed by Community fishing vessels.

Public sightings (Witt *et al.*, 2012) and boat-based surveys (Speedie *et al.,* 2009; HWDT, Unpub.) of basking sharks at the sea surface highlight Cornwall, Isle of Man and western Scotland as key areas for the species within UK and Irish waters, with peaks in public sightings between May and August (Witt *et al.*, 2012). Year-round aerial and boat-based surveys off the Cornwall coast, similarly highlight a seasonal pattern in surface sightings, with sharks recorded between April and October, peaking in August (Leeney *et al.,* 2012).

A5.1.2 Abundance & trends

There is limited information on population size in the north-east Atlantic, and satellite tracking data are relatively sparse, with only comparatively short-term (several months) movements being recorded (Sims *et al.*, 2003; Gore *et al.*, 2008; Stéphan *et al.*, 2011; Witt *et al.*, 2013b). The migratory biology of the species has still yet to be robustly described. An estimate of absolute abundance for basking sharks has been attempted in the north-west Atlantic using data collected from aerial surveys for whales for the Bay of Fundy, Gulf of St. Lawrence and Newfoundland, resulting in numbers of 4,200, 5,340 and 560 respectively, totalling 10,100 in the summer of 2007. No such estimates of population size exist for the north-east Atlantic and hence no trends in population size can be derived.

A5.1.3 Habitats

Basking sharks are most regularly seen at the surface from coastal areas to the continental shelf edge and slope and are often associated with areas between stratified and mixed water columns, known as tidal fronts, and at sites of high relative concentrations of zooplankton (Sims and Quayle, 1998). Basking sharks appear to inhabit a wide range of temperatures, but may show some preference (Sims, 2008). For example, sharks tagged in Firth of Clyde and the English Channel in 2001, exhibited movements into waters of a range of 9 to 16°C (Sims *et al.*, 2003), another shark equipped with a satellite tag travelled from the north-east coast of the US from Massachusetts to North Carolina and experienced temperatures between 5.8 and 21°C, but showed apparent 'preference' (72% of time) for temperatures between 15 and 17.5°C (Skomal *et al.,* 2004).

A5.1.4 Diet

The species is an obligate ram-feeding zooplanktivore (Matthews and Parker, 1950) with an apparent preference for calanoid copepod zooplankton, such as *Calanus helgolandicus* and *Calanus finmarchicus* at the surface. Their diet while occupying deeper waters is unknown. The main zooplankton species identified from shark feeding paths in the English Channel, off Plymouth, were *Calanus helgolandicus*, *Pseudocalanus elongatus, Temora longicornis, Centropages typicus* and *Acartia clausi* (Sims and Merrett, 1997). Basking sharks are frequently seen feeding on zooplankton at coastal or oceanic fronts, sometimes forming aggregations of over 100 individuals. The rostrum tip, dorsal fin and upper caudal fin may all break the surface as the shark swims slowly forward with open mouth, using gill-rakers to extract plankton from the water.

A5.1.5. Exploitation

Basking sharks have been exploited by targeted fisheries off Scotland, Ireland, Norway, Faroe Islands, Iceland, California, China, Japan, Peru and Ecuador (Compagno, 2001). In the North Atlantic, the basking shark was fished for several hundred years. Targeted fisheries have traditionally been driven by demand for oil contained within the sharks' livers. Basking shark oil was used as lighting fuel for lamps during the 18th Century (Sims, 2008). More recently, there has been increased demand due to the shark fin trade. Considerable exploitation by several nations fringing the North Atlantic during the past century is thought partly responsible for the declines in landings through the mid to later part of the 20th century. These declines and subsequent concern for the status of the population led to significant lobbying in the 1990s and 2000s for the inclusion of the basking shark into Multilateral Environmental Agreements, including CITES, CMS and IUCN (see section: status & distribution).

A5.1.6 Research in the north-east Atlantic

A wide range of research has been conducted on basking sharks in the north-east Atlantic in order to improve knowledge regarding their distribution and behaviour.

Satellite tracking

The first basking shark to be satellite tracked in UK waters was tagged off the west coast of Scotland in 1982 and was tracked for 17 days (Priede, 1984). Further telemetry studies include five basking sharks tagged in the Firth of Clyde and the English Channel in 2001-2002 (Sims *et al.*, 2003). A basking shark was tagged off the coast of the Isle of Man in 2007 and travelled a distance of over 9,500 km to Newfoundland with depth utilisation to over 1,200 m (Gore *et al.,* 2008). More recently, in 2009, ten sharks were satellite tagged in Brittany and the Isle of Man, with resulting data indicating southerly movements towards the Bay of Biscay and the Iberian Peninsula (Stéphan *et al.*, 2011). An ongoing study, conducted by Scottish Natural Heritage and the University of Exeter, has tagged 53 basking sharks during the summers of 2012 and 2013 using a variety of satellite tracking technologies. Resulting data enable a tentative general description of occupied habitats. For example, from a sample size of eight tagged sharks moving within the Sea of the Hebrides (first 4 weeks of tracking), 78% of locations occurred in waters overlaying rock or reef habitats and locations were received from sharks occupying surface waters with temperatures between 12.4 and 13.3 °C (Witt *et al.*, 2013a). Two sharks subsequently undertook migrations to the Canary Islands and the Iberian Peninsula (Witt *et al.*, 2013a). Satellite tracking studies are also active in Ireland and the Isle of Man.

Citizen science, surveys and photo-identification
Further insight into basking shark distribution and behaviour has been gained from sightings made by the general public (Witt *et al.*, 2012), by fishers (Berrow and Heardman, 1994), and from boat and aerial transect surveys (Speedie *et al.,* 2009; Leeney *et al.*, 2012). Photo-identification studies are underway, and show some promise in the re-identification of individuals across years (Sims *et al.*, 2000) providing deeper insight into species ecology. Foraging ecology studies have been conducted by the Marine Biological Association of the UK; see Sims (2008) for an overview.

Together, these studies have helped identify the key areas or 'hotspots' for basking sharks at the sea surface and when considered in their entirety, along with emerging genetic research at the University of Aberdeen (part funded by Scottish Natural Heritage; PP757: Basking shark research – Genetics contribution project 2013-2015), and habitat modelling (this report) will likely further aid an evidence-based management approach for the species.

A5.1.7 Modelled areas of persistence

Areas of modelled persistence for basking shark (see main report) in the Firth of Clyde, the Sea of the Hebrides and to a lesser extent the Solway Firth, support existing knowledge. Basking sharks are observed in these areas, from satellite tracking studies [for the Inner Hebrides and Firth of Clyde] (Witt *et al.*, 2013a) and from public sightings [all regions; but lesser so for the Solway Firth] (Witt *et al.*, 2012). The Sea of the Hebrides and the northern extent of the Firth of Clyde have received considerable survey effort from boat-based surveys dedicated to the sightings of basking sharks (Speedie *et al.,* 2009) and from surveys whose primary focus was for cetaceans, but where sightings for basking sharks were recorded (HWDT; Unpub.). The spatial coverage of survey effort reported by Speedie *et al.* (2009) was somewhat determined by areas thought to support surface sightings of basking sharks as the key aim of the research was to provide quantitative information of abundance and distribution; coverage was extensive and areas not traditionally known to provide sightings were investigated (but at a lower frequency). The spatial and temporal coverage of surveys by HWDT build upon those of Speedie *et al.* (2009), also including waters around Islay and Jura; two areas which appear to support 'high' persistence. Satellite tracking data collected in 2012 (Witt *et al.*, 2013a) and 2013 (Witt *et al.* Unpub.), along with a number of public sightings records (Witt *et al.*, 2012) confirm that basking sharks are to be found in this region. Survey effort is however less than that focused upon the Sea of the Hebrides.

New insight from the modelled persistence map includes areas to the west of the Outer Hebrides. Survey effort in this region has been relatively low *cf.* Sea of the Hebrides; satellite tracking studies have yet to identify individuals moving to this area and historically this was not an area where basking sharks were systematically hunted, so there is little data to suggest this region supports appreciable numbers of basking sharks. Nonetheless, the predictions highlight a need for dedicated survey effort (most likely aerial based) to determine whether the model has accurately described this region. Based on extant knowledge regarding the feeding and movement ecology of the species (see above sections), there seems no reason to discount the model predictions for this area.

The modelled persistence map also highlights areas to the east and north of the Scottish mainland, such as The Shetland and Orkney Islands and the Firth of Forth. These areas are not typically recognised as localities supporting appreciable number of sightings *cf.* Sea of the Hebrides, but this is not to say that sightings do not occur in these areas.

A5 references

See main reference list on page 91.

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