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Comparison of design- and model-based estimates of seabird abundance derived from visual, digital still transects and digital video aerial surveys in Carmarthen Bay

Louise Burt, Eric Rexstad and Stephen Buckland
Research Unit for Wildlife Population Assessment
Centre for Research into Ecological and Environmental Modelling
University of St. Andrews

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www.offshorewind.co.uk
E-mail: cowrie@offshorewind.co.uk

Contact details:

Louise Burt (louise@mcs.st-and.ac.uk) 01334 461805
Eric Rexstad (ericr@mcs.st-and.ac.uk) 01334 461833
Stephen Buckland (steve@mcs.st-and.ac.uk) 01334 461841
Centre for Research into Ecological and Environmental Modelling
The Observatory, Buchanan Gardens
University of St. Andrews
St. Andrews KY16 9LZ

Table of Contents

List of Tables

List of Figures

Executive Summary

This report describes design-based and model-based estimates of abundance for a group of seabirds who reside in large aggregations (scoters) and another group of seabirds that are less consistently clumped ('gulls') from three types of aerial surveys in Carmarthen Bay. Each type of survey was conducted on four dates during the month of March 2009 using different amounts of effort.

This work explores patterns in estimates derived from different data collection and data analysis methods for both types of seabird groups. The work follows on from an examination of a portion of this data set conducted by Rexstad and Buckland (2009).

No clear pattern emerged from examining the point estimates for the various survey-analysis method combinations. We have no measure of the true sizes of either of these populations against which to measure the point estimates. However we can assess the relative precision of these combinations using the coefficient of variation (ratio of the standard error of the point estimate to the point estimate itself).

The clumped distribution of scoters resulted in estimates with poor precision for most of the survey type-analysis method combinations. The average coefficient of variation across all survey-analysis combinations was slightly smaller for gulls (0.45) than for scoters (0.50). The range in these average coefficients of variation ran from 0.25 for design-based estimates from visual data to 0.85 for model-based estimates of digital still transect data. Among survey-analysis combinations for gulls, design-based visual and model-based digital video produced estimates with the highest average precision.

Coefficients of variation were higher for scoters. The only survey-analysis method that produced an average coefficient of variation smaller than 0.40 was the model-based estimate of digital video data, perhaps partially a consequence of the larger number of transects used for this survey method. However the range in average coefficients of variation was smaller for the scoter data than for the gull data. The similarity in precision of design- and model-based estimates for all survey types was higher for the scoter data than for the gull data, perhaps reflecting movement in and out of the study area during survey days by gulls.

Design-based estimators produced on average lower coefficients of variation for visual and digital still transect data for both gulls and scoters, but model-based estimators produced more precise estimates for digital video data.

Two points emerge from this comparison. First, an approach based on estimating calibration factors to make estimates from different approaches comparable is unlikely to be useful. The Carmarthen Bay surveys were conducted under controlled conditions with close attention to detail such as carrying out the surveys on the same days, at approximately the same time of day. Even under these conditions, estimates for the different methods were very variable, with little indication of any consistent differences between methods. Second, for a relatively small body of water such as Carmarthen Bay, application of a pro forma survey design such as 'place transects at 2km intervals' does not produce estimates with sufficient precision to detect change. There is no substitute for bespoke survey designs created with knowledge from pilot surveys so that sufficient effort can be deployed to produce defensible estimates. This insufficient amount of effort was highlighted for the common scoter, whose highly aggregated distribution would have necessitated even higher coverage of the study region.

Glossary

Acronyms

CDS – conventional distance sampling

DSM – density surface model

df – degrees of freedom

dc – distance from coast

esw – effective strip width

Units

Length of transects and survey effort – kilometres

Perpendicular distance from transect lines – metres

Animal density – birds·km^{-2}

1. Introduction

Two methods for conducting aerial surveys of seabirds currently exist: visual surveys where observers fly in small aircraft recording numbers of birds seen and photographic methods where images are collected from the air and processed on the ground. Photographic methods can be in the form of either still photos or continuous images recorded as video. The development of the photographic methods, made possible by advances in digital image capture, has raised the question of the comparability of estimates of seabird abundance derived from differing survey methods. A further question to be addressed by this comparison is whether the visual and photographic methods provide estimates with similar levels of precision.

Not only are there differing methods of collecting data, but there are also differing ways of analysing the data collected to produce estimates of abundance within the area of interest. Aerial surveys do not attempt to count every bird in an area, but instead survey a sample of areas, from which the total number of birds present in the region is estimated. Two conceptual approaches to estimating this number are termed design-based and model-based (Borchers *et al.* 2002). Design-based methods are based on the premise that the portions of the study area that are surveyed are 'representative' of the remainder of the study area, whereas model-based method use models to make inference about portions of the study area that were not surveyed. Our expectation was that model-based analyses would improve the precision of estimates for common scoters compared to the design-based results reported by Rexstad and Buckland (2009). However, model-based estimates, because they rely upon the veracity of a model fitted to data, run the risk of producing biased estimates. Design-based estimators should on average be unbiased and all else being equal, greater amounts of survey effort will produce greater levels of precision for these estimators.

We examine data collected during March 2009 in the Carmarthen Bay Special Protection Area (SPA) by three aerial survey methods (visual, digital stills and digital video) using both design- and model-based methods of analysis on two different groups of birds, scoters and gulls. Scoters (primarily common, but perhaps with some velvet scoters included) are a highly aggregated species, and form large floating rafts of birds, particularly during winter. Although scoters were the group of primary interest, counts of other species were also made, and we also analysed data on gulls, the only other species group for which sample size was adequate.

Previous attempts to contrast visual and photographic aerial survey methods have been conducted by CREEM researchers. Rexstad and Buckland (2009) present an analysis of these Carmarthen Bay surveys employing only design-based estimators applied to the scoter data sets. Burt *et al.* (2009) compared visual and photographic aerial survey data for the Round 3 Norfolk area using design-based and model-based estimators, but asynchrony in the collection of those data made that comparison ambiguous.

2. Methods

2.1 Data collection

2.1.1 Visual surveys

Surveys were flown 4 times (15, 21, 22, and 29) during the month of March in 2009. The aircraft flew at an altitude of 76m and at a speed of $200 km \cdot h^{-1}$. Transects were laid at 2km intervals across the Bay, and on average the visual surveys covered 25% of the SPA (Table 1). Observers searched both sides of the aircraft and for each group of birds detected recorded the species, number in the group, behaviour and the perpendicular distance to the transect. These distances were allocated to four distance bands covering a region from 44m to 1000m either side of the aircraft.

2.1.2 Digital surveys

For digital still transects, the number of transects and their lengths were effectively the same as for the visual surveys (i.e. 2 km spacing) using a single still camera with a visual footprint 300m wide perpendicular to the flight line. For digital video surveys transect spacing was approximately 1km, with roughly twice the number of transects across the SPA. Four cameras recorded along each transect, with each camera recording a strip 50m wide tilted to have 75m gaps between each strip for a total strip width (excluding gaps) of 200m for each transect. Any sightings recorded were categorised by species (with associated confidence of category into which the sighting was placed) and behaviour. If birds were very close to each other, a count of more than one bird might be recorded at a single location, but no attempt was made to define spatial bird groups. In analysis therefore, we made no attempt to estimate or model group size. See Thaxter and Burton (2009) for further discussion of digital survey methodology.

Because all survey methods had different effective strip widths (300m for stills and 200m for video) and amounts of effort (transect length flown), differing proportions of the Carmarthen Bay SPA were covered by the survey methods. The proportions of the SPA covered by each method during each of the surveys are described in Table 1.

2.2 Data analysis

2.2.1 Conventional distance sampling methods

Visual survey methods require the fitting of detection functions to the observed detections to account for birds in surveyed strips that are not detected (Buckland *et al.,* 2001). The digital surveys generate digital images which can be examined in detail, so that it is reasonable to assume that no birds sitting on the surface of the water or flying within the surveyed area were undetected.

2.2.1.1 Visual surveys

Conventional distance sampling methodology (Buckland *et al*., 2001) implemented in the program Distance (Thomas *et al*., 2009, Thomas *et al.*, 2010) will be used to estimate abundance (N) in each block (b) as follows

$$\hat{N}_b = A_b \frac{n_b}{2L_b\hat{\mu}}\hat{E}[s]$$

where A_b is size of the survey block, n_b is the number of detected groups, L_b is the length of transects searched, $\hat{\mu}$ is the estimate of the effective search half-width (ESW, the distance from the transect line beyond which as many birds are detected as are missed at distances smaller than ESW), and $\hat{E}[s]$ is the estimate of the mean group size. The ESW is obtained from a detection function model fitted to the distribution of perpendicular distances. The expected group size is obtained from a regression of probability of detection (obtained from the detection function) against the logarithm of group size. This takes into account the greater difficulty in seeing single birds and small groups further from the aircraft.

2.2.1.2 Digital surveys

Because all birds within the strip are detected, a simple strip transect estimator can be used to estimate abundance in each survey block b as follows

$$\hat{N}_b = A_b \frac{n_b}{2wL_b}$$

where A_b is size of the survey block, w is the strip half-width, n_b is the number of detected birds, L_b is the length of transects searched.

2.2.2 Density surface modelling

2.2.2.1 Visual surveys

Trend in the spatial distribution of the species groups were modelled using the 'count' method of Hedley and Buckland (2004). In this approach, the transect lines are divided into small segments (of length l_i) and the response variable is the number of birds counted within the segment, taking into account the probability of detection:

$$\hat{N}_i = \sum_{j=1}^{n_i} \frac{s_j}{\hat{p}}$$

where $\hat{N}_i$ is the number of birds estimated to be in the segment i, s_j is the recorded group size for group j and n_i is the number of groups recorded in segment i. The parameter $\hat{p}$ is the probability of detection and is obtained from $\hat{p} = \hat{\mu}/w$ where w is the strip half-width. See previous section for a description of $\hat{\mu}$. The response variable, $\hat{N}_i$, is modelled as a function of covariates with a generalised additive model (GAM) with the general formulation

$$E\left[\hat{N}_i\right] = \exp\left[\log(a_i) + \beta_0 + \sum_{k=1}^{K} f_k(z_{ik})\right]$$

The term $\log(a_i)$ is an offset (a term with known regression coefficient) that corresponds to the area of the segment ($a_i = 2wl_i$), β_0 is the intercept and f_k are smooth functions of the K covariates. This formulation assumes a logarithmic link function and an overdispersed Poisson distribution for the error distribution. Surveys of animals (particularly those that exhibit clumped distributions) tend to have portions of the survey region where there are no detections and others where there are many. This leads to overdispersion in the data, which may be modelled using a quasi-Poisson error distribution. The logarithm is the canonical link function for Poisson or quasi-Poisson error distribution families.

Having obtained a fitted model from the data, density can be estimated throughout the region of interest; abundance is estimated by integrating under this surface. The variance of the abundance estimate is obtained by a bootstrap – a data-based simulation method. A sample is drawn from the original data by sampling lines at random and with replacement and abundance is estimated from this bootstrap sample; the process is repeated a large number of times and the empirical variance is calculated from the distribution of the bootstrap abundance estimates.

2.2.2.2 Digital surveys

Methods of fitting GAMS to the digital data were identical to that described in section 2.2.2.1, with the exception that the number of birds in each segment did not need to be estimated, and was merely the sum of all birds counted in the segment.

3. Results

3.1 Design-based estimates for visual surveys

The region from directly under the aircraft out to 44m could not be seen by the observers. Therefore, the first distance bin started at 44m. Thus 44m was subtracted from all perpendicular distances and so the cutpoints for the bins became 0, 119, 238, 382 and 956m. Very few sightings were detected in the furthest distance band and so to avoid a long tail in the fitted model, the data were truncated at 382m. Location of detections for groups of gulls and scoters are shown in Figure 1.

Detection functions were fitted separately for each survey and each species grouping and both the half-normal and hazard rate forms of the detection function were considered. For gulls, the half-normal form for the detection function was chosen for all surveys on the basis of AIC and for common scoters, the hazard rate form was selected. The fitted models for the design-based estimates are shown in Figure 2 (along with the detection function for scoters used in the model-based analysis) and the effective half-strip widths are given in Table 3.

Observed group sizes for both species groups are shown in Table 2. We adjusted for the likelihood that our sample of groups overestimated the group size in the population because larger groups are more easily seen. Expected group size was estimated using regressions applied to each survey separately (Table 3). For common scoters, the size bias regression estimates for two surveys were slightly larger than the mean group size suggesting that the mean group size in the sample did not overestimate the group size in the population. In these cases, the mean group size was used although it is conceivable that expected group size exceeding observed mean group size is a consequence of the manner in which a 'group' is defined which may be correlated with the distance of a group from the transect.

Design-based estimates of abundance for visual surveys are given in Table 6 and in Figures 7 and 8.

3.2 Design-based estimates for digital surveys

The estimates of abundance for both types of digital surveys for the two species groups are provided in Table 6, as well as Figures 7 and 8.

3.3 Model-based estimates for visual surveys

Hedley and Buckland (2004) recommended that segments are approximately square and so with a truncation distance of 382m, transects were divided into segments of approximate length 1km. The number of segments that contained gulls varied between 25 to 84, but this number for common scoters was much lower; 4 – 41 (Table 4).

Half normal detection functions (Figure 2) were used in the DSM analysis to estimate the numbers in each segment. Figures 3 and 5 (left column) show the distribution and estimated numbers of sightings for each survey and segment. The explanatory variables available for inclusion in the density surface models were the easting (x) and northing (y) of the midpoint of the segment, included as both one-dimensional and two-dimensional smooths, and distance to the coast (*dc*). Other covariates such as depth or sediment type could have been used in the modelling effort but more complex models would not necessarily have resulted in estimates of bird numbers that possessed higher precision. Because neither common scoters nor gulls were seen on all transects, there is a tendency for GAMs to try to fit models with a large number of knots to conform to each peak and trough in the response data. To prevent this fitting of overly complex models, the degrees of freedom (df) was limited for both one and two-dimensional smooths. The Generalised Cross Validation (GCV) score was used to choose between the different models. The more complicated models could not be used for some of the common scoter surveys due to the small number of segments which contain sightings (Table 4). Increasing the size of the segments might decrease the proportion of 'empty' segments, but at the expense of the number of segments available for spatial modelling. The selected models are shown in Table 5.

Density surfaces for individual birds have been estimated and are shown in Figures 4 and 6 (left column). The abundance estimates are given in Table 6. The coefficients of variation (CV) and confidence interval have been estimated using 500 bootstrap samples. The 95% confidence interval (CI) is obtained from the 2.5% and 97.5% quantiles of the bootstrap abundance estimates distribution. While the CI is somewhat robust to a few extreme values in the bootstrap distribution, the CV is not. Therefore, outliers were identified using the method of Hoaglin *et al*. (1983) (i.e., outliers lie outside the extreme whiskers of a boxplot) and deleted before the CV and CI were calculated. Due to the restricted number of transects that contained sightings of common scoters, the bootstrap samples created problems when fitting the GAM. To overcome this, the degrees of freedom of the smooth functions were restricted so that the GAM fitted to the bootstrap sample was only allowed a maximum of 3 and 10 degrees of freedom for a one-dimensional and two-dimensional smooth, respectively. For common scoter individuals, the degrees of freedom for a two-dimensional smooth was limited further to 5.

3.4 Model-based estimates for digital surveys

Because of slight differences in the way in which animal encounters were handled in the two digital survey methods, here we summarise the survey data and the preparation of data for density surface modelling. This differing treatment of the data (treated as individuals in the digital stills and groups in the digital video) should not influence the results either with regard to point or interval estimates.

3.4.1 Digital still transects detections

Species categorised as either large or small gull were placed in the 'gull' category for analysis. Individual birds, rather than groups, were located. Sightings were allocated to segments on the basis of location, an average of roughly 175 segments in each survey (Table 4). Some sightings were recorded before the start, or after the end, of a transect or beyond 300m either side of the transect line and these sightings were ignored in the analysis. A total of 899 gulls and 10,443 common scoters were allocated to segments (Table 1).

3.4.2 Digital video detections

The locations of groups were recorded and detections were allocated to segments on the basis of location. Some sightings were recorded before the start, or after the end, of a transect or beyond a strip 0.01^{o} either side the transect and these sightings were ignored in the analysis. Species categorised as 'gull', 'herring gull', 'herring/common gull' or 'kittiwake' were placed in the 'gull' category, and those groups denoted as either 'common scoter' or 'scoter' were included in the scoter analysis. A total of 319 groups of gulls and 847 groups of common scoters were allocated to segments (Table 1). The majority of gulls detected were recorded as single birds whereas common scoters were recorded in small groups (Table 2).

As with the visual surveys, transects were divided into segments approximately 1km in length. This resulted in roughly 300 segments in the covered region from which to construct our density surface models. Had we used larger segment lengths, we would have had fewer segments from which to fit our density surface model. (If we used the same segment lengths as in our analysis of the Norfolk Round 5 survey, there would only have been around 60 segments, too few for our purposes.) Potential explanatory variables were also the same as in the model-based analysis of visual survey data.

3.4.3 Digital still transects estimation

Despite seeing large numbers of common scoters, the number of segments where birds were detected was small (Table 4). This caused problems in fitting reliable models, despite reducing the degrees of freedom allowed for the smooths and only considering the simpler models. Thus, models fitted to the common scoter data did not include any covariates; this fits a flat density surface. The selected models for gulls are shown (Table 5). Abundance estimates are shown in Table 6.

To overcome problems in fitting models to bootstrap samples of the gull data for surveys on the 22nd and 29th, the degrees of freedom allowed for the smooth functions were reduced to 3 for a one-dimensional model and 10 for a two-dimensional model. Even so, the precision was poor for two surveys despite a substantial number of bootstrap estimates being ignored as outliers.

Bootstrap samples were generated by selecting transects at random and with replacement. Since common scoters were concentrated on a few transects, bootstrap samples were generated that did not contain any detections. In these cases, the bootstrap abundance was taken to be zero.

3.4.4 Digital video estimation

The degrees of freedom in the two dimensional smooth were limited to 10 because of the low proportion of segments were birds were detected. The selected models are shown in Table 5 and the abundance estimates are shown in Table 6. To estimate the precision for gulls, no further restrictions of degrees of freedom were necessary to model the bootstrap samples and very few bootstrap abundance estimates were excluded. However, for scoter, the degrees of freedom were reduced to 3 and 5 for one- and two-dimensional smooths, respectively.

3.5 Synthesis

Concentrating only on comparisons of precision among survey types and analysis methods, we can reduce the number of comparisons to make by averaging coefficients of variation across replicate surveys. These averages are presented in Table 7. Averaging across all survey-analysis combinations for the species groups, gulls are estimated slightly more precisely than scoters. But the precision of estimates of gulls is more variable (range 0.25-0.85) than the precision of estimates of scoters (range of averages 0.32-0.67). Precision of the design-based estimators is higher than the precision of model-based estimators for visual and digital still transects (for both species) but precision in estimates from digital video surveys improves through the use of model-based analysis methods for both species.

4. Discussion

There can be no assessment of which survey method, or which analysis method, produces the 'most correct' estimate, because this exercise was conducted upon real animal populations, the size of which were unknown. However we undertook this comparative assessment to determine if there were patterns that emerged from examining species that aggregate (common scoters) and a species group (all gulls) that would be more ubiquitous. Our *a priori* belief was that the focal species for this survey (common scoters) would present difficulties for producing precise estimates because of their clumped distribution. Indeed this did present difficulties, particularly for digital still transects where the effective strip width was narrow and the number of replicate transects was small. For a study area the size of the Carmarthen Bay SPA, the investment in flight time is reasonably small, so it would be prudent to sample such a study area more intensively, by having more narrowly placed transects. This is particularly true for species such as common scoters that aggregate such that there is high variability between transects for design-based estimators. Likewise for model-based estimators, a more robust model can be fitted to response data where there are many segments containing birds. Reliable estimation still relies upon seeing sufficient of the study organism, for that there is no substitute.

We were disappointed to learn that gulls were also distributed in patches that might be missed by some survey techniques (this time digital video 15 March survey for example) and detected by other survey methods, perhaps due to gulls moving through the survey area while the surveys were underway on a given day. Temporal variation in gull numbers was perhaps expected to be high owing to perceived gull behaviour at Carmarthen Bay; on past aerial surveys of the bay (e.g. Banks et al. 2007), gulls recorded were often in flight, suggesting somewhat transient use of the areas surveyed (Alex Banks, personal observation). Our other *a priori* belief was that for the clumped scoter distributions we would achieve some improvement in the precision of estimates using the model-based approach. Scaling-up estimates from the portion of the study area flown to the entire study area using design-based estimators uses variability between transect as a measure of uncertainty. We knew from past experience (Rexstad and Buckland 2009) there was high between-transect variability in the common scoter data, so we felt the precision in our estimates would be improved by using model-based estimators. This belief was largely borne out. The point estimates for the design- and model-based estimates for scoters were somewhat close (notable exceptions being digital video in the 15 and 22 March surveys) and the precision for the model-based estimates were slightly smaller that their comparable design-based estimates.

It is difficult to find any compelling pattern from the gull data. Sometimes (22 March survey for digital still transects, 29 March visual) the design- and model-based estimates do not agree well at all. Other times (21 March survey) there is high conformity between design- and model-based estimates within all three survey types, but little agreement between survey types. This may be because gull numbers and distribution in the survey region vary appreciably through the day. There is also a challenge with field protocol. Because gulls may congregate near the water's edge, it is not obvious where the line is drawn demarcating the edge of the study area.

Different survey approaches may make different decisions, leading to differences in gulls counted as 'in' the study area.

Contrasting the precision achieved from these surveys of Carmarthen Bay with surveys of the Norfolk Zone 5 Round 3 study area (Burt *et al.* 2009) the precision achieved for the Norfolk study area was higher, even though the Norfolk survey was carried out over a longer period of time (heightening potential temporal variation in those survey results). The portion of the Norfolk study area subject to analysis in Burt *et al.* (2009) was an order of magnitude larger (3506 km^2) than the Carmarthen Bay SPA (352 km^2). Consequently there were many more sampling units (transects for design-based analysis or transect segments for model-based analysis). This greater degree of replication in the Norfolk study afforded the opportunity to produce estimates of bird abundance with greater precision.

If different methodologies gave precise but biased estimates, we might wish to calculate calibration factors, to make estimates from different approaches comparable. However, we have the opposite circumstance, in which precision is poor, but bias, at least for the designed-based estimates, is believed to be small. In this case, any attempt to calibrate methods will simply add greater uncertainty to the abundance estimates, because the calibration factor will be estimated with very poor precision. Another factor to bear in mind is that surveys by different methods are not simultaneous, unless they are conducted simultaneously from the same aircraft. For these Carmarthen Bay surveys, flights for the three survey methods commenced within 15 minutes of one another (Gareth Bradbury, WWT Consulting, personal communications) and their comparability may be compromised by movement in or out of the area in the short time between the surveys. This is especially problematic for a small survey region, such as Camarthen Bay, and for birds that are very mobile during the day, such as gulls. Should a calibration factor be estimated, it may be a function of various covariates, including visibility conditions, species, behaviour of the birds, and degree of aggregation of the birds, so that different calibration factors may be needed for different species, locations and seasons..

A consequence of substantial movement in and out of a region is that the abundance estimates will show considerable temporal variability, casting doubt upon the relevance of power calculations based upon measures of precision for single surveys: replication over time is required within a survey period, to allow the true variability to be estimated. As far as we are aware, this issue has not been addressed when assessing the power to detect change in animal populations associated with renewable energy development.

The findings of this comparative study suggest that neither survey methodology that removes uncertainty in detectability nor model-based rather than design-based analysis methods eliminate the highly stochastic nature of wildlife population assessment. There is no substitute for study designs that are bespoke to the study at hand. In the case of Carmarthen Bay, it is clear that greater amounts of survey effort could have been expended to reduce the sampling variability from the assessment process.

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Table 1. Summary of search effort and numbers of groups detected. Note that for digital still transects a) number of transects and lengths of those transects were the same as for the visual surveys, and b) each individual bird was recorded, so all 'groups' were of size one.

	Visual					Digital still transects			Digital video				
Survey date	transects	Length (km)	Cover	Gulls groups	Common scoters groups	Cover	Gulls (birds)	Common scoters (birds)	transects	Length (km)	Cover	Gulls groups	Common scoters groups
15 March	15	174.6	0.257	215	184	0.148	571	4 664	25	272.0	0.155	59	181
21 March	15	175.1	0.258	184	148	0.154	47	3 133	34	296.0	0.126	65	260
22 March	15	168.9	0.249	157	149	0.153	178	738	31	307.3	0.175	88	156
29 March	15	177.5	0.261	191	96	0.151	103	1 908	31	307.1	0.174	107	250
Total	60	696.1		747	577		899	10 443	121	1 182.3		319	847

Table 2 Numbers of groups detected in groups of various sizes. For digital still transects, each individual was given a coordinate, so all 'groups' were of size one. The numbers in brackets are the maximum recorded group size.

	Visual survey		Digital video	
Group size	Gulls	Common scoters	Gulls	Common scoters
1	516	41	265	69
2	83	103	32	165
3	36	61	12	92
4	16	62	6	91
5-9	41	120	6	228
10-19	22	72	(19) 6	144
20-49	17	81	0	36
50-99	12	28	0	13
≥100	(150) 4	(200) 9	0	(75) 15

Table 3 Estimates of encounter rate (n/L), esw ($\hat{\mu}$) and expected group size ($E[\hat{s}]$) for each visual survey. The number of groups have been truncated at 382m. Percentage coefficients of variation are given in parentheses. Asterisks indicate where mean group size was used.

	Gulls			Common scoter				
Survey	*n/L* (groups/km)	$\hat{\mu}$ (m)	$E[\hat{s}]$	*n/L* (groups/km)	$\hat{\mu}$ (m) Hazard rate	$E[\hat{s}]$ Hazard rate	$\hat{\mu}$ (m) Half normal	$E[\hat{s}]$ Half normal
15 March	1.197 (15.8)	174.6 (5.72)	2.03 (7.19)	0.922 (37.9)	255.5 (8.44)	15.48 (11.4) *	215.1 (7.09)	13.86 (13.2)
21 March	1.011 (27.8)	247.1 (7.25)	2.23 (7.93)	0.811 (44.0)	219.2 (7.70)	7.25 (8.92)	181.8 (7.03)	6.92 (8.95)
22 March	0.912 (30.9)	167.8 (6.58)	2.30 (7.79)	0.698 (41.9)	286.6 (10.9)	11.00 (13.1) *	249.9 (8.93)	11.00 (13.1) *
29 March	0.918 (17.0)	247.3 (7.55)	2.88 (10.6)	0.518 (39.7)	255.5 (11.2)	11.30 (16.6)	200.5 (9.08)	9.70 (16.8)

Table 4 The total number of segments for each survey and number of segments where birds were detected (so that the estimated number $\hat{N}_i$ is greater than zero).

		Visual		Digital still transects		Digital video	
Species group	Survey	Total	$\hat{N}_i > 0$	Total	$\hat{N}_i > 0$	Total	$\hat{N}_i > 0$
Gulls	15 March	174	84	174	48	273	41
	21 March	177	74	177	31	298	44
	22 March	169	61	169	25	305	52
	29 March	177	59	177	26	305	59
Common scoters	15 March	174	22	174	33	273	17
	21 March	177	17	177	7	298	24
	22 March	169	24	169	4	305	25
	29 March	177	21	177	9	305	41

Table 5 Summary of the density surface models and the percentage of deviance explained by the models for individual birds. Covariates were not included for the digital still density surface model for common scoter; instead a flat density surface (uniform density across the study area) was assumed. Abbreviations used for covariates are *x*-longitude, *y*-latitude and *dc*-distance from coast. Numbers associated with the model description is the effective degrees of freedom associated with the smooth.

	Visual		Digital still transects		Digital video	
Gulls						
Survey	Covariates	% Dev.	Covariates	% Dev.	Covariates	% Dev.
15 March	s(*x*,*y*,12.4) + s(*dc*,4.05)	59.5	s(*x*,*y*,13.7) + s(*dc*,3.2)	78.2	s(*x*,1.0)	9.8
21 March	s(*x*,3.74) + s(y,5.81) + s(*dc*,1.0)	63.9	s(*x*,1) + s(y,2.1) + s(*dc*,3.3)	28.0	s(*x*,3.0) + s(*y*,4.0) + s(*dc*,3.9)	41.5
22 March	s(*x*,2.93) + s(y,5.69) + s(*dc*,5.31)	84.1	s(*x*,*y*,10.4) + s(*dc*,3.5)	69.5	s(*x*,2.9) + s(*y*,1.0) + s(*dc*,3.5)	26.3
29 March	s(*x*,*y*,17.6) + s(*dc*,3.38)	84.3	s(*x*,3.4) + s(*y*,1) + s(*dc*,1.5)	48.1	s(*x*,*y*,13.8)	29.5
Common scoters						
15 March	s(*x*,*y*,18.5)	96.8			s(*x*,*y*,8.9) + s(*dc*,4.0)	77.7
21 March	s(*x*,3.96)	40.9			s(*x*,*y*,9.0) + s(*dc*,3.8)	93.6
22 March	s(*x*,*y*,18.5)	83.0			s(*x*,*y*,8.9) + s(*y*,3.9)	83.2
29 March	s(*x*,*y*,18.7)	91.2			s(*x*,*y*,9.0) + s(*y*,3.6)	69.9

Table 6. Abundance estimates and measures of precision for gulls from conventional distance sampling (visual) and strip transect sampling (digital) that constitute design-based methods and density surface modelling for model-based estimates; $\hat{N}$ is the abundance estimate, '%CV' is the coefficient of variation expressed as a percentage, '95% CI' is the 95% confidence interval (note that for design-based estimates this is a log-based CI and for model-based estimates this is the percentile CI).

Data source	Survey	Design-based			Model-based		
		$\hat{N}$	% CV	95% CI	$\hat{N}$	% CV	95% CI
Gulls							
Aerial	15 March	2443	18.2	1714 – 3483	4811	83.5	1844 – 23940
	21 March	1603	29.8	906 – 2837	1801	48.6	825 – 5030
	22 March	2194	32.5	1178 – 4086	1845	30.3	956 – 3557
	29 March	1880	21.4	1242 – 2845	5807	82.0	1754 – 37988
Digital still transects	15 March	4120	53.3	1583 - 8633	6084	137.8	685 – 73519
	21 March	325	26.3	200 - 500	252	21.9	159 – 403
	22 March	1350	42.5	466 - 2473	4524	141.2	435 – 31965
	29 March	726	24.0	428 - 1045	645	38.7	285 – 1410
Digital video	15 March	466	26.4	269 - 723	427	21.0	270 – 608
	21 March	904	50.6	308 - 1839	546	39.5	236 – 975
	22 March	750	40.3	321 - 1374	643	21.4	389 – 908
	29 March	1038	30.5	536 - 1646	871	29.3	466 – 1460
Common scoters							
Aerial	15 March	10427	40.7	4838 – 22472	11642	33.7	3345 – 19624
	21 March	5419	45.5	2318 – 12670	6101	48.0	1846 – 10481
	22 March	5396	44.8	2335 – 12469	4916	36.4	2291 – 10350
	29 March	4400	44.0	1929 – 10037	7656	80.3	771 – 27058
Digital still transects	15 March	32085	38.2	11220 - 57297	26793	42.8	6742 – 49804
	21 March	20378	72.3	3133 - 48964	17944	77.2	0 – 47107
	22 March	4942	83.8	754 - 14387	4381	86.6	0 – 13052
	29 March	12600	55.8	2211 - 26430	10779	61.3	358 – 24735
Digital video	15 March	25461	35.3	10658 - 44534	10827	33.3	4709 – 17813
	21 March	14492	54.1	2904 - 35222	7943	30.8	4172 – 15578
	22 March	19910	54.1	6242 - 41036	7659	32.7	3769 – 15698
	29 March	10662	41.4	4178 - 19677	8889	29.7	4758 – 15436

Table 7. Coefficients of variation averaged across the four replicate surveys for each survey type-analysis method combination.

	Gulls		Common scoters	
	Design-based	Model-based	Design-based	Model-based
Aerial	25	61	44	50
Digital still transects	36	85	63	67
Digital video	36	27	46	32
Average	45.5		50.1	

Figure 1 Plot of locations of detected groups of gulls and common scoters for visual surveys. The dashed line is the boundary of the study region and the blue line is the coastline.

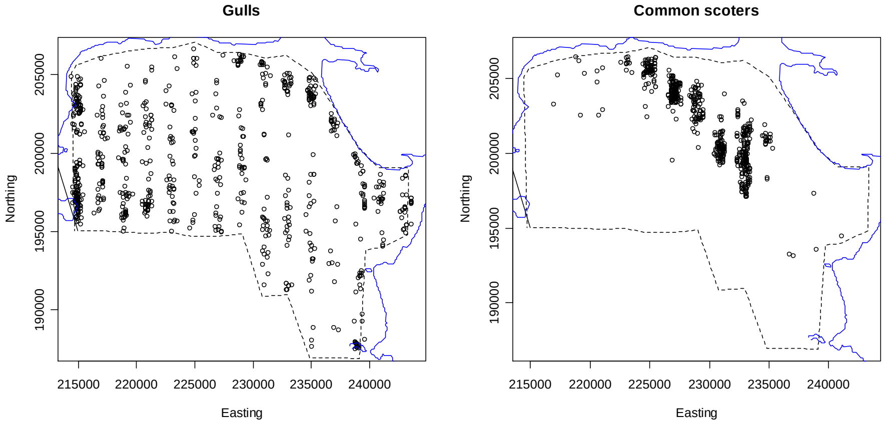

Figure 2 Fitted detection functions for each visual survey overlaid onto the scaled histograms of perpendicular distances. The first group of 4 histograms shows fitted detection functions for gulls, the second group of 4 shows fitted hazard rate detection functions for common scoters (used for design-based estimates) and the final group of 4 shows fitted half normal detection functions for common scoters (used for model-based estimates).

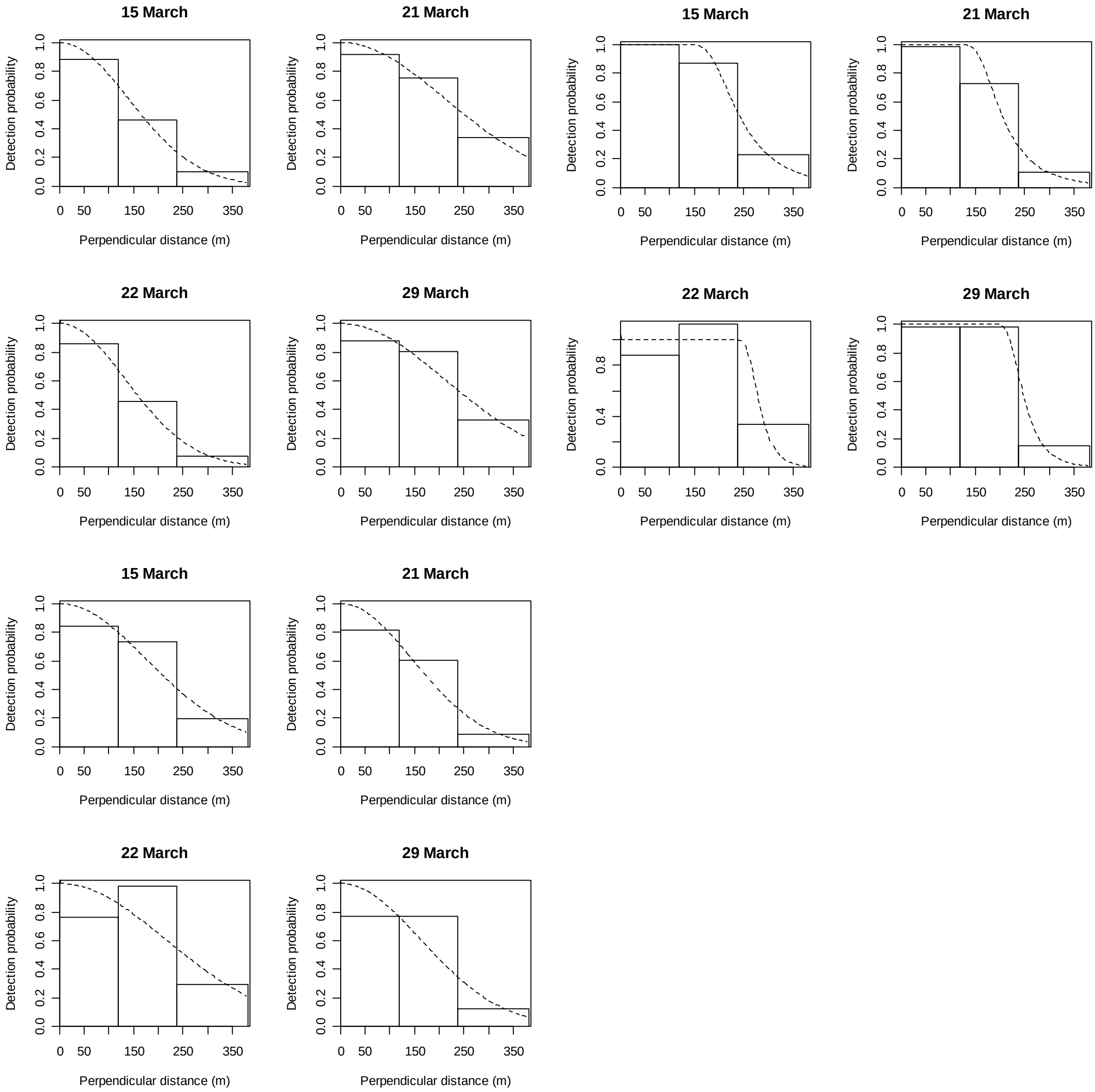

Figure 3 Estimated numbers of gulls in each segment. Left column is for visual surveys, middle column for digital still transects, and right column for digital video. Dots indicate the mid point of the segments; the size of the circle indicates the estimated number of birds in each segment and the maximum number (N) is given at the bottom of each plot.

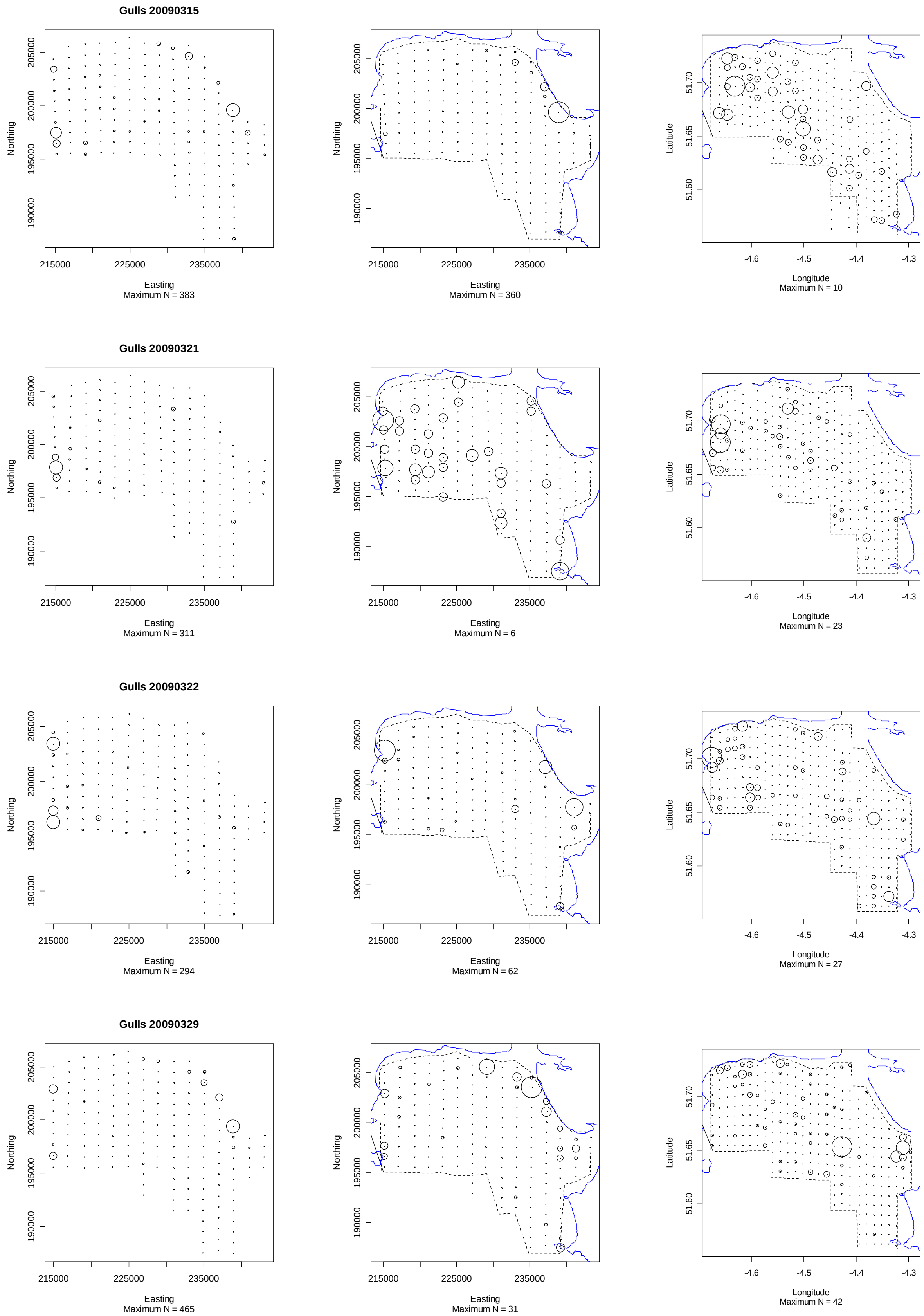

Figure 4. Final density surface for gulls, left column for visual surveys, middle column for digital stills, and right column for digital video. The scale is the logarithm of birds·km^{-2}. Note the coordinates for the visual survey and digital still transects are in northings and eastings whereas the coordinates for the digital video density surface maps are in latitude and longitude.

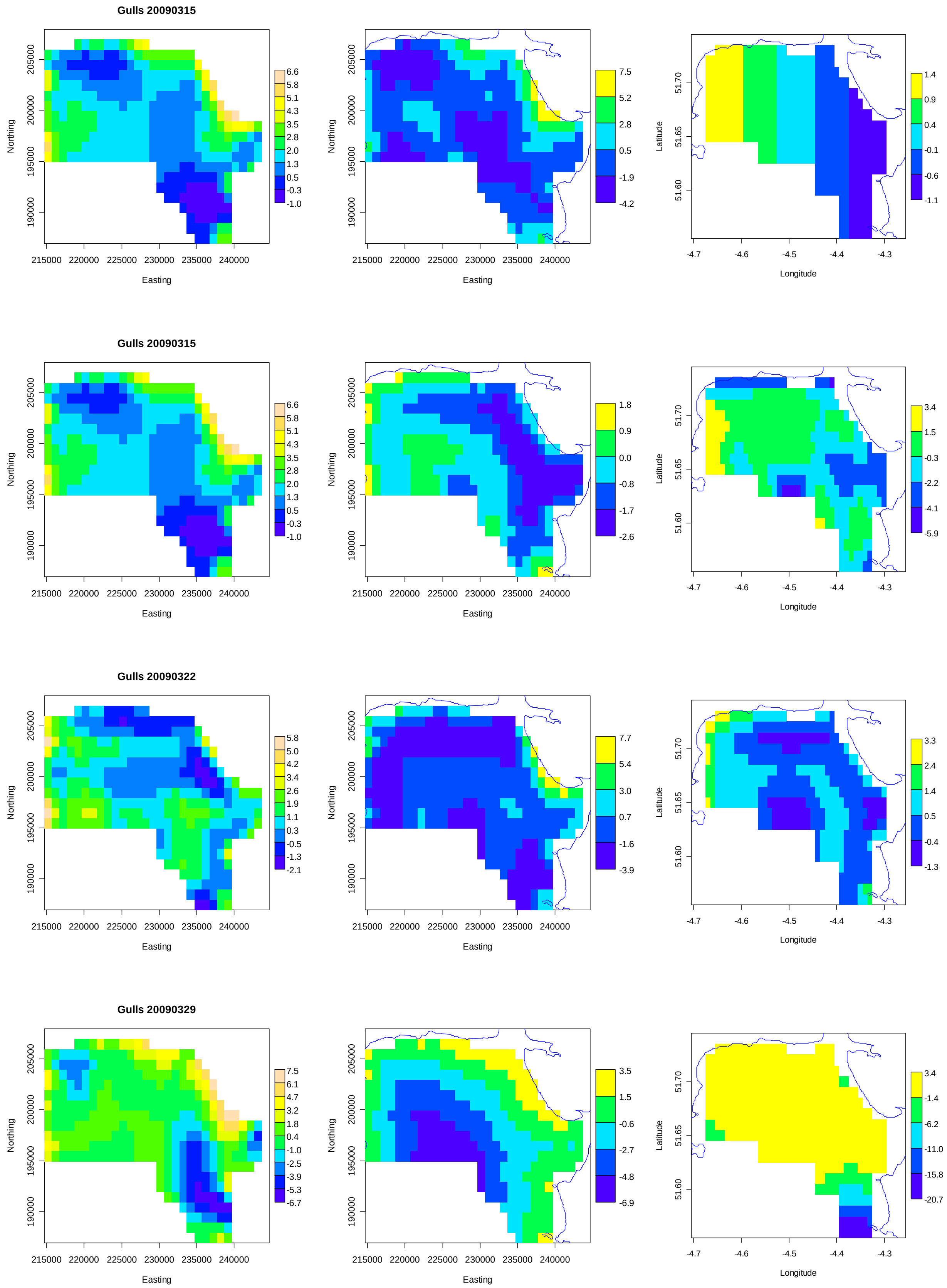

Figure 5 Estimated numbers of common scoters in each segment. Left column is for visual surveys, middle column for digital still transects, and right column for digital video. Symbology as in Figure 3.

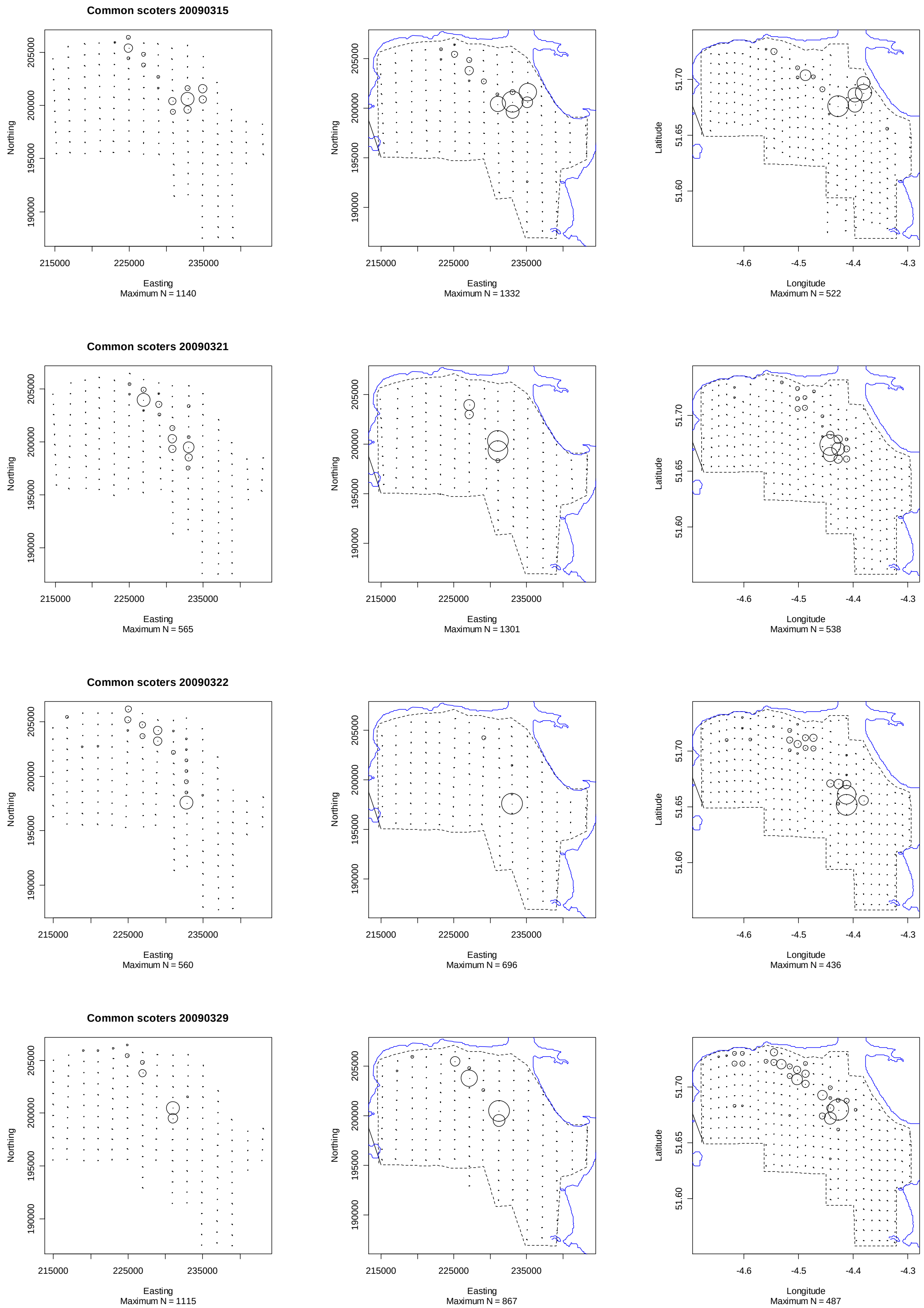

Figure 6. Final density surface for scoters, left column for visual surveys, a flat density surface model (not shown) was fitted for digital still transects, and right column for digital video. The scale is the logarithm of birds·km^{-2}. Note the coordinates for the visual survey are in northings and eastings whereas the coordinates for the digital video density surface maps are in latitude and longitude.

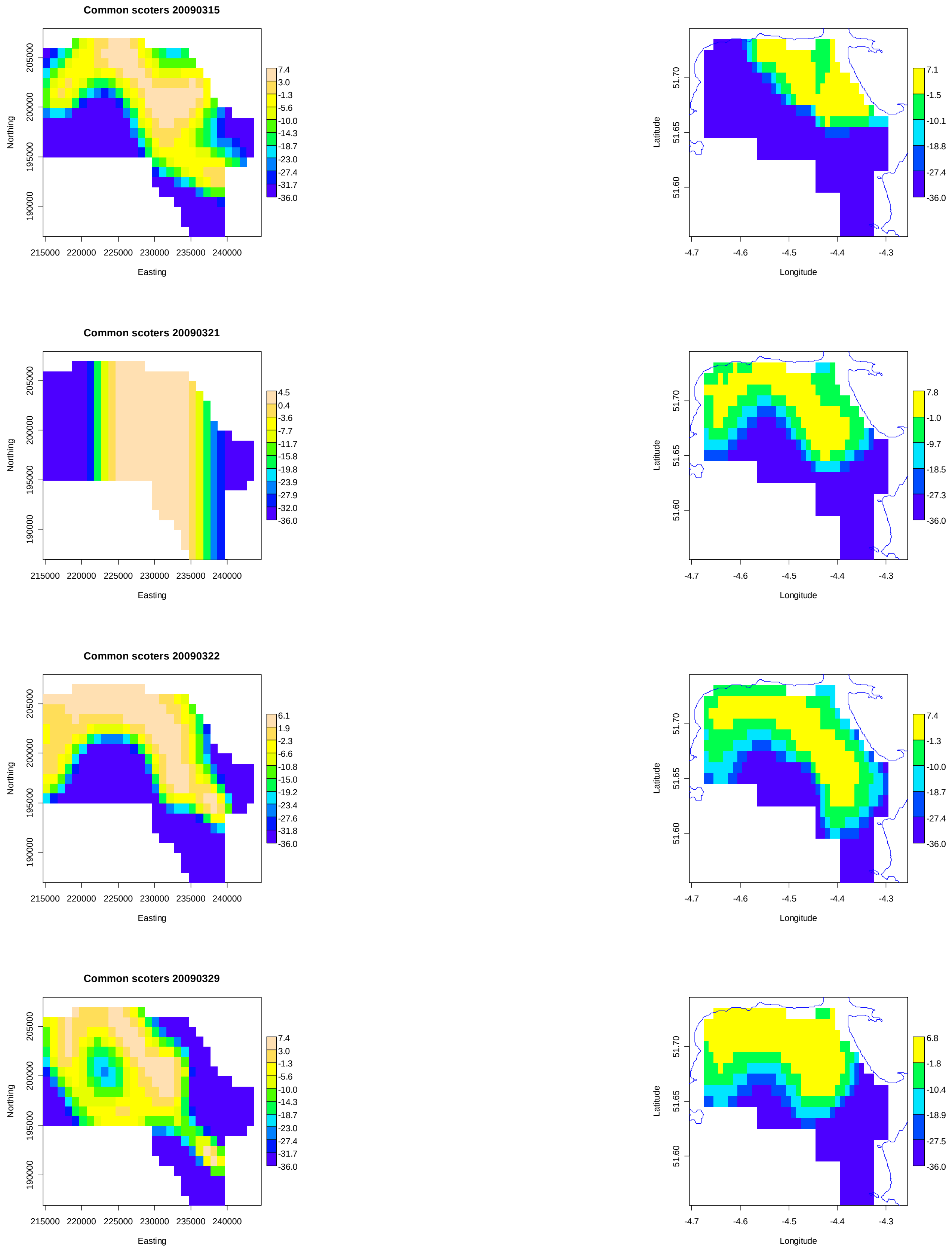

Figure 7. Point and interval estimates of gull abundance in the Carmarthen Bay SPA from all survey methods and estimation methods. Note the upper confidence limits are truncated for some estimates. Table 6 contains the numerical values from which this figure was created.

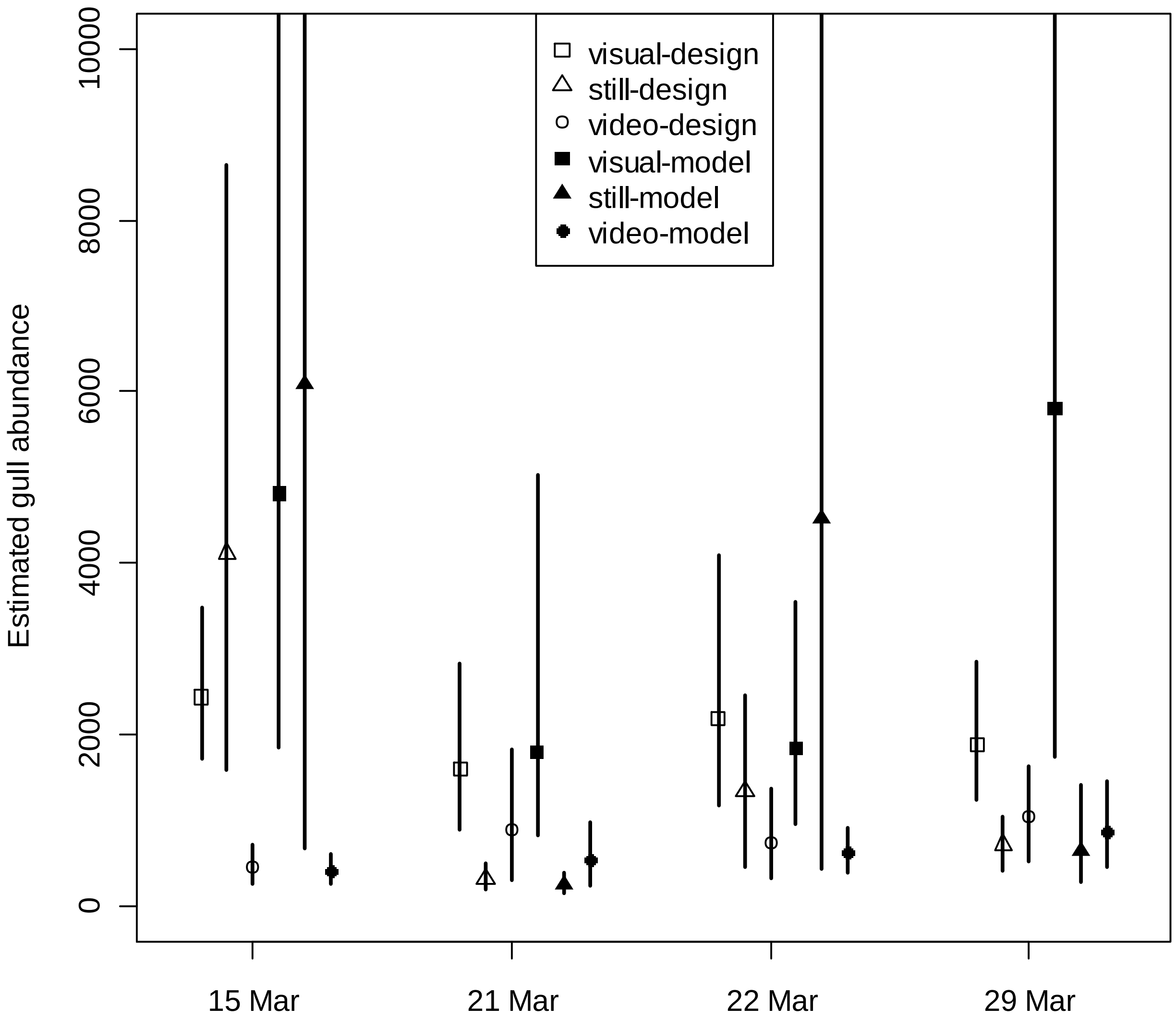

Figure 8. Point and interval estimates of common scoter abundance in the Carmarthen Bay SPA from all survey methods and estimation methods. Note the upper confidence limits are truncated for some estimates. Table 6 contains the numerical values from which this figure was created.