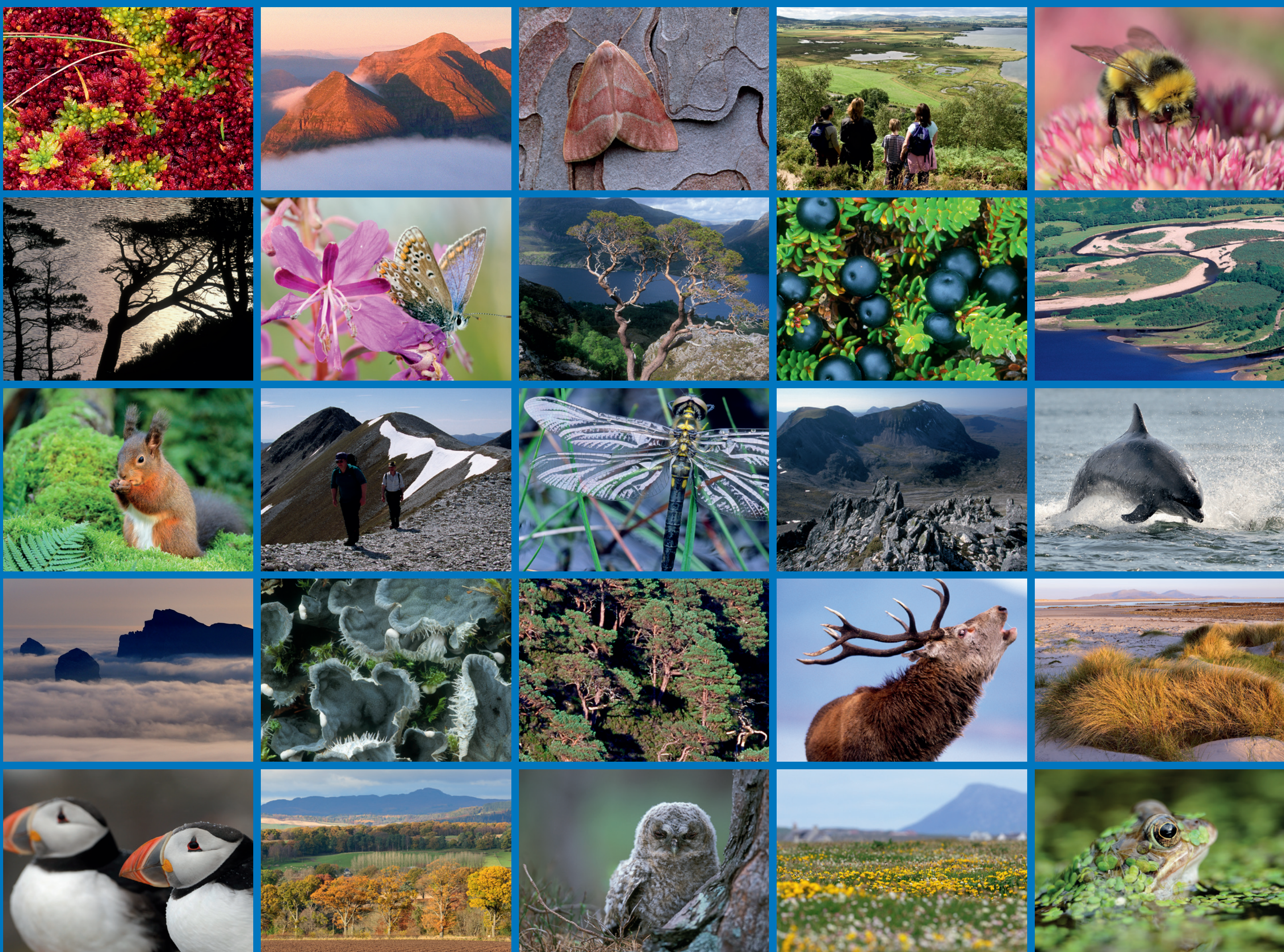
Scottish Natural Heritage
Research Report No. 974

Distribution and abundance of basking sharks (*Cetorhinus maximus*) and minke whales (*Balaenoptera acutorostrata*) within the Sea of the Hebrides MPA proposal – a pilot digital aerial survey



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RESEARCH REPORT

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For further information on this report please contact:

Dr Suz Henderson
Scottish Natural Heritage
Great Glen House
Leachkin Road
INVERNESS
IV3 8NW
Telephone: 01463 725238
E-mail: suzanne.henderson@nature.scot

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RESEARCH REPORT
Summary

Distribution and abundance of basking sharks (*Cetorhinus maximus*) and minke whales (*Balaenoptera acutorostrata*) within the Sea of the Hebrides MPA proposal – a pilot digital aerial survey

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Keywords

Basking shark; minke whale; common dolphin; bottlenose dolphin; harbour porpoise; Risso's dolphin; Sea of the Hebrides MPA; distribution; abundance; aerial surveys; monitoring.

Background

The Sea of the Hebrides Marine Protected Area (MPA) proposal has been identified for supporting large seasonal aggregations of basking sharks (*Cetorhinus maximus*) and minke whales (*Balaenoptera acutorostrata*). Recent studies have shown basking sharks to be aggregated in 'hotspots' within the MPA proposal.

This report presents the results of a pilot study to trial the suitability of digital aerial surveys for collecting data on basking sharks and minke whales for the purposes of assessing distribution and abundance in the Sea of the Hebrides MPA proposal. Recommendations are also made on the potential for the technique to be used for monitoring purposes in the future.

Main findings

- Three digital video aerial surveys were carried out on 15 August, 16 September and 30 September 2016 using transects spaced 15 km apart in a low-density stratum and 7.5 km apart in a high-density stratum. These surveys covered up to 719 km² of the 10,309 km² sea area of the MPA proposal.
- The survey technique proved successful in collecting data for basking sharks in August but was ineffective for minke whales over the survey period.
- Fifty three basking sharks were observed in survey 1 (15th August), ten in survey 2 (16th September) and none in survey 3 (30th September).
- It was only possible to estimate basking shark relative abundance from the August survey due to low numbers of observations in the subsequent surveys, and whilst a subsequent absolute abundance estimate was possible (using estimated availability bias from previous tagging studies), the confidence interval was high.
- Preliminary power analysis indicated that a decline in basking shark abundance could be detectable using digital aerial surveys methods after 15 years (with surveys every three years) if a CV precision of 13% of absolute abundance could be obtained. It is unclear from this pilot survey if this precision could be achieved.

- Recommendations for further power analysis and increasing precision in abundance estimates are discussed.
- One minke whale was observed on survey 1 and one on survey 3. The survey was not successful for detecting large numbers of minke whales, probably on account of the long and deep dives (and shorter periods of time at surface) made by this species in relation to the speed that aerial survey transects were carried out.
- Low availability of minke whales for detection and the difficulty of focusing the survey on a high-density stratum for this species suggest it may not be possible to achieve a useful level of digital aerial surveys that is cost effective for this species, and other methods may be more appropriate.

For further information on this project contact:
Suz Henderson, Scottish Natural Heritage, Great Glen House, Leachkin Road, Inverness, IV3 8NW.
Tel: 01463 725238 or suzanne.henderson@nature.scot
For further information on the SNH Research & Technical Support Programme contact:
Research Coordinator, Scottish Natural Heritage, Great Glen House, Leachkin Road, Inverness, IV3 8NW.
Tel: 01463 725000 or research@nature.scot

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Acknowledgements

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1. INTRODUCTION

In Scottish territorial waters, the Sea of the Hebrides Nature Conservation Marine Protected Area (MPA) proposal has been put forward to provide protection to basking sharks (*Cetorhinus maximus)* and minke whales (*Balaenoptera acutorostrata)* and the habitats they use.

This geographic area has been identified by Scottish Natural Heritage (SNH) based on it being important for key life cycle stages for basking sharks and minke whales. Further scientific work has been undertaken, including habitat modelling based on effort-corrected sightings surveys and shark satellite tagging, to further predict and inform the spatio-temporal use of different areas by these key species, and thus provide more robust and accurate data for the MPA proposals (see SNH, 2014; Paxton *et al.,* 2014; Witt *et al.,* 2016). Consideration of options for estimating abundances of these species within the area is also required to provide baseline figures and potential monitoring suggestions.

Basking sharks exhibit above-average densities generally during the warmer summer months, including the presence of particular shark hotspots, which are often in association with productive oceanic frontal zones. Seasonally high numbers of both basking shark and minke whale occur within the geographical area encompassed by the MPA proposal, as well as the presence of oceanographic topographical fronts (SNH, 2014).

As well as basking sharks and minke whales, several other marine megafauna use the MPA proposal site for feeding, breeding (based on the presence of calves) and transiting, including Risso's dolphin (*Grampus griseus),* common dolphin (*Delphinus delphis)*, harbour porpoise (*Phocoena phocoena)*, bottlenose dolphin (*Tursiops truncatus)*, killer whale (*Orcinus orca)* and humpback whale (*Megaptera novaeangliae)*.

1.1 Project objectives

The project aim was to conduct a pilot study to trial the suitability of digital aerial surveys for collecting data on basking sharks and minke whales for the purposes of assessing their distribution and abundance in the Sea of the Hebrides MPA proposal.

The report describes the pilot survey design and the trial of three digital video aerial surveys of the Sea of the Hebrides MPA proposal during August and September 2016 and the suitability of the technique for the two species. Data analysis was carried out to present information on the relative abundance, and distribution of species along with any behavioural observations and individual animal size information. Methods to allow an assessment of absolute abundance of basking sharks were presented using additional data on the diving depths of basking sharks, published in Witt *et al.* (2016). Additional megafauna were also observed and their distribution mapped. The conclusions contain the outcomes of the survey, an assessment of the success of the survey, and recommendations for future surveys in light of this pilot study.

2. METHODS

2.1 Survey design and rationale

Two aerial survey designs were considered to provide repeatable surveys for basking sharks and minke whales in the Sea of the Hebrides MPA proposal. Greatest focus was on basking sharks, which have not been surveyed by air previously in Scotland. The two potential designs were 1) transect-based sampling and 2) plot-based sampling.

Transect-based sampling, uses transects as the basic sample, in which data are collected along the entire length of line flown by the aircraft. In plot-based sampling, small quadrat-style samples are taken at intervals along the length of the line flown by the aircraft.

Plot-based sampling is advantageous at small sites, because it is possible to obtain large numbers of statistically independent samples, which in those cases can sometimes be useful for improving the statistical precision of abundance estimates. However, research has demonstrated that above a minimum number of independent samples, the number of independent samples becomes less important compared to the importance of obtaining a sufficient volume of data (Buckland *et al*., 2001; HiDef analysis). The most efficient way to increase the volume of data (expressed as the percentage coverage of a site), is to collect data along the entire line flown by the aircraft, which is why a transect-based strategy is proposed and is particularly advantageous for large sites. Plot-based sampling was rejected on the grounds of inefficiency, because a considerably greater amount of flying is required to achieve the same amount of coverage of the study area.

Consequently, a stratified, random survey using design-based estimators for the orientation of the transects was proposed. Stratified sampling is a type of sampling method in which the total population to be sampled is divided into smaller groups, or strata. Each stratum is formed based on some common characteristics in the population data such as population density, habitat characteristics. Two key strata were proposed: a region of high basking shark density focussed on the regions around the islands of Tiree, Coll and Canna where consistently high density of basking sharks have been found in boat-based surveys (Paxton *et al.,* 2014) and from tagging studies (Witt *et al.,* 2016), surrounded by a low-density stratum. The boundaries of this region were determined using the above publications and enlarged slightly to ensure capture of the core concentrations to the south-west of Tiree. In a stratified design, the sampling regime is varied in each stratum to suit the population or habitat characteristics of that stratum, and is valuable for basking shark due to their strongly aggregated distribution. However, a stratified design would offer no advantage for minke whale which do not have such highly concentrated distributions during August (the proposed time of survey), even though this month falls in the period of peak abundance for this species (MacLeod *et al.,* 2004).

Two options to survey these strata were considered: 1) a design which obtains approximately 10% coverage in the low-density stratum and 20% coverage in the high-density stratum; and 2) a design obtaining 5% coverage in the low-density stratum and 10% coverage in the high-density stratum. The project budget permitted only one high intensity survey (Option 1) or two or possibly three lower intensity surveys (Option 2).

A 3 cm Ground Sample Distance (GSD) camera image resolution setting was considered sufficient for this survey in order to enable all marine megafauna to be detected and identified to species level. This means that adjacent pixel locations in final images equate to 3 cm apart on the ground. This would use four high resolution video cameras, each sampling a 187.5 m strip with approximately 30 m gap between them (combined total strip width of 750 m; Effective Strip Width of 375 m). This would be achieved by flying at an altitude of 610 m (2000 ft) above sea level. With this strip width, the low intensity survey would require transects to be spaced at 15 km apart in the low-density stratum and 7.5 km apart in the high-density stratum in order to achieve 5 and 10 percentage coverage of these strata.

Multiple low intensity surveys offer an advantage over a single high intensity survey for the key study species because generally they deliver higher precision abundance estimates when combined and better capture the range of abundances over the survey period and the range of distribution patterns within the study area. In a pilot study, which sought to obtain a baseline from which to test different potential survey design options, multiple surveys offer opportunities to simulate a greater range of potential future survey design options. Multiple low intensity surveys are more desirable than a single high intensity survey because there is likely also to be a temporal component to the aggregation behaviour of basking sharks, and such behaviour would more likely be captured than in a single survey. Consequently, multiple low intensity surveys were chosen as the final survey design because these could be completed in a single day and avoid bias introduced from animal movements between days, unlike the high intensity survey design (Thaxter & Burton, 2009).

The survey transects should, ideally, cross the principal habitats perpendicular to their gradient. The purpose of such a design is to reduce the amount of variance in abundance between the sample transects and therefore improve the precision of the abundance estimates. In a highly heterogeneous environment such as the Sea of the Hebrides, it is not possible to orient all of the sample transects at right angles to the main habitat features, these being bathymetry, tide and tidal current (Paxton *et al.,* 2014). For the large part, the design incorporated transects oriented from south-east to north-west to cross perpendicular to the main depth gradients except in the Cuillin Sound between the islands of Skye and Rum; here, the transects were oriented from south-west to north-east (Figure 1).

The study area is the entire MPA proposal and encompasses 10,309.4 km^2. The final design consisted of randomly placed parallel strip transects spaced 15 km apart in a low basking shark density stratum (5% coverage of study area) and 7.5 km apart in a high basking shark density stratum (10% coverage of study area). These transects were placed by eye perpendicular to the depth contours along the coast. Such a design ensured that each transect sampled as similar a range of habitats as possible (relating primarily to water depth) and thus helping to reduce the between-transect difference in shark and marine mammal encounter rate.

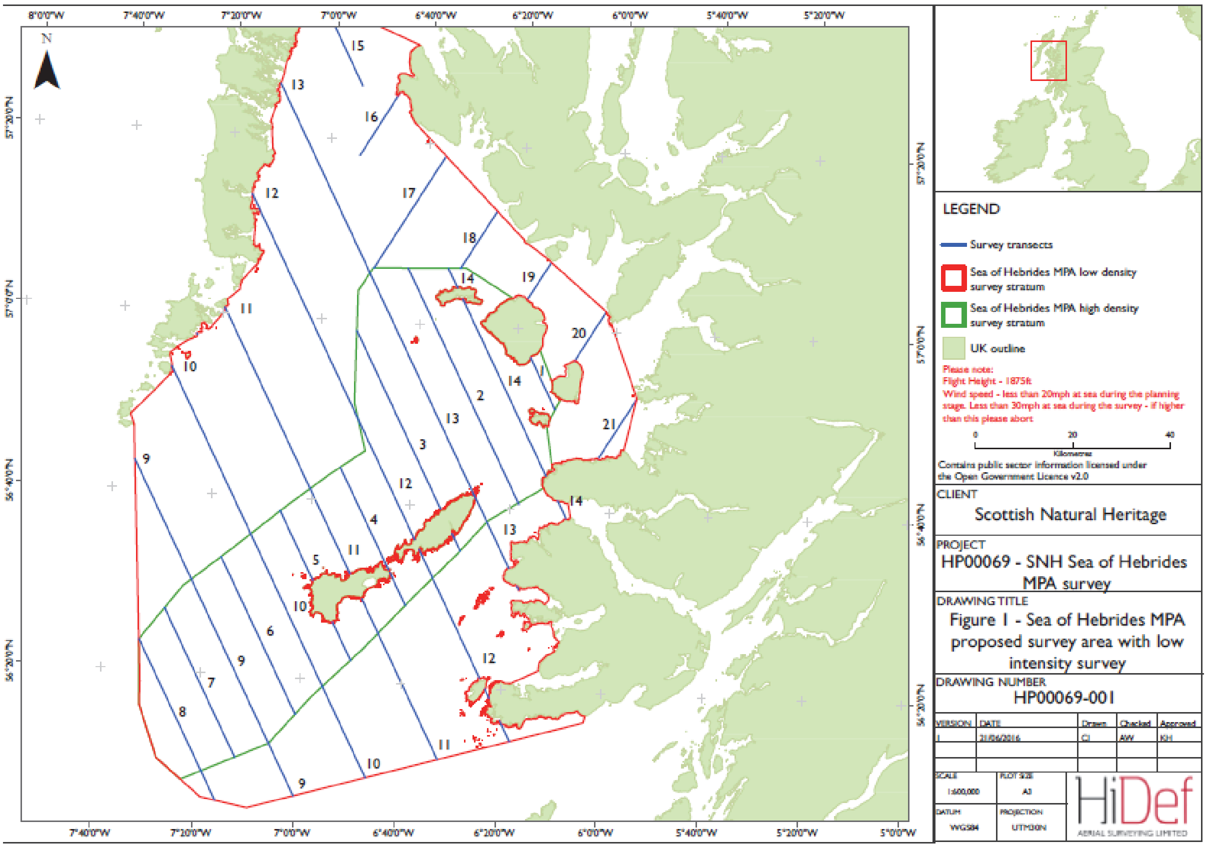

Figure 1. Survey design showing the survey area, low and high density strata and the transect placement and numbers.

2.2 Data recording

Surveys were undertaken using a Cessna F406 aircraft equipped with four HiDef Gen II cameras with sensors set to a resolution of 3 cm GSD. Each camera sampled a strip of 187.5 m width, separated from the next camera by approximately 25 m, thus providing a combined sampled total strip width of 750 m within an 825 m overall strip. This is equal to an effective strip (half) width of 375 m.

The surveys were flown along the transect pattern shown in Figure 1 at a height of approximately 610 m (approximately 2000 ft) above sea level, with an average flying speed of 220 km/hr (120 knots). The position of the aircraft was taken from a Garmin GPSMap 296 receiver with differential GPS enabled to give 1 m accuracy for the positions and recording location updates at one second intervals (which is equivalent to a horizontal distance of 61.1 m) for later matching to animal observations.

2.3 Data review and object detection and identification

Video data were viewed by trained reviewers who marked any objects in the footage as requiring further analysis, as well as determining which were birds, marine megafauna (defined within this report as cetaceans, pinnipeds, sharks, other fish or sea turtles) or anthropogenic objects such as ships or buoys.

Objects were only recorded where it reached a reference line (known as "the red line") which defines the true transect width of 187.5 m for each camera. By excluding objects that do not cross the red line, biases to abundance estimates caused by flux (movement of objects in the video footage relative to the aircraft, such as 'wing wobble') are eliminated.

Objects requiring further analysis were blind-reviewed by species specialists with experience of identification from boat-based and aerial surveys. Each object was assigned to the lowest taxonomic level possible and assessed for approximate age and sex where possible, as well as recording any behaviour traits visible from the imagery.

In addition, at least 20% of all taxonomic identifications were subjected to an external ‘blind’ QA by more senior contracted freelance staff. If greater than 10% disagreement was attained then corrective action was initiated: if appropriate, the failed identifier’s data was discarded and re-identified. Any disputed identifications were passed to a third-party expert for a final decision.

The species identifications were given a confidence rating of possible, probable or definite which equate to low, medium and high confidence levels, respectively; this relates to how clear/visible the animal was in video footage. Even low confidence level identifications were based on at least one identification feature that made it more likely to be one species over another. Any animals that could not be identified to species level were assigned to a category of ‘No ID’. Identification of species with all confidence ratings were used in data analysis, as basking sharks and minke whales are not easily confused with other species. This was borne out by there being no low confidence levels for either of these two species. Surfacing behaviour was defined as: any part of the body seen to break the sea surface while the animal was visible during the video sequence. However, for the purposes of calculating absolute abundance, a separate behaviour of ‘snapshot surfacing’ was also classified if the dorsal fin of the basking shark or cetacean was above the water in the frame nearest to the ‘red line’.

Any behaviours, such as feeding (gills open for basking sharks) or apparent courtship behaviour were noted. All animals were measured using a calibrated measuring tool from tail tip to snout/rostrum, which gave the length accurate to 3 cm.

An assessment was made of the weather conditions, primarily sun glare and sea state. This was assessed on the first frame of every video sequence and on every 500th thereafter, using the following classification for sun glare (Table 1) related to a set of HiDef standard reference images of each class, and for sea state using the World Maritime Organisation (WMO) classification system (Table 2). Data collected in conditions of sun glare of 4 and sea state of 6 were not analysed, and conditions of sun glare 3 and sea state 5 required more careful review (i.e. at a reduced speed of video footage) to ensure objects were not missed and to avoid QA failures during the review process.

Table 1. Classification of sun glare conditions on the sea surface of video footage

Score	Criteria
0	Not Recorded e.g. over land
1	None present over sea
2	Slight
3	Moderate
4	Strong

Table 2. Classification of sea state conditions in video footage based on WMO code

WMO Sea State Code	Wave height	Characteristics
0	0 metres (0 ft)	Calm (glassy)
1	0 to 0.1 metres (0.00 to 0.33 ft)	Calm (rippled)
2	0.1 to 0.5 metres (3.9 in to 1 ft 7.7 in)	Smooth (wavelets)
3	0.5 to 1.25 metres (1 ft 8 in to 4ft 1 in)	Slight (first whitecaps)
4	1.25 to 2.5 metres (4 ft 1in to 8 ft 2in)	Moderate (many whitecaps)
5	2.5 to 4 metres (8 ft 2in to 13 ft 1in)	Rough (some spray)
6	4 to 6 metres (13 to 20 ft)	Very rough (large waves, many whitecaps, much spray)
7	6 to 9 metres (20 to 30 ft)	High (streaks of wind-blown foam)
8	9 to 14 metres (30 to 46 ft)	Very high
9	Over 14 metres (46 ft)	Phenomenal

2.4 Final processing

All data were geo-referenced, taking into account the offset from the transect line of the cameras, and compiled into Geographical Information System (GIS) files for the Observation and Track data (in ArcGIS shapefile format), using UTM30N projection, WGS84 datum.

2.5 Data analysis

2.5.1 Abundance / density estimates

The abundance of each species observed was estimated separately using a design-based strip-transect analysis with variance and confidence intervals (CIs).

In a strip-transect analysis, each transect is treated as an independent analysis unit, and the assumption is made that transects can be treated as statistically independent random samples from the study area. The length of each transect and its breadth (i.e. the combined width of the field of view of the cameras) multiplied together give the transect area; dividing the number of observations on that transect by the transect area gives a point estimate of the relative density of that species. The relative density of animals at the survey area (and hence the relative abundance), the standard deviation, 95% CI and coefficient of variance (CV) are then estimated using 10,000 non-parametric bootstrap method with replacement (Buckland *et al.* 2001). The bootstrapping technique uses total length of transect to limit selection rather than total number of transects. This method has an advantage when transects are of unequal length and provides better precision estimates.

The relative density estimate is expressed as the average number of animals seen below or above the surface per square km surveyed in the surveyed strata (either high or low-density). The overall relative density estimate for the two regions combined (D_t) was obtained from the density of animals within each stratum calculated by the bootstrap method (Buckland *et al.* 2001), weighted by the respective survey effort to account for different total areas flown in each stratum (equation i):

$$D_t = \frac{(D_h \times a_h) + (D_l \times a_l)}{a_h + a_l} \qquad \text{(i)}$$

Where D_h = high density stratum density as calculated by bootstrapping, D_l = low density stratum density as calculated by bootstrapping, a_h = high density stratum transect area and a_l = low density stratum transect area (equation 3.122 in Buckland *et al.,* 2001).

Generically, multiplying the relative density estimate (D) by the total area (a) gives the estimate of relative abundance (N; equation ii).

$$N = D \times a \qquad \text{(ii)}$$

The standard deviation is a measure of the variance of the relative abundance estimate, standardised by the number of samples (transects). The upper and lower CI define the range that the relative abundance estimate falls within with 95% certainty. The CV (equation iii), also referred to as the relative standard error, is a measure of the precision of the relative abundance and density estimates and greatly affects the power available in the data to detect a change in abundance.

The coefficient of variation (CV_t) of the pooled relative abundance estimate was obtained from:

$$CV_t = \sqrt{\frac{(CV_h{}^2 \times N_h{}^2) + (CV_l{}^2 \times N_l{}^2)}{N_t{}^2}} \qquad \text{(iii)}$$

Where CV_h = CV for the high-density stratum, CV_l is the CV for the low-density stratum, N_h is the relative abundance in the high density stratum, N_l is the relative abundance in the low density stratum and N_t is the combined relative abundance in both strata. This is derived from the delta equation (Equation 3.5) in Buckland *et al.* (2001) but weights the contribution of the CV from each stratum according to the relative abundance estimate.

2.5.2 Availability bias

The proportion of sharks or marine mammals that spend any time in deeper water escaping surface detection will lead to an under-estimate of their abundance during surveys, which is known as availability bias. For species that make long dives underwater, this bias will be greater (for example, marine mammals and sharks).

There are two main approaches to accounting for availability bias: by using double platform surveys (for example Borchers *et al.,* 2002; Hiby & Lovell, 1998) and by using data on time spent underwater (e.g. from tagging studies) to apply correction factors to abundance estimates (for example Barlow *et al*., 1988).

Barlow *et al.* (1988) used equation (iv) to determine the probability that an animal will be at the surface during the passage of the aircraft:

$$Pr = \frac{(s+t)}{(s+d)} \qquad \text{(iv)}$$

Where *Pr* is the proportion of time that an animal is available (visible), *s* is the average time the animal spends at the surface, *d* is the average time spent below the surface, and *t* is the total time that the animal is within view (either below or above the surface).

In the case of digital video surveys, the value of *t* is negligibly small and is treated as 0, thus the value of *Pr* in this case represents the proportion of time that an animal is available at the surface.

The proportion of time that an animal is not available is 1 – *Pr*.

We used a method described by Webb *et al.* (2015) in which we estimate absolute abundance A_t as:

$$A_t = N \times \frac{P_S}{Pr} \tag{v}$$

Where N is the relative abundance, P_S is the proportion of animals recorded at the surface and *Pr* is the proportion of time an animal is available at the surface (see equation iv above). P_S was calculated for each survey from the surfacing behaviour of basking sharks (Section 3.8) and *Pr* was calculated from data supplied from tagged animals, first published in Witt *et al.* (2016) and re-analysed in Annex 1. The value of P_S divided by Pr provides the correction factor for the relative abundance (N), which we define as the availability bias.

2.5.3 Average depth of detection and subsequent abundance estimates

To estimate the average depth at which basking sharks were detected during the digital aerial surveys, we first assumed that individuals would not be detected at depths greater than 10 m. We felt this to be a reasonable assumption due to issues with general water clarity (e.g., waves, glare, turbidity) preventing us from accurately detecting an animal deeper than this. We split this into 11 depth bands (surface, surface to 1 m, surface to – 2 m, etc.) and estimated hypothetical absolute abundances and densities for each depth band. We did this by assuming that all observations of basking sharks occurred within each depth band (i.e. we applied the absolute abundance of all sharks seen above and below the surface to each depth band). We divided that absolute abundance by the proportion of tagged sharks at specific depth bands (e.g. those depth bands we defined; surface, surface to 1 m, surface to 2 m, etc…) as determined by data provided by Witt *et al*. (2016) and analysed Annex 1.

Using the absolute density estimate (as calculated by correcting the relative density estimate by the availability bias; *Pr*), we visually compared the value against the hypothetical absolute densities at each depth band. The depth range at which the hypothetical absolute density matched the absolute density estimate was then determined to be the average depth at which we could detect individuals.

2.5.4 Estimating power to detect change

A power analysis allows the probability of detecting an upward or downward trend in abundance using linear regression, given a number of samples and estimates of sample variability and rate of change (Gerrodette, 1987). The power of a statistical test is the probability that the test will reject H_0 when H_0 is false. To obtain the statistical power to detect a change, Gerrodette (1987 and 1991) developed a method based on the number of annual surveys (*t*), the annual rate of change (*r*, assuming an exponential decline), the precision of the estimate ($\boldsymbol{CV}(\widehat{\boldsymbol{N}})$) and the significance level of the test (*α*, taken to be 0.05):

$$\boldsymbol{ncp} = \frac{\boldsymbol{ln}(\mathbf{1}+\boldsymbol{r})}{\sqrt{\dfrac{\ln\left(\mathbf{1}+\boldsymbol{CV}(\widehat{\boldsymbol{N}})^{2}\right)}{\boldsymbol{t}(\boldsymbol{t}-\mathbf{1})(\boldsymbol{t}+\mathbf{1})/\mathbf{12}}}} \tag{vi}$$

The numerator is equation 13 from Gerrodette (1987), while the denominator is the equivalent of σ_b in Gerrodette (1991) and is derived from equation 16 in Gerrodette (1987).

The power (1-β) is given by:

$$\mathbf{1-\boldsymbol{\beta} = 1 - \Phi\left(z_{\frac{1-\alpha}{2}} - ncp\right) + \Phi\left(z_{\alpha/2} - ncp\right)} \qquad \text{(vii)}$$

where $\phi(\mu)$ is the cumulative distribution function of a standardised Normal variable μ and μ_x is the value of a standardised Normal variate which has probability α of being exceeded (Gerrodette, 1991).

The annual, or more accurately the inter-survey rate of an exponential population change (r; i.e. the rate of change per unit time between surveys that leads to the change) can be calculated from the overall fractional rate of change (R) from:

$$r = (R+1)^{1/(n-1)} - 1 \qquad \text{(viii)}$$

where n is the number of samples (equation 22 in Gerrodette, 1987), and R is the overall decline that needs to be detected. Thus, for a 50 % exponential decline over 10 years with surveys every three years, R is -0.5, n is 3, giving a value of -29 % per year for r. For a 33 % decline over 10 years, r is -18 % per year. An alternative way of presenting this is:

$$r = (R+1)^{i/G_3} - 1 \qquad \text{(ix)}$$

where i is the interval between n-1 surveys and G_3 is the length of time over which the decline R needs to be detected. E.g. if 10 years is the length of time for R of -33 % to be detected (G_3), and surveys need to be performed every three years (making for 4 total surveys), then i becomes 3.33 (surveys every 3.33 years). The value of r is then calculated as -0.18 (-18 % per year).

An exponential decline was used here as opposed to a linear decline; this approach is generally more useful when examining growth or decay processes (Gerrodette, 1987). An exponential model provides more flexibility for estimating the power to detect change within a smoothed trend model than would be the case for a linear trend model (see Buckland *et al.* 2008 for a more detailed discussion of such an approach).

If there is more than one survey per year, then the variance of the mean will be reduced. The coefficient of variation of the mean of m independent replicate estimates is $\mathrm{CV}_1/\sqrt{\mathrm{m}}$ (Gerrodette, 1987). Note that if the surveys are taken close together in time, they may not be independent and so $\mathrm{CV}_1/\sqrt{\mathrm{m}}$ may be an underestimate. Note also that taking multiple surveys per year may not lead to a reduction in variance of mean values if there are considerable population fluctuations between surveys.

Different survey scenarios were calculated using the software TRENDS (Gerrodette, 1993).

2.5.5 Estimating group size

When analysing group size, if more than one animal was present in the same camera frame, adjacent frames and the same frame numbers of adjacent cameras, then they were assumed to be part of a group.

2.5.6 Density Mapping

The density maps have been derived using a Watson-Nadaraya type kernel density estimation (KDE) technique (Simonoff, 1996). In KDE, a small 'window' function (the kernel) is used to calculate a local density at each point in the study area. To evaluate the density at a given point, the kernel is centred on that point and all the observations within the window are summed to obtain a local count. The total area of the transect(s) intersecting the window is then summed to obtain a local measure of effort. By dividing the local count by the local effort, a local density estimate is obtained. To build a density map, the study area is covered with a fine mesh (1 km x 1 km) of study points and the density is calculated at each point in the mesh in turn.

Kernel techniques are robust and not as complex as other density estimation techniques because they have few parameters; as a result, they are arguably the easiest density surface technique to reproduce independently. The only variables are the size and shape of the kernel or window function. For these analyses, we have used a Gaussian window function, which has the advantages of being smooth, rotationally symmetric and easy to compute. The shape of the Gaussian is determined by a single width parameter; the selection of this parameter is the only variable in the computation of the density maps.

Rather than set the width parameter arbitrarily, we have used a leave-one-out cross validation method (Simonoff, 1996). Cross validation estimates the predictive power of a model by removing some of the data from the data set and using the remainder of the data and the model to predict the values for the data that were removed. The closer the predicted values represent the removed data, the better the model performance and the width parameter used in the model.

To apply cross validation to the survey area, each transect is subdivided into 1 km long segments. To evaluate a choice of kernel width, each segment is removed in turn, use the kernel and the remaining data to predict the density of the missing segment and subtract the known value from the prediction to obtain an error score. This process is repeated for every segment and the error scores for all segments are squared and summed to give a total performance score for that choice of kernel width. The kernel width is then varied and the process repeated; if the new score is lower than the old, the new kernel width is a better choice than the previous value. An exhaustive search over all kernel widths is then used to identify the best global choice. The result of the process is a smooth density estimate which has been derived without any manual parameter selection. The whole process is repeated from scratch for each map, as different kernel sizes are appropriate for different species.

It should be noted that several of the KDE maps are effectively flat. These correspond to distributions where the density surface as obtained from a small local kernel was not effective at predicting missing data; this can happen with evenly distributed animals but can also happen for very sparse distributions. In the case of sparse distributions, the 'flat' map does not necessarily mean that the true underlying distribution is 'flat'; it could mean that the data doesn't contain enough evidence to determine what the underlying distribution is. It is therefore useful to refer to the abundance estimates for the corresponding map when looking at these 'flat' densities; we have also overlaid the relevant observations as dots to help with interpretation of the maps. In extreme cases, the maps were not included in the results section, and the data presented as dot maps.

3. RESULTS

3.1 Survey details and environmental data

A series of three strip transect surveys were flown in August 2016 and September 2016, as presented in Figure 1 and Table 7. The total transect length per survey over both strata amounts to 950 km, 959 km and 784 km in surveys 1, 2 and 3 respectively (Table 3 and Table 4).

Three surveys as described above were planned to be carried out during August – the peak month for basking shark and minke whales sightings in the study area. Weather window opportunities in August were not conducive so two surveys were carried out in September, on the basis that volunteers on land and on boats in the survey area reported that basking sharks were still present.

The same transect lines were used for each survey, although effort differed slightly between surveys. The differences between the surveys on 15th August and 16th September were caused by minor differences in start and stop times for transects and minor deviations of the aircraft from the transect line, as is typical for all transect-based surveys.

Due to a restriction in the available survey weather window on 30th September (there was less than a whole day with cloud above the survey altitude (typically 560 – 610 m depending on the camera resolution) across the entire study area), it was necessary for the pilot to shorten some transects or in some cases in the low-density stratum to omit some transects When having to reduce the survey effort, the aim was to achieve even coverage of the main bathymetric habitats in both the high and low density strata, whilst operating safely in suitable weather conditions. Details of spatial survey effort are shown in Annex 4.

Surveys were carried out, for the most part, under optimal conditions. The sun glare was either completely absent or slight for the majority of the time during the surveys with moderate conditions experienced for 26 % of the time on 15th August, 17.8 % of the time on 16 September and 0.6 % of the time on 30th September (Table 5). The sea state was greatest during the survey on 15th August with 60% of weather observations at sea state 4 and 7.3 % of observations at sea state 5. The sea state was similar on 16th September with 62 % of observations at sea state 4, and much lower on 30th September with all observations at sea state 3 or less (Table 6). Environmental data are in Annex 3 for all observations made.

Table 3. Survey effort across the study area during August 2016 and September 2016 in the high density stratum (total area of 3300 km²)

Survey date	Number of transects	Total transect length surveyed (km)	Area Covered (km²)
15 August 2016	14	523.33	392.50
16 September 2016	14	525.97	394.47
30 September 2016	14	456.18	342.13

Table 4. Survey effort across the study area during August 2016 and September 2016 in the low density stratum (total area of 6963.1 km²)

Survey date	Number of transects	Total transect length surveyed (km)	Area Covered (km²)
15 August 2016	18	426.60	319.95
16 September 2016	18	433.12	324.84
30 September 2016	14	327.79	245.85

Table 5. Number of observations at different levels of sun glare and percentage of total in parentheses. Sun glare definitions are given in section 2.3.

	Sun glare: number of observations (% of total observations)			
Survey date	**1**	**2**	**3**	**4**
15 August 2016	35 (18.2%)	107 (55.7%)	50 (26.0%)	0 (0%)
16 September 2016	78 (39.6%)	84 (42.6%)	35 (17.8%)	0 (0%)
30 September 2016	133 (86.4%)	20 (13.0%)	1 (0.6%)	0 (0%)

Table 6. Number of observations at different levels of sea state and percentage of total in parentheses. Sea state definitions are given in section 2.3

	Sea state: number of observations (% of total observations)					
Survey date	**1**	**2**	**3**	**4**	**5**	**6**
15 August 2016	0 (0%)	2 (1.0%)	60 (31.3%)	116 (60.4%)	14 (7.3%)	0 (0%)
16 September 2016	0 (0%)	4 (2.0%)	69 (35.2%)	123 (62.8%)	0 (0%)	0 (0%)
30 September 2016	11 (7.1%)	105 (68.2%)	38 (24.7%)	0 (0%)	0 (0%)	0 (0%)

3.2 Survey results

During three digital survey flights between 15th August and 30th September, the number of marine megafauna observed totalled 720 individuals (Table 7). The number of animals varied between survey flights. Basking sharks could all be determined to species level with 53 individuals sighted during Survey 1, ten during Survey 2 and none during Survey 3. During Surveys 1 and 3, one minke whale was sighted, and none in Survey 2. Common dolphins and harbour porpoise were the most abundant species with 32, 116 and 341 (common dolphin) and 6, 1 and 127 (harbour porpoise) individuals observed during Survey 1, 2 and 3 respectively. Both of these species were most abundant during Survey 3. An additional 59 marine mammals were determined only to their genus level (Table 8).

Table 7. Number of animals detected during each survey assigned to species level in the high-density stratum ('H'), low density stratum ('L') and total study area ('T') in August and September 2016

Species	**Scientific Name**	**Survey 1 15 Aug 16**			**Survey 2 16 Sep 16**			**Survey 3 30 Sep 16**			**Total**		
		H	**L**	**T**	**H**	**L**	**T**	**H**	**L**	**T**	**H**	**L**	**T**
Basking shark	*Cetorhinus maximus*	53	0	53	5	5	10	0	0	0	58	5	63
Grey seal	*Halichoerus grypus*	1	0	1	11	1	12	0	0	0	12	1	13
Harbour seal	*Phoca vitulina*	2	2	4	0	0	0	0	0	0	2	2	4
Minke whale	*Balaenoptera acutorostrata*	0	1	1	0	0	0	1	0	1	1	1	2
Common dolphin	*Delphinus delphis*	22	10	32	11	105	116	66	275	341	99	390	489
Risso's dolphin	*Grampus griseus*	5	0	5	0	0	0	0	0	0	5	0	5
White-beaked dolphin	*Lagenorhynchus albirostris*	0	0	0	0	0	0	0	10	10	0	10	10
Harbour porpoise	*Phocoena phocoena*	3	3	6	0	1	1	79	48	127	82	52	134
Total		**86**	**16**	**102**	**27**	**112**	**139**	**146**	**333**	**479**	**259**	**461**	**720**

Table 8. Number of animals with no species ID detected during each survey assigned to species groups in the high-density stratum ('H'), low-density stratum ('L') and total study area ('T') in August and September 2016

Species group (No ID)	**Survey 1 15 Aug 16**			**Survey 2 16 Sep 16**			**Survey 3 30 Sep 16**			**Total**		
	H	**L**	**T**	**H**	**L**	**T**	**H**	**L**	**T**	**H**	**L**	**T**
Seal species	2	2	4	0	2	2	11	2	13	13	6	19
Dolphin species	0	0	0	1	0	1	3	10	13	4	10	14
Cetacean species	0	0	0	0	2	2	6	16	22	6	18	24
Seal / small cetacean species	0	0	0	0	0	0	2	0	2	2	0	2
Total	**2**	**2**	**4**	**1**	**4**	**5**	**22**	**28**	**50**	**25**	**34**	**59**

3.3 Abundance estimates for all species observed

Basking sharks and minke whales
Numbers of basking sharks observed were low with the exception of the August survey, and very low for minke whales for all three surveys. This makes accurate calculations of relative density and abundance from the data difficult. Estimates were calculated for basking shark and minke whale where data allowed and the results with upper and lower 95% CI and CV for each species are presented in Table 9 to Table 13.

The relative abundance was not estimated for all three surveys combined for basking sharks owing to the large disparity in the abundance of basking sharks between the three surveys. Lower numbers of individuals were observed in Survey 2 and 3. It is possible that many of these animals had either migrated from the region or had become unavailable for detection, although, the low shark numbers contradict the land-based sightings of sharks from the same time.

Basking sharks were observed in two of the three surveys with peak relative density recorded at 0.15 animals/km² in Survey 1 in the high-density stratum. They were absent from the low-density stratum (Table 10). This equated to a relative abundance estimate of 615 individuals (± 95% CI 132 – 1324). Basking sharks were recorded in the low and the high-density stratum in Survey 2 in which the relative density estimate in both stratums was 0.01 animals/km². This equated to a relative abundance estimate of 59 individuals (± 95% CI 10 – 122) in the high-density stratum, and a relative density of 0.02 animals/km² equating to a relative abundance estimates of 61 individuals (± 95% CI 0 – 157) in the low-density stratum. The relative density in the entire study area was 0.01 animals/km² equating to a relative abundance estimate of 120 individuals (± 95% CI 10 – 279) (Table 12). The absolute density and abundance was estimated and presented in Section 3.4.

Minke whales were the least abundant species observed with a relative density estimate recorded at <0.01 animals/km² (rounded to the nearest two decimal places) in the low-density survey area during Survey 1. This equated to a relative abundance estimate of 12 animals (± 95% CI 0 – 37) (Table 10). In the high-density survey area in Survey 3, relative density estimates were recorded at <0.01 animals/km². This equated to a relative abundance estimate over the entire survey area of 13 animals (± 95% CI 0 – 35) (Table 14). No minke whales were recorded in Survey 2.

Other species
Low relative densities of grey seals were present in Survey 1 and Survey 2. In the high-density survey stratum, relative density estimates were recorded at <0.01 animals/km² and 0.03 animals/km². This equated to a relative abundance estimate of 11 animals (± 95% CI 0 – 31) and 132 animals (± 95% CI 20 – 304) in Survey 1 and Survey 2, respectively (Tables 10 and 12).

Harbour seals were observed in the high-density and low-density survey stratum in Survey 1 with a relative density estimate of 0.01 animals/km² for both stratum. This equated to a relative abundance estimate of 22 individuals (± 95% CI 0 – 51) and 23 individuals (± 95% CI 0 – 75) for the high and low density survey stratums, respectively (Table 10).

Common dolphin were the most abundant species recorded with an increase in relative density from Survey 1 to Survey 3. The peak relative density was during Survey 3 at 0.22 animals/km² in the high-density survey stratum and 1.39 animals/km² in the low-density survey stratum. This equated to a relative abundance estimate of 897 animals (± 95% CI 70 – 2593) and 4167 animals (± 95% CI 1011 – 8843) in the high density and low density survey stratums, respectively (Table 14).

White-beaked dolphins were only observed in the low-density survey stratum in Survey 3, when relative density estimates were recorded at 0.05 animals/km² which equated to a relative abundance estimate of 153 individuals (± 95% CI 0 – 390) (Table 14).

Harbour porpoise were recorded in all three surveys with a peak relative density estimate during Survey 3 of 0.26 animals/km² equating to 1051 animals (± 95% CI 105 – 2570) in the high-density survey stratum and 0.23 animals/ km² equating to a relative abundance estimate of 703 (± 95% CI 158 – 1425) (Table 14).

Table 9. Relative density and abundance of species groups with 95% confidence intervals and coefficient of variance during Survey 1 on 15th August 2016 for the total study area and the high and low density strata

Category	Total study area		High density stratum		Low density stratum	
	Relative density (n/km²)	**Relative abundance (±95% CI; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
All marine megafauna	0.16	**1203** (310 – 2543; 44.2)	0.24	**997** (244 – 2159; 52.6)	0.07	**206** (66 – 384; 40.3)
Shark species	0.08	**602** (132 – 1324; 53.1)	0.15	**602** (122 – 1324; 53.2)		
Seal species	0.01	**102** (20 – 204; 35.8)	0.01	**56** (20 – 92; 34.6)	0.02	**46** (0 – 112; 67.23)
Dolphin species	0.06	**417** (9 – 1075; 53.3)	0.07	**304** (0 – 794; 69.2)	0.04	**113** (9 – 281; 63.3)
Cetacean species	0.01	**81** (9 – 184; 41.5)	0.01	**34** (0 – 81; 65.1)	0.02	**47** (9 – 103; 53.8)

Table 10. Relative density and abundance of species with 95% confidence intervals and coefficient of variance during Survey 1 on 15th August 2016 for the total study area and the high and low density strata. Key species for this pilot survey are highlighted in grey.

Category	Total study area		High density stratum		Low density stratum	
	Relative density (n/km²)	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
Basking shark	0.08	**602** (122 – 1324; 53.1)	0.15	**602** (122 – 1324; 53.1)		
Grey seal	<0.01	**11** (0 – 31; 91.0)	<0.01	**11** (0 – 31; 91.0)		
Harbour seal	0.01	**45** (0 – 126; 54.1)	0.01	**22** (0 – 51; 63.6)	0.01	**23** (0 – 75; 86.7)
Minke whale	<0.01	**12** (0 – 37; 87.8)			<0.01	**12** (0 – 37; 87.8)
Risso’s dolphin	0.01	**57** (0 – 153; 91.6)	0.01	**57** (0 – 153; 91.6)		
Common dolphin	0.05	**361** (9 – 892; 49.0)	0.06	**248** (0 – 611; 65.3)	0.04	**113** (9 – 281; 63.3)
Harbour porpoise	0.01	**69** (0 – 165; 46.3)	0.01	**34** (0 – 81; 65.1)	0.01	**35** (0 – 84; 65.9)

Table 11. Relative density and abundance of species with 95% confidence intervals and coefficient of variance during Survey 2 on 16th September 2016 for the total study area and the high and low density strata.

Category	**Total study area**		**High density stratum**		**Low density stratum**	
	Relative density (n/km²)	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
All marine megafauna	0.24	**1630** (420 – 3580; 46.0)	0.08	**330** (162 – 547; 30.3)	0.43	**1300** (258 – 3033; 57.1)
Shark species	0.01	**120** (10 – 279; 38.0)	0.01	**59** (10 – 122; 50.5)	0.02	**61** (0 – 157; 70.9)
Seal species	0.02	**168** (20 – 387; 47.2)	0.03	**132** (20 – 304; 57.5)	0.01	**36** (0 – 83; 63.3)
Dolphin species	0.19	**1308** (196 – 3189; 56.2)	0.03	**139** (30 – 294; 48.8)	0.39	**1169** (166 – 2895; 62.6)
Cetacean species	<0.01	**35** (30 – 294; 62.7)	N/A	N/A	0.01	**35** (0 – 83; 62.7)

Table 11. Relative density and abundance of species with 95% confidence intervals and coefficient of variance during Survey 2 on 16th September 2016 for the total study area and the high and low density strata. Key species for this pilot survey are highlighted in grey.

Category	**Total study area**		**High density stratum**		**Low density stratum**	
	Relative density (n/km²)	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
Basking shark	0.01	**120** (10 – 279; 43.8)	0.01	**59** (10 – 122; 50.1)	0.02	**61** (0 – 157; 70.9)
Grey seal	0.02	**144** (20 – 341; 53.2)	0.03	**132** (20 – 304; 57.5)	<0.01	**12** (0 – 37; 86.5)
Common dolphin	0.19	**1296** (186 – 3169; 56.7)	0.03	**127** (20 – 274; 53.8)	0.39	**1169** (166 – 2895; 62.6)
Harbour porpoise	<0.01	**12** (0 – 37; 87.2)	N/A	N/A	<0.01	**12** (0 – 37; 87.2)

Table 12. Relative density and abundance of species groups with 95% confidence intervals and coefficient of variance during Survey 3 on 30th September 2016 for the total study area and the high and low density strata

Category	Total study area		High density stratum		Low density stratum	
	Relative density (n/km²)	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
All marine megafauna	1.09	**7701** (2557 – 14854; 30.4)	0.56	**2253** (584 – 4415; 44.0)	1.82	**5448** (1973 – 10439; 40.0)
Seal species	0.03	**177** (58 – 318; 29.1)	0.04	**147** (58 – 245; 32.9)	0.01	**30** (0 – 73; 59.2)
Dolphin species	0.76	**5408** (1430 – 11875; 40.2)	0.23	**936**(82 – 2593; 70.7)	1.49	**4472** (1255 – 9282; 46.3)
Cetacean species	0.30	**2089** (516 – 4405; 39.8)	0.29	**1143** (175 – 2663; 65.4)	0.32	**946** (341 – 1742; 38.5)
Seal/small cetacean sp.	0.01	**27** (0 – 58; 62.1)	0.01	**27**(0 – 58; 62.1)		

Table 13. Relative density and abundance of species with 95% confidence intervals and coefficient of variance during Survey 3 on 30th September 2016 for the total study area and the high and low density strata. Key species for this pilot survey are highlighted in grey.

Category	Total study area		High density stratum		Low density stratum	
	Relative density (n/km²)	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**	**Relative density (n/km²)**	**Relative abundance (±95%; CV%)**
Minke whale	<0.01	**13** (0 – 35; 91.4)	<0.01	**13** (0 – 35; 91.43)	N/A	N/A
Common dolphin	0.75	**5064** (1081 – 11436; 41.9)	0.22	**897** (70 – 2593; 74.1)	1.39	**4167** (1011 – 8843; 48.3)
White-beaked dolphin	0.02	**153** (0 – 390; 68.4)			0.05	**153** (0 – 390; 68.4)
Harbour porpoise	0.25	**1754** (258 – 3995; 46.8)	0.26	**1051** (105 – 2570; 71.6)	0.23	**703** (158 – 1425; 46.6)

3.4 Calculating availability bias

The estimates of absolute density and abundance are shown in Tables 9 – 14. The absolute density of basking sharks, within the Sea of the Hebrides MPA proposal was 0.24 animals/km² and an estimated absolute population for the same area of 1815 animals (95% CI 368 - 3992) during the only August survey (Table 15). The availability bias correction (i.e., the value of P_S divided by Pr in equation v) of basking sharks for this survey can be estimated as the proportion of animals detected swimming at the surface during our survey (P_S; 0.4151) divided by the proportion of time that a tagged animal swims at the surface (Pr; 0.1377; Annex 1, Table 22). Thus, the availability bias correction was calculated as 3.015, which was used to adjust the relative abundances and densities.

3.5 Calculating average depth of detection and subsequent abundance estimates

We calculated hypothetical absolute densities of sharks at varying depth bands (Table 16) and visually compared these values against our absolute density estimate of 0.24 animals/km^2 obtained from Table 15 which was calculated using the number of observations of sharks at the surface as a percentage of all shark observations (*Ps*) divided by the proportion of estimated proportion of time spent at the surface (*Pr*). The hypothetical absolute density was calculated by assuming that all observations of basking sharks during the only August survey occurred within the range of depths under investigation. We assumed that all observations occurred at the surface and divided the relative density by the estimated proportion of time that basking sharks spent at the surface in Annex 1 (0.1377) to give the figure of 0.58 animals//km^2. This value is much higher than the value of absolute abundance we calculated in Section 3.4, which is unsurprising given a number of sharks recorded during the survey were completely submerged and clearly not swimming at the surface. We found that the absolute density estimate from section 3.4 best matched the hypothetical absolute density from the range of surface to 3 m (estimated at 0.24 animals/km^2). This suggests that the average maximum detection depth during this survey was approximately 3 m. This justified our use of a 10 m maximum depth range for detection. In the second survey on 16th September, the absolute abundance of basking sharks could not be estimated using data for animals only at the surface, because all of the animals recorded were completely submerged.

No local data on time spent at different depths whilst diving were available to allow estimation of availability bias for minke whale or other cetacean species. Diving data does exist for seals; however, these species were not the main focus of this study.

Table 14. Adjusted density and population estimates for basking shark in the Sea of the Hebrides survey area (combined high and low density strata) between August 2016 and September 2016 taking into account the estimated number of animals that are estimated as being unavailable for detection.

Basking shark	**Relative density and abundance**					**Estimated absolute density and abundance**			
	Relative density estimate (n/km^2)	**Relative population estimate**	**Lower 95% confidence limit of population**	**Upper 95% confidence limit of population**	**Estimated availability bias (%)**	**Absolute density estimate (n/km^2)**	**Absolute population estimate**	**Lower 95% confidence limit of population**	**Upper 95% confidence limit of population**
15 August 2016	0.08	602	122	1324	33.16	0.24	1815	368	3992
16 September 2016	0.01	120	10	279	N/A	N/A	N/A	N/A	N/A
30 September 2016	0	0	0	0	N/A	0	0	0	0

Table 15 . Estimated absolute density and absolute abundance if assumed that all basking sharks detected (surfacing and submerged) during the survey were swimming at a given depth range

Depth range	Estimated absolute density	Estimated absolute abundance
Surface	0.58	4468
0 – 1 m	0.37	2840
0 – 2 m	0.31	2359
0 – 3 m	0.24	1871
0 – 4 m	0.23	1749
0 – 5 m	0.22	1691
0 – 6 m	0.22	1660
0 – 7 m	0.21	1622
0 – 8 m	0.21	1586
0 – 9 m	0.20	1554
0 – 10 m	0.20	1515

3.6 Potential improvements in data dispersion by increased survey effort

Using the CVs of the target species (basking shark and minke whale), it is possible to estimate the improvement in the CV that can be achieved by repeating the surveys during a time of year when basking shark and minke whale are consistently found in the region (i.e. August Speedie *et al*. (2009), Macleod *et al*. (2004)). Where the variances of the abundance estimates are fairly similar (as was the case for minke whales) the same method can be used to merge different abundance estimates (Buckland *et al.,* 2001; equation 3.5). We do this by using the highest CV values originally calculated (i.e. higher dispersion of data; 0.531 for basking sharks, and 0.914 for minke whale) in either survey and simulating a new CV based on the number of surveys.

This was done as per:

$$CV_{new} = \sqrt{\frac{(CV^2 \times N^2) \times n}{(N \times n)^2}}$$

Where n is the total number of surveys, *CV* is the original CV calculated, and *N* is the relative abundance.

These amalgamations and calculations are shown in Table 16.

Table 16 . Estimated improvements from repeat surveys using mean CVs obtained from the Tables 10, 12 and 14 in which positive values were measured.

Number of surveys per year	2	3	4	6	8	16	25
Basking shark CV	0.38	0.31	0.27	0.22	0.19	0.13	0.11
Minke whale CV	0.64	0.53	0.46	0.37	0.32	0.23	0.18

3.7 Spatial distribution in the study area

The spatial distribution of basking shark and minke whale, as well as the most abundant species are presented as density maps, in which a density surface depicts the estimated density of individuals per km² (Figure 2 to Figure 19). Species or species groups for which there were few observations are presented as dot maps only.

3.7.1 Spatial distribution of basking sharks

Basking sharks were observed in offshore waters in two surveys on 15th August and 16th September (Figure 2 and Figure 3). In Survey 1, all the observations were located in the high-density stratum, most of these to the south and west of Tiree and none north of northern Coll. In Survey 2, observations included a group of four sharks that were engaged in possible courtship behaviour to the south-west of Tiree (as described by Speedie *et al.,* 2009).

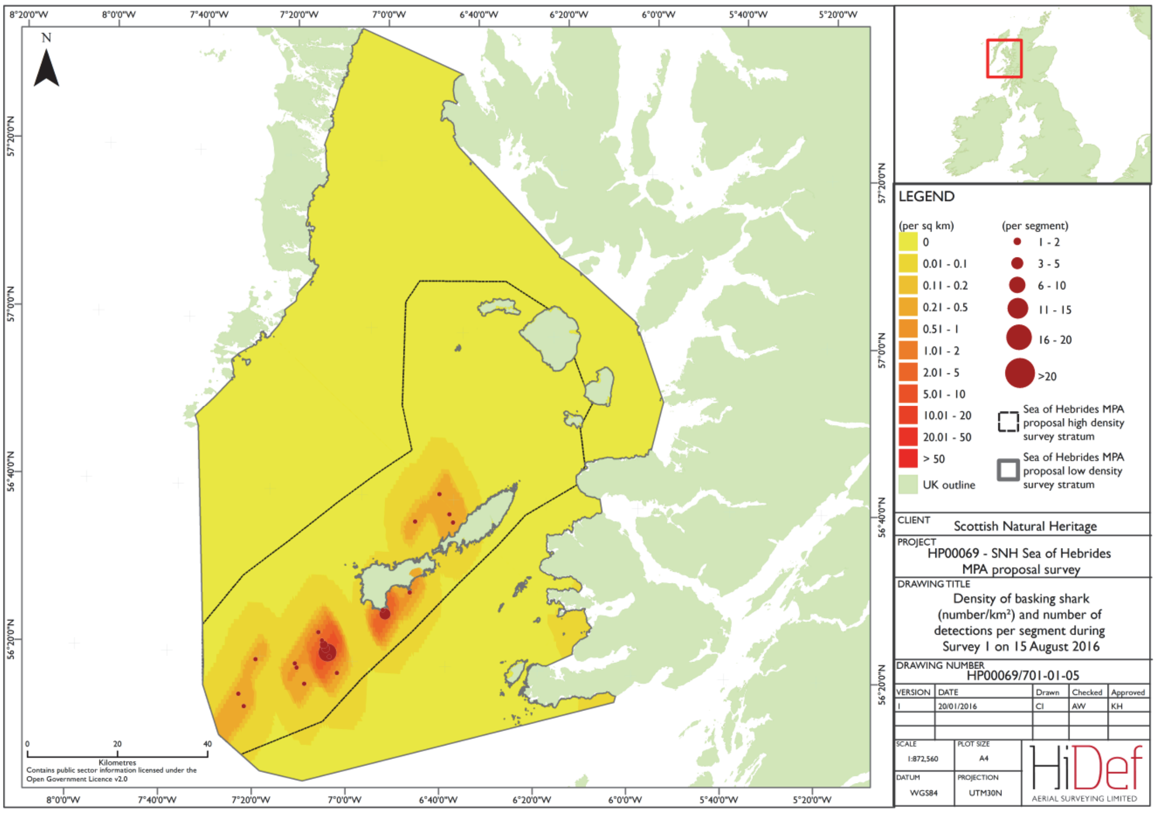

Figure 2. Relative density of basking shark (number/km²) and number of detections per 1 km segment during Survey 1 on 15th August 2016

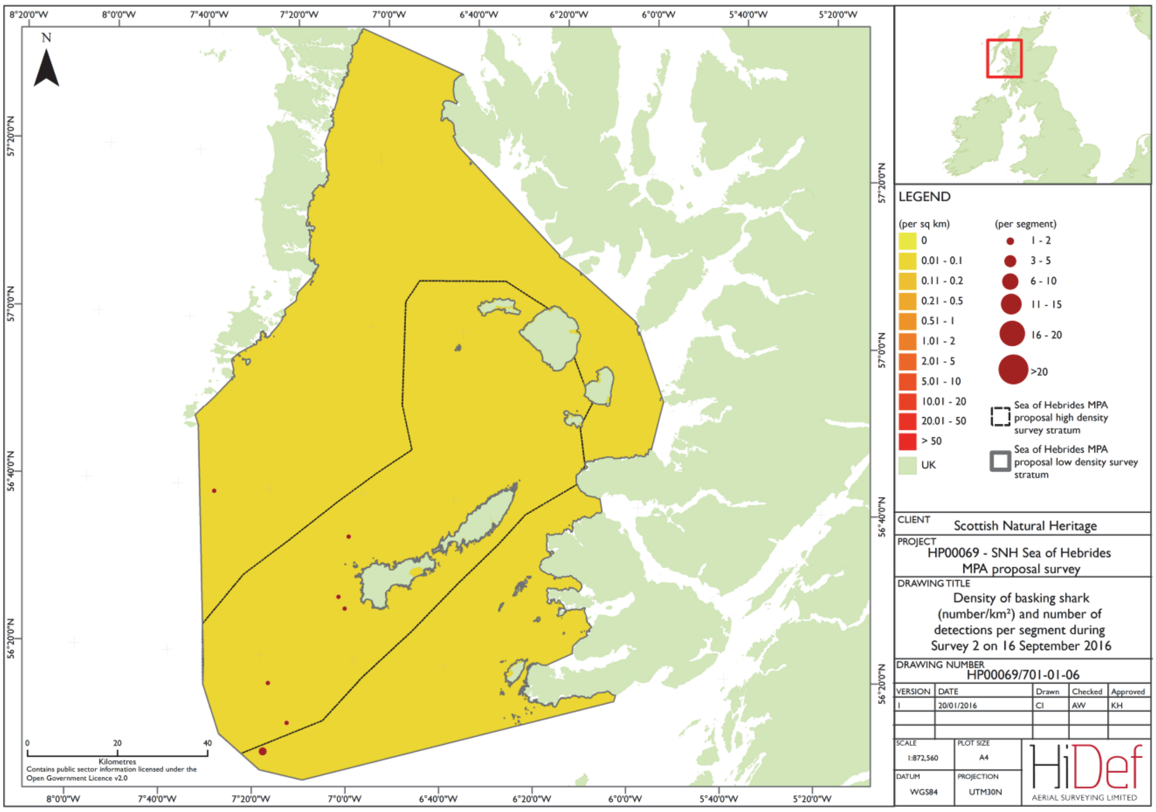

Figure 3. Relative density of basking shark (number/km²) and number of detections per 1 km segment during Survey 2 on 16th September 2016

3.7.2 Distribution maps for minke whale and other species observed during individual surveys

Other marine megafauna were observed in all three surveys on 15th August, 16th September and 30th September (Figure 4 and Figure 5).

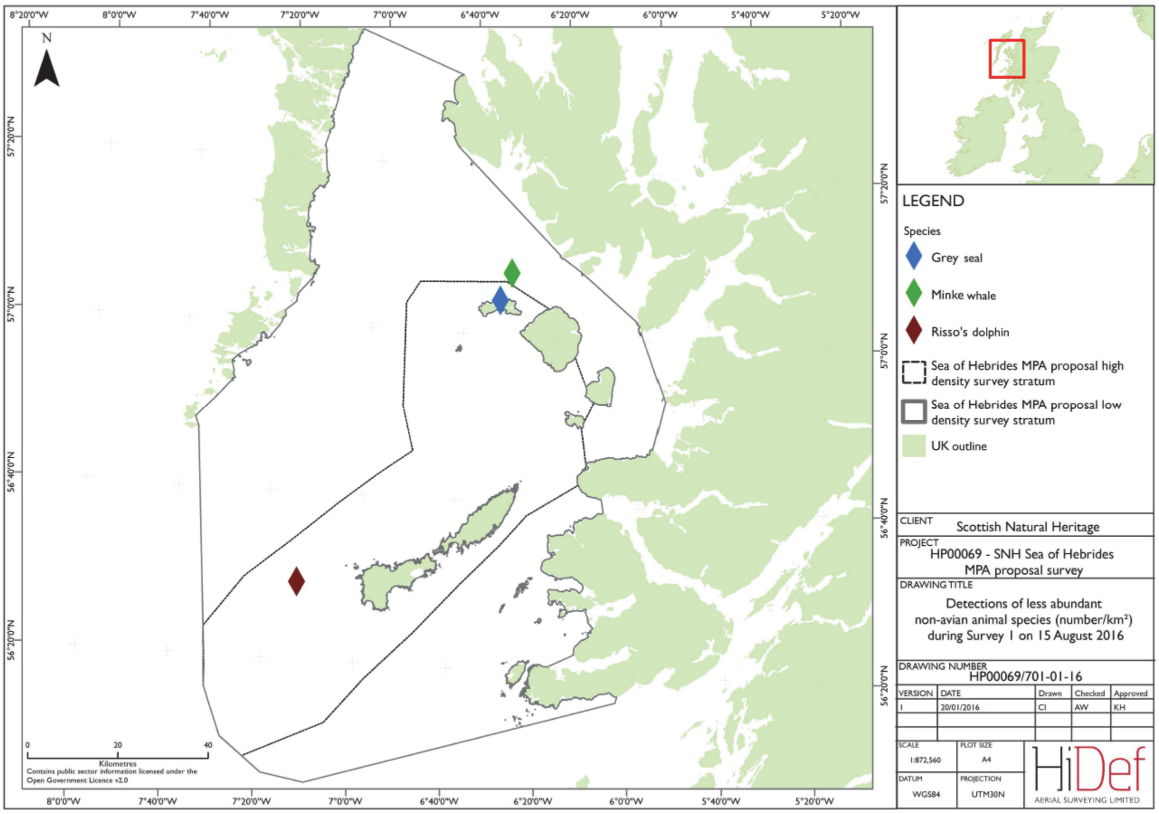

Figure 4. Detections of minke whale, Risso's dolphin and grey seal during Survey 1 on 15th August 2016

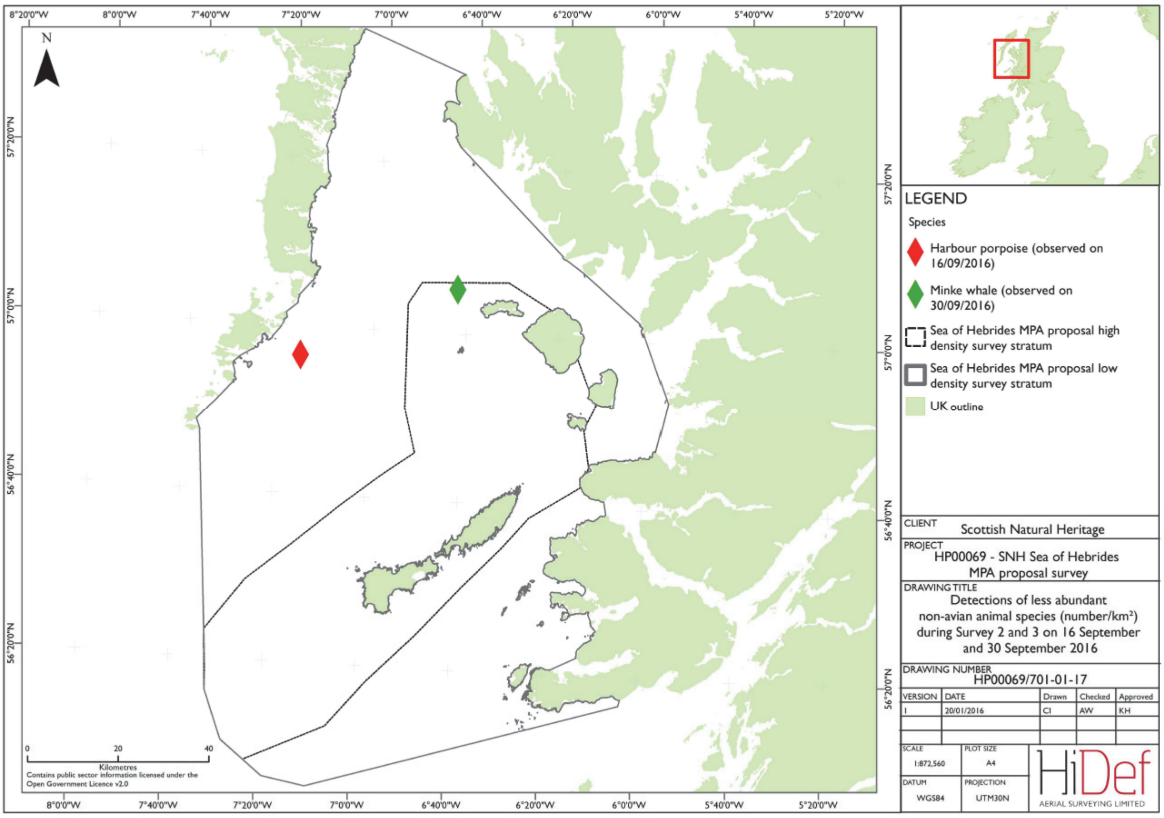

Figure 5. Detections of minke whales and harbour porpoise during Survey 2 on 16th September 2016 and Survey 3 on 30th September 2016

3.7.3 Spatial distribution of grey seals

Grey seals were observed in two surveys on 15th August and 16th September (Figure 6). The majority were recorded around Tiree with one observation around the north coast of Rum. A single grey seal was observed during Survey 1 as shown in Figure 4.

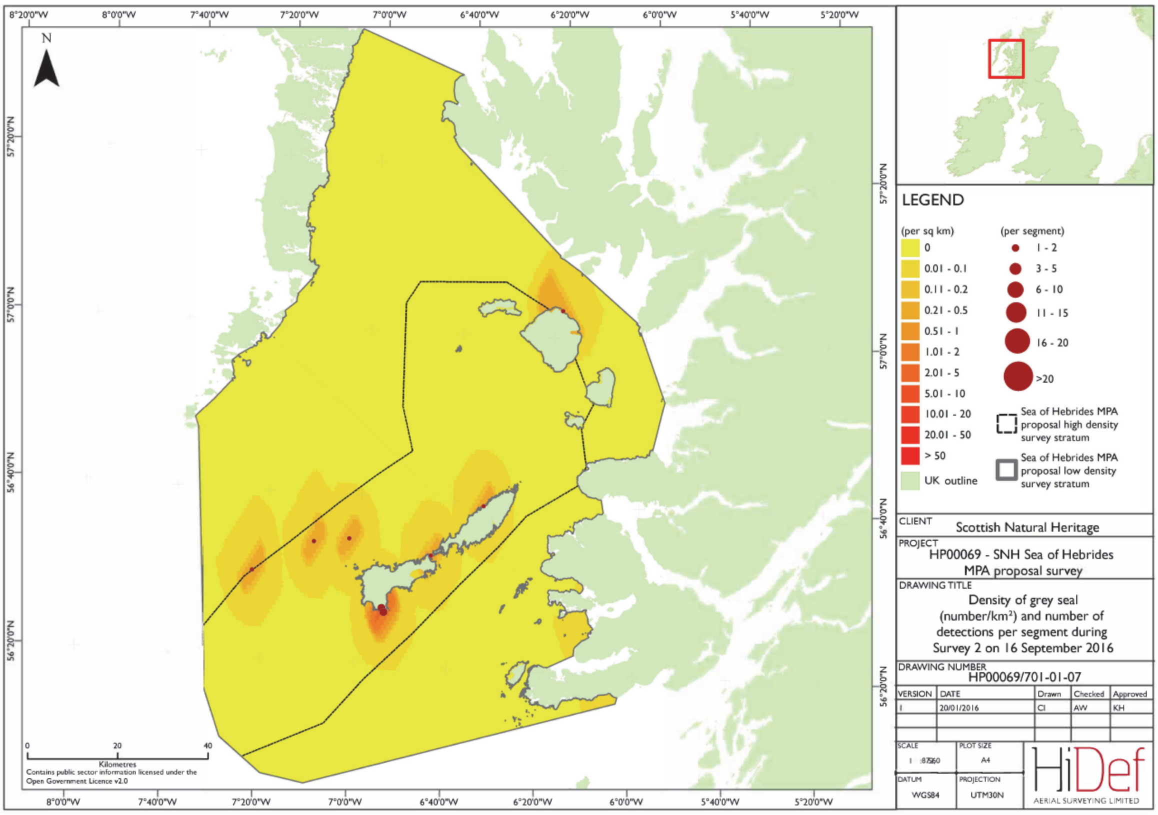

Figure 6. Relative density of grey seal (number/km²) and number of detections per 1 km segment during Survey 2 on 16th September 2016

3.7.4 Distribution maps for harbour seal

Harbour seal were observed in Survey 1 only on 15th August (Figure 7). The observations of this species were widely dispersed but generally close to land, east of Barra, in Coll Sound, and around the west coast of Mull.

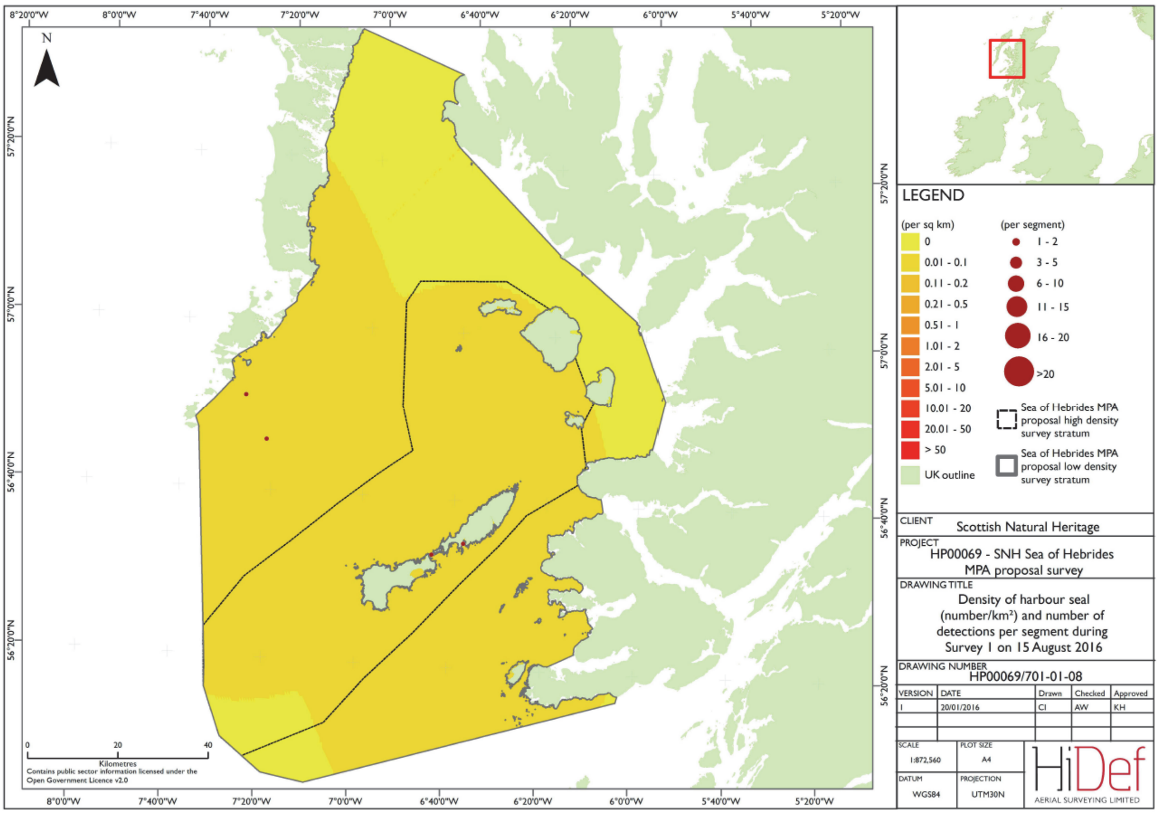

Figure 7. Relative density of harbour seal (number/km²) and number of detections per 1 km segment during Survey 1 on 15th August 2016

3.7.5 Distribution maps for common dolphin

Common dolphins were observed in all three surveys on 15th August, 16th September and 30th September (Figure 8 to Figure 10). In Survey 1, the relatively few observations were distributed widely around the study area (Figure 8), but in Survey 2 and especially in Survey 3, the species became more concentrated in the deeper water between the islands of Coll and Tiree, and Barra in the Outer Hebrides (Figure 9 and Figure 10).

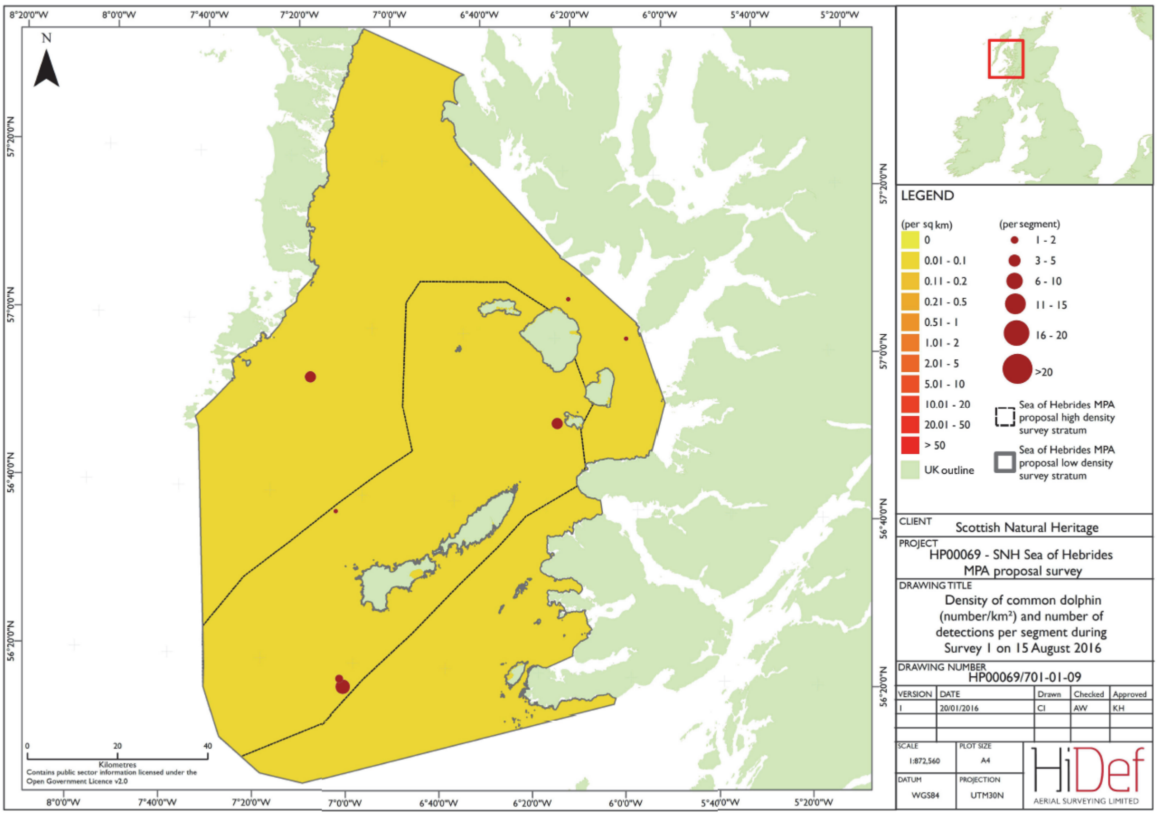

Figure 8. Relative density of common dolphin (number/km²) and number of detections per 1 km segment during Survey 1 on 15th August 2016

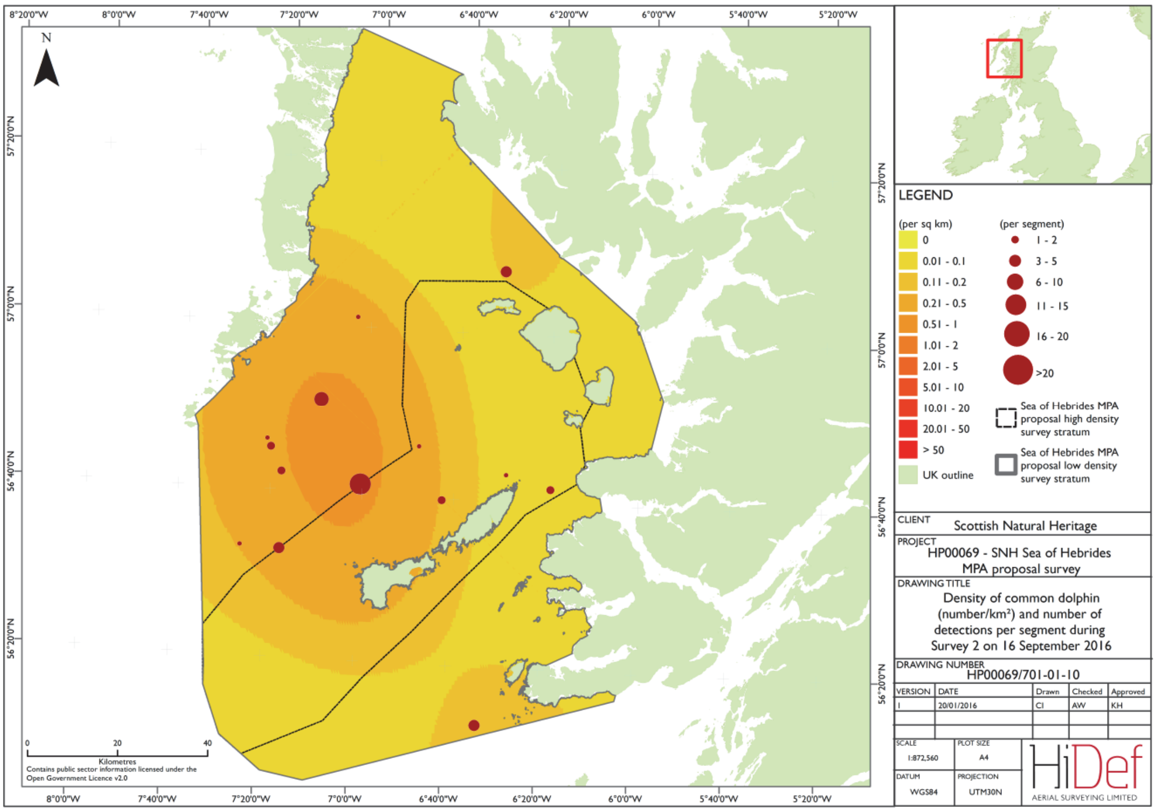

Figure 9. Relative density of common dolphin (number/km²) and number of detections per 1 km segment during Survey 2 on 16th September 2016

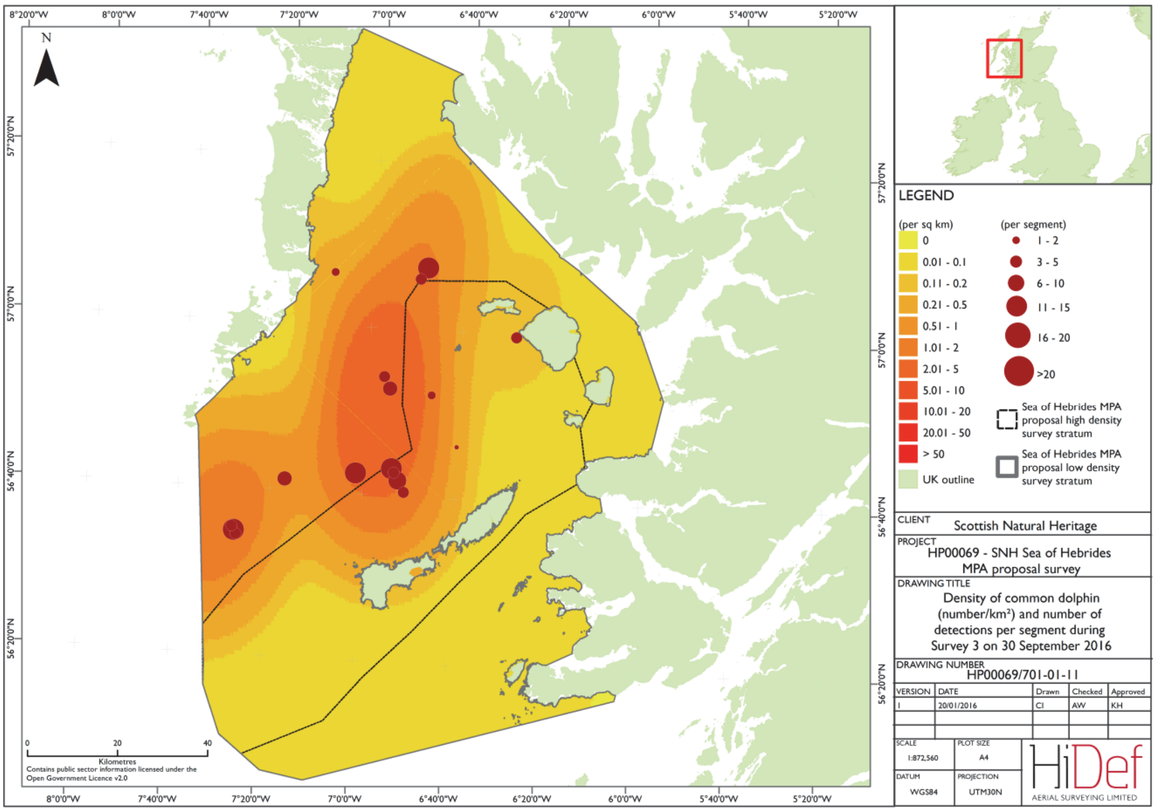

Figure 10. Relative density of common dolphin (number/km²) and number of detections per 1 km segment during Survey 2 on 16th September 2016

3.7.6 Distribution maps for white-beaked dolphin

White-beaked dolphins were observed in Survey 3 only, on 30th September in Figure 11 to the north-west of Tiree. During this survey, the largest groups occurred to the west of Tiree and in the far north of the study area east of North Uist, with smaller groups recorded north of Eigg and west of Mull (Figure 11).

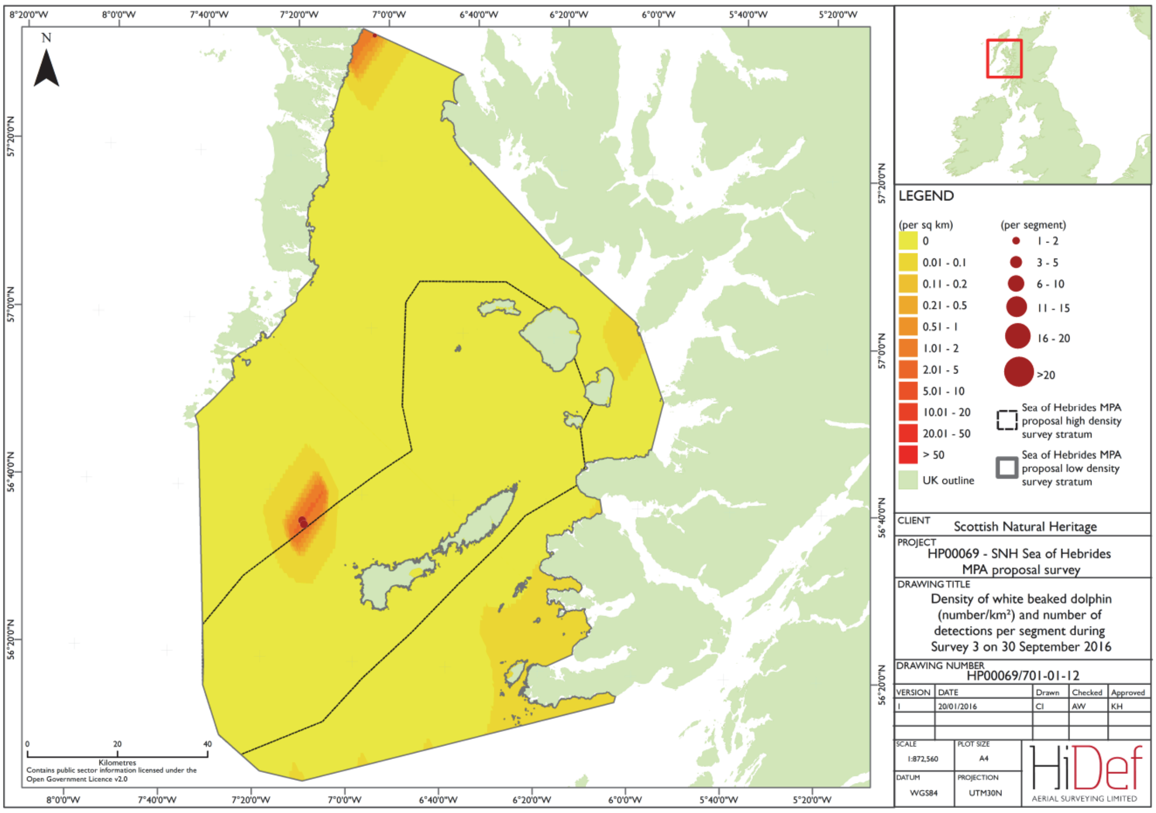

Figure 11. Relative density of white-beaked dolphin (number/km²) and number of detections per 1 km segment during Survey 3 on 30th September 2016

3.7.7 Distribution maps for harbour porpoise

Harbour porpoise were observed in all three surveys on 15th August (Figure 12), 16th September (Figure 5; only one was observed) and 30th September (Figure 13). In Survey 1, the low numbers of observations were widely dispersed in the north-eastern part of the study area (Figure 12). In Survey 3, when the number of observations was much greater than in the other surveys, most observations were in the northern part of the survey area, with no particular preference to the high-density stratum (Figure 13).

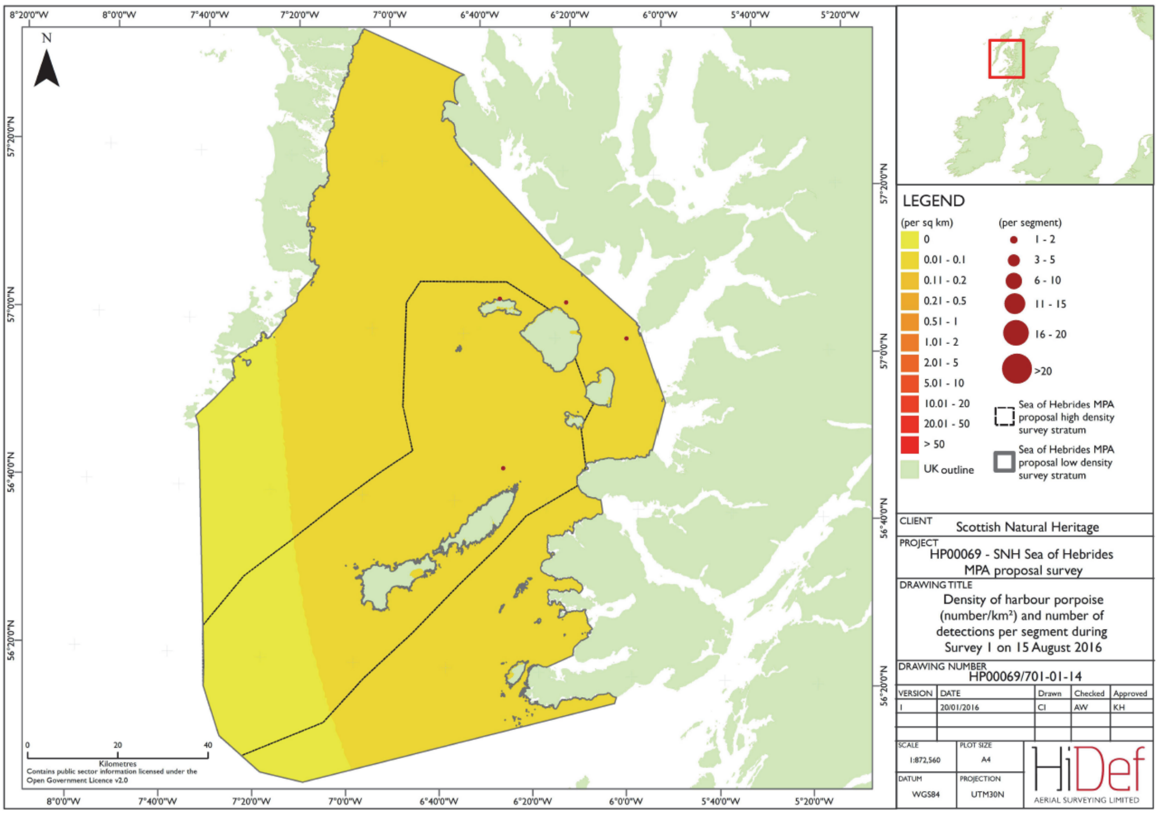

Figure 12. Relative density of harbour porpoise (number/km²) and number of detections per 1 km segment during Survey 1 on 15th August 2016

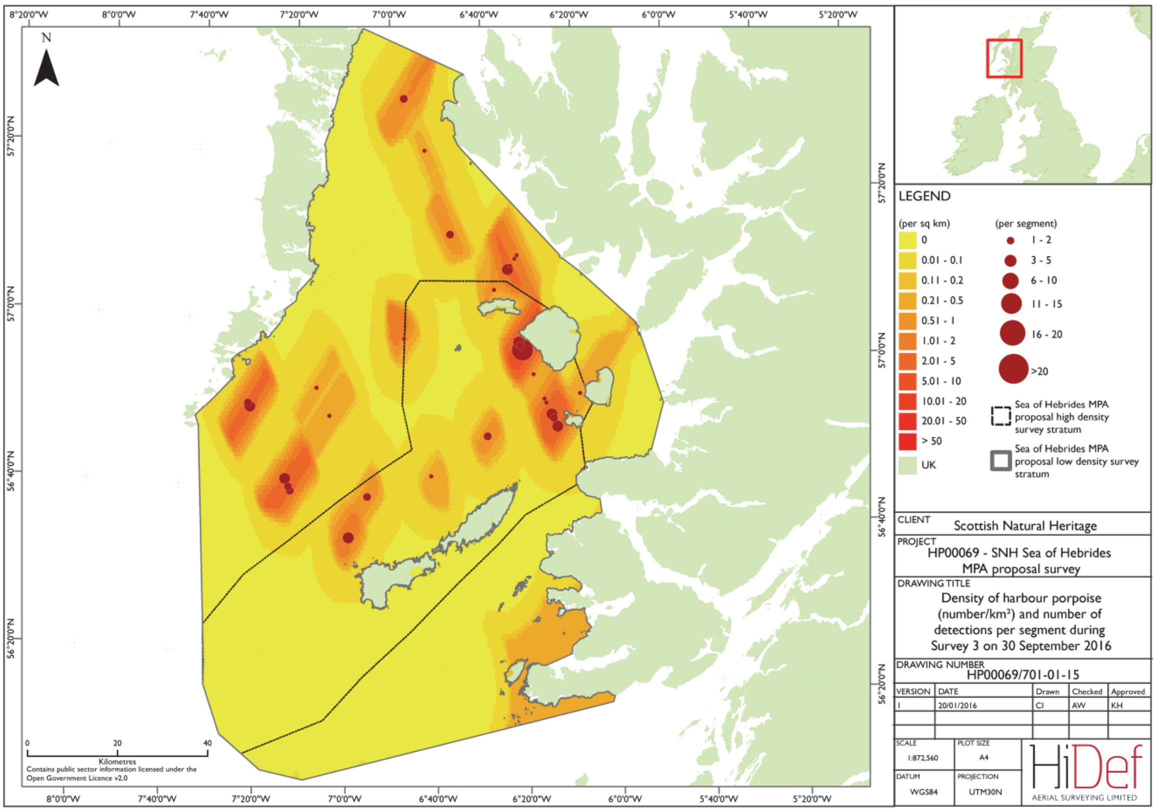

Figure 13. Relative density of harbour porpoise (number/km²) and number of detections per 1 km segment during Survey 3 on 30th September 2016

3.7.8 Distribution maps for unidentified megafauna

Unidentified marine mammals were observed in all three surveys on 15th August, 16th September and 30th September (Figure 14 to Figure 16).

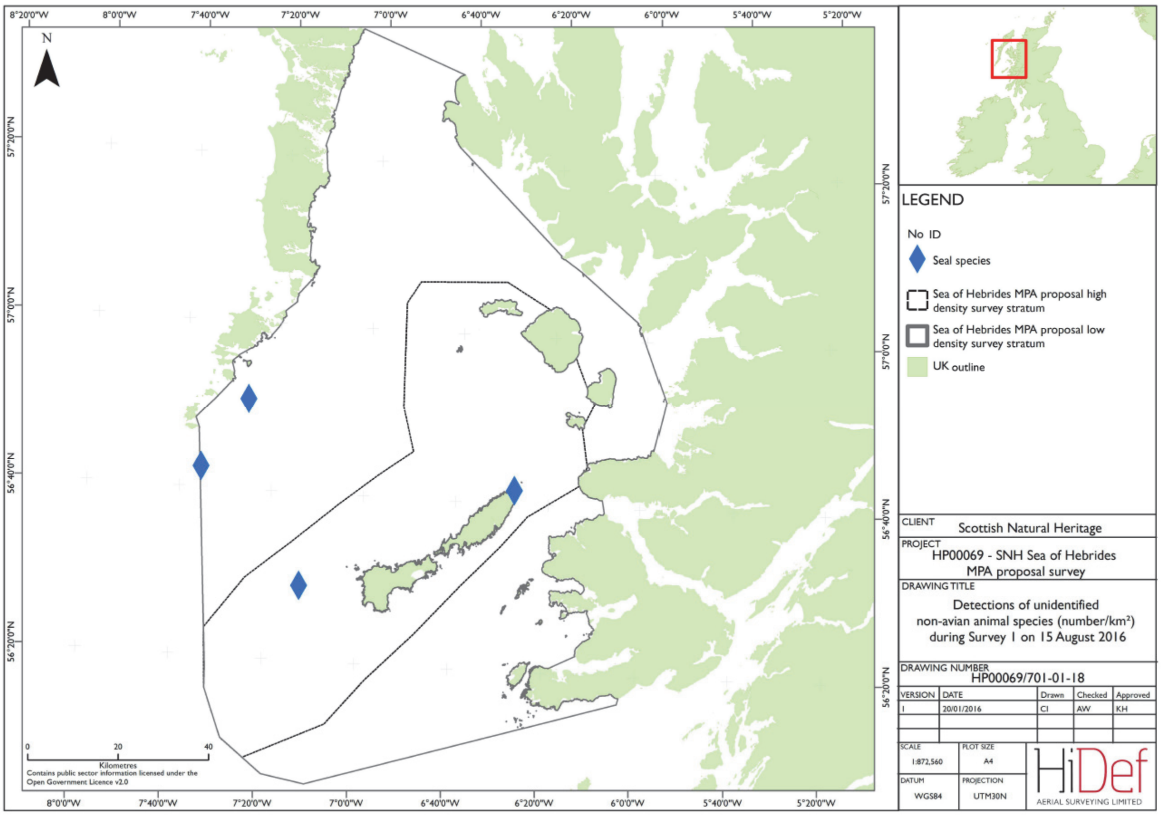

Figure 14. Detections of unidentified seal species during Survey 1 on 15th August 2016

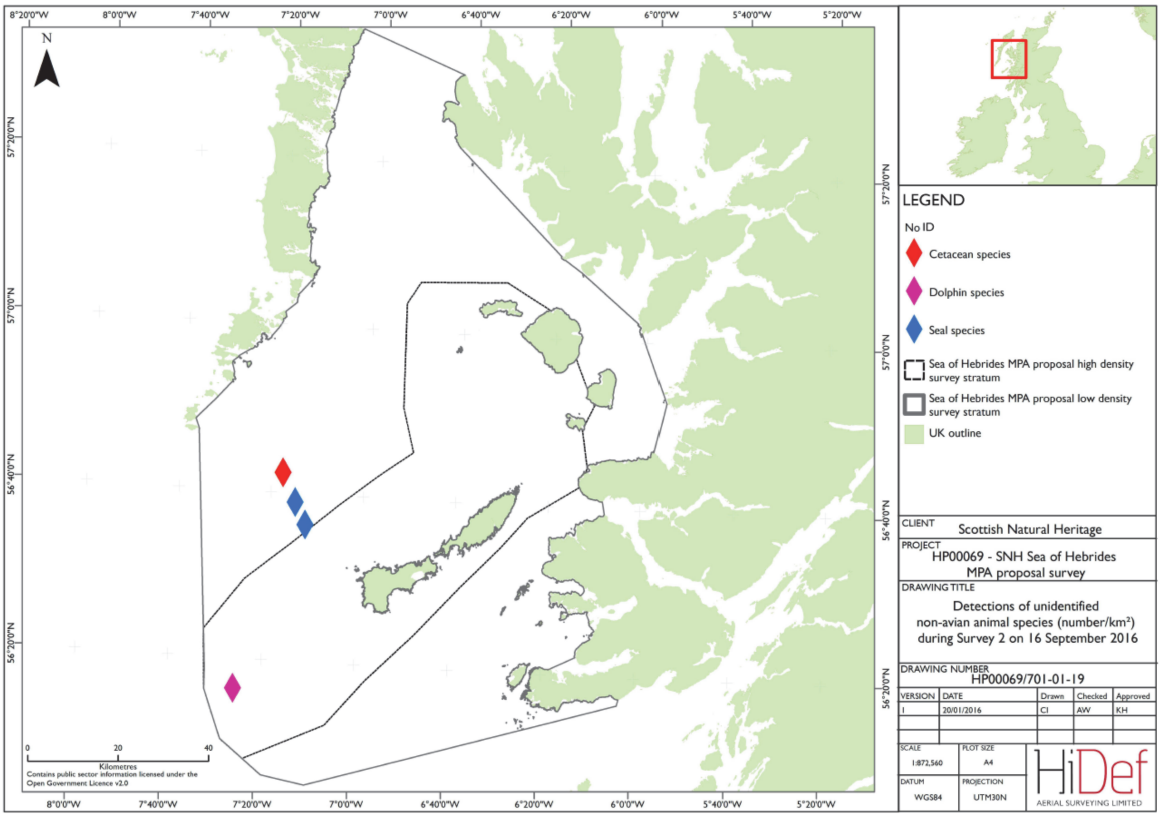

Figure 15. Detections of unidentified seal and cetacean species during Survey 2 on 16th September 2016

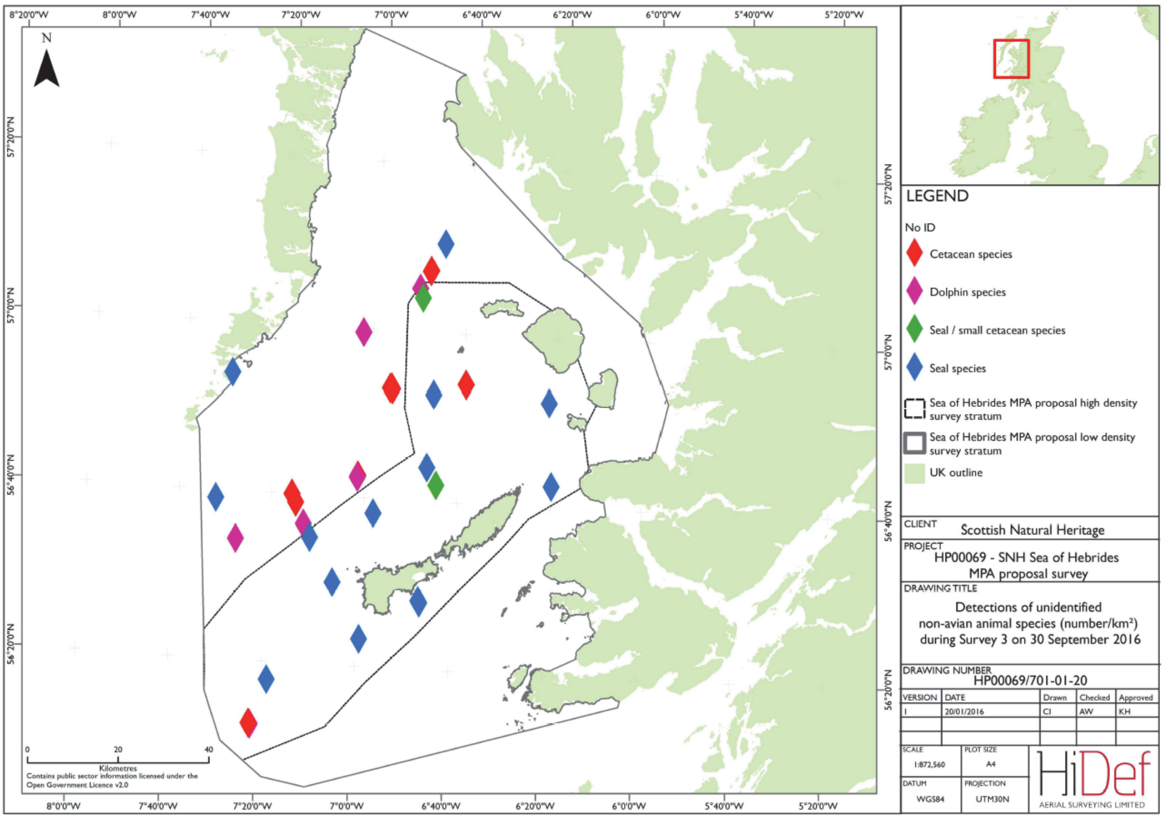

Figure 16. Detections of unidentified seal and cetacean species during Survey 3 on 30th September 2016

3.7.9 Spatial distribution of all marine megafauna

The monthly maps for all marine megafauna species show observations recorded across the survey area (Figure 17 to Figure 19) with the highest densities in Survey 3 (driven by the large numbers of common dolphins, Figure 19).

Marine megafauna were observed in all three surveys (Figure 17 to Figure 19). Section 3.1 provides details of the species observed. In Survey 1, most marine megafauna were distributed near to land around the Small Isles, to the east of Barra and around Coll and Tiree with relatively few observations in deeper water between the Outer Hebrides and Coll and Tiree (Figure 17). In Surveys 2 and 3, this pattern changed so that most observations occurred in relatively deep water in a region bounded by the Outer Hebrides, the Small Isles and Coll and Tiree (Figure 18 and Figure 19).

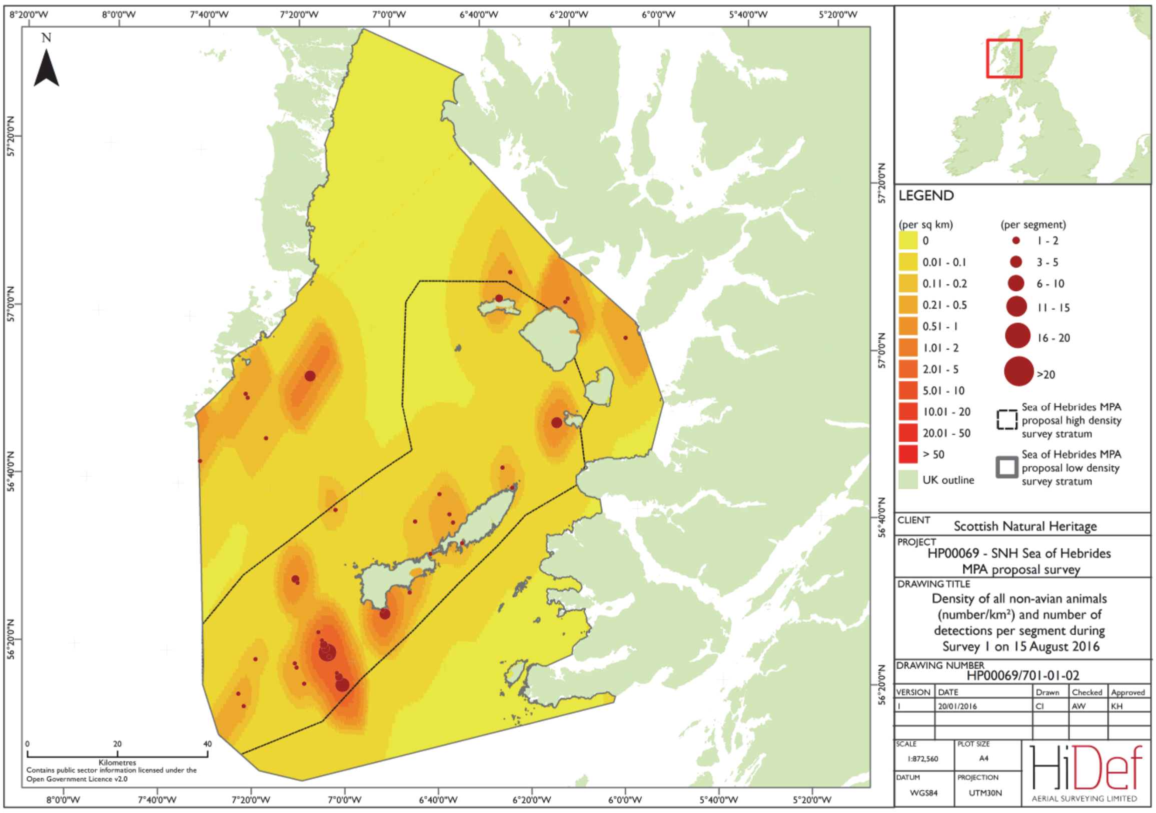

Figure 17. Relative density of all marine megafauna (number/km²) and number of detections per 1 km segment during Survey 1 on 15[th] August 2016

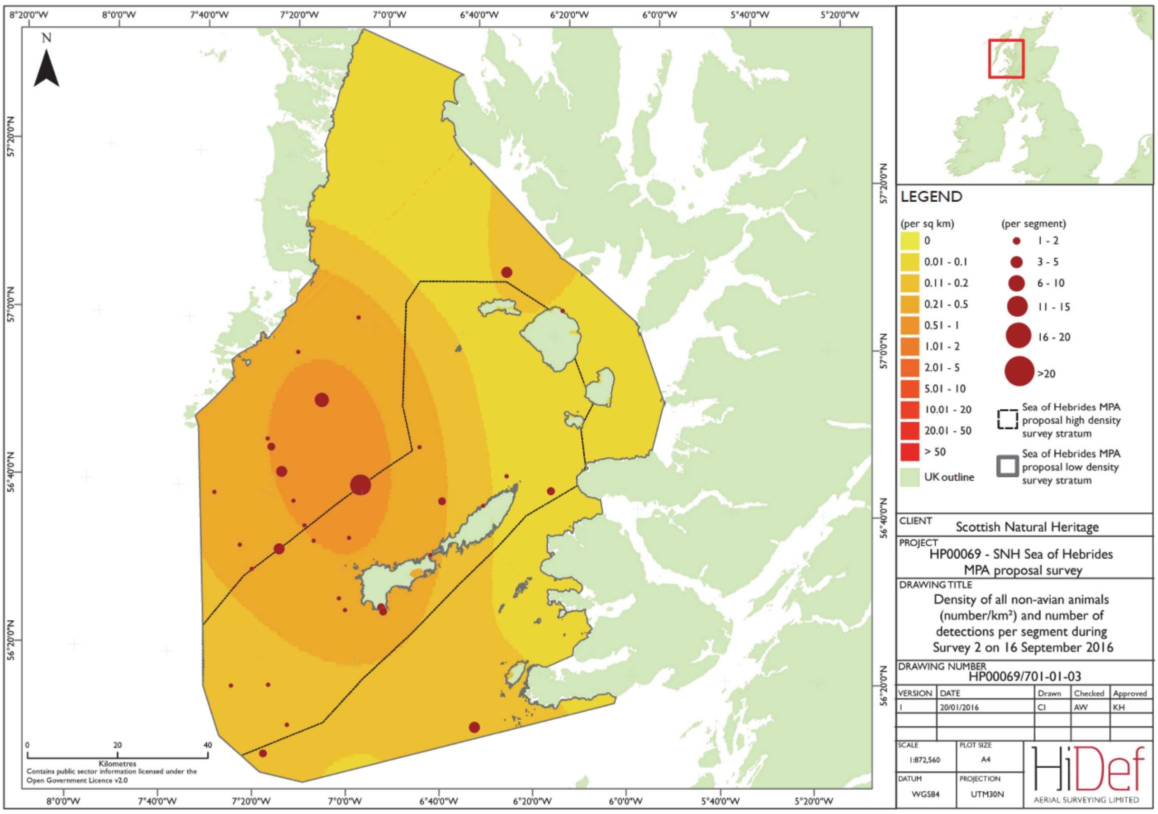

Figure 18. Relative density of all marine megafauna (number/km²) and number of detections per 1 km segment during Survey 2 on 16th September 2016

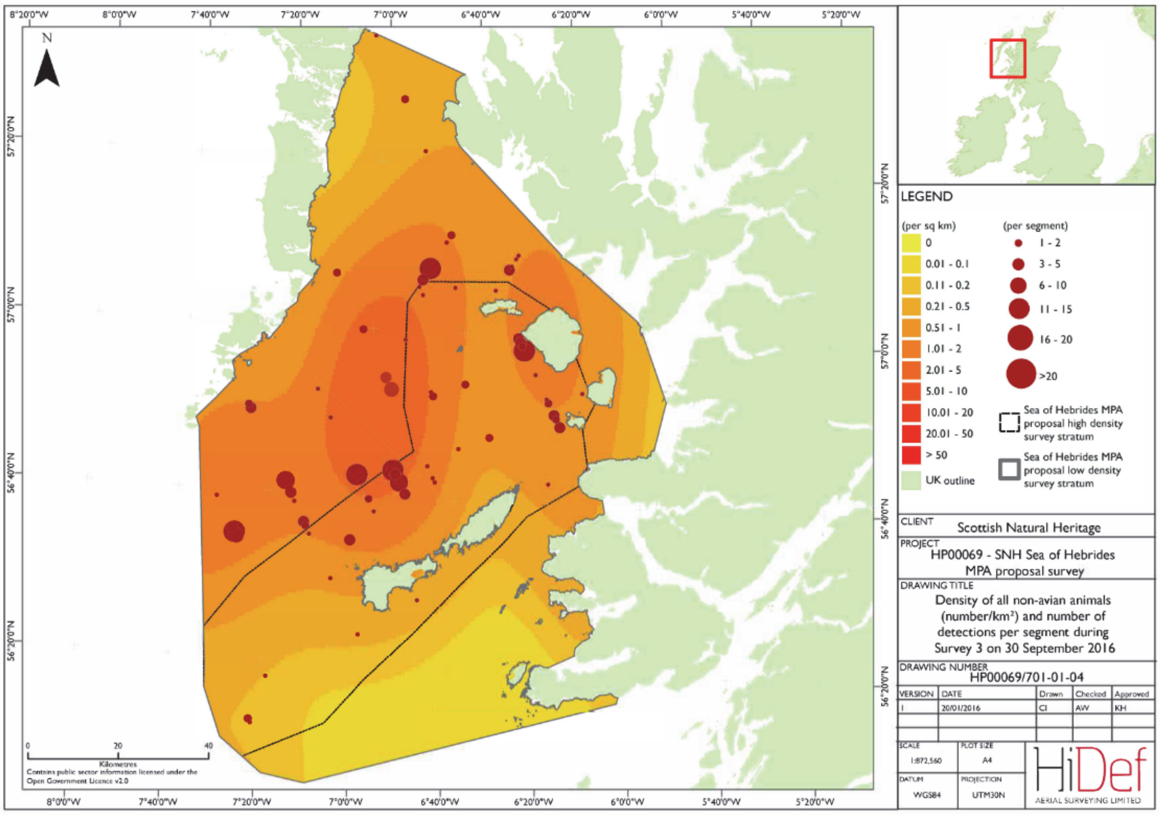

Figure 19. Relative density of all marine megafauna (number/km²) and number of detections per 1 km segment during Survey 3 on 30th September 2016

3.8 Behaviour observations

A total of 45 basking sharks (84.9%) observed during Survey 1 were recorded as feeding (see Annex 2 Figure 20), three (5.7%) were recorded as 'slow swimming' (i.e. not feeding) (see Annex 2 Figure 21) and five (9.4%) were not assigned a behaviour. In Survey 1, two basking sharks were recorded in nose-to-tail formation (Annex 2 Figure 22) and in Survey 2, four basking sharks were recorded in a single group in possible courtship behaviour due to the noise to tail positioning and parallel swimming (Speedie *et al.*, 2009) (Annex 2 Figure 23). Of the six remaining animals in Survey 2, two were clearly identified as feeding.

During Survey 1, common dolphins were recorded across seven groups, one of which appeared to contain a mother and calf. In Survey 2, the common dolphins were recorded across 12 groups, one of which contained at least 50 individuals, including a single mother-calf pair. One other mother-calf pair was also recorded in one of the smaller groups. A total of eight animals were fast swimming and eight were recorded as tail slapping. In Survey 3, the common dolphins were recorded across 12 groups, the largest of which comprised of at least 149 individuals. Seven mother-calf pairs were identified and recorded. Some 52 animals were recorded fast swimming.

The white-beaked dolphins recorded in Survey 3 were in groups of two, five and three individuals. No calves were detected in these groups. In Survey 1, all Risso's dolphins occurred in one group and included a mother-calf association. Harbour porpoise were recorded in Survey 1 as singles or as pairs. In Survey 3, harbour porpoises were recorded in larger groups of up to six individuals. One loosely associated group consisted of 26 individuals spread over adjacent frames and cameras. Only one adult-calf pair was noted during this survey.

The behavioural observations for all species are presented in Table 17 to Table 19. Snapshot surfacing (which is used for estimating absolute abundance) is defined as: when the head of a seal or dorsal fin of a cetacean are clear of the water surface in the middle frame of the sequence in which the animal is present. All basking sharks that were noted to be surfacing were also noted to be snapshot surfacing (Annex 2 Figure 24), whereas for cetaceans, the dorsal fin was not necessarily breaking the surface in the central frame. In other words, this means that cetaceans tend to have a distinct rolling motion when surfacing, diving and swimming, whereas the basking sharks remained relatively horizontal to the water surface in the video imagery. In Survey 2, all basking sharks were completely submerged (Annex 2 Figure 25).

Table 17 . Summary of surfacing behaviour during survey 1 on 15th August 2016. Definitions of behaviour are explained in section 2.3

Species	**Submerged**	**Surfacing (excludes snapshot surfacing)**	**Snapshot surfacing (within true transect)**	**% Surfacing**	**Total**
Basking shark	31	0	22	41.5%	53
Grey seal	0	0	1	100%	1
Harbour seal	0	0	4	100%	4
Minke whale	1	0	0	0%	1
Common dolphin	28	0	4	12.5%	32
Risso’s dolphin	3	0	2	40%	5
Harbour porpoise	4	0	2	33.3%	6
No ID					
Seal species	0	0	4	100%	4
Total	**67**	**0**	**39**	**36.8%**	**106**

Table 18 . Summary of surfacing behaviour during Survey 2 on 16th September 2016. Definitions of behaviour are explained in section 2.3 Note no minke whales were observed on this survey.

Species	**Submerged**	**Surfacing (excludes snapshot surfacing)**	**Snapshot surfacing (within true transect)**	**% Surfacing**	**Total**
Basking shark	10	0	0	0%	10
Grey seal	8	1	4	38.46%	13
Common dolphin	77	14	25	33.62%	116
Harbour porpoise	1	0	0	0%	1
	No ID				
Seal species	1	0	1	50%	2
Dolphin species	0	0	1	100%	1
Cetacean species	2	0	0	0%	2
Total	**99**	**15**	**31**	**31.72%**	**145**

Table 19 . Summary of surfacing behaviour during Survey 3 on 30th September 2016. Definitions of behaviour are explained in section 2.3 Note no basking sharks were observed on this survey.

Species	**Submerged**	**Surfacing (excludes snapshot surfacing)**	**Snapshot surfacing (within true transect)**	**% Surfacing**	**Total**
Minke whale	1	0	0	0%	1
Common dolphin	293	25	23	14.08%	341
White-beaked dolphin	4	1	5	60%	10
Harbour porpoise	102	15	11	20.31%	128
No ID					
Seal species	4	0	10	71.43%	14
Dolphin species	12	0	1	7.69%	13
Cetacean species	19	2	1	13.64%	22
Seal / small cetacean species	1	1	0	50%	2
Total	**436**	**44**	**51**	**17.89%**	**531**

3.9 Basking shark sizes

The length of all basking sharks observed was measured, although some individuals that appeared to be deep in the water proved too difficult to measure with precision. Some statistics for these measurements are given in Table 20. There was no difference in the mean lengths of surfacing and submerged animals. Therefore, the length data was combined to give results from both surveys (excluding only 6 individuals that were obviously deep diving individuals). Sizes of animals varied from 4.28 m to 7.85 m (mean 5.86 m) with most being less than 6 m and none less than 4 m (Table 20).

Table 20. Frequency of basking shark lengths, with minimum, maximum, mean and standard error of measured lengths

Length in meters (m)	Survey 1	Survey 2	Total
4 – 4.99	9 (18%)	2 (29%)	11 (19%)
5 – 5.99	23 (46%)	3 (43%)	26 (46%)
6 – 6.99	11 (22%)	1 (14%)	12 (21%)
7 – 7.99	7 (14%)	1 (14%)	8 (14%)
Minimum length	4.28	4.25	4.28
Maximum length	7.85	7.60	7.85
Mean length	5.88	5.69	5.86
Standard error of mean	0.125	0.417	0.120

4. DISCUSSION

4.1 Suitability of surveys for collecting data on basking sharks

Abundance estimates and distribution

The first survey carried out on 15th August 2016 detected 53 basking sharks. The September surveys had fewer numbers, despite information that basking sharks were sighted from sea and land at this time. Tagged basking sharks have shown marked changes to deeper depths during September/October as they move away from coastal waters (Witt *et al*. 2016), so it is possible the low numbers observed in later surveys were due to the them migrating out of the area or unavailable for detection. Data were not combined from all three surveys due to there being disparity in the abundances.

Abundance was estimated using data from the August survey which gave a relative abundance of 602 (± 95%CI 122 – 1324; CV 53.1%) and an estimated absolute abundance of 1815 (± 95%CI 368 – 3992; CV 53.1%), although precision of these estimates was low as indicated by the broad confidence intervals and high CVs. Weather conditions during the first survey were not ideal for detecting submerged animals (60% of observations were at sea state 4), thus it is likely that the estimate of relative abundance is lower than might have been the case if carried out in sea state of 3 or less. In addition to the broad confidence intervals and weather conditions, some caution must be applied to the calculations of the estimates of availability, as these used time at depth data collected in a different year to the relative abundance observations).

Within the Sea of the Hebrides MPA proposal, previous abundance estimates of basking shark have related to sub-regions, generally within what was defined in this study as the high-density stratum. A boat-based survey was carried out around the previously proposed Argyll Array Offshore Wind Farm to the west of Tiree, in which an estimated 1645 (± 95%CI 1255 – 2155; CV 13.57%) individuals occurred in an area of approximately 1000 km² (Booth *et al.* 2013). Gore *et al.* (2016) estimated the basking shark population within a 25 km radius circle covering the islands of Mull, Coll and Tiree as 985 individuals (± 95%CI 494 – 1683) during a 6 to 9 day period in late August and early September 2010 and 201 individuals (± 95%CI 143 – 340) during a five-day period in late August 2011. These estimates were calculated from a database of 710 individual sharks that could be individually identified from markings and damage on their dorsal fins (Gore *et al*., 2016).

Boat based survey data for the Argyll Array Offshore Wind Farm (Booth *et al.,* 2013) were pooled over several months during a three-year period, but no information is provided on how time of year was considered in this abundance estimate and the extent to which this estimate represented an average over the whole year, or was biased towards the period in the summer months when sharks per unit effort have been recorded at their highest (Speedie *et al*., 2009). The survey took two days to complete (Booth *et al.,* 2013) and thus may be biased if the timing means that the transects consistently sample different regions at the same state of tide leading potentially to double counting of individuals. Given the proximity of the basking shark concentrations in the present study during the 15th August 2016 survey to a similar region in size and location to the Argyll Array study area, and the short-comings of both methods, this suggests that the estimates of absolute abundance are similar between the two survey approaches. The estimate of Gore *et al.* (2016) from 2010 (985) is within the same range of estimates to the current study (taking precision into account), but their estimate from 2011 (201) is considerably lower.

The estimated absolute abundance of basking sharks in the Sea of the Hebrides MPA proposal from this pilot study represents a considerable proportion of the only previously estimated global population of 8200 breeding adults, based on genetic studies from 2006 (Hoelzel *et al.,* 2006). The ratio between effective breeding adults to census population sizes has been shown to be on average only 10% (Frankham, 1995). This can be due to unequal sex-ratios, genetic variance (genetic drift), and the rate of reproductive success and inbreeding within a population.

The numbers of basking sharks recorded during the second survey on 16th September were considerably lower and the species was not recorded at all during the final survey on 30th September. The observations appear to reflect a likely dispersal of basking sharks from the Sea of the Hebrides and/or animals feeding at depths greater than it would be possible to detect in an aerial survey. This is despite local sightings of animals during September from boats and land. Evidence from tagged animals (Witt *et al.,* 2016) also suggests that mid-September to mid-October represents a time when basking sharks begin to change depth use; moving deeper into the water column and spending less time at the surface.

Because of the wide gap in the timing of these surveys *and* the disparity in the relative abundance estimates, it would be meaningless to combine these survey results for basking sharks into a single relative abundance estimate. This means that one of the principle benefits of the survey strategy, (to carry out multiple surveys at low intensity instead of one intensive survey), which was to combine abundance estimates and give a single, precise abundance estimate, was not possible. This is reflected in the broad confidence intervals (and high CV of 53.1%) and means that there is low power to detect any change in relative abundance from this survey.

The majority of basking sharks observed were concentrated around the island of Tiree and in shallow waters to the south-west of the island during Survey 1. This concurs with previous effort-corrected boat-based surveys (Booth *et al.,* 2013) and tagging work (Witt *et al.,* 2016), that have highlighted areas of increased sightings and shark use in an area to the south-west of Tiree.

A high proportion of these animals were observed to be feeding during this survey. The region to the south-west of Tiree is known to be a region of high thermal frontal activity based on satellite-derived information (Miller, Xu & Lonsdale, 2014). Miller *et al.* (2015) noted a correlation between basking shark hotspots around the UK and regions of frontal activity and suggested that the planktivorous basking sharks were exploiting dense prey patches that formed in these regions of frontal activity, where predictable blooms of chlorophyll occur in regions where thermal stratification of the water column in summer breaks down. Miller, Xu & Lonsdale (2014) noted several regions within the Sea of the Hebrides where there was frontal activity, which does not explain why the area to the south-west of Tiree is so important for basking sharks.

It is possible that this region is more productive than the other regions of frontal activity in the Sea of the Hebrides. Alternatively, the region to the south-west of Tiree may be no more productive than the surrounding areas, but that the currents concentrate zooplankton in such a way as to make it easier for basking sharks to locate and exploit their prey.

Behaviour and size information

While feeding was the most commonly observed behaviour during these surveys, two basking sharks were observed in nose-to-tail formation during Survey 1 on 15th August (Annex 2 Figure 22) and four basking sharks were observed in a nose-to-tail formation during the second survey on 16th September (Annex 2 Figure 23). This has been commonly interpreted as being courtship behaviour for this species (e.g. Speedie *et al*., 2009) and is also similar to shoaling behaviours exhibited by other members of the shark and ray family (Jacoby *et al*., 2011).

Measurement of the lengths of animals from the air was possible to an accuracy of 3 cm (excluding the deepest of the submerged animals observed) and unbiased. The lengths of basking sharks ranged between 4.25 m and 7.85 m with a mean of 5.86 m, with the majority less than 6 m. There is a relationship between size and age of animals for this species, with the largest animals likely to be very old individuals. As such, a profile of animal sizes is likely to be a proxy for the age profile of basking sharks using the survey area. Our observations compare with those of Speedie *et al.* (2009), who found that 57% of sharks observed in a survey over a wider area of western Scotland were longer than 7m, and Witt *et al.* (2016) who reported that tagged sharked ranged between 4 m and 9 m, with the majority between 5 m and 6 m. Both of these estimates were based on using the survey boat length to gauge shark size and so should be reasonably accurate. On the other hand, Nicholson *et al.* (2000) reported that most measured animals in the Marine Conservation Society basking shark public sightings database covering the whole of the UK were less than 6 m in length. However, there has been a more recent analysis of these data that suggests that the number of basking sharks over 6 m in length reported in the UK has increased since 2005 (Solandt and Chassin. undated). The reasons for different studies yielding different length profiles of basking sharks could be down to different survey timings or because the studies sampled different geographical locations where the size structure of the populations were different. Public sightings estimates may have also been from records where individuals were further away from sharks than estimates made during boat-based studies. Notably, no animals were measured at less than 4 m by either Speedie *et al.* (2009) or this study, suggesting that these surface waters were not being used by juvenile basking sharks (1.5 to 4 m); newly born pups are ~ 1.5 m in length (Fairfax, 1998) and basking sharks have been estimated to become sexually mature at 4-5 m for males and 8-10 m for females (Compagno, 1984).

4.2 Suitability of surveys for collecting data on minke whales

Only two minke whales were encountered at or near the surface during any of the surveys carried out; one in Survey 1 and one in Survey 2.

Although minke whale abundance may have been low during the current pilot surveys, the results suggest that digital aerial surveys were not useful for estimating abundance and showing distribution within the MPA proposal for this species. Minke whales undergo relatively long and deep dives, so might have low availability during digital surveys. Hammond *et al.* (2013) used visual aerial surveys for cetaceans around the west of Scotland and did not detect any minke whales in that region, although the SCANs III survey observed 5 individuals on the west coast of Scotland using visual aerial survey (blocks I and G – see Hammond *et al*., 2016). Aerial survey methods have a relatively short detection window compared to boat-based methods, and for species with long and deep dive cycles, such as minke whales, this may result in a strong effect of availability bias on abundance estimates.

Relative abundance estimates for minke whales were considered inaccurate from this pilot study (e.g. 13 individuals ± 95% CI 0 – 35; CV 91.4%) within the survey area.

4.3 Other marine megafauna

Four other cetacean and two pinniped species were recorded during the three surveys. Of these, Risso's and white-beaked dolphins, and grey and harbour seals were recorded only in small numbers, therefore it is difficult to interpret the findings of the surveys for these species. It is perhaps noteworthy that one of the Risso's dolphin groups was a single calf with its mother. Sufficient data for both common dolphins and harbour porpoises were collected during the pilot study, despite not being the prime reason for the survey.

Common dolphins were the most abundant marine megafauna during these surveys, with an estimate of relative abundance of 361 (± 95% CI 9 – 982; CV 49.0%), 1296 (± 95% CI 186 – 3169; CV 56.7%) and 5064 (± 95% CI 1081 – 11436; CV 41.9%) in Surveys 1, 2 and 3, respectively. A total of eleven mother-calf pairs of common dolphins were observed during these surveys. The only comparable figures for common dolphin abundance available are from Hammond *et al.* (2013). They estimated the relative abundance of common dolphins for the entire west coast of Scotland, approximately three times the surface area of the Sea of the Hebrides MPA proposal, as 2199 (CV = 0.60) from a July-based aerial survey. Hammond *et al.* (2013) did not provide confidence intervals for their estimate of relative abundance, but they are likely to be quite wide given the high CV; however, their point estimate seems low in comparison to our third survey in September and might be a reflection of the different timing of the surveys. The peak abundance occurred in the final survey at the end of September and might reflect a movement of common dolphins into or through the Sea of the Hebrides. However, our abundance estimates were not corrected for availability bias, which might have been affected by higher sea states in the first two surveys. The most important part of the study area for this species was the relatively deep water between the Outer Hebrides, Small Isles and Coll and Tiree. These waters are also likely to be thermally stratified during the summer months (Ellett & Edwards, 1983).

Harbour porpoise were the second most abundant species recorded during the surveys, with estimates of relative abundances of 69 (± 95% CI 0 – 165; CV 46.3%), 12 (± 95% CI 0 – 37; CV 87.2%) and 1754 (± 95% CI 258 – 3995; CV 46.8%) in surveys 1, 2 and 3, respectively. The estimates and CI varies considerably and the differences in relative abundance might be a reflection on differing levels of availability owing to the higher sea states experienced in the first two surveys than in the last survey, or it could also be a reflection of real changes in abundance. They were more widely dispersed than the common dolphins and generally they occurred closer to land. Hammond *et al.* (2013) surveyed the distribution and abundance of harbour porpoise around western Scotland in 2008 and estimated absolute numbers of over 12,000 animals (CV = 43%) in a surface area approximately three times larger than the Sea of the Hebrides MPA proposal. Their estimated absolute density ranged between 0.2 and 0.4 animals/km² in the survey area.

4.4 Power to detect change

The International Union for the Conservation of Nature ("IUCN") Vulnerable criterion for a declining species is defined as being a ≥ 30% decline over three generations (or over the last 10 years (IUCN, 2001)). There is no clear definition of the length of a generation, but Pauly (1978) has suggested a mean age of first maturity for basking sharks of 18 years, thus meaning that a decline of 30% would need to be detected in 54 years (18 years per generation x 3 generations as per IUCN criterion). For minke whales, the average age of sexual maturity is 6 to 8 years (Olsen & Sunde, 2002) meaning that a decline of 30% would need to be detected in 21 years (using a mean of 7 years per generation).

The annual rate of decline that would need to be detected to signify a Vulnerable criterion would be 0.658% for basking shark and 1.684% for minke whale. If surveys were to take place on a 6-year cycle, then declines of 3.89% and 9.69% for basking shark and minke whale respectively would need to be detected between surveys. Using TRENDS (Gerrodette, 1993) to calculate the CV required to be able to detect this level of decline on a 6-year monitoring cycle gives values of '0%' for both species. Clearly, there is no known monitoring programme that could achieve this level of precision.

Looking for more realistic targets, Bohlin (1990) developed a three-class system of varying levels of precision and identifiable change, whereby:

- Class 1 studies require a high degree of precision, corresponding to the possibility of detecting a population change of a factor as small as 1.2, (e.g. 83,< 100 > 120);

- Class 2 studies require an intermediate level of precision, corresponding to the possibility of detecting a population change of a factor as small as 1.5 (e.g. 67 < 100 > 150); and
- Class 3 studies require a lower precision, corresponding to the possibility of detecting a population change of a factor as small as 2 (e.g. 50 < 100 > 200), that is if the population is reduced to more than half its original size, or is doubled.

TRENDS was used to determine the CV required to detect the above classes of precision and thus detect various levels of decline (Table 21). We found that higher CVs can be attained by increasing the number of surveys. We also found that by increasing the frequency of surveys, we can detect declines sooner. The scenarios based on annual surveys give quite high CVs for declines that would be detectable in a trend after ten years of surveys. Surveys on a six-year cycle with a target detection time of three generations for basking shark and minke whale would be ten and five years, respectively, but the detection time of three generations is unlikely to be sufficiently quick to be able to take conservation action. A sensible compromise might be to target achieving the levels of precision required to detect a desired level of change based on surveys every three years and aim to be able to detect the change within 15 years (two generations for minke whales and one generation for basking sharks) (greyed cells in Table 22).

Table 21 .Calculation of the CV (%) required to detect different classes of decline based on $\alpha = 0.05$, power = 0.8, normally distributed data and CV that is proportionate to 1/square root of abundance

Duration of surveys (years)	6	9	15	10	54	24
Frequency of surveys (years)	6	3	3	1	6	6
Number of survey years	2	4	6	11	10	5
CV for 17% decline (Class 1)	1%	2%	4%	6%	5%	3%
CV for 33% decline (Class 2)	2%	5%	8%	12%	11%	7%
CV for 50% decline (Class 3)	2%	8%	13%	19%	18%	11%

Improving precision of abundance estimates

There are two approaches for improving the precision (or CV) of abundance estimates: by adjusting the survey metrics or by using modelling approaches. The former uses covariates such as depth, chlorophyll or changes in survey conditions to include in models to account for variance in the abundance between transects in conventional models or segments of transects for spatially explicit models. Survey metric adjustments can improve abundance estimate precision by adjusting the encounter rate by widening the strip width or improving the depth at which animals can be detected; by increasing the number of samples (or transects in this case) or by increasing the number of repeat surveys in a given year. Using modelling approaches and also simulation with survey data to adjust transect width and number of transects go beyond the scope of this report, but it is possible to consider the improvements that might be possible from these measures.

It is relatively simple to consider the number of repeat surveys in a year and these can be obtained from Table 16. These measures from the survey data presented in this report suggest that it would be necessary to repeat the survey design used in this study somewhere in the region of eight times in any one year to achieve something approaching usable measures of CV for basking sharks and more than 25 times for minke whale. Given the difficulty of achieving three surveys in 2016, and the need to ensure that surveys are not spaced too closely together to ensure independence, increasing the number of surveys might be difficult and likely too expensive. One potential solution would be to target the improvements at the high intensity area, given that all basking sharks encountered occurred in this region during our 15th August survey (Survey 1), from which we based our analysis.

Other adjustments, such as using modelling approaches, surveying in calmer conditions to improve the possibility of detecting submerged animals or increasing the transect width would all help to improve the precision of the abundance estimates. Similarly, increasing the number of transects would also improve the precision.

A detailed re-analysis of the survey data would be required to determine what additional measures (other than simply increasing the number of surveys) would be required to detect a desired level of change. Such an analysis would use environmental (e.g., sea surface temperature) and survey (e.g., sea state, glare) covariates to model the impact of these on precision. The analysis would also simulate varying encounter rates and number of transects. We are aware, however, that this exercise would only be reflective of one surveys worth of data which would likely limit interpretation.

Given the low encounter rate for minke whales for this survey and the difficulty of focusing the survey on a high-density stratum for this species, it may not be possible to achieve the desired level of digital aerial surveys in such a way as to be cost-effective, and other methods may be more appropriate.

4.5 Strengths and weaknesses of this series of surveys

These surveys were a pilot to assess suitability as a potential future monitoring method for basking shark and minke whale in the survey area. As such, the survey was able to detect basking sharks and a wide range of other megafauna species, but not able to detect minke whales. Relative abundance estimates were achieved for basking shark during the first survey and an estimation of absolute abundance was possible using a correction based upon tagging data for animals in the same region.

Poor detection rates for minke whales is likely to be a result of the survey design on account of their long dive times, compared to smaller cetaceans (Øien *et al.,* 2009; Baumgartner, 2008). Low detection rates of Risso's and white-beaked dolphins may be due to a range of factors (e.g. dive times, low numbers, time of year etc.). The surveys provided useful information on how basking sharks in particular were using the survey area, as well as accurate size information, which may prove a good proxy for the age structure of the animals using the area.

Wide CIs and high CVs were obtained for all species and in all surveys which was a concern with respect to this suite of surveys. This was mainly because of the low encounter rate of most species and the variation in the number of encounters between transects. The strategy for the original survey design was to combine the abundance estimates from different surveys with low intensity coverage to improve the encounter rate instead of a single, higher intensity coverage survey. However, the wide temporal spacing of the surveys and large disparity in abundance estimates between the first and last surveys meant that combined abundance estimates had little value. The decision to fly the last survey was taken because there was evidence from land and boat-based surveys in the area, that basking sharks were still present; however only 10 sharks and zero sharks were recorded in the final two surveys. The long temporal separation was caused by a combination of poor weather and availability of the survey aircraft; two suitable weather windows in August were missed because of aircraft maintenance requirements at the time. More closely-spaced surveys in time would have allowed the data from each survey to be combined more easily, and thus permit calculation of abundance estimates with tighter confidence intervals and more predictive power for detecting change. Witt *et al.* (2016) found that basking sharks tagged in the months of July and August started to disperse from the study area between mid-September and mid-October and at the same time tended to occur less in the surface waters. Given our experiences, it would seem sensible to try to carry out surveys when the population is relatively homogeneous through time and therefore not to extend surveys into September; any extension, if at all, should be brought forward into the last week of July.

Ensuring repeat surveys occur during a condensed time frame during July/August may allow the combining of survey abundance estimates and increase precision in future years. Alternatively, the high density and low density strata could have been surveyed on different days or by different aircraft on the same day, although it is debatable whether breaking the survey into smaller chunks would have made it any more likely that all three surveys could have been completed in the same month given the problems with aircraft availability. If a second aircraft were available, then this would mean that the low-density stratum could be surveyed by one aircraft and the high-density stratum could be surveyed by a second aircraft on the same day leaving more time to survey more transects. In addition, there are environmental influences such as sea state that were not adjusted for in this pilot but could be taken into account in abundance estimates in further modelling.

5. CONCLUSIONS AND RECOMMENDATIONS

A series of three digital video aerial surveys were completed during the months of August and September 2016. The technique proved to be a useful tool for collecting data on basking shark but not for minke whale; further improvements in the methods are necessary (see below). Estimates of relative and absolute abundance for basking shark (and common dolphin and harbour porpoise) were possible, although their precision was low. Additional information was collected successfully on basking shark distribution, some inferred behaviours and also the body length of individuals, which, as a proxy, could give insights into the age structure of the population. The abundance of other species detected was too low to provide useful abundance estimates, or in the case of minke whale, may have been compromised by low availability of the animals for detection during the aerial surveys (as a result of long dive durations).

For future years and to allow this method to be used for monitoring purposes, it will be necessary to find ways to improve the precision of abundance estimates by doing the following:

- The ability to measure a 30% decline within three generations (IUCN, 2001) is perhaps an unrealistic goal for any marine megafauna, given 6-year reporting cycles (e.g. Article 17 of the Habitats Directive). Based on our power analysis, a 50% decline in abundance detectable after 15 years of surveys every three years is achievable for basking sharks, if a CV precision of 13% is achieved. This frequency of future surveying is recommended, however, it is unclear from this pilot survey if this precision could be achieved.
- The high-density stratum and low-density stratum should be used in future surveys, but the intensity of the transects in the high-density stratum should be doubled to increase the precision of the basking shark abundance estimates; This could be done using a second aircraft to ensure the survey can still be completed in one day.
- The survey period should be fixed to commence at the start of the last week in July and run to the end of August only, with surveys happening closer together where weather allows;
- The use of TRENDS software suggests a minimum of three surveys (ideally four) should be completed in that period;
- Consideration should be given to widening the transects by lowering the camera resolution to 4cm to increase the encounter rate and improve abundance estimates; and
- A data modelling exercise should be carried out, perhaps using power analysis techniques such as those offered in the package MRSeaPower (www.gov.scot/Topics/marine/marineenergy/Research/SB9), to investigate the extent to which it is possible to improve the precision of abundance estimates based on the pilot survey data. Environmental and survey covariates should be used to improve the precision initially. Simulations should be used to examine how much to increase the number of transects in the high-density stratum and how much to increase the transect width to bring precision to abundance estimates.

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ANNEX 1: BASKING SHARK SWIMMING DEPTH

1. INTRODUCTION

The probability of basking sharks being at different depths was estimated using a sample of ten basking sharks that were fitted with time depth recorders ('TDRs') and satellite tags around the islands of Coll and Tiree in July and August 2012 (described in detail by Witt *et al.* (2016)).

2. METHODS

The amount of time that each animal spent at the surface and at 1 m depth bins below the surface down to 10 m was calculated from the tag recording as a proportion of the total daylight hours on each day. Each animal and each day was treated as an independent sample and used to calculate the mean, standard error, and 95% confidence limits of the mean proportion of daylight spent at each depth for each animal separately and for all ten basking sharks combined. A bootstrap mean and standard error with replacement (Buckland *et al.,* 2001) was calculated 1000 times. The bootstrap mean and standard error values were used to calculate the 2.5 and 97.5 percentiles of the bootstrap means, and thus the 95% confidence intervals of the mean.

3. RESULTS

A total of ten animals, fitted with TDR tags (Witt *et al.,* 2016) were re-analysed in order to facilitate calculations of availability bias for basking sharks in Section 3.4. Treating day and animal as independent samples resulted in a total sample size of 388. This resulted in a profile of the proportion of time spent by these animals at different ranges from the surface (Table 22). These animals only spent 14% of their time during daylight hours at the surface, and only 41% of their time between the surface and 10 m depth, indicating that the availability bias for these animals is likely to be very high.

Table 22 . Bootstrapped mean proportion of time spent at different depth ranges occupied by ten basking sharks in August 2012 (after Witt et al. 2016). Also provided are the bootstrapped lower and upper 95% confidence intervals and the mean of the bootstrapped standard error of the mean values

	Bootstrapped proportion of daylight hours at depth			
Depth range	**Average**	**Lower 95% CI**	**Upper 95% CI**	**Mean std error**
Surface	0.14	0.12	0.16	0.012
Surface – 1 m	0.22	0.18	0.25	0.016
Surface – 2 m	0.26	0.23	0.29	0.016
Surface – 3 m	0.33	0.30	0.36	0.017
Surface – 4 m	0.35	0.32	0.38	0.017
Surface – 5 m	0.36	0.33	0.40	0.018
Surface – 6 m	0.37	0.34	0.41	0.018
Surface – 7 m	0.38	0.35	0.41	0.018
Surface – 8 m	0.39	0.35	0.42	0.018
Surface – 9 m	0.40	0.36	0.43	0.018
Surface – 10 m	0.41	0.37	0.44	0.018

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ANNEX 2: SELECTED IMAGES OF BASKING SHARKS AND OTHER MARINE MEGAFAUNA

Figure 20. Example image of basking shark slow swimming during Survey 1 on 15 August 2016

Figure 21. Example image of basking shark filter feeding during Survey 1 on 15 August 2016

Figure 22. Image of nose-to-tail behaviour of two basking sharks during Survey 1 on 15 August 2016

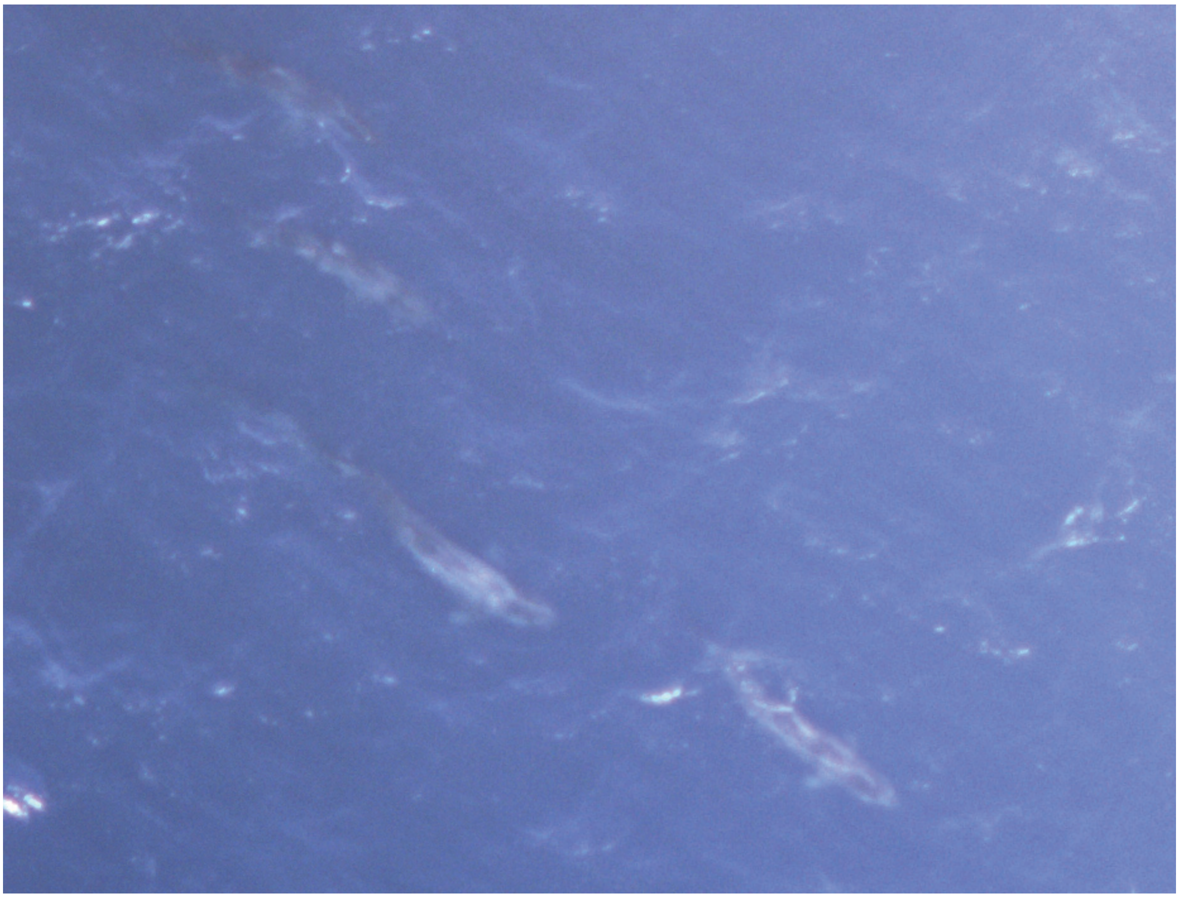


Figure 23. Four basking sharks engaged in nose-to-tail behaviour during Survey 2 on 16 September 2016

Figure 24. Example image of basking shark with dorsal fin breaking the surface during Survey 1 on 15 August 2016

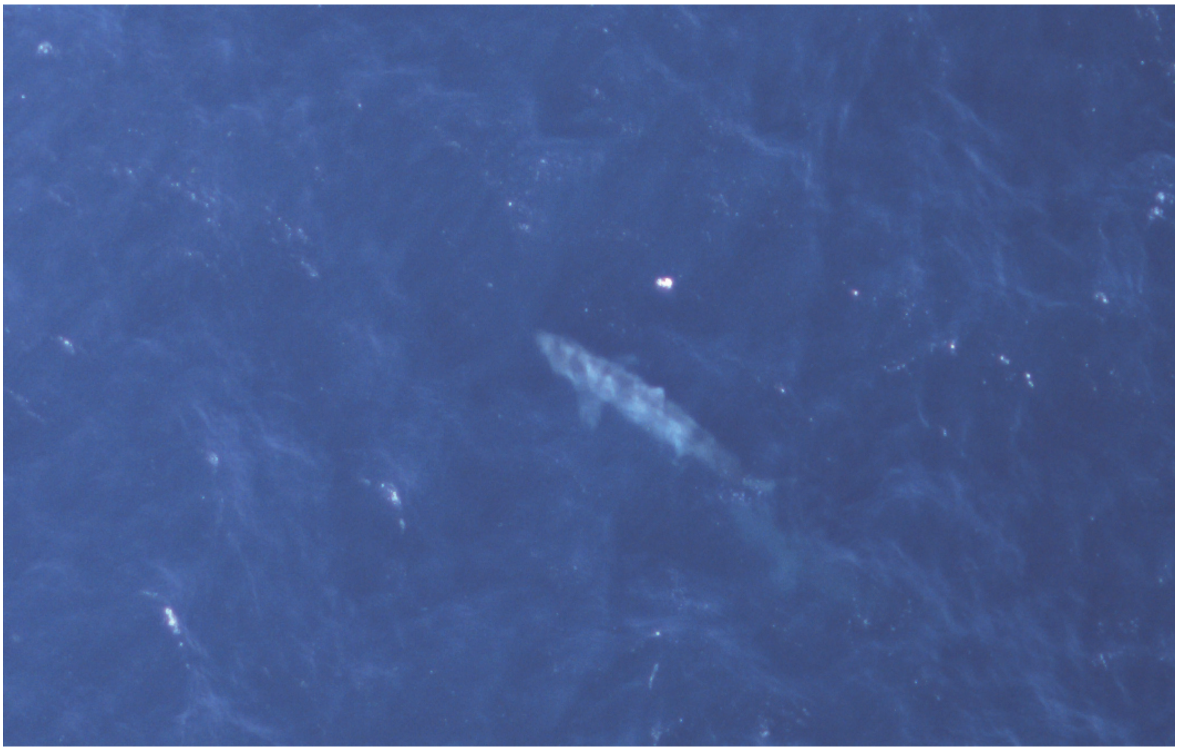
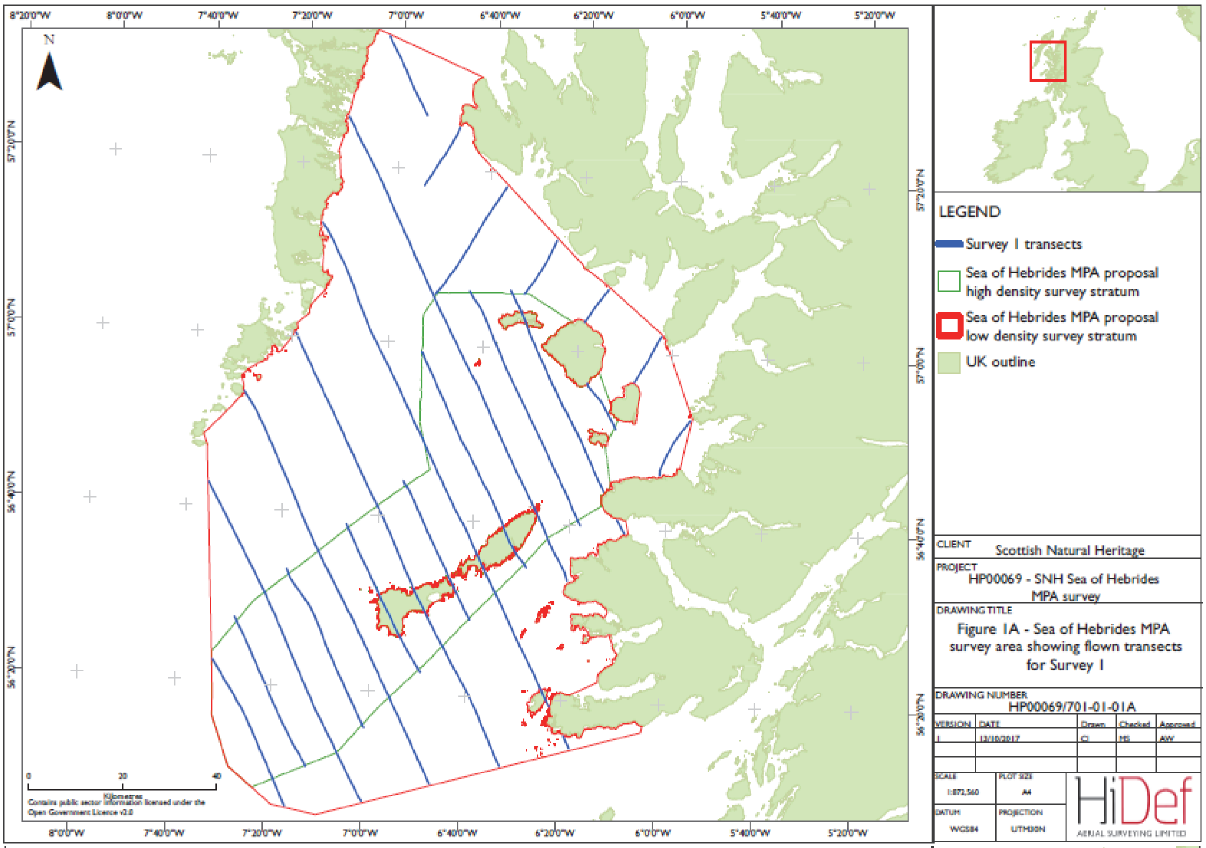


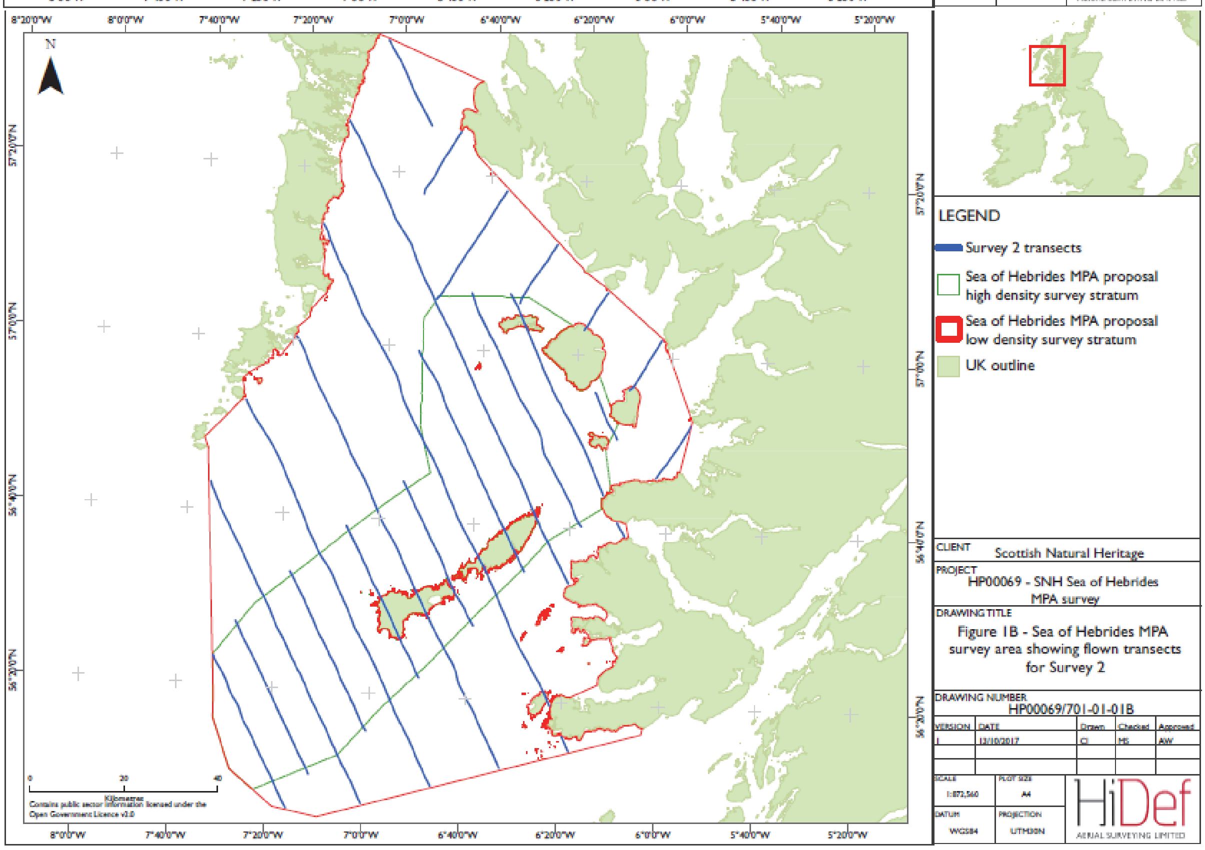
Figure 25. Example image of fully submerged basking shark during Survey 1 on 15 August 2016

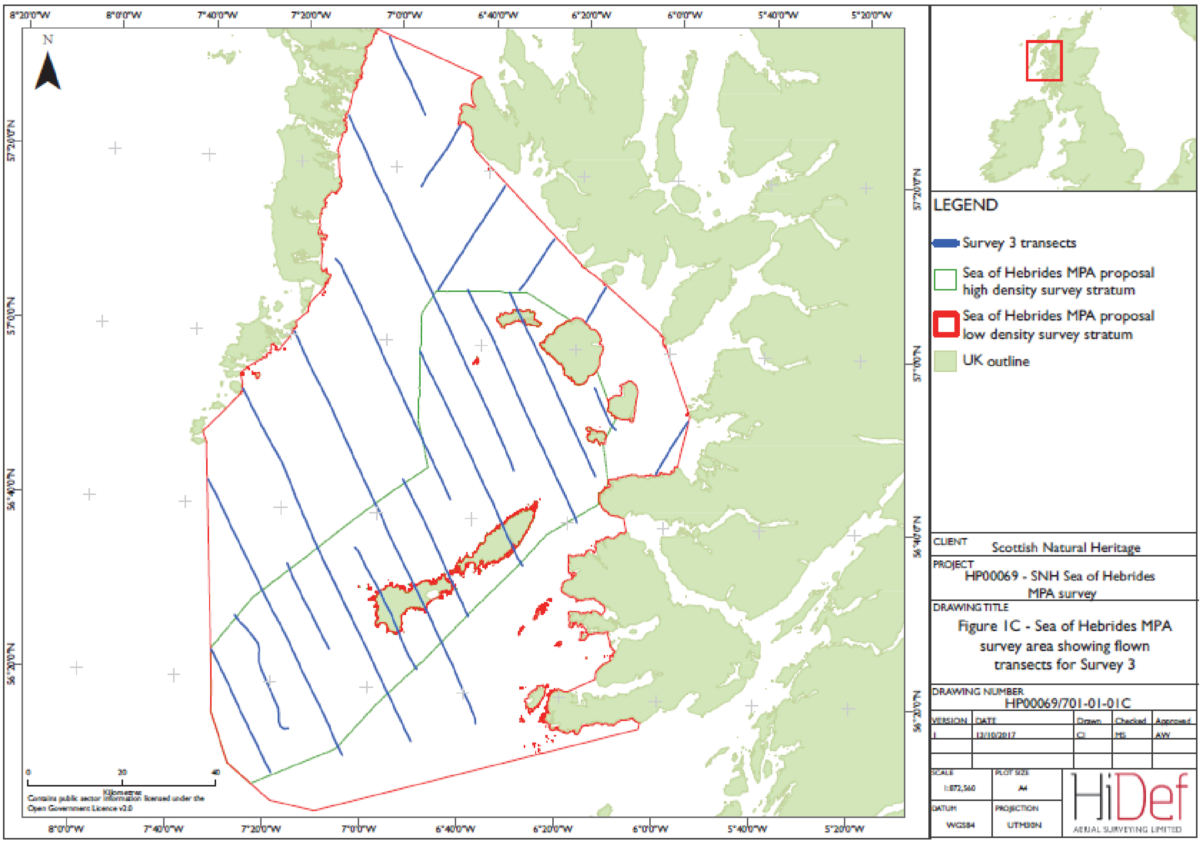
ANNEX 3: RAW DATA COLLECTED OVER ALL THREE SURVEYS WHERE OBSERVATIONS WERE RECORDED

This annex can be downloaded as a separate document.

ANNEX 4: EXTENT OF SURVEY EFFORT FOR SURVEYS 1, 2 AND 3







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6°40'0"W
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5°20'0"W
57°20'0"N
57°0'0"N
56°40'0"N
56°20'0"N
N
0
20
40
Kilometres
Contains public sector information licensed under the Open Government Licence v2.0
LEGEND
Survey 3 transects
Sea of Hebrides MPA proposal high density survey stratum
Sea of Hebrides MPA proposal low density survey stratum
UK outline
CLIENT
Scottish Natural Heritage
PROJECT
HP00069 - SNH Sea of Hebrides MPA survey
DRAWING TITLE
Figure 1C - Sea of Hebrides MPA survey area showing flown transects for Survey 3
DRAWING NUMBER
HP00069/701-01-01C
VERSION
DATE
Drawn
Checked
Approved
1
13/10/2017
CI
MS
AW
SCALE
1:872,560
PLOT SIZE
A4
DATUM
WGS84
PROJECTION
UTM30N
HiDef
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Great Glen House, Leachkin Road, Inverness, IV3 8NW
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