ARTICLE
NAMMCO Scientific Publications

ESTIMATED ABUNDANCES OF CETACEAN SPECIES IN THE NORTHEAST ATLANTIC FROM TWO MULTIYEAR SURVEYS CONDUCTED BY NORWEGIAN VESSELS BETWEEN 2002–2013

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ABSTRACT

Two shipboard line-transect surveys of the Northeast Atlantic were conducted between 2002–2007 and 2008–2013 to meet the ongoing requirements of the Revised Management Procedure (RMP) for common minke whales (*Balaenoptera acutorostrata acutorostrata*) developed by the International Whaling Commission's Scientific Committee. Here we present estimated abundances for non-target species for which there were sufficient sightings, including fin whales (*Balaenoptera physalus*), humpback whales (*Megaptera novaeangliae*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), harbour porpoises (*Phocoena phocoena*), and dolphins of genus *Lagenorhynchus*. The 2 surveys were conducted using a multiyear mosaic survey design with 2 independent observer platforms operating in passing mode, each with 2 observers. The abundances of *Lagenorhynchus* spp. from the 2002–2007 survey were estimated using single-platform standard distance sampling methods because of uncertainty in identifying duplicate sightings. All other estimates were derived using mark-recapture distance sampling techniques applied to a combined-platform dataset of observations, correcting for perception bias. Most notably, we find that the abundance of humpback whales, similar in both survey periods, has doubled since the 1990s with the most striking changes occurring in the Barents Sea. We also show that the pattern in distribution and abundance of fin whales and sperm whales is consistent with our earlier surveys, and that abundances of small odontocete species, which were not estimated in earlier surveys, show stable distributions with some variation in their estimates. Our estimates do not account for distributional shifts between years or correct for biases due to availability or responsive movement.

Keywords: North Atlantic, cetacean, abundance, line-transect, fin whales, humpback whales, sperm whales, killer whales, harbour porpoises, dolphins.

INTRODUCTION

Two multi-year surveys, targeting North Atlantic common minke whales (*Balaenoptera acutorostrata acutorostrata*), were conducted in the Northeast Atlantic between 2002–2007 and 2008–2013. The intent of the surveys was to achieve management targets under the Revised Management Procedure (RMP) for common minke whales, developed by the International Whaling Commission's Scientific Committee (IWC, 1994). Similar surveys have been conducted in Norwegian and adjacent waters to varying degrees since 1988 (Christensen, Haug, & Øien, 1992; Øien, 2009, 1990). All surveys preceding 1995 covered portions of the total study area (described under Materials and Methods), while a complete synoptic survey of the region was achieved in 1995. A cyclical mosaic survey design was implemented in 1996 to cover the Northeast Atlantic with a patchwork of smaller-scale surveys over a multi-year timeframe (Øien & Schweder, 1996). These are the second and third complete surveys under the mosaic survey design. The survey methodology has remained essentially the same, with slight improvements to ensure best possible estimates of minke whale abundance as the target species (Schweder, Skaug, Dimakos, Langaas, & Øien, 1997; Skaug, Øien, Schweder, & Bøthun, 2004).

Here we present abundance estimates of non-target cetacean species from the Norwegian 2002–2007 and 2008–2013 surveys, including: fin whales (*Balaenoptera physalus*), humpback whales (*Megaptera novaeangliae*), sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), harbour porpoises (*Phocoena phocoena*), and dolphins of genus *Lagenorhynchus* (Figure 1). Combined platform estimates are provided, except in the case of *Lagenorhynchus* spp. in the 2002–2007 survey, where only single platform sightings were used. In this paper, the term *Lagenorhynchus* spp. refers collectively to white-beaked dolphins (*Lagenorhynchus albirostris*) and white-sided dolphins (*Lagenorhynchus acutus*). Estimates of minke whale abundances are published elsewhere (Bøthun, Skaug, & Øien, 2009; Solvang, Skaug & Øien, 2015).

Earlier surveys have resulted in published estimates for non-target species including fin, humpback, and sperm whales from surveys conducted in 1988, 1989, 1995, and 1996–2001 (Christensen et al., 1992; Øien, 2009, 1990), in which abundance estimates were made assuming that all animals on the transect line were detected ($p(0)=1$). This analysis differs in that it uses the double platform configuration to estimate $p(0)$, accounting for perception bias to improve the abundance estimates.

Leonard, D. M. & Øien, N. I. (2020). Estimated Abundances of Cetaceans Species in the Northeast Atlantic from Two Multiyear Surveys Conducted by Norwegian Vessels between 2002–2013. *NAMMCO Scientific Publications 11*. https://doi.org/ 10.7557/3.4695

Figure 1. (a) White-beaked dolphin, (b) Fin whale, (c) Killer whales, and (d) Humpback whales. Photo credit: Deanna Leonard

MATERIALS AND METHODS

Survey Design

The study area covers the Northeast Atlantic from the North Sea to the ice edge, and from the Greenland Sea in the west to the Barents Sea in the east. It consists of the 5 Small Management Areas (SMA) of the North Atlantic Minke Whale Implementation (IWC, 2004): CM, ES, EB, EW, and EN (Figure 2). Within each SMA, a block structure was fitted to create areas of similar densities of minke whales, with survey effort distributed proportional to area. Within each block, transects were constructed as zig-zag tracks with a random starting point (Buckland et al., 2001). Block areas used to estimate species density were adjusted for ice-cover. In 2003, the SMA structure was modified by the IWC Scientific Committee, shifting the eastern boundary of the Barents Sea SMA westward to 28°E and extending the upper boundary of North Sea SMA southward to 62°N (IWC, 2004). This necessitated splitting the blocks BAW and FI each into 2 blocks, and because block FI was surveyed before the boundary change, it was further subdivided into Fl1 and Fl2, and re-stratified (Figure 2a).

Due to the fragmentation of the strata through redefinitions of SMA boundaries that occurred in 2003 (IWC, 2004), it was necessary to redesign the block structure within the SMAs prior to the 2008–2013 survey (Skaug et al., 2004). The updated block design and names used in the 2008–2013 survey are illustrated in Figure 2b.

The surveys

In 2002–2007, two vessels operated simultaneously each summer, covering different parts of the survey area. Every year, the surveys began in late June and lasted until early August. In 2002, the survey covered the area north of the coast of Finnmark and a northeast section of the Norwegian Sea (SMA EB); in 2003, the Svalbard area (SMA ES); in 2004 the North Sea area (SMA EN); in 2005, the Jan Mayen area (SMA CM); in 2006, the entire Norwegian Sea (new SMA EW); and in 2007, the eastern Barents Sea (SMA EB). Due to the changes to the SMA structure that occurred in 2003 (described in the Survey Design section above), some blocks (FI, NOS, NC1) were surveyed twice, both in 2002 and 2006. Based on advice from the NAMMCO Abundance Estimates Working Group in October 2018 (NAMMCO, 2018), the duplicate effort in some blocks was retained and used to improve abundance estimation. The block BA2 was modified from the original BAW block mid survey cycle, in 2003. As a result, it was partially surveyed twice, and due to differing amounts of ice cover affecting the total area of the block, 2 separate estimates were obtained (BA2_a and BA2_b).

During 2008–2013, one or two vessels conducted the surveys each year, with a total of 7 vessels operating over the 6-year period. In 2008 the Svalbard area was surveyed; in 2009 the North Sea; in 2010 the Jan Mayen area; in 2011 the Norwegian Sea; and in 2013 the Barents Sea was surveyed.

Field methodology

Both surveys used a double-platform design with two platforms that were visually and acoustically separated from each other and thus independent. Platform 1 was positioned in a barrel on the mast above platform 2, which was located on the roof of the bridge. The two platforms varied in eye height depending on the vessel, with an average of 13.8 m for platform 1 and 9.7 m for platform 2.

Each platform operated continuously during daylight hours (between 05:00 and 23:00, depending on the latitude) with a team of 2 observers. Each team worked on 1- or 2-hour shifts with teams rotating between platforms. The searching speed was 10 knots with surveys conducted in passing mode. Searching was conducted by naked eye. The designated search area was the 90^{o} sector centred around the transect line, within 1500 m of the vessel. When searching, one observer in each team scanned the port 45^{o} sector from the transect line while the other scanned the starboard 45^{o} sector. All sightings were recorded regardless of whether they were sighted within the designated search area.

Observers recorded observations using a microphone connected to a central computer equipped with a GPS. Each observation documented the species, the angle from the transect line read from an angle board, the radial distance estimated by eye, and the group size. Tracking procedures were followed for minke whales, where the observer dedicated their effort to recording each repeat surfacing until it passed abeam of the ship. During tracking procedures, the other team member took over searching the entire 90º search area. When both observers were occupied tracking minke whales, other minke whale sightings, along with all non-target species, were recorded as initial sightings only. After each completed recording of a minke whale or other large whale sighting, observers reported the sighting to the team leader by radio. The platforms operated on separate radio channels to maintain independence. During the surveys, regular training in distance estimation was conducted, including accuracy of angle-board readings and distance estimation using buoys as targets.

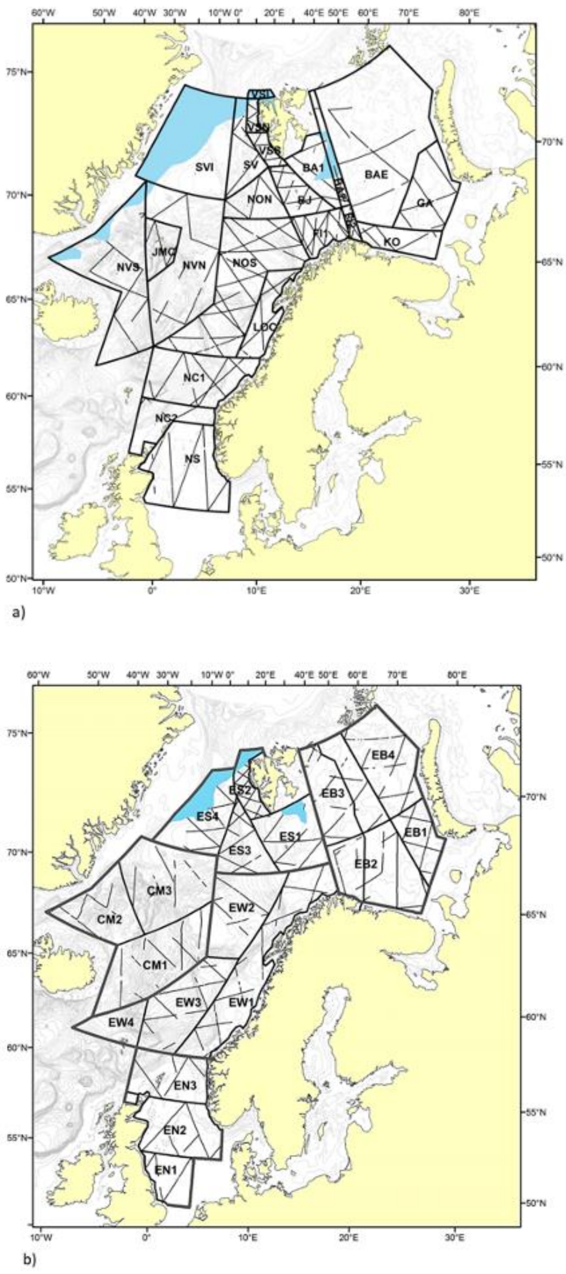

Figure 2. Survey blocks and realized search effort (Beaufort Sea State ≤ 4) on predetermined transect lines during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

Measures of covariates including glare, visibility, Beaufort Sea State (BSS) and weather conditions were recorded hourly and/or when conditions changed notably. Covariate classifications and definitions are detailed in Øien (1995). Acceptable survey conditions were defined as BSS of 4 or less and meteorological visibility greater than 1 km.

Data treatment

Sightings used in the abundance-estimate analyses were included based on the following criteria: the sighting was initially detected before abeam; the sighting was recorded from platform 1 or 2; and the species (or genus in the case of *Lagenorhynchus* spp.) was confirmed.

Observations from the two independent platforms were combined through a process of determining duplicate sightings. When possible, duplicates were identified in the field by the team leader operating from the bridge; otherwise, they were determined post-cruise.

The criteria used to determine duplicates, both in the field and in the post-cruise analysis, involved accounting for the timing and position of the sightings relative to the vessel (given a speed of 300 m per minute and allowing for some error in radial-distance estimates by different observers). Since only the initial sightings were recorded for non-target species, there was occasionally the need to match duplicates of disparate surfacings of the same whale. Given the relatively short designated search distance for the target species (1500 m), it was possible to have one platform make an initial sighting of a whale thousands of meters away, while the second platform observed it much later, once the ship moved closer to it. The team leader played an important role in identifying these duplicates in the field. When only one platform reported a sighting, the team leader could assist by tracking the whale so that if the other platform detected it closer to the ship, it could be identified as a duplicate.

In rare cases where one observer of a clear pair of duplicate sightings recorded the species as 'unidentified large whale' while the other confirmed the species, the positive ID was accepted for that sighting. In cases where there was uncertainty in species identification by one or both observers, the team leader, operating from the bridge, used binoculars to confirm uncertain identifications. Species identification was not always possible, so some sightings were left recorded as 'unidentified large whales.'

For all duplicate sightings, the information recorded by the platform from which the whale was first sighted was used in the combined-platform analyses, as the analytical method used requires that these fields be identical (Laake & Borchers, 2004). Abundance estimates were calculated for the double platform for all species apart from *Lagenorhynchus* spp. in the 2002–2007 survey, where only a single platform (platform 1) was used due to uncertainty in judging duplicates. The certainty in judging duplicates improved between the 2002–2007 and 2008–2013 surveys due to a change in emphasis for the observers who were instructed to make a greater effort to discern and report smaller groups of dolphins rather than larger aggregations. In earlier surveys, some observers would classify nearby groups of dolphins as a single group, while others would classify them as separate groups. This caused greater uncertainty in judging duplicates, such that we did not feel they were reliable.

Analysis

These analyses were performed using the DISTANCE 7.2 software package (Thomas et al., 2010). Encounter rate and group size for each species and each survey were estimated by block. The effective search half-width (*eshw*) was estimated using pooled data over all survey blocks (globally) for each survey period as there were insufficient data to support stratified estimates.

To account for perception bias by estimating *p*(0), mark-recapture distance sampling (MRDS) techniques were used (Laake & Borchers, 2004). The fully independent platform design allowed for the “independent observer configuration” to be used (Laake & Borchers, 2004). Both “full independence” (FI) and “point independence” (PI) were tested (Laake & Borchers, 2004). Models were chosen based on a comparison of the Akaike’s information criterion (AIC) values. The “point independence” configuration requires the estimation of 2 detection functions: one for the probability of detection by one or more observers (Distance Sampling model: DS model), and a second conditional detection function (Mark Recapture model: MR model) for detection probabilities conditioned on detection by the other platform (Laake & Borchers, 2004). The “full independence” configuration requires only the conditional detection function. The conditional detection function is modelled logistically with the same covariates available for the primary detection function, selected based on AIC values.

The detection function models were selected based on AIC, goodness of fit test statistics, and visual inspection, particularly of data around the transect line. Hazard-rate and half-normal models were tested. The covariates considered were BSS, vessel identity, weather, group size, glare, and visibility. Some covariates were aggregated into categories for simplification and to improve model convergence, as detailed in

Table 1. Data exploration also included truncation of the data by up to 5% if it improved the test statistics (Chi-square and Kolmogorov-Smirnov) and the shape of the q-q plot.

Encounter-rate variances were estimated using R2, the default in the mark recapture (MRDS) engine in DISTANCE 7.2, which is a design-based empirical estimator that assigns weights to transect lines based on length (Fewster et al., 2009). The confidence intervals of the abundance estimates were calculated assuming that estimated abundance is log-normally distributed (Buckland et al., 2001).

RESULTS

General

In 2002–2007 a total effort of 27,009 km of transects were searched over the survey period (Figure 2a), covering a total area of 2,962,269 sq. km. The distributions of search effort by BSS were 3% in BSS 0, 15% in BSS 1, 22% in BSS 2, 32% in BSS 3 and 28% in BSS 4. The surveys conducted between 2008–2013 covered a total area of 3,268,243 sq. km and 24,300 km of transects were searched (Figure 2b). The distributions of search effort by BSS were 0.5% in BSS 0, 16% in BSS 1, 20% in BSS 2, 29% in BSS 3 and 33% in BSS 4.

In both survey cycles there were parts of the survey area that were not covered due to ice and unsuitable survey conditions. In 2002–2007, blocks VSI and SVI were not covered due to ice

Table 1. Covariates descriptions included to improve model fit. Some covariates were aggregated into levels for simplification.

			Aggregated covariates	
Covariate	**Description**	**Symbol**	**Levels**	**Definition**
Beaufort	5 categories	B	BI, BII, BIII	BI: [0-1], BII: [2], BIII: [3-4]
Weather	12 categories	W	good, bad	good: W01-W04, bad: W05-W12
Vessel	5 vessels	Ves	-	-
Visibility	numerical	V	high, low	low < 50% Max high > 50% Max
Glare	4 categories	G	glare, no glare	G0: no glare, G1: glare
Group size	numerical	S	-	-
Distance	numerical	D	-	-

and poor weather. In 2008–2013, block EW4 was not covered due to consistently poor weather and parts of the northernmost blocks (ES) were not surveyed due to ice cover. Block areas used in calculating abundance estimates were adjusted to exclude ice-covered areas.

Large whales

In 2002–2007 there were 893 unique records of large whale sightings (Table 2) and of these, 218 were identified as fin whales, 229 as sperm whales, 245 as humpback whales, 11 as blue whales, and 1 was identified as a sei whale. 189 sightings were categorized as 'unidentified large whales'. In 2008–2013, there were 611 records of large whale sightings (Table 3) and of these, 224 were identified as fin whales, 92 as sperm whales, 179 as humpback whales, 2 as blue whales, and 1 as a sei whale. 113 were categorised as 'unidentified large whale'.

Smaller odontocetes

There were 1042 unique records of smaller odontocete groups sighted during the 2002–2007 survey period (Table 2). Of these, 96 were identified as killer whales, 294 as harbour porpoises, 628 as *Lagenorhynchus* spp., and 12 as northern bottlenose whales. In 2008–2013, there were 487 records of small odontocete groups sighted (Table 3) and of these, 35 were identified as killer whales, 50 as harbour porpoises, 392 as *Lagenorhynchus* spp., and 10 of the sightings were identified as northern bottlenose whales.

The observations by platform, duplicates, and estimated $p(0)$ for each species are shown in Table 4. In all cases, the PI models produced lower AICs than the FI models. Therefore, the PI method was used exclusively. Covariates included in the final model for each species, for both the Distance Sampling model (DS model) and the Mark Recapture model (MR model), are detailed in Table 5.

Fin whales

2002–2007

The sightings of fin whales are shown in Figure 3a. They were found throughout the survey area but were especially abundant west of Spitsbergen, in the Barents Sea, and in the western survey blocks near Iceland/Jan Mayen (NVN, NVS, JMC). The final detection function models used a half-normal key function, truncated to a perpendicular distance of 4000 m and included BSS as a covariate in the DS model (Figure 4a). The resulting *eshw* was 1858 m. The abundance of fin whales was corrected with $p(0)$=0.72 (CV=0.10) to 10,004 (CV=0.18, 95% CI: 6,937–14,426). Detailed results by survey block are reported in Table 6a.

2008–2013

The highest encounter rate of fin whales occurred west of Spitsbergen (ES1, ES2) and in the western Iceland/Jan Mayen survey blocks (CM2, CM3) (Figure 3b). The best-fitting models used a half-normal key function with truncation to 4000 m. The DS model was fit with BSS and weather as covariates and the MR model was fit with BSS as a covariate. Plots of the detection probabilities for each model are shown in Figure 5a. The resulting *eshw* was 1909 m. The abundance estimate of fin whales was corrected with $p(0)$=0.77 (CV=0.08) to be 10,861 (CV=0.26, 95% CI: 6,433–18,339) (Table 6b).

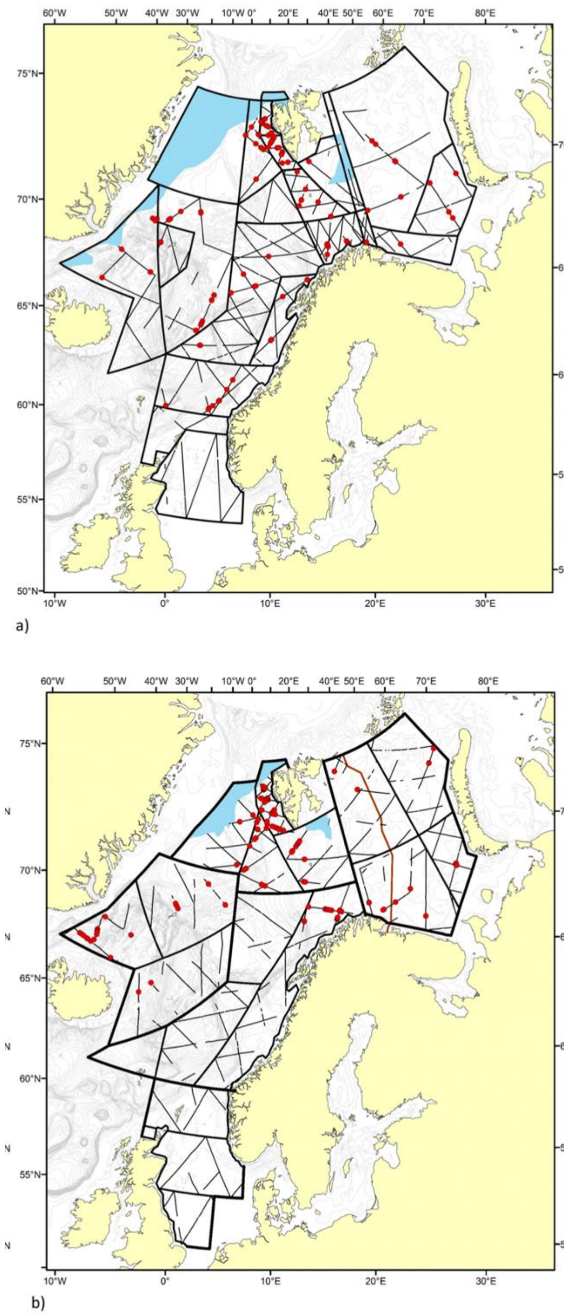

Figure 3. Distributions of sightings recorded as fin whales during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

Humpback whales

2002–2007

Humpback whales were found almost exclusively around Bear Island, in the northern Barents Sea, and in the western-most survey block north and east of Iceland (NVS), as depicted in Figure 6a. The best-fitting models used a half-normal key function truncated at a perpendicular distance of 4000 m and resulted in an *eshw* of 2240 m. The fitted detection function and conditional detection probability plots are shown in Figure 4b.

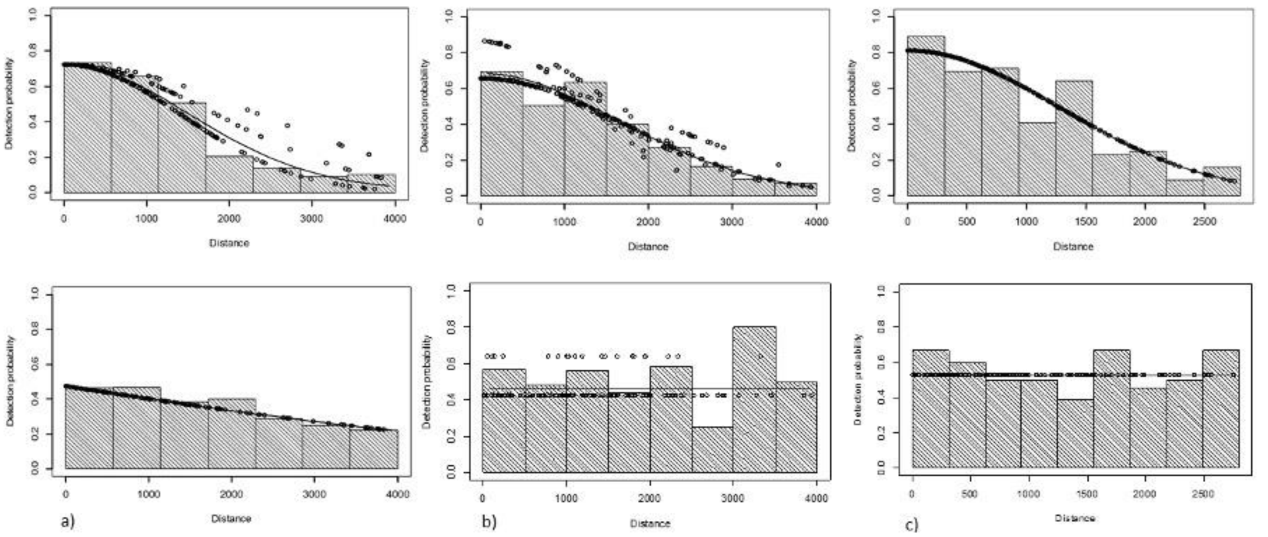

Figure 4. 2002–2007 survey detection function curves for pooled detections (top) and the conditional detection probabilities of platform 1 (bottom) for (a) fin whales, (b) humpback whales, and (c) sperm whales.

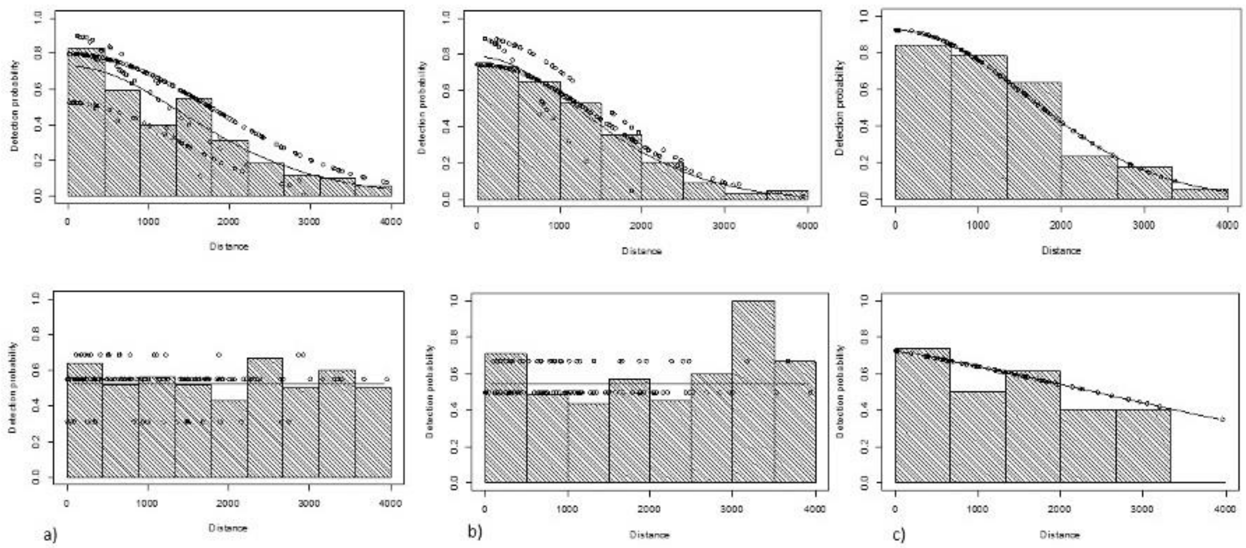

Figure 5. 2008–2013 survey detection function curves for pooled detections (top) and the conditional detection probabilities of platform 1 (bottom) for (a) fin whales, (b) humpback whales, and (c) sperm whales.

Weather was included as a covariate in both the DS and the MR models. This produced a total estimate for humpback whales of 9,749 (CV=0.34, 95% CI: 4,947–19,210), corrected with $p(0)$= 0.70 (CV=0.09) (Table 7a).

2008–2013

Humpback whales concentrated in 3 main areas: north and east of Iceland (CM2), around Bear Island (ES1), and in the northern Barents Sea (EB3) (Figure 6b). Detection function models were fit with a half-normal key function truncated to 4000 m, producing an *eshw* of 1760 m (Figure 5b). The probability of sighting a humpback whale on the trackline was estimated to be $p(0)$=0.79 (CV=0.05). Visibility was included as a covariate in the DS model and weather was included in the MR model. The total estimate of humpback whales (corrected for perception bias) was 12,411 (CV=0.30, 95% CI: 6,847–22,497) (Table 7b).

<u>Sperm whales</u>

2002–2007

Table 7a depicts the distribution of sperm whale sightings from the 2002–2007 sightings surveys. Most of the sightings were made in the deep waters of the Norwegian Sea, south of the Mohn Ridge between Jan Mayen and Bear Island. A half-normal key function produced the best fit to the data, truncated to 2800 m (Figure 4c). The resulting *eshw* was 1564 m and the probability of sighting sperm whales on the trackline was estimated to be $p(0)$=0.81 (CV=0.06). With correction for perception bias, the sperm whale abundance was estimated to be 8,134 (CV=0.18, 95% CI: 5,695–11,617). Detailed estimates by block are detailed in Table 8a.

2008–2013

Similar to the 2002–2007 survey, most of the sightings were made over the deep waters of the Norwegian Sea (EW1), south of Jan Mayen (CM1) (Figure 7b). A half-normal key function produced the best fit to the data truncated at 4000 m (Figure 5c). The resulting *eshw* was 1964 m. Sperm whale abundance was corrected with $p(0)=0.91$ (CV=0.03) to a total corrected estimate of 3,962 (CV=0.29, 95% CI: 2,218–7,079). Detailed results by survey block are reported in Table 8b.

Killer whales

2002–2007

Sightings of killer whales occurred mainly in the Norwegian Sea south of the Mohn Ridge in block NOS (Figure 8a). They were also abundant in the Icelandic/Jan Mayen survey blocks (NVN, NVS). The best fitting models used a half-normal key function. Data were truncated at 2000 m and resulted in an *eshw* of 996 m. BSS and weather covariates improved the fit of the DS model and group size improved the fit of the MR model (Figure 9a).

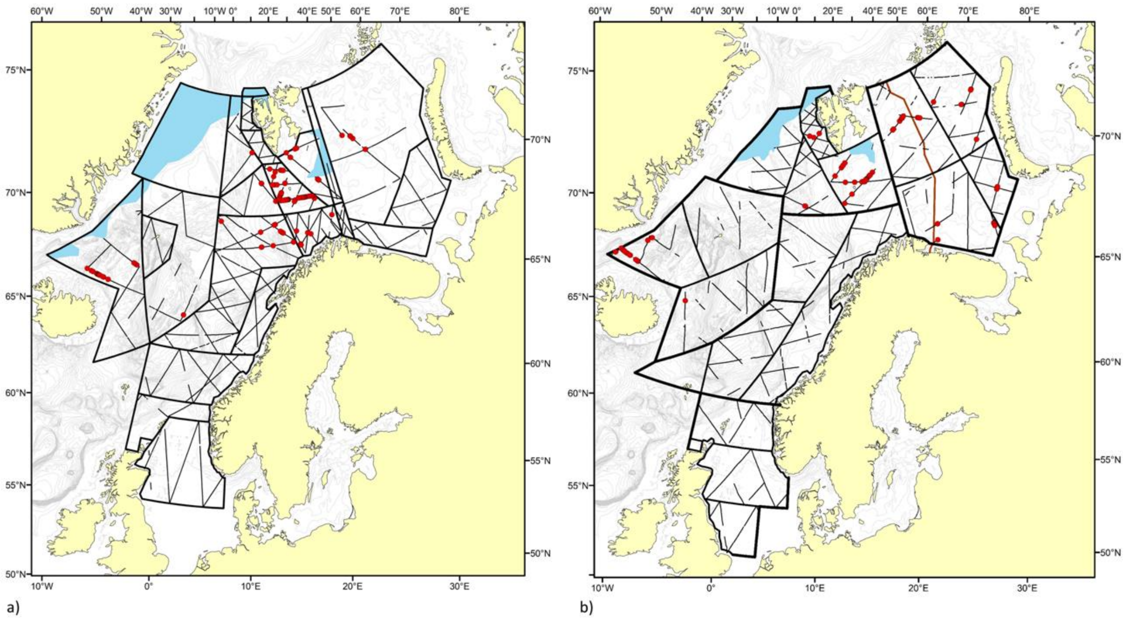

Figure 6. Distributions of sightings recorded as humpback whales during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

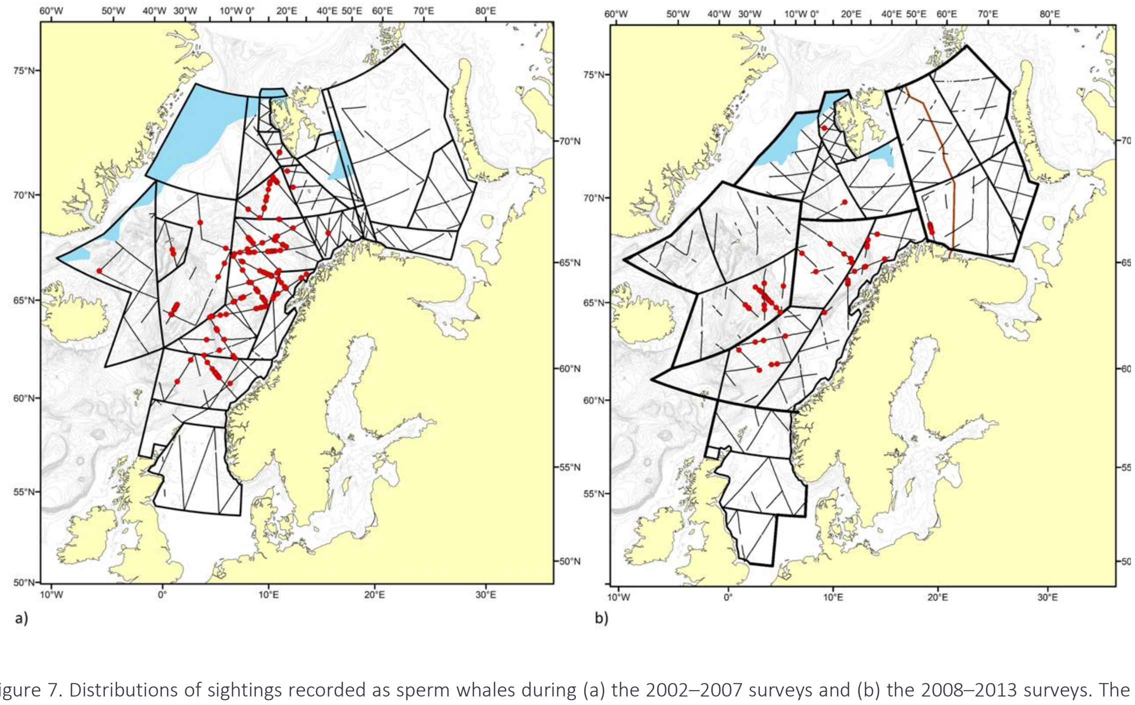

Figure 7. Distributions of sightings recorded as sperm whales during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

The probability of sighting a killer whale on the trackline was $p(0)$=0.93 (CV=0.04) and the total corrected estimate was 18,821 (CV=0.24, 95% CI: 11,525–30,735). Detailed estimates by block are reported in Table 9a.

2008–2013

As in 2002–2007, most of the sightings were made in the Norwegian Sea (EW1, EW2) south of the Mohn Ridge. They were also abundant in the Icelandic/Jan Mayen survey blocks (CM1, CM3) (Figure 8b). Models were fit with a half-normal key function (Figure 10a). Distances were truncated at 2200 m, resulting in an *eshw* of 1377 m. BSS improved the fit of the MR model. Once corrected for perception bias ($\underline{p}(0)$=0.92, CV=0.05) the total estimate for killer whales was 9,563 (CV=0.36, 95% CI: 4,713–19,403). Detailed estimates by block are provided in Table 9b.

Harbour Porpoises

2002–2007

Harbour porpoises were found in highest concentrations in the North Sea blocks NS and NC2 with additional concentrations in the Barents Sea (blocks KO and GA). They displayed a general shelf distribution within the study region and were absent from the western and northern-most survey blocks (Figure 11a). A half-normal key function with distances truncated to 600 m generated the best fitting models, resulting in an estimated *eshw*=279 m and $p(0)$=0.52 (CV=0.15) (Figure 9b). The DS model

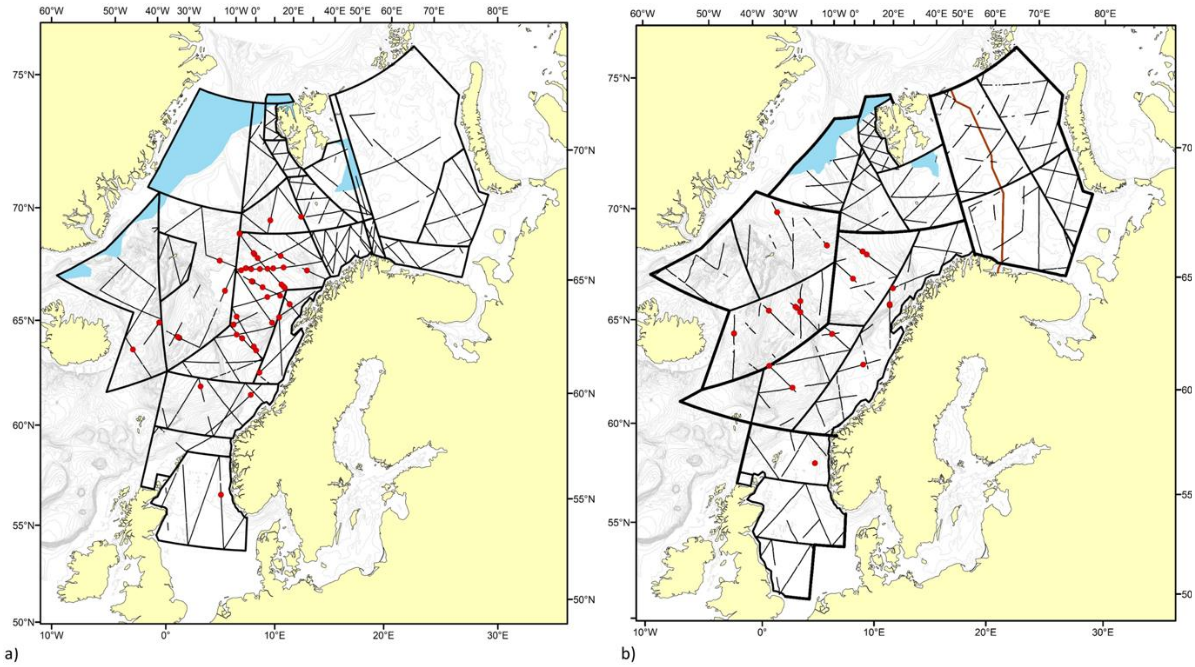

Figure 8. Distributions of sightings recorded as killer whales during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

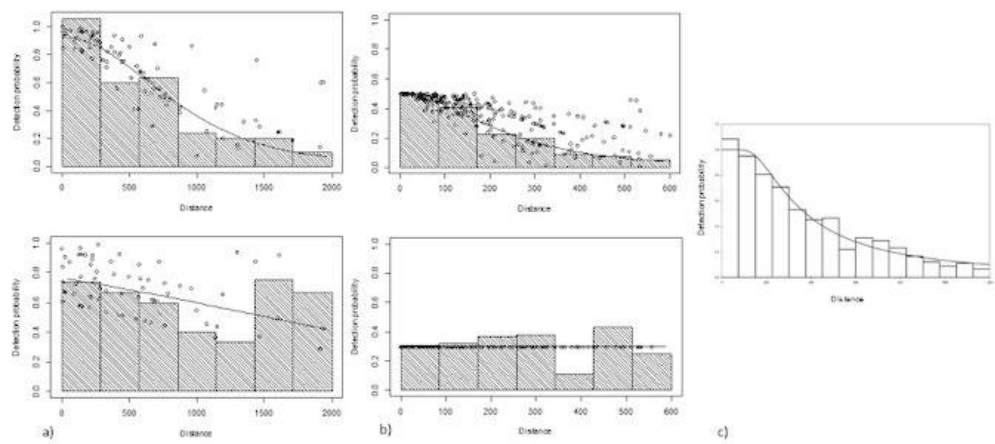

Figure 9. 2002–2007 survey detection function curves for pooled detections (top) and the conditional detection probabilities of platform 1 (bottom) for (a) killer whales (a); harbour porpoises (b); and the detection function curve of the platform 1 detection distances for *Lagenorhynchus* spp. (c)

included BSS, visibility, vessel, and group size as covariates. The MR model included the covariates BSS and weather. Once corrected for perception bias, the harbour porpoise abundance was 189,604 (CV=0.19, 95% CI: 129,437–277,738). Detailed estimates by block are provided in Table 10a.

<u>2008–2013</u>

Harbour porpoises were sighted most commonly in the Barents Sea (EB1, EB2) and the Norwegian Sea (EW1) and were completely absent from the western and northern-most survey blocks (Figure 11b). A half-normal key function with distances truncated to 500 m generated the best fitting models, with an *eshw* of 375 m. The proportion of harbour porpoises sighted on the trackline was estimated to be $p(0)$=0.36 (CV=0.49). Both the DS model and MR models included BSS as a covariate (Figure 10b). The corrected harbour porpoise abundance was 38,351 (CV=0.58, 95% CI: 13,158–111,777). Detailed estimates by block are provided in Table 10b.

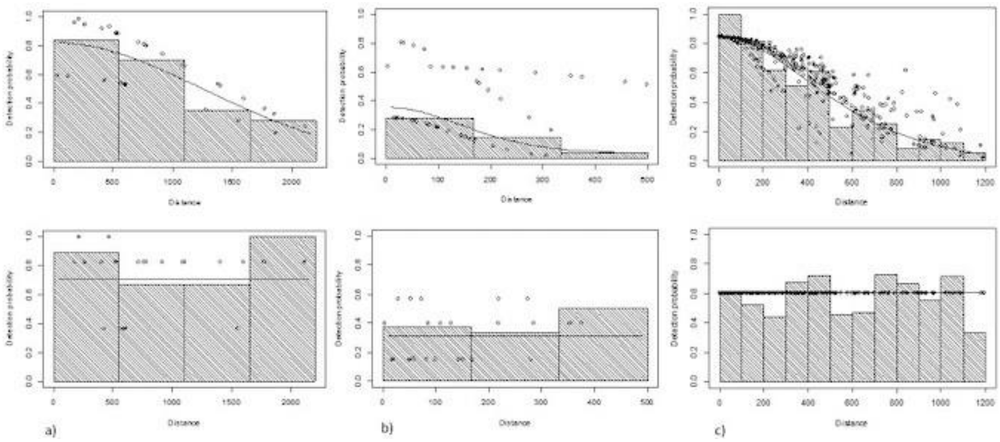

Figure 10. 2008–2013 survey detection function curves for pooled detections (top) and the conditional detection probabilities of platform 1 (bottom) for killer whales (a), harbour porpoises (b), and *Lagenorhynchus* spp. (c).

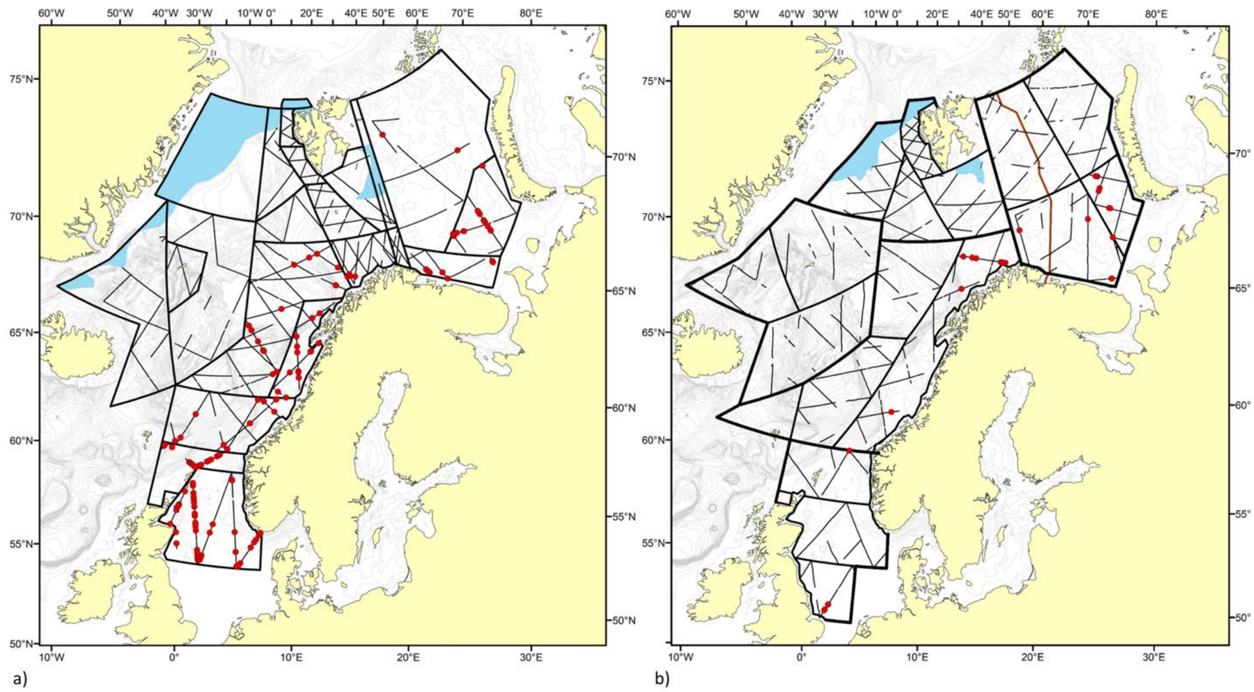

Figure 11. Distributions of sightings recorded as harbour porpoises during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

Table 2. Summary of effort and sightings for the 2002–2007 survey for each species by survey block and year.

Year	Block	Area sq. km	Total Transect length	Large whales	Fin whales	Humpback whales	Sperm whales	Blue whales	Sei whales	Northern bottlenose	Killer whales	*Lags* spp.**	Harbor porpoise	Northern bottlenose	Totals
2002	**FI1***	78,602*	1,736	12	11	6	1					115	6		151
	FI2*	16,033*	249	1								28	1		30
	NOS*	396,746*	4,314	28	17	12	101			1	39	12	16	1	227
2003	**BA1**	73,918	645	11	6	5						36	1		59
	BA2a	12,514	220	5	1	13						18			37
	BJ	75,479	1,228	45	13	144	1					79			282
	VSS	28,866	485	2	38		5					42			87
	NON	90,432	760	4		3	23			2	2	33		2	69
	SV	79,929	792	16	19	2						20			57
	VSN	18,259	339	10	22							1			33
2004	**NC1***	211586*	1,295	3	4		1			2	1	2	15	2	30
	NC2	99,537	372									0	51		51
	NS	261,311	2,154								3	81	107		191
2005	**JMC**	66,632	438	5	4		3	3		3		0		3	21
	NVN	351,582	1,823	13	24	1	17	2		1	13	1		1	73
	NVS	310,021	1,834	15	14	41	1	6		3	7	11		3	101
2006	**LOC**	97,352	1,253	6	9		24				7	1	21		68
	FI1*	78,602*	463	7	7	1						45	4		64
	NOS*	39,6746*	1,565	1		3	36		1		23	6	2		72
	NC1*	21,1586*	813		6		16				1	5	9		37
2007	**BA2b**	34,850	240									13	1		14
	BAE	401,721	1,783	3	11	14						39	4		71
	KO	95,965	768		1							26	27		54
	FI2*	16,033	129		2							4			6
	GA	160,934	1,310	2	9							10	29		50
Total		**2,962,269**	**27,009**	**189**	**218**	**245**	**229**	**11**	**1**	**12**	**96**	**628**	**294**	**12**	**1,935**

**partially surveyed in different years*

*** sightings from platform 1 only*

Table 3. Summary of effort and sightings for the 2008–2013 survey for all species by survey block and year.

Year	Block	Area sq. km	Total transect length	Large whales	Fin whales	Humpback whales	Sperm whales	Blue whales	Sei whales	Killer whales	*Lags.* spp.	Harbor porpoise	Northern bottlenose	Totals
2008	**ES1**	161,660	1,378	17	33	66	1	1			80			198
	ES2	46,525	1,116	33	73	3	1	1			116		1	228
	ES3	118,765	1,414	6	18	4	1				26		7	62
	ES4	131,447	1,348	3	4						3		1	11
2009	**EN1**	95,675	765									5		5
	EN2	197,293	1,283								6	1		7
	EN3	160,660	916							1	18	3		22
2010	**CM1**	297,396	1,779	1	2	1	30			10				44
	CM2	177,961	958	20	25	45			1		15			106
	CM3	295,929	1,002	6	9					3	2			20
2011	**EW1**	333,180	2,909	5	32		31			12	24	12		116
	EW2	218,943	969	2			9			5			1	17
	EW3	228,406	1,852	2			9			4				15
	EW4*	84,625	0											0
2013	**EB1**	107,105	1,199	2	9	6					3	19		39
	EB2	278,964	2,122	2	7	8	10				15	10		52
	EB3	269,058	1,579	8	3	33					19			63
	EB4	233,900	1,711	6	9	13					65			93
Total		3,268,243	24,300	113	224	179	92	2	1	35	392	50	10	1,098

** Block not surveyed due to poor weather*

Table 4. Estimated *p*(0) for each species showing the total number of sightings (n), sightings by platform, and duplicates.

Species	**2002–2007**						**2008–2013**					
	Observations				*p*(0)		Observations				*p*(0)	
	n	Plat 1	Plat 2	Duplicates	Estimate	CV	n	Plat1	Plat2	Duplicates	Estimate	CV
Fin whales	212	137	127	52	0.724	0.100	222	159	143	80	0.772	0.083
Humpback whales	241	174	139	72	0.705	0.092	170	119	115	64	0.788	0.048
Sperm whales	229	161	150	82	0.811	0.063	94	76	64	46	0.908	0.031
Harbour porpoises	279	177	150	48	0.518	0.145	46	31	24	9	0.355	0.489
Killer whales	91	66	72	47	0.930	0.040	31	26	23	18	0.820	0.049
Lagenorhynchus spp.	597	597	-	-	1.0*	0.000	354	246	261	153	0.835	0.041

**p(0)* was assumed = 1 for *Lagenorhynchus* spp., estimated from a single platform.

Table 5. Covariates included in the final models for each species in the 2002–2007 and 2008–2013 surveys for the Distance Sampling model (DS model) and the Mark Recapture model (MR model). Distance (D) is automatically added as a covariate in the DS Model. B=Beaufort, W=weather, Ves=vessel, V=visibility, G=glare, S=group size, D=distance.

	2002–2007		**2008–2013**	
Species	**DS Model**	**MR Model**	**DS Model**	**MR Model**
Fin whales	B	D	B+W	B
Humpback whales	W	W	V	W
Sperm whales				D
Harbour porpoises	B+V+Ves+S	B+W	B	B
Killer whales	B+W	D+S		B
Lagenorhynchus spp.		-	B+W+S	

Lagenorhynchus spp.

2002–2007

Lagenorhynchus spp. were found in almost all blocks within the study area, with the highest number of sightings around Bear Island (Figure 12a). A hazard-rate key function, without covariates, provided the best fit to the data from platform 1, which were truncated at a perpendicular distance of 1200 m. The detection function (Figure 9c) resulted in an *eshw* of 498 m and a total Platform-1 estimate of 213,070 (CV=0.18, 95% CI: 144,720–313,690). Block-wise estimates are detailed in Table 11a. As noted previously, the abundance was not corrected for perception bias.

2008–2013

Lagenorhynchus spp. were found throughout the survey area and were most commonly sighted around Bear Island (ES1) and the Barents Sea (EB4) (depicted in Figure 12b). A half-normal key function was used to fit the data (Figure 10c), with covariates BSS, weather, and group size in the DS model. The *eshw* was 585 m, with the data truncated to 1200 m. Detection of *Lagenorhynchus* spp. on the transect line was estimated to be $p(0)$=0.84 (CV=0.04). The corrected survey estimate of *Lagenorhynchus* spp. was 163,688 (CV=0.18, 95% CI: 112,673–237,800). Block-wise estimates are detailed in Table 11b.

Other species

Other species recorded, for which abundance has not been estimated due to an insufficient number of observations, include blue whales, sei whales, and northern bottlenose whales. Their distributions are displayed in Figure 13. No sightings of pilot whales were made, but block EW4 near the Faroes, where they would be expected (Pike et al., 2019a, 2019b), has not been covered in recent surveys.

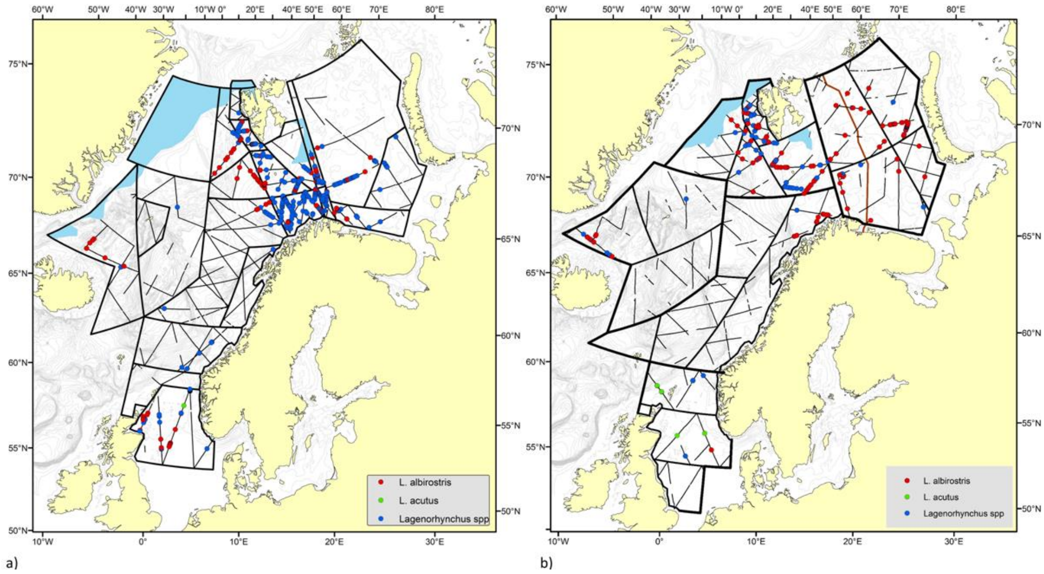

Figure 12. Distributions of sightings recorded as *Lagenorhynchus* spp. during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

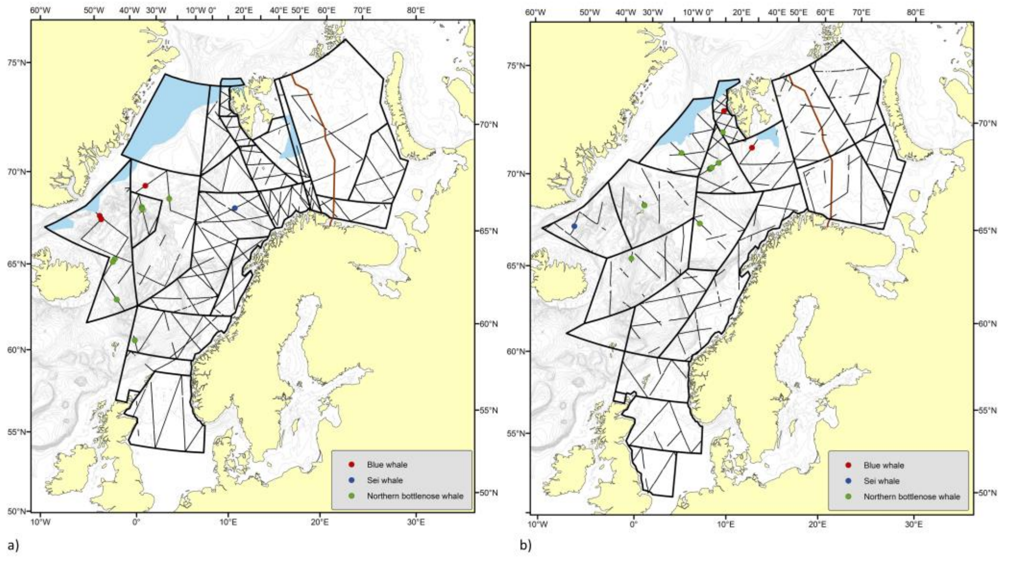

Figure 13. Distribution of blue whales, sei whales, and northern bottlenose whales sighted during (a) the 2002–2007 surveys and (b) the 2008–2013 surveys. The blue areas represent ice coverage.

Table 6. Estimated density and abundance of fin whales from the 2002–2007 survey (a) and the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study area. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block and corrected for perception bias, with the estimated $p(0)$.

a)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
BA1			0.016	1.030	1.67	0.000	0.006	1.036	448	1.036	12	16,228
BA2_a			0.005	0.000	1.00	0.154	0.002	0.158	84	0.158	55	128
BA2_b												
BAE			0.011	0.489	1.82	0.067	0.004	0.515	1,552	0.515	517	4,662
BJ			0.011	0.352	1.08	0.076	0.004	0.371	323	0.371	142	733
FI1			0.010	0.502	1.19	0.114	0.004	0.526	287	0.526	98	842
FI2			0.013	1.279	2.50	0.000	0.005	1.284	83	1.284	4	1,863
GA			0.006	0.572	1.00	0.000	0.002	0.580	330	0.580	94	1,157
KO			0.004	0.949	3.00	0.000	0.002	0.956	146	0.956	16	1,336
SV			0.025	0.465	1.05	0.053	0.010	0.473	763	0.473	250	2,332
VSN	1,858	8.14	0.074	0.329	1.33	0.093	0.026	0.349	469	0.349	178	1,234
VSS			0.099	0.339	1.30	0.056	0.033	0.402	946	0.402	344	2,597
JMC			0.012	0.912	1.75	0.000	0.004	0.918	286	0.918	33	2,446
NVN			0.016	0.334	1.25	0.179	0.006	0.345	2,146	0.345	1 027	4,486
NVS			0.008	0.596	1.06	0.068	0.003	0.646	925	0.646	240	3,563
NON												
NOS			0.004	0.448	1.31	0.156	0.001	0.486	537	0.486	207	1,394
LOC			0.007	0.620	1.13	0.044	0.003	0.630	273	0.630	57	1,306
NC1			0.005	0.465	1.11	0.112	0.002	0.461	406	0.461	147	1,119
NC2												
NS												
Total							**0.003**	**0.186**	**10,004**	**0.186**	**6,937**	**14,426**

b)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
CM1			0.001	0.666	1.00	0.000	0.000	0.775	137	0.775	29	644
CM2			0.034	0.540	1.35	0.067	0.017	0.595	2,989	0.595	858	10,417
CM3			0.013	1.011	1.37	0.110	0.004	0.984	1,190	0.984	123	11,538
ES1			0.031	0.689	1.22	0.051	0.010	0.685	1,593	0.685	329	7,714
ES2			0.093	0.291	1.44	0.107	0.027	0.280	1,275	0.280	696	2,335
ES3			0.015	0.337	1.25	0.161	0.006	0.385	682	0.385	288	1,616
ES4			0.003	0.326	1.00	0.000	0.001	0.423	165	0.423	67	411
EW1			0.013	0.579	1.18	0.068	0.005	0.545	1,577	0.545	522	4,764
EW2	1,908.9	5.14										
EW3												
EB1			0.007	0.469	1.00	0.000	0.002	0.374	239	0.374	93	614
EB2			0.004	0.553	1.13	0.068	0.001	0.514	324	0.514	113	930
EB3			0.004	0.671	2.00	0.492	0.001	0.677	280	0.677	73	1,076
EB4			0.005	0.782	1.00	0.000	0.002	0.811	409	0.811	78	2,163
EN1												
EN2												
EN3												
Total							**0.003**	**0.262**	**10,861**	**0.262**	**6,433**	**18,339**

Table 7. Estimated density and abundance of humpback whales from the 2002–2007 survey (a) and the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study region. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block and corrected for perception bias, with the estimated *p*(0).

a)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
BA1			0.008	0.457	1.00	0.000	0.003	0.478	210	0.478	38	1,163
BA2_a			0.073	0.000	1.23	0.107	0.026	0.004	331	0.170	215	509
BA2_b												
BAE			0.010	0.603	1.28	0.096	0.004	0.618	1,501	0.618	412	5,470
BJ			0.152	0.510	1.32	0.055	0.054	0.520	4,040	0.520	1,304	12,515
FI1			0.005	0.295	1.42	0.119	0.002	0.314	124	0.314	64	238
FI2												
GA												
KO												
SV			0.003	0.701	1.00	0.000	0.001	0.713	72	0.713	14	364
VSN	2,240	6.36										
VSS												
JMC												
NVN			0.001	1.036	1.00	0.000	0.000	1.048	72	1.048	10	501
NVS			0.027	0.734	1.27	0.016	0.009	0.742	2,925	0.742	644	13,292
NON			0.004	0.959	1.00	0.000	0.001	0.970	114	0.970	4	3,273
NOS			0.003	0.435	1.00	0.000	0.001	0.453	359	0.453	147	879
LOC												
NC1												
NC2												
NS												
Total							**0.004**	**0.311**	**9,749**	**0.336**	**4,947**	**19,210**

b)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
CM1			0.001	0.915	1.00	0.000	0.000	0.924	61	0.919	10	371
CM2			0.051	0.609	1.14	0.066	0.022	0.578	3,747	0.574	1,073	13,084
CM3												
ES1			0.067	0.460	1.59	0.022	0.026	0.509	3,963	0.499	1,197	13,117
ES2			0.003	0.646	1.00	0.000	0.001	0.659	46	0.652	12	175
ES3			0.002	0.910	1.00	0.000	0.001	0.919	93	0.914	14	618
ES4												
EW1			0.002	0.668	1.25	0.148	0.001	0.681	210	0.674	55	804
EW2	1,760.3	5.11										
EW3												
EB1			0.005	0.916	1.00	0.000	0.002	0.925	197	0.920	23	1,704
EB2			0.006	0.692	1.63	0.167	0.002	0.704	628	0.697	158	2,495
EB3			0.028	0.710	1.42	0.136	0.011	0.721	2,754	0.715	673	11,272
EB4			0.008	0.459	1.06	0.045	0.003	0.473	713	0.466	253	2 013
EN1												
EN2												
EN3												
Total							**0.004**	**0.305**	**12,411**	**0.295**	**6,847**	**22,497**

Table 8. Estimated density and abundance of sperm whales from the 2002–2007 survey (a) and the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study region. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block and corrected for perception bias, with the estimated *p*(0).

a)

Survey Block	***eshw***		**Encounter Rate**		**Group Size**		**Density**		**Corrected Abundance**		**95% Confidence Interval**	
	Estimate	**CV**			**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Lower**	**Upper**
BA1												
BA2_a												
BA2_b												
BAE												
BJ			0.001	0.953	1.00	0.000	0.000	0.957	24	0.957	4	162
FI1			0.000	0.977	1.00	0.000	0.000	0.980	14	0.980	2	86
FI2												
GA												
KO												
SV												
VSN	1,564	5.33										
VSS			0.008	0.969	1.00	0.000	0.004	0.972	118	0.972	12	1,117
JMC			0.003	0.912	1.00	0.000	0.00	0.566	137	0.566	32	578
NVN			0.007	0.407	1.12	0.091	0.004	0.440	1,448	0.440	565	3,711
NVS			0.001	1.019	2.00	0.000	0.000	1.022	134	1.022	19	935
NON			0.024	0.259	1.04	0.034	0.012	0.259	1,129	0.259	452	2,822
NOS			0.016	0.223	1.01	0.008	0.009	0.228	3,680	0.228	2,317	5,845
LOC			0.010	0.575	1.00	0.000	0.008	0.643	737	0.643	147	3,697
NC1			0.007	0.798	1.06	0.009	0.003	0.839	714	0.839	128	3,986
NC2												
NS												
Total							**0.003**	**0.180**	**8,134**	**0.180**	**5,695**	**11,617**

b)

Survey Block	***eshw***		**Encounter Rate**		**Group Size**		**Density**		**Corrected Abundance**		**95% Confidence Interval**	
	Estimate	**CV**			**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Lower**	**Upper**
CM1			0.017	0.531	1.06	0.031	0.005	0.563	1,516	0.563	457	5,032
CM2												
CM3												
EN3												
ES1			0.001	1.179	1.00	0.000	0.000	1.189	35	1.189	3	380
ES2			0.001	0.969	1.00	0.000	0.000	0.973	11	0.973	2	72
ES3			0.001	1.001	1.00	0.000	0.000	1.006	23	1.006	3	177
ES4												
EW1	1,964.1	8.42	0.011	0.417	1.06	0.031	0.003	0.447	1,080	0.447	428	2,726
EW2			0.009	0.320	1.00	0.000	0.003	0.333	559	0.333	239	1,307
EW3			0.005	0.318	1.00	0.000	0.001	0.331	305	0.331	145	640
EB1												
EB2			0.005	0.966	1.09	0.000	0.002	0.970	434	0.970	72	2,593
EB3												
EB4												
EN1												
EN2												
EN3												
Total							**0.001**	**0.286**	**3,962**	**0.286**	**2,218**	**7,079**

Table 9. Estimated density and abundance of killer whales from the 2002–2007 survey (a) and the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study region. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block and corrected for perception bias, with the estimated $p(0)$.

a)

Survey Block	***eshw***		**Encounter Rate**		**Group Size**		**Density**		**Corrected Abundance**		**95% Confidence Interval**	
	Estimate	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Lower**	**Upper**
BA1												
KO												
LOC			0.024	0.337	4.17	0.041	0.015	0.353	1,469	0.353	605	3,568
NC1			0.008	0.840	6.30	0.798	0.003	0.814	717	0.814	135	3,815
NC2												
NON			0.004	0.499	1.00	0.000	0.002	0.458	205	0.458	41	1,015
NOS			0.043	0.213	4.45	0.101	0.023	0.243	9,134	0.243	5,612	14,866
NS			0.006	0.918	3.97	0.049	0.003	0.927	696	0.927	94	5,157
NVN			0.019	0.579	2.45	0.097	0.015	0.695	5,180	0.695	1,291	20,788
NVS			0.009	0.837	2.68	0.052	0.003	0.758	1,016	0.758	222	4,654
SV	995.91	7.5										
BA2_a												
VSN												
VSS												
BA2_b												
BAE			0.002	0.992	4.00	0.000	0.001	1.000	404	1.000	60	2,726
BJ												
FI1												
FI2												
GA												
JMC												
Total							**0.006**	**0.242**	**18,821**	**0.242**	**11,525**	**30,735**

b)

Survey Block	***eshw***		**Encounter Rate**		**Group Size**		**Density**		**Corrected Abundance**		**95% Confidence Interval**	
	Estimate	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Estimate**	**CV**	**Lower**	**Upper**
CM1			0.028	0.220	5.21	0.186	0.011	0.370	3,528	0.388	1,601	7,776
CM2												
CM3			0.010	0.821	3.33	0.211	0.003	0.836	1,049	0.836	147	7,497
ES1												
ES2												
ES3												
ES4												
EW1			0.018	0.625	5.87	0.125	0.008	0.771	3,048	0.783	708	13,112
EW2	1,377.3	14.43	0.013	0.444	2.63	0.061	0.005	0.432	1,194	0.416	462	3,084
EW3			0.009	0.510	4.25	0.284	0.003	0.535	744	0.535	237	2,343
EB1												
EB2												
EB3												
EB4												
EN1												
EN2												
EN3												
Total							**0.003**	**0.355**	**9,563**	**0.362**	**4,713**	**19,403**

Table 10. Estimated density and abundance of harbour porpoises from the 2002–2007 survey (a) and the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study region. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block and corrected for perception bias, with the estimated *p*(0).

a)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
BA1			0.002	1.058	1.00	0.000	0.004	1.081	274.68	1.081	8.25	9,144
BA2_a												
BA2_b			0.004	0.000	1	0.040	0.026	0.206	1,239	0.206	829	1,851
BAE			0.003	0.478	1.43	0.299	0.015	0.516	5,972	0.516	2,083	17,119
BJ												
FI1			0.007	0.436	1.41	0.107	0.018	0.494	1,413	0.494	520	3,837
FI2			0.003	0.468	1.00	0.000	0.012	0.512	191	0.512	52	703
GA			0.032	0.463	1.25	0.124	0.128	0.387	20,545	0.387	9,065	46,561
KO			0.079	0.731	1.61	0.153	0.255	0.595	24,504	0.595	5,844	102,737
SV												
VSN	279.2	4.71										
VSS												
JMC												
NVN												
NVS												
NON												
NOS			0.003	0.431	1.09	0.069	0.013	0.472	5,266	0.472	2,108	13,154
LOC			0.024	0.279	1.30	0.076	0.080	0.304	7,768	0.304	4,006	15,063
NC1			0.015	0.273	1.26	0.066	0.064	0.313	13,548	0.313	6,994	26,244
NC2			0.180	0.118	1.23	0.066	0.669	0.191	66,551	0.191	45,432	97,486
NS			0.065	0.387	1.36	0.086	0.162	0.374	42,332	0.374	18,283	98,014
Total							**0.063**	**0.194**	**189,604**	**0.194**	**129,437**	**277,738**

b)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
CM1												
CM2												
CM3												
ES1			0.001	0.995	1.00	0.000	0.008	1.158	1,231	1.158	153	9,904
ES2												
ES3												
ES4												
EW1			0.004	0.700	1.00	0.000	0.031	1.063	10,304	1.063	1,679	63,228
EW2	375.2	10.79										
EW3												
EB1			0.019	0.426	1.30	0.079	0.132	0.690	14,107	0.690	3,790	52,514
EB2			0.007	0.552	1.29	0.250	0.028	0.544	7,683	0.544	2,712	21,761
EB3												
EB4												
EN1			0.007	0.765	1.5	0.000	0.011	0.869	1,050	0.869	152	7,240
EN2												
EN3			0.003	0.656	1	0.000	0.025	0.853	3,976	0.853	733	21,572
Total							**0.011**	**0.575**	**38,351**	**0.575**	**13,158**	**111,777**

Table 11. Estimated density and abundance of *Lagenorhynchus* spp. for platform 1 from the 2002–2007 survey (a) and for the combined-platform data for the 2008–2013 survey (b). The *eshw* (effective search half width (m)) was estimated for the entire study area. Encounter rate, group size, density, abundance, and upper and lower confidence limits were estimated by block.

a)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Platform 1 Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
BA1			0.029	1.058	3.21	0.321	0.054	1.091	4,028	1.086	127	127,860
BA2_a			0.082	0.000	2.94	0.171	0.166	0.179	2,079	0.170	1,465	2,951
BA2_b			0.054	0.000	5.15	0.209	0.277	0.216	9,663	0.242	5,761	16,208
BAE			0.024	0.733	4.88	0.075	0.082	0.740	32,966	0.740	7,257	149,760
BJ			0.056	0.449	4.65	0.109	0.195	0.449	14,685	0.466	5,300	40,688
FI1			0.075	0.199	5.79	0.074	0.373	0.219	29,279	0.219	18,484	46,381
FI2			0.079	0.289	5.87	0.184	0.373	0.332	6,172	0.332	2,711	14,053
GA			0.008	0.630	6.27	0.266	0.048	0.737	7,767	0.725	1,870	32,260
KO			0.033	0.574	4.68	0.114	0.144	0.604	13,858	0.589	3,222	59,601
SV			0.027	0.307	3.95	0.164	0.088	0.358	7,048	0.368	3,184	15,604
VSN	494.8	0.062	0.003	0.918	3.00	0.000	0.009	0.919	163	0.919	14	1,947
VSS			0.093	0.313	3.38	0.139	0.278	0.349	8,035	0.343	3,525	18,313
JMC												
NVN			0.001	0.941	1.00	0.000	0.001	0.942	163	0.942	32	1,181
NVS			0.005	0.494	1.00	0.212	0.022	0.543	8,035	0.550	2,204	20,879
NON			0.018	0.743	4.00	0.191	0.075	0.760	6,810	0.760	477	97,220
NOS			0.002	0.574	5.43	0.186	0.013	0.602	5,087	0.602	1,607	16,100
LOC			0.001	1.001	6.00	0.000	0.005	1.002	471	1.002	47	4,743
NC1			0.003	0.584	6.83	0.684	0.013	1.460	2,849	1.049	376	21,573
NC2												
NS			0.044	0.447	5.20	0.098	0.197	0.232	51,445	0.460	17,252	153,410
Total									**213,070**	**0.184**	**144,720**	**313,690**

b)

Survey Block	*eshw*		Encounter Rate		Group Size		Density		Corrected Abundance		95% Confidence Interval	
	Estimate	CV			Estimate	CV	Estimate	CV	Estimate	CV	Lower	Upper
CM1												
CM2			0.039	0.570	3.21	0.142	0.039	0.022	6,876	0.560	2,010	23,520
CM3			0.011	0.954	3.56	0.112	0.011	0.010	3,162	0.959	342	29,267
ES1			0.181	0.324	3.26	0.093	0.213	0.064	34,389	0.301	16,569	71,376
ES2			0.285	0.108	2.67	0.087	0.279	0.038	12,969	0.135	9,725	17,295
ES3			0.055	0.417	3.52	0.081	0.058	0.024	6,933	0.410	2,720	17,676
ES4			0.002	1.037	1.40	0.034	0.002	0.002	285	1.043	35	2,296
EW1			0.035	0.460	4.50	0.088	0.030	0.014	10,066	0.461	3,851	26,314
EW2	585.19	3.86										
EW3												
EB1			0.008	0.599	5.04	0.157	0.009	0.005	936	0.621	199	4,396
EB2			0.042	0.447	5.43	0.160	0.035	0.015	9,775	0.433	3,970	24,069
EB3			0.053	0.268	4.29	0.138	0.049	0.012	13,097	0.242	7,816	21,944
EB4			0.205	0.466	5.68	0.119	0.177	0.087	41,426	0.489	14,026	122,352
EN1												
EN2			0.025	0.241	6.14	0.362	0.023	0.007	4,632	0.290	2,356	9,108
EN3			0.131	0.688	6.09	0.062	0.119	0.082	19,141	0.685	2,740	133,699
Total							**0.049**	**0.009**	**163,688**	**0.182**	**112,673**	**237,800**

DISCUSSION AND CONCLUSIONS

Bias and estimation issues

Survey coverage

Ice coverage hampered effort in the northernmost regions of the study area. In 2002–2007, the entire SVI block was not surveyed due to ice. However, given that SVI accounted for only 2% of the total sightings (all species) in the previous survey period (Øien, 2009), the lack of effort in this area is not expected to have had a large effect on total abundance. In 2008–2013, ice also reduced the survey area coverage in the northern regions by 2.4%. Additionally, the EW4 block was not surveyed in 2008–2013 due to poor weather. However, the EW4 block was also not covered in the 2002–2007 survey, nor in the earlier 1996–2001 and 1995 surveys because it was not included as part of the SMAs under the minke whale RMP until 2003 (Øien, 2009; IWC, 2004).

Species identification

This study used survey methods specifically designed for minke whales (Skaug et al., 2004), which resulted in less optimal data collection for other species. The effective search half-width (*eshw*) for minke whales is in the range of half to one third of that for larger baleen whales. The designated search area for the observers was within 1500 m of the ship and observers were instructed to dedicate more of their effort to look for minke whales and also track them; thus, the detection of large whales was likely reduced by these patterns.

Some negative bias was likely introduced in the abundance estimates given that the surveys were conducted in passing mode and none of the sightings were closed upon. An examination of effective search half-widths for 'unidentified large whale' sightings, truncated at 4000m, resulted in estimates of 2107 m (CV=0.06) in 2002–2007 and 2509 m (CV=0.07) in 2008–2013, indicating that they are associated with greater sighting distances. It can therefore be assumed that the unidentified sightings do not bias the estimates proportional to their occurrence in the dataset. Additionally, an effort to improve identifications has reduced the proportion of 'unidentified large whales' in 2002–2007 and 2008–2013 to 19%, down from 30% in 1996–2001 (Øien, 2009). We did not allocate unidentified whales to species based on their occurrence in the dataset. The effect of uncertainty in species identification could be measured in future surveys by including a confidence rating for each identification, which would allow for a sensitivity analysis of the magnitude of bias in species identification.

Pooling robustness

The detection functions and effective search widths were fitted over the complete survey region because most blocks did not yield enough sightings to allow separate detection functions to be fitted. This may lead to bias in the estimates for some blocks if the detection distances vary between blocks. The bias is hopefully low simply due to the consideration that the survey blocks with the highest estimates—and therefore the greatest vulnerability to bias—also had the greatest influence over the detection functions.

Availability bias

The corrected estimates account for perception bias by estimating for the values of $p(0)$, but do not correct for availability, which may be a concern for sperm whales in this study. Given that sperm whales have long dive times (Drouot, Gannier, & Goold, 2004; Watkins, Moore, Tyack, 1985), they may remain submerged during vessel passage, and therefore undetectable. Availability bias is likely less of a concern for fin and humpback whales, which exhibit shorter dives (Dolphin, 1987; Panigada, Zanardelli, Canese, & Jahoda, 1999) and are therefore more likely to be detected within the window of time that they are in proximity to the ship. This should also not be a concern with small odontocete species because they tend to surface frequently and display conspicuous surface behaviour.

Duplicate judgement

Our methods for recording observations of non-target species—by recording only initial observations, without tracking—likely results in a higher level of uncertainty in judging duplicates compared to survey designs with tracking, such as the Buckland-Turnock (BT) method (Buckland & Turnock, 1992). The level of uncertainty is also likely higher in our surveys because the analyses rely heavily on post-cruise duplicate judgements and a largely subjective approach. Developing a more empirical and reproducible method, like that used for minke whales (Bøthun et al., 2009; Solvang et al., 2015), would reduce the potential error associated with judging duplicates. Additionally, including a confidence rating would allow for a sensitivity analysis of the effect of error in duplicate judgement.

Responsive movement

Responsive movement (i.e. when animals move toward or away from the ship before they are first detected), is a source of potential bias in any line transect survey studying cetaceans (Buckland et al., 2001). Movement toward the ship would result in a larger than expected number of sightings near the trackline (positive bias), whereas avoidance behaviour would have the opposite effect. Avoidance behaviour has been detected in harbour porpoises (Palka & Hammond, 2001), while white-beaked dolphins have been shown to display both attraction and avoidance behaviour, depending on their distance from the observation platform (Hammond et al., 2002; Palka & Hammond, 2001). Given the designated search distance for minke whales in the survey (1500 m), it is possible that responsive movement could occur with small odontocetes before they are first detected.

Evidence for responsive movement in baleen whales is more mixed. A 2007 survey conducted in European waters found some evidence that fin whales were attracted to vessels (Macleod et al., 2009), whereas a similar survey in 2016 found no responsive movement (Hammond et al., 2017). Similarly, minke whale avoidance behaviour has been detected in some surveys (Palka & Hammond, 2001), but not in others (Paxton, Gunnlaugsson, & Mikkelsen, 2009). These findings suggest that responsive movement may be survey-specific and depend on region, vessel type, and possibly other factors. Our survey did not measure responsive movement; thus, there is likely some unaccounted-for bias, although the degree and direction are unknown.

Distance estimation

There is a large potential for bias in distance measurements in line transect surveys such as ours, which rely on naked-eye estimates of distance by trained observers (Leaper, Burt, Gillespie, & Macleod, 2010). Error of this type can bias abundance estimates by influencing the detection function models and affecting the identification of duplicate sightings (Buckland et al., 2001). Leaper et al. (2010) have demonstrated that both distance and angle errors make a substantial contribution to the variance of abundance estimates and may cause considerable bias. They also found that naked eye estimates were negatively biased, but non-linear in that observers tended to overestimate shorter distances and underestimate greater distances.

To mitigate error in distance estimation, observers received regular training using buoys as targets and newer observers were paired with more experienced observers. Observers also tested and trained their distance estimation skills opportunistically using floating objects (such as buoys and birds) by estimating their distance, then verifying distances with a stopwatch using the speed of the vessel (300m/min). Leaper et al. (2010) have shown that using measurements of distance to objects at the surface such as buoys, were not predictive of the actual biases found in measurements during the surveys. In future surveys, more could be done to reduce this type of error by incorporating a means of validating some proportion of the measurements, for example using cameras or reticle binoculars.

Distributional shifts

Given that the survey is conducted over a multi-year period any shifts in distribution between survey years and between survey blocks could have an effect on the abundance estimates. To reduce additional variance due to distributional shifts, the goal of the surveys is to cover each minke whale SMA within one survey year (Skaug et al., 2004). This was achieved in the 2008–2013 survey cycle. However, in the 2002–2007 cycle, some SMAs were surveyed over multiple years and within the SMAs, some blocks were surveyed twice (NOS, FI), increasing the potential for this type of variance. As a result, there may be additional variance in the minke whale estimates for the 2002–2007 survey due to the added potential for the duplication/omission of sightings between years. The block design is for minke whales; thus, constraining the area surveyed to a single SMA in a given year doesn't necessarily reduce additional variance for other species, although it may help for more regional species (such as small odontocetes) due to the fact that the minke whale SMAs are oceanographic regions with natural physical and biological distinctions.

Variance due to distributional shifts likely differs between species. Killer whales in the Norwegian Sea and *Lagenorhynchus* spp. in the Barents Sea, for example, are local populations with large home ranges and their distribution is likely to vary within and between seasons in relation to prey distribution (Christensen, 1982, 1988; Øien, 1996). Other species like humpback whales, which are mostly migratory, show a generally consistent pattern of annual habitat use (Kennedy et al., 2013), but they can also display complex variation in distribution affected by larger climatological patterns as well as small-scale local effects (Keen et al., 2017; Visser, Hartman, Pierce, Valavanis, & Huisman, 2011).

Additional variance due to year-to-year shifts in distribution has been accounted for in minke whale estimates (Bøthun et al., 2009; Solvang et al., 2015). The estimates from prior synoptic and multi-year surveys and knowledge about population growth are used to model the random effects and estimate additional variance assuming a closed population based on genetic evidence and historic catch statistics. Corresponding information is not available for the non-target species that are locally abundant in smaller parts of the survey area.

Encounter rate variance

Variance in estimating encounter rate can be problematic for species other than minke whales, for which this survey was designed. Ideally, a transect design is stratified across a species' density in order to ensure precision in estimating the encounter rate variance (Buckland et al., 2001). The survey stratification was not considered for species other than minke whales, which may affect the precision of the estimates for other species. To aim for higher precision, a spatial modelling method could be applied to take spatial variation into account. This type of analysis has been shown to reveal habitat preferences of minke, fin and sperm whales and *Lagenorhynchus dolphins* (Skern-Mauritzen, Skaug, & Øien, 2009).

Harbour porpoise estimates and Beaufort Sea State

Typically for harbour porpoises, only survey effort at a BSS of 2 or less is used to estimate abundance, due to a rapid decline in detection at higher sea states (Barlow, 1988; Hammond et al., 2002). This approach was tested initially; however, our surveys exhibited a relatively high encounter rate at higher BSS compared to what has been observed in other multi-species surveys (e.g. Hammond et al., 2002) and lower variance when using total effort. As discussed at the NAMMCO Abundance Estimates Working Group meeting in October 2019, due to these factors it was agreed that total effort (BSS 4 or less) could be used for all of our survey cycles (NAMMCO, 2019). Given that the maximum sighting distance for harbour porpoises in these surveys was 600 m, and observers were asked to focus within a 1500 m range to detect minke whales, our survey method might generate reasonable abundance estimates for harbour porpoises.

Comparison to past surveys

Fin whales

The fin whale estimates for both surveys were very similar with a total abundance estimate of 10,004 (CV=0.19, 95% CI: 6,937–14,426) in 2002–2007 and 10,861 (CV=0.26, 95% CI: 6,433–18,339) in 2008–2013. Taking our corrections for perception bias into account (0.72 CV=0.10 in 2002–2007 and 0.77 CV=0.08 in 2008–2013), the previous uncorrected estimates of 10,369 CV=0.24, 95% CI: 6,277–17,128) in 1996–2001 and 5,034 (CV=0.21, 95% CI: 3,314–7,647) in 1995 are within the range of our estimates (noting that the 1995 survey did not cover block NVS, which was an important area for fin whales in all other surveys) (Øien, 2009).

The distribution of fin whales in our surveys was consistent with past surveys where fin whales were most abundant in the Icelandic blocks (JMC, NVN, NVS; CM1, CM2, CM3) and in the Svalbard blocks along the continental slope from Bear Island ranging northwards to the top of Spitsbergen (VSS, VSN; ES1, ES2) (Øien, 2009).

Humpback whales

We have found that the abundance of humpback whales in our study area has increased dramatically since earlier surveys. We estimate 9,749 (CV=0.34, 95% CI: 4,947–19,210) and 12,411 (CV=0.30, 95% CI: 6,847–22,497) humpback whales in 2002–2007 and 2008–2013, respectively. Previously, the survey in 1996–2001 estimated 4,695 (uncorrected, CV=0.39, 95% CI: 2,124–10,378), while the synoptic survey in 1995 estimates just 1,059 (uncorrected CV=0.25, 95% CI: 645–1,738) (Øien, 2009). Notably, block NVS was not surveyed in 1995, which estimated the highest abundance of humpback whales in 1996–2001 (3,246 CV=0.51, 95% CI: 1,137–9,264). The consistency we find in our estimates suggests the increase may have stabilized, which is a conclusion that is also supported by the most recent survey-cycle estimate from 2014–2018, published concurrently, of 10,708 (CV=0.39, 95% CI: 4,906–23,370) humpback whales (Leonard & Øien, 2020).

The humpback whales in our study area are part of a much larger population with a continuous distribution across feeding areas around Iceland, Greenland, and Eastern Canada and US (Smith, 2010; Smith et al., 1999). Humpback whales increased in abundance in the feeding grounds around Iceland at a rate of 11% between 1986–2001 (Pike et al., 2009). Since 2001, humpback whale distribution around Iceland has seen a shift to higher densities to the north of Iceland and a significant overall decline in density between 2001–2007 (Pike, Gunnlaugsson, Sigurjónsson, & Víkingsson, 2020b). The 2015 NASS survey, covering a broader region around Iceland and the Faroe Islands, also found a lower abundance compared to a 2007 survey (Pike et al., 2019b). The increase we observe in our surveys between 2002–2013 (and a more recent survey (Leonard & Øien, 2020) may be a northeastward continuation of the trend initially documented around Iceland (Pike et al., 2009). However, without further effort to track and identify the humpback whales observed in our study area, it is not possible to know whether the increase reflects population growth or immigration from other feeding areas.

The increase in abundance of humpback whales occurred largely in the Bear Island shelf area (BJ) and the Barents Sea. Our estimate around Bear Island in 2002–2007 (4,040 CV=0.52 95% CI: 1,304–12,515 in block BJ) was very similar to our estimate in 2008–2013 (3,963 CV=0.45, 95% CI: 1,197–13,117) in ES1). However, both estimates were substantial increases from the uncorrected 1996–2001 and 1995 survey estimates (144 CV=0.61, 95% CI: 34–601 and 656 (CV=0.31, 95% CI: 344–1,253), respectively (Øien, 2009). In past surveys, humpback whales were largely absent from the Barents Sea blocks (BAE, KO, GA) (Øien, 2009), but were abundant in our surveys, with a substantial increase between our 2 survey periods (summed block estimates: 1,358 in 2002–2007 and 3,220 in 2008–2013). These increases are likely related to ecosystem changes affecting the distributions of important prey species, as was concluded for the increase in abundance around Iceland (Pike et al., 2020b; Víkingsson et al., 2015). Large ecosystem changes have occurred in the Barents Sea during the past few decades, including collapses and subsequent recoveries of Atlantic herring and capelin and changes in herring over-wintering areas to areas of northern Norway (Gjøsæter, Bogstad, & Tjelmeland, 2009). An analysis of ecosystem surveys coincident with the 2002–2007 whale sighting surveys found that fin, humpback, and minke whales were spatially associated with the northern polar front and northern prey species including krill, amphipods and polar cod (Skern-Mauritzen, Johannesen, Bjørge, & Øien, 2011).

Sperm whales

The distribution of sperm whales is generally consistent between survey periods, as they are reliably found in the central Norwegian Sea (NOS, NON, and NVS), associated with deep water of the Norwegian Sea Basin. The estimate for 2002–2007 (8,134 CV=0.18; CI: 5,695–11,617) is most comparable to the 1996–2001 uncorrected estimate of 6,375 (CV=0.22; CI: 4,163–9,762) (Øien, 2009). However, our estimate for 2008–2013 (3,962 CV=0.29; CI: 2,218–7,079) is lower and more in line with the synoptic survey conducted in 1995, which estimated 4,319 (CV=0.20; CI: 2,903–6,424) whales (Øien, 2009). Although the earlier surveys were not corrected for perception bias, we found the probability of sighting sperm whales on the transect line was quite high (81% (CV=0.06) in 2002–2007 and 91% (CV=0.03) in 2008–2013 (Table 4); thus, the comparisons to uncorrected estimates are reasonable.

Killer whales

The estimated abundance of killer whales for the 2002–2007 survey (18,821 CV=0.24, 95% CI: 11,525–30,735) was roughly double the estimate from the 2008–2013 survey of 9,563 (CV=0.36, 95% CI: 4,713–19,403). In general, the abundance of killer whales in the study region is not well understood; however, a photo-identification study conducted in the fjords of northern Norway estimated a total population size of 731 individuals in 1986–2003 (Kuningas, Similä, & Hammond, 2014). The Norwegian Orca Project has identified approximately 1000 unique individuals associated with the over-wintering herring in Tysfjord over a 20-year-period (Jourdain & Karoliussen, 2018). This is likely a fragment of the total population of the North Atlantic. The population has been previously approximated to be 7,000 animals in the northern North Sea and the Barents Sea up to Bear Island (NAMMCO, 1998), consistent with our 2008–2013 estimate, but much lower than that from the 2002–2007 survey.

The variation between survey-cycle estimates may be due to survey design factors, such as spatial variation in density or interannual shifts in distribution (described under Bias and estimation issues), which are not considered for non-target species. The 2002–2007 survey cycle covered blocks within the Norwegian Sea in different years, with some repeat effort. The variation in estimates may also be a natural phenomenon, possibly due to dynamic prey distributions, with which killer whales in the Norwegian Sea have been shown to be closely associated (Nøttestad, 2015). Earlier studies of killer whale abundance in the eastern North Atlantic between the Faroe Islands and East Greenland, conducted in 1987, 1989, 1995 and 2001, also found high variability among their estimates, which ranged from 4,413 to 26,774 (Foote et al., 2007). A recent report on the status of killer whales in the North Atlantic summarizes all of the estimates currently available in the North Atlantic (Jourdain et al., 2019). Our survey estimates will hopefully aid in clarifying the population status of North Atlantic killer whales.

Harbour Porpoises

The total corrected abundance of harbour porpoises in 2002–2007, estimated to be 189,604 (CV=0.19, 95% CI: 129,437–277,738), is reasonable given that a 1989 survey estimated a total uncorrected abundance of 93,612 (CV=0.22) (Bjørge and Øien, 1995) and our probability of sighting harbour porpoises on the track line was roughly 50% (p(0)=0.52 CV=0.15). The 1989 estimate was based on a partial single-platform survey.

The estimate of harbour porpoises in the 2008–2013 survey is much lower than our 2002–2007 estimate and older estimates (Bjørge and Øien, 1995). The greatest discrepancy occurred in the North Sea, where the 2002–2007 survey estimated 108,883 (summed blocks NS and NC2) harbour porpoises and the 2008–2013 survey estimated 3,923 (summed EN blocks). Although there were no concurrent surveys for the North Sea for direct comparison, the SCANS surveys estimated an abundance for the North Sea of 355,408 (CV=0.22) in 2005 and 245,373 (CV=0.18) in 2016 (Hammond et al., 2013, 2017). Additionally, Gilles et al. (2016) developed seasonal habitat-based models for the North Sea for a period overlapping the 2008–2013 survey and found estimates in line with the SCANS surveys. Our most recent survey in 2014–2018 estimated 154,726 harbour porpoises in the North Sea blocks (EN) and a total estimate for the study area of 255,929 (CV=0.20, 95% CI:172,742–379,175) (Leonard & Øien, 2020). This aberrant estimate was discussed at the NAMMCO Abundance Estimates Working Group in October 2019 and it was agreed that the corrected estimate based on total effort could be accepted but that it should be treated as anomalously low and inconsistent with other estimates for the same area (NAMMCO, 2019).

***Lagenorhynchus* spp.**

According to past surveys, approximately 90% of the *Lagenorhynchus* spp. are white-beaked dolphins (Øien, 1996). Past surveys have indicated that the population size of white-beaked dolphins may be about 60,000–70,000 animals in the Barents Sea (Øien, 1996). Comparing similar areas in this study, the summed estimates in blocks BAE, GA, KO, BA2 and FI1 was 70,426 animals (single platform) in 2002–2007 and 65,234 animals (corrected) in 2008–2013 in the EB blocks. In the North Sea, however, our estimates show a large disparity from other survey estimates. We estimated 54,294 animals (single platform) for blocks NS and NC1 in 2002–2007 and 23,773 animals (corrected) in 2008–2013 compared to the 2005 SCANS survey, which produced an estimate of ~10,000 animals (white-beaked only) in roughly equivalent blocks (Hammond et al., 2013). These differences may be due to our estimates having high contributions to the CV from both encounter rate and group size, which have resulted in wide 95% confidence intervals for the North Sea blocks (Table 11).

ADHERENCE TO ANIMAL WELFARE PROTOCOLS

The research presented in this article has been done in accordance with the institutional and national laws and protocols for animal welfare that are applicable in the jurisdictions where the work was conducted.

ACKNOWLEDGEMENTS

The project was funded by IMR and grant no. 111043/S40 from the Norwegian Research Council with analysis support from NAMMCO. We are grateful to the Scientific Committee of NAMMCO and the NAMMCO Secretariat for their contributions to reviewing our analyses and coordinating this publication. We are very grateful to the Norwegian coast guard for having made vessels available to us, and to the crew of all participating vessels, observers and team leaders for dedicated and pleasant cooperation in conducting this research. Kjell Arne Fagerheim and Siri Hartvedt are gratefully acknowledged for their work in preparing and validating the data.

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