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Abundance Estimates of Cetaceans from the 2018 Pacific Region International Survey of Marine Megafauna

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Several marine mammal species on the west coast of Canada are reported as bycatch in fisheries. A provision of the United States (US) *Marine Mammal Protection Act* (MMPA) requires Canada, as an exporter of fish products, to provide population estimates and rates of incidental mortality from fisheries operations. However, abundance estimates in Canadian Pacific waters are lacking for most cetacean species, especially for the offshore areas, or are too old to meet MMPA requirements. The objectives of the Pacific Region International Survey of Marine Megafauna (PRISMM) were to provide recent abundance estimates and distribution data for large marine species in inshore and offshore waters of the Canadian Pacific.

The survey was conducted between July 4–September 5, 2018, using two Canadian Coast Guard vessels, and produced a total of 8,400 km of visual effort and resulted in 2,000 sightings of 20 marine mammal species. Using design-based distance sampling methods, new abundance estimates were provided for nine cetacean species in Pacific Canadian waters: 30,117 Dall's Porpoises (95%CI 22,142–40,965), 12,244 Humpback Whales (8,214–18,252), 7,352 Harbour Porpoises (3,547–15,237), 5,882 Pacific White-sided Dolphins (2,941–11,766), 3,829 Fin Whales (2,145–6,834), 2,207 Northern Right Whale Dolphins (726–6,709), 920 Risso's Dolphins (178–4,758), 199 Blue Whales (59–670), and 70 Sei Whales (24–209). These estimates are corrected for availability bias based on time-in-view and diving behaviour, but uncorrected for perception bias.

Except for Pacific White-sided Dolphins, the 2018 abundance estimates for cetaceans in inshore waters suggests that several populations are stable (Dall's Porpoises, Harbour Porpoises, Fin Whales) or are continuing to recover from past depletion and are expanding to new areas (Humpback Whales). The return of these predators to habitats from which they were previously extirpated will have important ecosystem-level implications. These coast-wide, updated abundance estimates can also inform Potential Biological Removal limits for anthropogenic mortality.

1. INTRODUCTION

Abundance and density of animal populations are essential information for stock assessments and evaluations of management procedures (Taylor et al. 2007). In particular, abundance estimates are necessary to assess whether human activities have a detrimental effect on populations (Wade 1998). Several marine mammal species are reported as bycatch in fisheries on the west coast of Canada. In January 2017, the United States (US) National Oceanic and Atmospheric Administration (NOAA) enacted a new rule requiring countries exporting seafood to the United States to demonstrate that their fisheries comply with the US *Marine Mammal Protection Act* (MMPA). To ensure accountability, the MMPA mandates periodic estimation of abundance (and uncertainty) to set a Potential Biological Removal (PBR) and compare it against estimates of bycatch mortality for each population. As an exporter of fish products, Canada must prove compliance by providing abundance estimates of its marine mammal populations and rates of incidental mortality from fisheries operations by January 1, 2022.

In Canadian Pacific waters, recent abundance estimates are available for the two populations of Resident Killer Whales (*Orcinus orca*, e.g., DFO 2019), Grey Whales (*Eschrichtius robustus*, Calambokidis et al. 2002), Sea Otters (*Enhydra lutris*, Nichol et al. 2020), and most pinnipeds (e.g., Majewski and Ellis 2022), all of which are surveyed at scheduled intervals. Other marine mammal species, however, are not covered by current monitoring programs. As a result, abundance estimates are often limited in geographical scope, out of date, or lacking altogether. For instance, mark-recapture analysis of photo-identification studies have yielded abundance estimates of Humpback Whales (*Megaptera novaeangliae*) for local areas (Ashe et al. 2013) but larger scale estimates are not available past 2008 (Ford et al. 2009). A combination of systematic and opportunistic surveys were used to model encounter rates and relative abundance of Humpback Whales in coastal British Columbia (BC) but did not yield estimates of absolute abundance (Dalla Rosa et al. 2012). Aerial surveys providing abundance estimates for Harbour Porpoises (*Phocoena phocoena*) were limited to inland waters of Washington State and a portion of southern BC waters (Jefferson et al. 2016).

Systematic line transect surveys were conducted by non-government researchers in BC’s coastal waters over multiple years and seasons (summer 2004, 2005, 2008, and spring/autumn 2007) and generated abundance estimates for ten marine mammal species (Williams and Thomas 2007; Best et al. 2015). For several species, these were the only available estimates and were used to inform sustainable limits for small cetacean bycatch in fisheries (Williams et al. 2008). In addition, these studies provided a baseline to monitor trends in abundance. However, these estimates are not recent enough to meet the MMPA standard of eight years (NMFS 2016).

Recent abundance estimates for coast-wide Canadian Pacific waters (including offshore areas) were therefore lacking for several cetacean species, and had to be assessed using a dedicated survey. Systematic surveys with the specific goal of estimating abundance of marine mammal species over the entire range of Canadian jurisdiction have been made in Atlantic Canada in 2007 and 2016 and in the Central Arctic in 2013, but never in Canadian Pacific waters. To meet the US MMPA requirements, DFO Science completed the Pacific Region International Survey of Marine Megafauna (PRISMM), a large-scale survey of inshore and offshore waters from July–September 2018. Its objectives were to document the distribution of marine mammals in Pacific Canada, as well as sea turtles and large fish species such as Basking Sharks and sunfish, and to estimate the abundance of cetacean species for which information is lacking or outdated.

2. METHODS

2.1. SURVEY DESIGN AND STRATIFICATION

PRISMM was a ship-based, multi-species survey using distance sampling methods to estimate abundance. Vessels travelled along pre-determined systematic transect lines within a stratified survey design. The goal was to survey all Canadian waters from the Alaskan border to Washington State, and from the coast of BC to the 200 nm limit of the Canadian Exclusive Economic Zone (EEZ). The study area was divided into two main blocks: an *inshore* block that covered the area previously surveyed by Williams and Thomas (2007) and Best et al. (2015), and an *offshore* block that corresponded to areas west of Vancouver Island and Haida Gwaii, for which no previous cetacean abundance estimates were available (Fig. 1).

The inshore block was further divided into four strata, following the survey design from Thomas et al. (2007), which had been developed specifically for this area with a complex coastline and has been proven effective over the course of five previous surveys (Best et al. 2015). Stratum *North Coast* (NC) encompassed waters north of Johnstone Strait while stratum *South Coast* (SC) included the Strait of Georgia and Juan de Fuca Strait. Because of their narrow shape, Johnstone Strait and Discovery Passage were assigned to their own stratum (JS). The fourth stratum encompassed an ensemble of fjords, passages, straits and inlets on the mainland of BC. These inlets were cut into 33 Primary Sampling Units (PSUs), from which a sample of five was selected using a systematic random design (with probability of sampling proportional to area, for details see Thomas et al. 2007).

Surveys within strata NC and SC were designed as a sample of equal-spaced zig-zag lines with a random start point (Fig. 2), using the software DISTANCE (Thomas et al. 2010). This approach ensures that each point within a stratum has the same probability of being surveyed, allowing unbiased abundance estimation (coverage probability throughout the study area was evaluated based on 10,000 simulations in Thomas et al. (2007). Spacing between zig-zag waypoints was 36 km in NC and 18 km in SC (which was sub-divided into a three substrata because of its non-convex shape). Because of their narrow and complex shapes, it was impossible for the DFO survey vessel to run parallel or zig-zag lines in the mainland inlets, unlike the smaller platform used in the 2004–2008 surveys reported by Williams and Thomas (2007) and Best et al. (2015). Instead, our vessel often had to navigate in the middle of the most narrow channels (e.g., Johnstone Strait), and, when possible, used non-systematic zig-zags to cover wider bodies of water.

The offshore block consisted of a single stratum (OFF, Fig. 1). Following the design of Barlow and Forney (2007) for offshore ship surveys along the US west coast, transects followed a systematic grid that was established to uniformly cover waters between the west coast of Vancouver Island and Haida Gwaii and 370 km (200 nm) offshore. This grid was created using two designs of parallel systematic transect lines separated by 60 km, each anchored by a randomly chosen start point. One set of lines ran in a SSW-NNE orientation and the other in a WSW-ENE orientation (Fig. 2). Together, the lines generally ran across the main habitat gradients (continental shelf and slope, abyssal plains, sea mounts). Segments between grid nodes constituted the main survey unit and were not necessarily surveyed in order.

2.2. SURVEY METHODOLOGY

2.2.1. Survey platform and visual effort

The survey ships were the 52-m Canadian Coast Guard Ship (CCGS) *Tanu* for the inshore block and the 69-m CCGS *John P. Tully* for the offshore block. They travelled along survey transects at a speed of approximately 18.5 km h^{-1} (10 kts) when on-effort. Visual survey effort started in the morning when enough light was available (usually around 6 AM) and occurred as long as viewing conditions were favourable. Visual effort was halted when seas were greater than sea state 4 on the Beaufort scale (swell height > 2 m and wind > 16 kts), or when visibility was less than 3 nm from directly forward of the beam of the ship to 45° to port and to starboard, or when it became dark (usually around 9 PM). In the inshore block, the vessel did not continue moving at night, except to reposition to the start of the another transect. In the offshore block, however, the ship usually continued to sail at night and in poor viewing conditions because it collected acoustic data (not shown in this document).

The survey was planned to take place in July–August, which is the period of peak abundance of several migrating species of marine mammals, as well as the best season for weather conditions. Because many cetacean populations range over wide areas of the north Pacific, the timing of the Canadian PRISMM survey was also aligned with that of NOAA's major cetacean survey of US eastern Pacific waters (which takes place every five years), to provide a more synoptic view of cetacean distribution.

Most of the survey was conducted in passing mode, during which the ship did not divert from the trackline when detections were made. A closing mode, during which the ship could divert to allow closer estimation of group size and species composition, was only used when deemed necessary. Additional sightings made during closing mode were not retained in the abundance analysis, but were kept to inform distribution maps.

2.2.2. Data collection

When on-effort, three observers were stationed on the observation deck (above the bridge) to collect sightings. Two of the observers (primary observers) were stationed on each side of the bow from where they scanned continuously from 10 degrees on one side of the transect line to 90 degrees on the opposite side (i.e., directly abeam) using 7x50 Fujinon binoculars. These observers worked independently to report sighting information and environmental conditions to a data recorder who was stationed on the navigation deck (bridge) by way of Ultra High Frequency (UHF) radio fitted with a headset and microphone. Observers rotated through the port and starboard primary observer positions and the data recorder position every half-hour, after which they took a period of rest to prevent fatigue.

The data recorder entered all information into a laptop computer equipped with Mysticetus software (Steckler and Donian 2018). Sighting information included time, species, and group size. Positions of sightings relative to the transect line were determined using the binocular's reticles to measure distance. When animals were within 500 m of the ship (i.e., too close for the binocular's reticles), distance was estimated using custom-made measuring sticks adapted to each observer's height). Radial angles were measured by the observers using electronic angle boards made from digital protractors located at each of the primary observer stations. The latitude, longitude and speed of the survey vessel were recorded automatically using a GPS. The speed and direction of travel of the ship were used to assess a given animal's expected position over time to avoid double-counting sighted animals.

A third observer on a separate two-hour rotation used Fujinon 25x150 MTM heavy-duty military binoculars with reticles to assist the two primary observers with species identification and group size counts. This "big-eye" observer did not contribute to detections of animal groups, and only provided species identification and group size information for sightings first reported to the data recorder by a primary observer. Blow shapes and patterns were not considered sufficient to confirm species. If there was uncertainty about species identity that could not be clarified by the "big-eye" observer, the species was considered unknown.

Environmental conditions were recorded at each observer rotation time (i.e., every 30 min), and were also updated at any time if they changed rapidly. Environmental conditions recorded were: sea state (Beaufort scale), visibility (Excellent – horizon unobstructed from 0° to +/- 90° , Good – horizon unobstructed from 0° to +/- 45°, Fair – horizon partially obstructed from 0° to +/- 45° but visibility > 3 nm, Poor – < 3 nm visibility from 0° to +/- 45°), swell height (No swell, Low < 1 m, Moderate 1-2 m, Big > 2 m, Confused), precipitation (Clear, Fog, Mist, Light rain, Heavy rain, Snow, Haze, Smoke), percent cloud cover (Clear, < 25%, 25% to 50%, 50% to 75%, 75% to 99% and 100%) and glare (None, Mild, Severe, with angles of glare reported as angles to port or starboard from the ship's heading).

Prior to the start of the first survey day on both ships, observers were given training to familiarize themselves with the survey protocol. Most of the observers had prior experience with the protocol from more than one prior marine mammal ship-based survey.

2.2.3. Buckland-Turnock trials

Two commonly violated assumptions of distance sampling are that detection on the trackline is perfect and that animals are detected at their initial positions. One recommended way of dealing with the issue of perception bias (i.e., animals are missed by observers even at close distances) is the use of a double-platform, with two sets of independent observers. However, such a set-up was not logistically possible on the PRISMM vessels. Therefore, in addition to the main protocol described above, a secondary data collection protocol was implemented in an attempt to incorporate corrections for animals missed on the transect line and to account for responsive movement, following the methods of Buckland and Turnock (1992).

The so-called Buckland-Turnock (BT) protocol is a trial configuration with asymmetric observers (in the sense that secondary observers are aware of primary detections, but not the other way around). While primary observers conduct their regular scans of the area, a secondary observer, using the "big-eye" binoculars, searches farther ahead of the vessel with the aim of detecting animals before they have been detected by the primary observers and before they may respond to the approaching vessel. This protocol was not implemented continuously but was used whenever possible (i.e., when the secondary observer is not busy with tracking primary detections and confirming group sizes and species identity for a primary observer).

Sightings made by this secondary observer were recorded separately and were used to set up "trials". The secondary observer was aware of detections made by primary observers and determined if the trial was successful (i.e., detected by primary observer) or unsuccessful. This determination was made only after the group had passed abeam and had been clearly missed by the primary team. A trial result could also be "unknown" if the situation was ambiguous, or "abandoned" if it proved impossible to continue tracking a particular sighting. These data can then be used in a mark-recapture distance sampling analysis to estimate the proportion of sightings missed by the primary team (Laake and Borchers 2004). Moreover, perpendicular distances from repeated observations of the same groups were inspected for signs of responsive movement (attractive or repulsive) in relation to the survey platform.

2.3. DATA PROCESSING

Data were controlled for quality and consistency. Perpendicular distances to sightings were calculated from the radial distance and angle measurements using trigonometry. In coastal regions, the presence of the shoreline prevents the proper use of the binocular's reticles because the horizon cannot be used as a reference. For this reason, sightings data were analysed with a custom-made script in R that checked for the distance to the nearest shore in the direction recorded by the observer and corrected the position and distance of sightings for which it was determined that the shore had been used as a reference instead of the true horizon.

Sightings without radial distances, angles or species identifications were discounted from further analysis. Sightings made on-effort but while in transit between transects were kept for the fitting of detection functions but were omitted from the calculation of abundance estimates. The length of each transect surveyed while on visual effort was calculated and strata areas were computed in QGIS.

2.4. DETECTION FUNCTIONS

Detection functions were fitted to perpendicular distance data from sightings of each species using the “ds” function in the R package “Distance” (Miller 2017). To maximize the number of available detections, sightings from transit segments that were surveyed while on-effort and in acceptable conditions were included in the fitting (with their covariates) but later excluded from the abundance estimation. Candidate models included half-normal, hazard-rate and uniform keys fit using either conventional distance sampling (CDS), with and without adjustment terms, or fitted using multi-covariate distance sampling (MCDS) with combinations of the following covariates: visibility, Beaufort sea state, observer, vessel, and group size.

We first fitted a key-only CDS detection function and then began adding covariates using a stepwise forward selection process, starting with single-covariate MCDS detection functions. Comparison of Akaike information criterion (AIC) values between the CDS (key-only) and MCDS candidate detection functions was used to determine whether a covariate should be retained. Additional covariates were added to the MCDS detection function as long as the resulting AIC value of the fitted model continued to decrease. In addition to AIC values, we also used quantile-quantile plots to visually assess the fits of candidate detection functions.

Once a detection function had been chosen, we applied a right-truncation distance equivalent to the distance at which the probability of detection, $\hat{f}(x)$, dropped to approximately 0.15, as recommended by Buckland et al. (2001). By truncating the perpendicular distance data in this way, we were able to minimize the number of lower-value inclusion probabilities, thereby reducing the bias in the resulting Horvitz-Thompson-like estimators of abundance (D.L. Borchers, personal communication).

Beaufort sea state and visibility categories were pooled to ensure a sufficient number of sightings within each covariate level. Pooling depended upon how changes in the covariate levels were perceived to impact the detectability of the different species. For instance, Beaufort categories 0-2, 3, and ≥ 4 were used for Humpback Whales and Fin Whales, categories 0–2 and ≥ 3 were used for Dall’s Porpoises (*Phocoenoides dalli*), whereas categories 0–1 and ≥ 2 were used for Harbour Porpoises (*Phocoena phocoena*).

2.5. ABUNDANCE ESTIMATES

Within an MCDS framework, the abundance N_i of each species in each stratum i was estimated using a Horvitz-Thompson-like estimator (equation 3.32 in Marques and Buckland 2003):

$$\widehat{N}_i = \frac{A_i}{2L_i}\sum_{j=1}^{n_i} f(0|z_j) \cdot s_j$$

where A_i is the area of stratum i, L_i= the length of on-effort transect line in stratum i; $f(0|z_j)$ = the probability density function at zero perpendicular distance for group *j* with associate covariates *z*; s_j = the number of individuals in group j; and n_i = the number of groups of that species sighted in stratum i.

Note that in the special case of a CDS framework, this equation reduces to:

$$\widehat{N}_i = \frac{A_i \cdot n_i \cdot \hat{s}_i}{2L_i \cdot w \cdot \hat{p}}$$

where $\hat{s}_i$ = the estimated average group size in stratum i; w = the truncation distance; and $\hat{p}$ = the probability of detection over the truncation distance.

The variance of $\widehat{N}_i$ was calculated following Innes et al. (2002) to include the sampling error involved in extrapolating the abundance to the entire survey region from a sample of transects. Using the delta method, this estimate of the variance also incorporates the variance component due to estimation of the parameters of the detection function and the component due to estimating the mean group size (equations 3.35 to 3.38 in Marques and Buckland 2003).

Total abundance $\widehat{N}$ for a species was estimated as the sum of abundances $\widehat{N}_i$ over all strata. Log-normal, *t*-based, two-sided 95% confidence limits for the estimates of density and abundance were obtained using equations 3.72–3.76 of Buckland et al. (2001).

2.6. AVAILABILITY CORRECTION

In addition to a potential perception bias (observers not detecting animals that are at the surface), estimates of marine mammal abundance can also suffer from availability bias (observers not detecting whales because the animals are submerged below the surface). In ship surveys, where the observation platform is moving relatively slowly, it is often assumed that this bias is less severe than for fast moving platforms like aerial surveys, except for long-diving species that may be submerged for the entire time that the ship is within visual range.

To investigate the magnitude of this bias in PRISMM and propose potential correction factors, we adapted the model developed by McLaren (1961), which incorporates the dive cycle of the animal and the search time of the observer. In this model, we assume that the observers scanned a quarter circle on each side of the ship, with a radius *r* corresponding to the maximum distance at which a given species could be detected. Within this area, the time θ that any point at the surface remains in view (i.e., time-in-view) for a given perpendicular distance *x* from the trackline, while the ship is travelling at speed v was calculated as:

$$\theta(x, v) = \frac{\sqrt{r^2 - x^2}}{v}$$

McLaren's (1961) model has two components: the probability that an animal is at the surface when entering the observer's view, expressed as $s/(s+d)$, with s being the time the animal can be seen at the surface and d the period when animals are submerged), and the probability that an animal is in a dive while entering the viewing area $d/(s+d)$ multiplied by the probability of surfacing within the viewing area, which Laake et al. (1997) proposed expressing as $\left(1 - e^{-\theta(x,v)/d}\right)$. Therefore, for a given perpendicular distance and speed, the correction factor for availability is given by:

$$C_a(x, v) = \frac{\mathrm{s}}{\mathrm{s} + \mathrm{d}} + \frac{d \cdot \left[1 - e^{-\theta(x,v)/d}\right]}{s + d}$$

The total availability correction factor, C_A, was calculated as the mean of the $C_a(x, v)$ for all observed groups and was then applied to the uncorrected abundance estimate for each species using:

$$\widehat{N}_c = \frac{\widehat{N}}{C_A}$$

For PRISMM data, we set the maximum radial distance equal to the right-truncation distance of the corresponding detection function, and calculated C_a for each perpendicular distance within truncation limits using the vessel speed recorded at the time of that sighting. As much as possible, we informed parameters s and d using values from the literature.

3. RESULTS

3.1. EFFORT

The PRISMM survey was conducted between July 4–September 5, 2018, and produced a total of 8,394 km of on-effort transects (Table 1, Fig. 2) as well as transiting legs that occurred between some of the transects, but for which observers still logged sightings as if they were on a regular transect. Overall, 50% of planned survey effort was realized in visual conditions, with 86% of planned effort in the inshore block and 43% of planned effort the offshore block. The offshore part of the survey was hampered by thick fog for long periods of time, especially in the northern part of the stratum. In contrast, the southern part was surveyed extensively and some segments that had been surveyed only at night (i.e., acoustic effort only) were surveyed a second time in daylight. Closing mode was used less than 10 times, to confirm the species identity of suspected rare species (Blue and Sei Whales, beaked whales) and did not result in additional sightings that would have had to be discarded.

3.2. SIGHTINGS

Overall, PRISMM resulted in 2,000 sightings of 20 marine mammal species. The total number of detected sightings, individuals, and the mean group size for each cetacean species is presented in Table 2. Humpback Whales were the most commonly encountered cetacean in Pacific Canadian waters (767 groups) and were found in all survey blocks, including mainland inlets, with fin whales the second most common mysticete (235 groups). Only 6 sightings of Blue Whale groups and 4 sightings of Sei Whale groups were made (all in the offshore stratum). Dall's Porpoises (287 groups) were commonly encountered throughout the offshore and NC strata, while Harbour Porpoises (246 groups) were mostly seen in the SC stratum. Only 25 sightings of Pacific White-sided Dolphins were made during the entire survey. Other cetacean sightings included (number of individuals): 13 Minke Whales, 14 Sperm Whales, 2 Baird's, 1 Cuvier's and 5 unidentified beaked whales, 6 Northern Right Whale Dolphins and 4 Risso's Dolphins. One group of Short-finned Pilot Whales was observed while off-effort. Killer Whales were seen on 27 occasions (all ecotypes). A total of 19 Sea Otter groups were observed, and pinniped sightings comprised (number of individuals): 205 Harbour Seals, 83 Northern Elephant Seals, 44 Northern Fur Seals, 35 Steller Sea Lions. Maps of sightings for cetacean species or species groups are presented in Figs. 3–9.

Although its main focus was on cetacean species, PRISMM also aimed at obtaining new information on other marine megafauna. However, no Leatherback Sea Turtles or Basking Sharks were seen in any of the blocks. Smaller sharks were seen close to the ship on numerous occasions but species identity could not be ascertained by the observers. A total of 72 Ocean Sunfish (*Mola sp.*) sightings were made, always in very close proximity to the vessel bow and with very little time-in-view.

3.3. DETECTION FUNCTIONS

Four species had sufficient (> 50) sightings with perpendicular distance data to reliably fit a detection function without having to pool species together: the Humpback Whale, Fin Whale, Dall's Porpoise, and Harbour Porpoise.

The best-fit detection function for Humpback Whales was a hazard-rate key with the covariates of vessel, observer, sea state, visibility and group size (Fig. 10). It had a right-truncation distance of 4,000 m and an effective strip (half)-width (ESW) of 1,479 m. Sightings (n=19) made by one of the observers were omitted from the Humpback Whale detection function because a high proportion of them (32%) were located on the trackline itself, which resulted in a failure of the truncated model to fit properly at distances close to zero. These sightings were re-introduced to the data set during the abundance estimation phase of the analysis.

The best-fit fin whale detection function was also a hazard-rate key, but only included the covariates of visibility and group size (Fig. 10). It had a slightly larger right-truncation distance of 5,000 m and a greater ESW of 2,377 m.

The best supported model for Dall's Porpoise detection function was a hazard-rate key with visibility and vessel as covariates, a right-truncation distance of 1,200 m and ESW of 398.7 m. However, this model exhibited a moderate spike near zero. Given that Dall's Porpoise are known to bow-ride (although there was only one instance recorded during PRISMM), it is possible that the spike near zero is due to responsive movement. Clustering of sightings very close to the vessel confirmed that at least some Dall's Porpoises exhibited a positive movement response to the survey vessel (Fig. 11). Therefore, we forced the use of a half-normal key for Dall's Porpoises (even though it had ΔAIC of 6.19 compared to the hazard-rate key) because half-normal detection functions help to reduce positive bias in estimated densities due to animals being attracted to the survey vessel (Best et al. 2015; Turnock and Quinn 1991). This half-normal model resulted in an ESW of 499 m (Fig 10).

A CDS hazard-rate model with no covariates, but with a cosine(2,3) adjustment was selected as the best detection function for Harbour Porpoises. It had a right-truncation distance of 1,200 m and an ESW of 443.6 m (Fig. 10). This model also showed a spike near zero perpendicular distance, potentially suggesting attractive behaviour. Since there is no evidence that Harbour Porpoises are attracted to large vessels (in fact, the opposite has been observed), the hazard-rate model was deemed appropriate.

There were only 25 sightings of Pacific White-sided Dolphins. Attempts at fitting a detection function failed to converge or did not provide satisfactory fit. To enrich the dataset, we added sightings of unidentified dolphins and other dolphin species, for a total of 38 sightings. Using a truncation distance of 1,500 m (leaving 35 sightings), the detection function that best fit the data was a half-normal key with group size as a categorical covariate (with two categories: less or equal than 10, and more than 10 individuals). The resulting ESW was 870 m (Fig. 12). There was no sign of responsive movement. This detection function was then applied to the subset of the 24 sightings of Pacific White-sided Dolphins made within the truncation distance to estimate their abundance. The same detection function was then used to estimate abundance of Risso's and Northern Right Whale Dolphins.

After investigation of the distance data, we assumed that Sei Whales (4 groups, 5 individuals) and Blue Whales (6 groups, 10 individuals) were detected using a similar process to that of fin whales and sightings for these two species were therefore pooled with fin whale sightings to create detection function for large rorquals and estimate their abundance. No such pooling was performed for Sperm Whales and beaked whales, which are likely detected differently due to their particular dive cycle, nor for Minke Whales, which are smaller and have more discreet blows than larger rorquals.

3.4. ABUNDANCE ESTIMATES

Tables 3–11 show surface (i.e., uncorrected for availability) abundance estimates and associated uncertainty (total and per stratum).

3.5. PERCEPTION BIAS (BUCKLAND-TURNOCK PROTOCOL)

B-T protocol was conducted in the offshore block on 11 days but only resulted in 69 trials being set up by the secondary observers. Of these 69 trials, 4 were abandoned, 2 had unknown results, 33 were successes (had been sighted by primary observers) and 30 were failures. The breakdown of group sightings by species was: 23 Humpback Whale trials (74% success rate), 8 Fin Whale trials (50% success rate), 10 Dall's Porpoise trials (40% success rate), 12 Harbour Porpoise trials (33% success rate), 1 Northern Right Whale Dolphin trial (failed), 1 Sei Whale trial (success) and 9 unidentified animals. Although these numbers indicate some level of perception bias, especially for the smaller species, the sample sizes were considered too low to perform a mark recapture distance sampling analysis. Moreover, there were concerns about the ability of B-T observers to correctly match their trials to the primary observations and correctly identify duplicates (see Discussion).

3.6. AVAILABILITY CORRECTION

For Humpback Whales, using published values of 0.69 and 2.43 min for mean surface and dive times, respectively (Dolphin 1987) and applying these parameters to the observed distribution of perpendicular distances within the 4 km truncation distance and using the associated vessel speeds results in a correction factor of 0.989 (CV = 0.03). For Fin Whales, using values of 2.07 and 4.23 min for mean surface and dive times (Keen et al. 2019) results in a correction factor of 0.976 (CV = 0.03). The same surface and dive times were assumed for Sei Whales. For Blue Whales, we used the values reported in Doniol-Valcroze et al. (2011) for day-time dives at depths over 50 m (i.e., 2.20 and 10.25 min) resulting in a correction factor of 0.803 (CV = 0.08). Because of the scarcity of data for Dall's Porpoise diving behaviour, we used published values of 43 and 65 sec from Westgate et al. (1995) for mean surface and dive times for the two species of porpoises. This resulted in a correction factor of 0.975 (CV = 0.03) for both porpoise species. For dolphins, we used published values for Risso's Dolphins of 21 sec and 4.3 min for surface and dive times (Arranz et al. 2019), respectively, resulting in a correction factor of 0.937 (CV = 0.02).

Once corrected for diving behaviour, abundance was estimated at 30,117 Dall's Porpoises (95%CI 22,142–40,965) , 12,244 Humpback Whales (8,214–18,252), 7,352 Harbour Porpoises (3,547–15,237), 5,882 Pacific White-sided Dolphins (2,941–11,766), 3,829 Fin Whales (2,145–6,834), 2,207 Northern Right Whale Dolphins (726–6,709), 920 Risso's Dolphins (178–4,758), 199 Blue Whales (59–670), and 70 Sei Whales (24–209). Breakdown by strata are shown in Table 12.

4. DISCUSSION

4.1. SURVEY DESIGN

PRISMM was the first systematic cetacean sighting survey conducted by DFO in Canadian Pacific waters, but it benefited greatly from previous survey efforts by other researchers. For the inshore block, the design used was that of Thomas et al. (2007), which had been prepared specifically for the complex shape of the coast of BC, and had already shown its effectiveness at producing robust and precise abundance estimates on several occasions (Williams and Thomas; Best et al. 2015). In addition, reusing this design makes it easier to compare abundance estimates obtained during PRISMM to those of the 2004–2008 period for the inshore strata.

Based on the available ship time (and anticipated down time due to weather), it was decided to use the same effort allocation across strata and transect spacing within strata as that proposed in Thomas et al. (2007), except in Juan de Fuca Strait where additional effort was possible at the end of the survey. One difference between PRISMM and previous uses of this design was that our survey vessel in the inshore block could not go into waters as shallow as the motorized sailboat used by Williams and Thomas (2007), which meant that some parts of the transects in the NC stratum could not be surveyed. This may have reduced the number of sightings of species that prefer shallow waters such as minke whales and harbour porpoises. For the same reason, we could not conduct systematic parallel transect lines perpendicular to shore in the inlet PSUs as initially designed by Thomas et al. (2007) and instead considered each surveyed PSU as a single transect.

For the offshore block, we followed the design approach used by Barlow and Forney (2007) during several offshore surveys of the California Current ecosystem. One of the advantages of the grid design was the flexibility it offered, for instance being able to branch off one transect towards the segment of another transect to adapt to weather conditions and logistical considerations, while maintaining good coverage of various habitats throughout the stratum.

4.2. DETECTION FUNCTIONS

Detection functions could be fitted to five species. The high number of sightings for Humpback and Fin Whales, and Dall's and Harbour Porpoises, allowed us to try numerous combinations of key functions and covariates, and to select robust model fits. Since the two survey vessels differed in terms of platform height, we initially considered fitting separate detection functions for each vessel for each species (i.e., a stratified approach). Pooling all data together and including "Vessel" as a covariate, however, is a more parsimonious approach that allowed us to maintain large sample sizes within covariate categories and maximize the inference from the available data (Oedekoven et al. 2013).

The best models for both Dall's and Harbour Porpoises according to AIC were hazard rate functions that showed a spike near the trackline (perpendicular distances approaching 0 m). This could indicate responsive movement, especially for Dall's Porpoises which are known to bow-ride. Following Williams and Thomas (2007) and Best et al. (2015), we chose a half-normal model with higher AIC to correct most of the attractive movement, based on the distribution of recorded sightings around the vessel (i.e., forward and perpendicular distances), as well as ancillary observations of bow-riding Dall's Porpoises. The Harbour Porpoise model showed a similar pattern, although less pronounced. Since there is no evidence that Harbour Porpoises are attracted to large vessels (in fact, the opposite has been often observed), we concluded that the drop in detection probabilities was true. One of the objectives of the B-T protocol was to quantify this issue, but sample sizes were too low to derive a correction factor.

There were not enough sightings of Pacific White-sided Dolphins to fit a detection function without adding sightings of other species of dolphins (Risso's and Northern Right Whale Dolphins) and unidentified delphinids. The underlying assumption is that different types of dolphins are detected in the same way by observers, which may not be realistic given that group size had a significant effect on detection probabilities and that grouping behaviour likely varies among dolphin species.

4.3. TRENDS IN ABUNDANCE

Previous available abundance estimates for cetaceans in Pacific Canadian waters were not corrected for availability bias, and therefore trends in abundance over times can only be inferred by comparing uncorrected estimates. The total (uncorrected) abundance estimate for Humpback Whales in 2018 in Pacific Canadian waters based on PRISMM was 12,115. This includes the offshore area (8,466 whales) for which no previous abundance estimate was available, and where the vast majority of sightings were made on the continental shelf off the west coast of Vancouver Island. The abundance for the North Coast and Inlets strata combined was 3,286 (1,954–5,529), which can be compared to the earlier estimate by Best et al. (2015) of 1,541 (95%CI 1,187–2,000) in the same strata based on survey data collected between 2004–2008 and shows a substantial increase over the last decade. The increase in the number of sightings and estimated abundance in inlets alone suggests that Humpback Whales have continued to recolonize and to expand their range within BC waters. Moreover, the 2004–2005 surveys reported by Best et al. (2015) did not detect any Humpback Whales in the Salish Sea region, where we estimated an abundance of 362 (95%CI 167–784), indicating that Humpback Whales have recolonized an area from which they were still largely absent in the early 2000s. Citizen science sightings submitted to the BC Cetacean Sightings Network (BCCSN) since 2009, while not effort-corrected, provide further evidence of a return of Humpback Whales to the Salish Sea since the whaling era (BCCSN, unpublished data; Ford 2014).

Total abundance for Fin Whales in 2018 in Pacific Canadian waters based on PRISMM was estimated at 3,737, with 3,469 whales in the offshore area for which no previous abundance estimate was available, and where the vast majority of sightings were made on the shelf break and further offshore, as well as near prominent seamounts. The abundance for the North Coast and Inlets strata combined was 268 (95%CI 144–499), which is lower but not statistically different than the earlier Best et al. (2015) estimate of 446 (95%CI 262–760) in the same strata based on 2004–2008 survey data or the estimate of 405 Fin Whales (95%CI 363–469) based on a photo-identification mark-recapture analysis of 2009–2014 data (Nichol et al. 2018). This suggests that Fin Whale numbers in inshore waters have been stable over the last ~15 years but our ability to detect trends is limited by the uncertainty around the estimates. No Fin Whales were encountered in the Salish Sea stratum during PRISMM, a result which is consistent with the earlier findings of Best et al. (2015). However, infrequent sightings of Fin Whales in Juan de Fuca Strait and the Salish Sea have been recorded between 2005 and 2017 (Towers et al. 2018).

Abundance of Dall's Porpoises based on PRISMM was estimated at 29,375 in total and 7,365 (95%CI 5,132–10,569) in the inshore block. Best et al. (2015) estimated an abundance of 6,232 (95%CI 4,165–9,324), in the same inshore block, which suggests that Dall's Porpoises have been stable or increasing in coastal BC waters. The abundance of Harbour Porpoises during PRISMM was estimated at 7,161 in total and 6,146 (95%CI 2,846–13,276) in the inshore block, which is similar to the 6,631 (95%CI 3,366–13,065) Harbour Porpoises estimated in the same area during the 2004–2008 surveys, with a similar breakdown across strata (Best et al. 2015).

In contrast, our estimate of 5,513 Pacific White-sided Dolphins in Canadian Pacific waters in 2018, with only 462 (95%CI 157–1,355) in the inshore block is considerably lower than the estimate of 32,637 (95%CI 20,087–53,029) presented in Best et al. (2015) for the same inshore area. This species seemed to be mostly absent from the study area at the time of PRISMM. There is no reason to believe that such a drastic difference corresponds to an actual population decline, based on anecdotal observations by DFO teams that same summer. It should also be noted that this population showed strong inter-annual and inter-seasonal variation in abundance during the 2004–2008 surveys (Best et al. 2015) and that these patterns may be linked to variability in environmental conditions (although these linkages have not been explored yet).

To estimate abundance for Sei and Blue Whales, which had too few sightings to fit a species-specific detection function, we assumed that the detection process for these two species was the same as that of Fin Whales (i.e., we used the Fin Whale detection function and applied it to Sei and Blue Whale sightings). The resulting abundance for Sei and Blue Whales in the offshore block was 64 (95%CI 21–197) and 159 (95%CI 46–552), respectively, suggesting that these species are present but still rare in offshore Canadian Pacific waters. Such groupings and assumptions are commonly done in multi-species surveys (e.g., Barlow and Forney 2007), but do increase the uncertainty around the estimate and caution should be used when applying these results to management issues.

No such calculation was performed for Sperm Whales and beaked whales, which are likely detected differently due to their long dive cycles, nor for Minke Whales which are smaller and have more discrete blows than larger rorquals, and thus application of the Humpback or Fin Whale detection function would not have been appropriate. Abundance and density were not estimated for Grey Whales because their inshore habitats were inadequately covered in our study (we did not have a single sighting), however, recent abundance estimates are available for this species from specialized studies (Calambokidis et al. 2002). The same is true for Sea Otters, which are the subject of dedicated count surveys (Nichol et al. 2020). Likewise, the coastal distribution of most pinnipeds in shallow waters, their inconspicuousness while in the water, and the large amount of time they spend hauled out on land, makes other census techniques more efficient (e.g., Majewski and Ellis 2022). Killer Whales are not ideal species for a survey of this scope because of their small population sizes and the need to use photo-identification or acoustic techniques to distinguish among ecotypes and populations, which is why they are censused using different approaches (e.g., DFO 2019).

4.4. SOURCES OF BIASES

An attempt was made at using the Buckland-Turnock (BT) protocol (Buckland and Turnock 1992) to investigate potential responsive movements and to quantify perception bias. While ideal in theory for its flexibility and because it could be done with an asymmetric observer configuration (since full separation of the observer platforms was not possible), the protocol was actually difficult to implement in the field and yielded a low sample size. One of the main difficulties was to confidently identify duplicates between primary and secondary observers when there were several animals of the same species in the field of view. Moreover, the tasks linked to BT trials often conflicted with requests by primary observers to track and confirm their detections. Since marine mammal distribution is often patchy, this meant that most of the opportunities for BT trials occurred in conditions that either conflicted with the BT observer’s ability to track trials or made it confusing to identify duplicates. It also proved difficult to detect animals ahead of the primary observers. This issue is concerning, because the low sample size available does suggest that the number of animals missed by observers close to the trackline is not negligible, especially for small cetaceans and to a lesser extent for large whales. One clear improvement in future attempts would be to have a dedicated BT observer with no conflicting priorities. Any technique to improve duplicate identification and tracking would also improve the results.

Availability bias for ship-based surveys, where the observation platform is moving relatively slowly, is often assumed to be less severe than for fast moving platforms like aerial surveys, except in the case of long-diving species that may be submerged for the entire time that the ship is within visual range. To investigate the magnitude of this bias and estimate potential correction factors, we used a model developed by McLaren (1961) and later adapted by Laake et al. (1997). This allowed us to use the empirical data on perpendicular distances to calculate the time-in-view of each species during PRISMM. However, the estimation of correction factors is highly dependant on values from studies of diving behaviour, which are often based on a small sample size of individuals and seldom available for the same area and season (or even species) as that of the survey. Moreover, the actual dive times of cetaceans are known to vary considerably depending on their behavioural state (e.g., foraging, travelling, resting), dive depth, and the time of day. Therefore, it is unlikely that a single correction factor properly conveys the uncertainty around availability bias.

Another potential source of bias is the low search effort in areas with shallow waters or close to the coast on the shelf of Vancouver Island and Haida Gwaii. Lower effort in those areas occurred because it was not possible to get the research vessels close to shore (e.g., compared to the vessel used in Best et al. 2015). The large number of sightings that occurred at the edge of the covered nearshore areas suggest that some cetacean species may have been undercounted (especially small odontocetes, Grey Whales and Minke Whales).

Together, these issues suggest that our abundance estimates are biased negatively and are probably more uncertain than expressed in the calculated coefficients of variation.

4.5. POST-STRATIFICATION

The offshore block comprised a single stratum because there was little previous knowledge of marine mammal density in this region to devise a better stratification theme. In general, post-stratification should not be performed on the basis of observed densities and spatial patterns in sightings. However, it is appropriate to post-stratify based on other factors such as realized effort or habitat types, if ecological justification can be found for differences in marine mammal densities across different habitats. For instance, it would be possible to stratify offshore sightings into habitat types such as continental shelf, shelf slope, abyssal plains and seamounts as was done in Yack et al. (2015). Such a stratification scheme would potentially reduce the variance around the abundance estimates and provide insights into ecological relationships. Analysis of the PRISMM offshore data could also be post-stratified to answer management questions such as the abundance of a species in specific fishery management zones or candidate Marine Protected Areas.

4.6. CONCLUSIONS AND RECOMMENDATIONS

PRISMM represents the most current and spatially comprehensive effort to estimate the abundance and distribution of all cetacean species in Canadian Pacific waters. In contrast to similar efforts by DFO in the Arctic and the Atlantic, which were conducted with aircraft, PRISMM was a ship-based survey similar to the NOAA surveys of the California Current (Barlow and Forney 2007) and some of the SCANS platforms (Hammond et al. 2013). The main advantages of a ship-based survey were that observers had more time to detect animals, identify species and determine group size, as well as the ability to use complementary survey techniques such as passive acoustics. The main limitations included a limited ability to reposition to other survey areas to adapt to weather conditions and lesser coverage due to the slow speed of the platform. The cost, personnel needs and logistic constraints also limits the possibility of repeating this survey as often as would be needed ideally to decrease uncertainty and build a robust time-series.

Despite difficult weather conditions and some gaps in the coverage (especially in the northern part of the offshore block), PRISMM achieved its main objective of providing new or updated abundance estimates for seven cetacean species. Combined with the results of the model-based analysis of cetacean densities based on the same survey data (Wright et al. 2021), our results can be compared with previous surveys as well as historic whaling catch data, to document population trends and the extent of recovery of previously harvested populations.

Except for Pacific White-sided Dolphins (for which PRISMM abundance estimates seemed implausible), the 2018 abundance of cetaceans in inshore BC waters suggests that several populations are stable (Dall's Porpoises, Harbour Porpoises, Fin Whales) or are continuing to recover from past depletion and are expanding to new areas (Humpback Whales). The return of these predators to habitats from which they were previously extirpated will have important ecosystem-level implications. These coast-wide, updated abundance estimates can also inform Potential Biological Removal limits for fisheries bycatch.

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APPENDIX A. TABLES

Table 1. Size of PRISMM strata and realized effort.

Stratum	Area (km^2)	Effort (km)
North Coast (NC)	64,653	1,541
Johnstone Strait (JS)	420	135
Inlets (INL)	11,965	860
South Coast (SC)	8,337	553
Offshore (OFF)	369,410	5,305
Total	**454,785**	**8,394**

Table 2. Number of sightings, number of individuals and average group size (± standard deviation) for each species detected visually during the PRISMM survey.

Species	Number of sightings	Number of individuals	Mean group size (±SD)
Humpback Whale	767	1,145	1.5 (±1.3)
Fin Whale	235	357	1.5 (±0.9)
Minke Whale	13	14	1.1 (±0.3)
Blue Whale	6	10	1.7 (±0.5)
Sei Whale	4	5	1.2 (±0.4)
Unidentified large baleen whale	153	188	1.2 (±0.5)
Sperm Whale	14	14	1.0 (±0)
Killer Whale (all ecotypes)	27	177	6.6 (±4.8)
Pacific White-sided Dolphin	25	344	13.8 (±17.9)
Northern Right Whale Dolphin	6	64	10.7 (±16.9)
Risso’s Dolphin	4	46	11.5 (±10.7)
Unidentified dolphin	3	13	4.3 (±3.2)
Dall’s Porpoise	287	845	2.9 (±1.8)
Harbour Porpoise	246	403	1.6 (±0.9)
Unidentified porpoise	24	32	1.3 (±0.9)
Baird’s Beaked Whale	2	12	6.0 (±0)
Cuvier’s Beaked Whale	1	5	5.0 (N/A)
Unidentified beaked whale	5	10	2.0 (±1.0)
Unidentified cetacean	52	63	1.2 (±0.6)

Table 3. Humpback Whale sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	82	0.000053 (0.27)	1.35 (0.07)	1,940 (0.31)	1,060–3,551
Johnstone Strait	0	0.000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	157	0.000180 (0.48)	1.38 (0.05)	1,346 (0.45)	547–3,311
South Coast	33	0.000060 (0.28)	1.67 (0.10)	362 (0.40)	167–784
Offshore	333	0.000063 (0.22)	1.56 (0.05)	8,466 (0.27)	4,933–14,530
Total	**605**	**0.000064**	**1.49 (0.04)**	**12,115 (0.20)**	**8,069–18,189**

Table 4. Fin Whale sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	19	0.0000120 (0.30)	1.79 (0.15)	265 (0.32)	141–496
Johnstone Strait	0	0.0000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	1	0.0000012 (0.94)	1 (0.00)	3 (0.95)	1 - 15
South Coast	0	0.0000000 (0.00)	0 (0.00)	0 (0.00)	0 - 0
Offshore	179	0.0000340 (0.26)	1.5 (0.05)	3,469 (0.32)	1,834–6,561
Total	**199**	**0.0000290**	**1.52 (0.04)**	**3,737 (0.30)**	**2,057–6,788**

Table 5. Dall's Porpoise sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	48	0.0000310 (0.21)	2.38 (0.10)	5,193 (0.21)	3,415–7,895
Johnstone Strait	1	0.0000074 (0.00)	2 (0.00)	6 (0.41)	0–496
Inlets	39	0.0000450 (0.41)	2.82 (0.08)	1,550 (0.44)	639–3,761
South Coast	26	0.0000470 (0.50)	1.62 (0.08)	616 (0.46)	251–1,516
Offshore	99	0.0000190 (0.16)	3.43 (0.06)	22,010 (0.20)	14,810–32,711
Total	**213**	**0.0000220**	**2.85 (0.04)**	**29,375 (0.16)**	**21,539–40,062**

Table 6. Harbour Porpoise sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	20	0.0000130 (0.61)	2.05 (0.15)	1,929 (0.74)	504–7,388
Johnstone Strait	1	0.0000074 (0.00)	1 (0.00)	3 (0.60)	0–74
Inlets	29	0.0000340 (0.51)	1.59 (0.11)	718 (0.57)	240–2,149
South Coast	129	0.0002300 (0.33)	1.6 (0.04)	3,496 (0.44)	1,514–8,073
Offshore	7	0.0000013 (0.41)	1.86 (0.38)	1,015 (0.61)	327–3,154
Total	**186**	**0.0000081**	**1.66 (0.04)**	**7,161 (0.38)**	**3,449–14,870**

Table 7. Blue Whale sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Johnstone Strait	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
South Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Offshore	6	0.00000110 (0.54)	1.67 (0.10)	160 (0.68)	46–560
Total	**6**	**0.00000092**	**1.67 (0.10)**	**160 (0.68)**	**46–560**

Table 8. Sei Whale sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Johnstone Strait	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
South Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Offshore	3	0.00000057 (0.54)	1.33 (0.20)	68 (0.60)	22–212
Total	**3**	**0.00000046**	**1.33 (0.20)**	**68 (0.60)**	**22–212**

Table 9. Pacific White-sided Dolphin sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	3	0.0000019 (0.75)	4.33 (0.40)	343 (0.74)	88–1,337
Johnstone Strait	3	0.0000220 (0.00)	19 (0.80)	75 (0.30)	41–137
Inlets	1	0.0000012 (1.00)	5 (0.00)	44 (1.01)	7–259
South Coast	0	0.0000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Offshore	15	0.0000028 (0.29)	10.2 (0.20)	5,052 (0.39)	2,368–10,779
Total	**22**	**0.0000026**	**10.4 (0.20)**	**5,513 (0.36)**	**2,713–11,202**

Table 10. Risso's Dolphin sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Johnstone Strait	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
South Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Offshore	2	0.00000038 (0.97)	14.5 (0.70)	862 (1.00)	157–4,724
Total	**2**	**0.00000031**	**14.5 (0.70)**	**862 (1.00)**	**157–4,724**

Table 11. Northern Right Whale Dolphin sightings, encounter rates, group sizes and surface (uncorrected) abundance estimates in each stratum.

Stratum	Sightings	Enc. rate (CV)	Group Size (CV)	Abundance (CV)	95%CI
North Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Johnstone Strait	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Inlets	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
South Coast	0	0.00000000 (0.00)	0 (0.00)	0 (0.00)	0–0
Offshore	6	0.00000110 (0.35)	10.7 (0.60)	2,068 (0.62)	657–6,515
Total	**6**	**0.00000092**	**10.7 (0.60)**	**2,068 (0.62)**	**657–6,515**

Table 12. Abundance estimates for cetaceans in 2018, corrected for availability bias. CVs are indicated below the abundance estimates in parentheses.

Stratum	**Dall's Porpoise**	**Humpback Whale**	**Harbour Porpoise**	**Pacific White-sided Dolphin**	**Fin Whale**	**Northern Right Whale Dolphin**	**Risso's Dolphin**	**Blue Whale**	**Sei Whale**
North Coast	5,324 (0.21)	1,961 (0.31)	1,980 (0.74)	366 (0.74)	271 (0.32)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Johnstone Strait	6 (0.41)	0 (0.00)	4 (0.60)	80 (0.30)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Inlets	1,589 (0.44)	1,361 (0.45)	737 (0.57)	47 (1.01)	3 (0.95)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
South Coast	632 (0.46)	366 (0.40)	3,589 (0.44)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
Offshore	22,566 (0.20)	8,556 (0.27)	1,042 (0.61)	5,390 (0.39)	3,555 (0.32)	2,207 (0.62)	920 (1.00)	199 (0.68)	70 (0.60)
Total	**30,117 (0.16)**	**12,244 (0.21)**	**7,352 (0.39)**	**5,882 (0.37)**	**3,829 (0.30)**	**2,207 (0.62)**	**920 (1.00)**	**199 (0.68)**	**70 (0.60)**

APPENDIX B. FIGURES

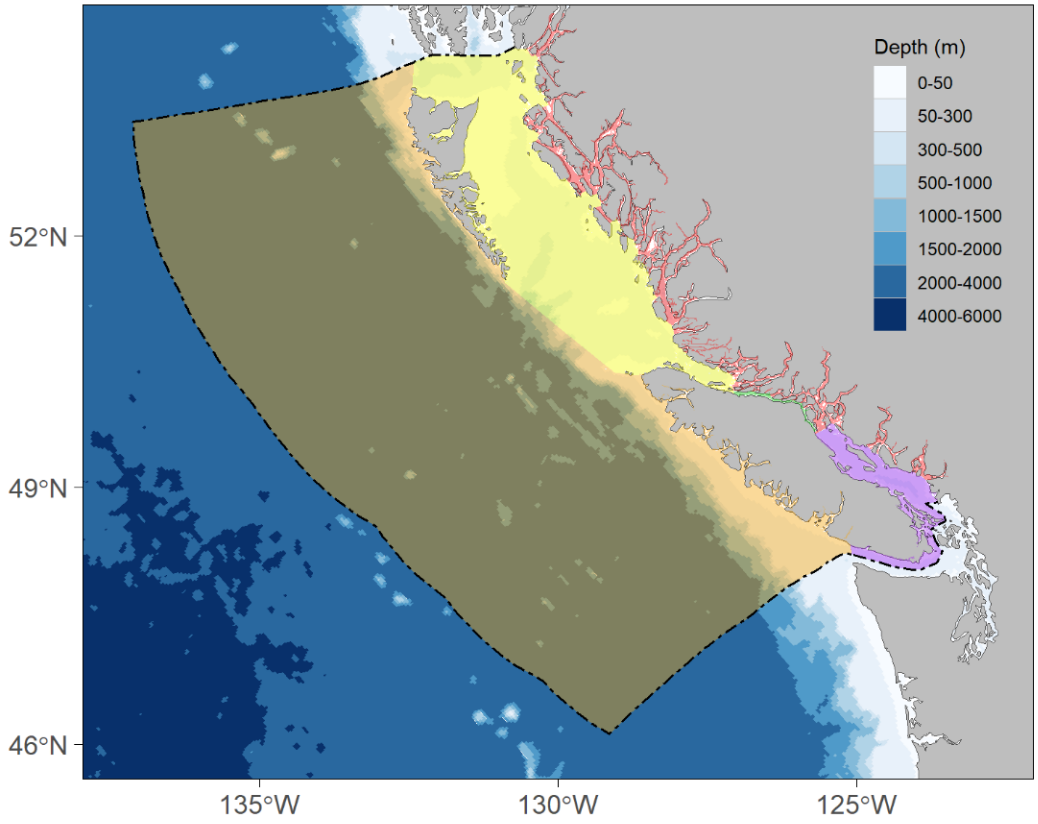

Figure 1. Stratification of the survey area, showing the offshore block (orange) and the strata of the inshore block: 1: North Coast (yellow), 2: South Coast (purple), 3: Johnstone Strait (green), 4: Mainland Inlets (red).

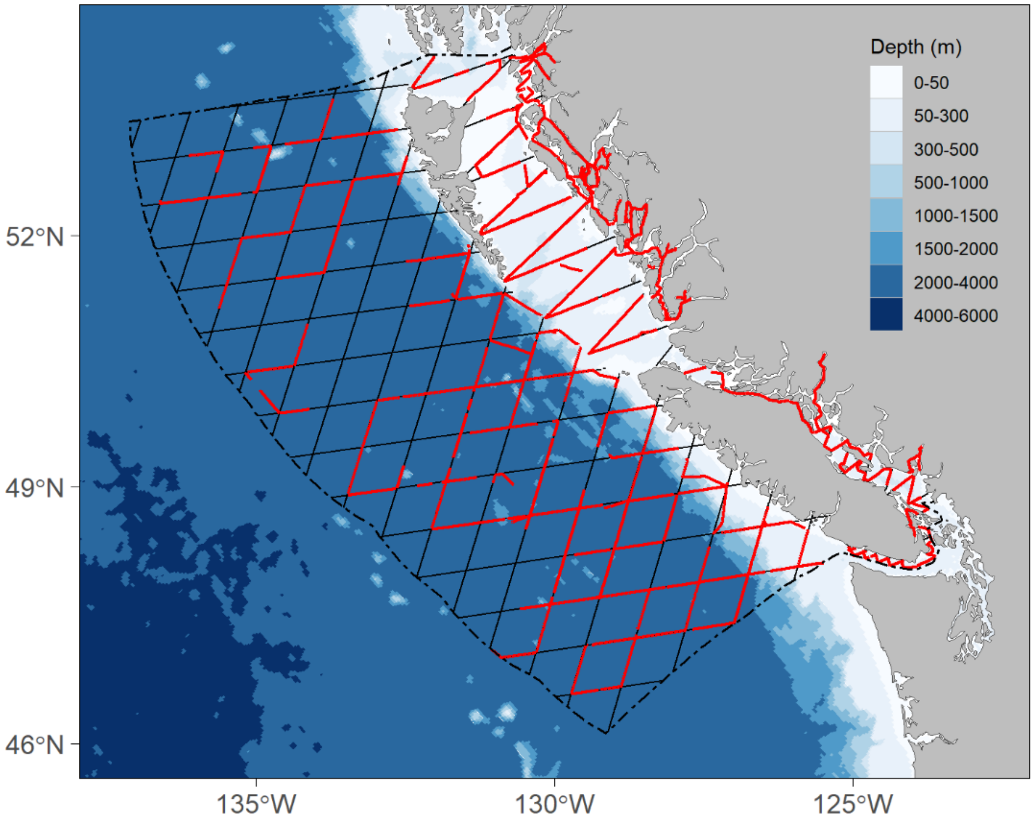

Figure 2. Planned survey tracks (black lines) and realized survey tracks (red lines) during visual effort conditions. Dashed lines indicate the extent of the study area (i.e., the Canadian EEZ).

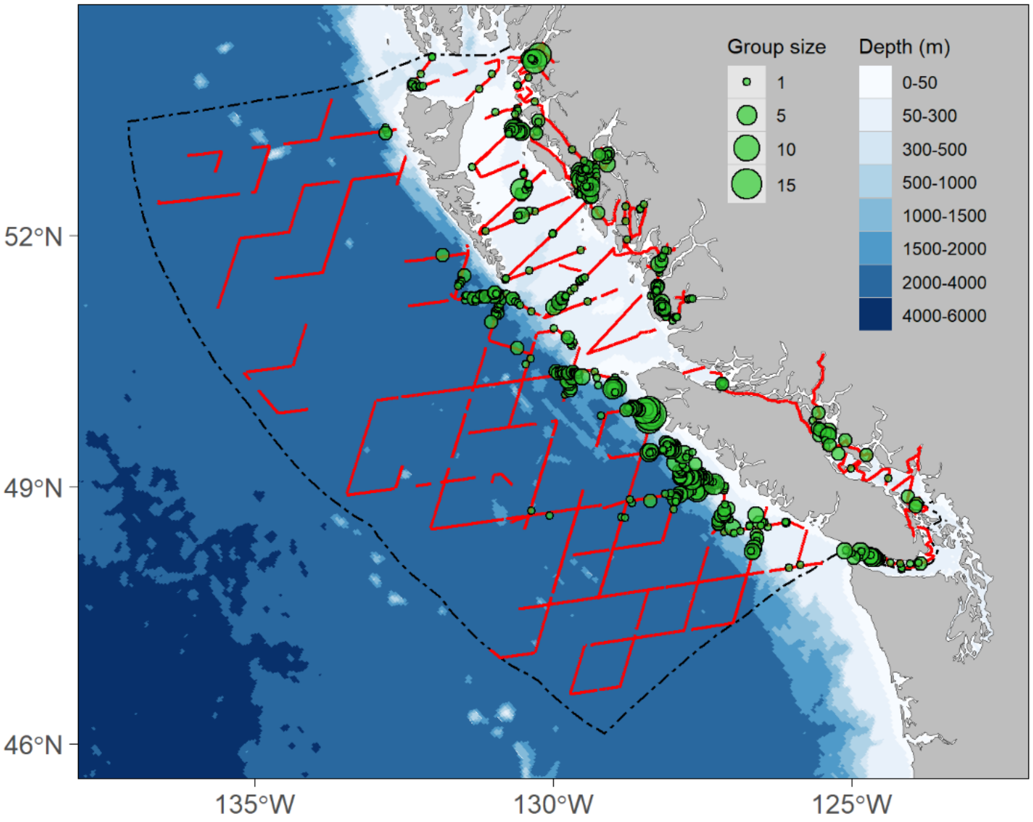

Figure 3. Distribution of Humpback Whale sightings (circles) and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size for each sighting.

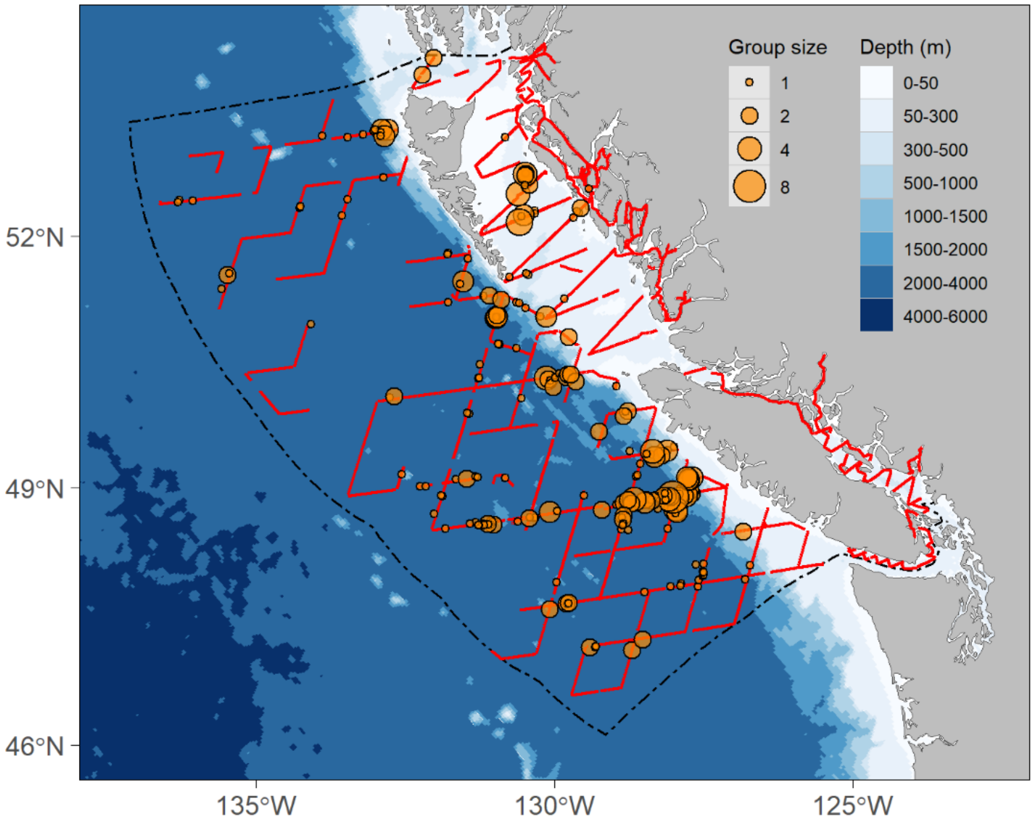

Figure 4. Distribution of Fin Whale sightings (circles) and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size for each sighting.

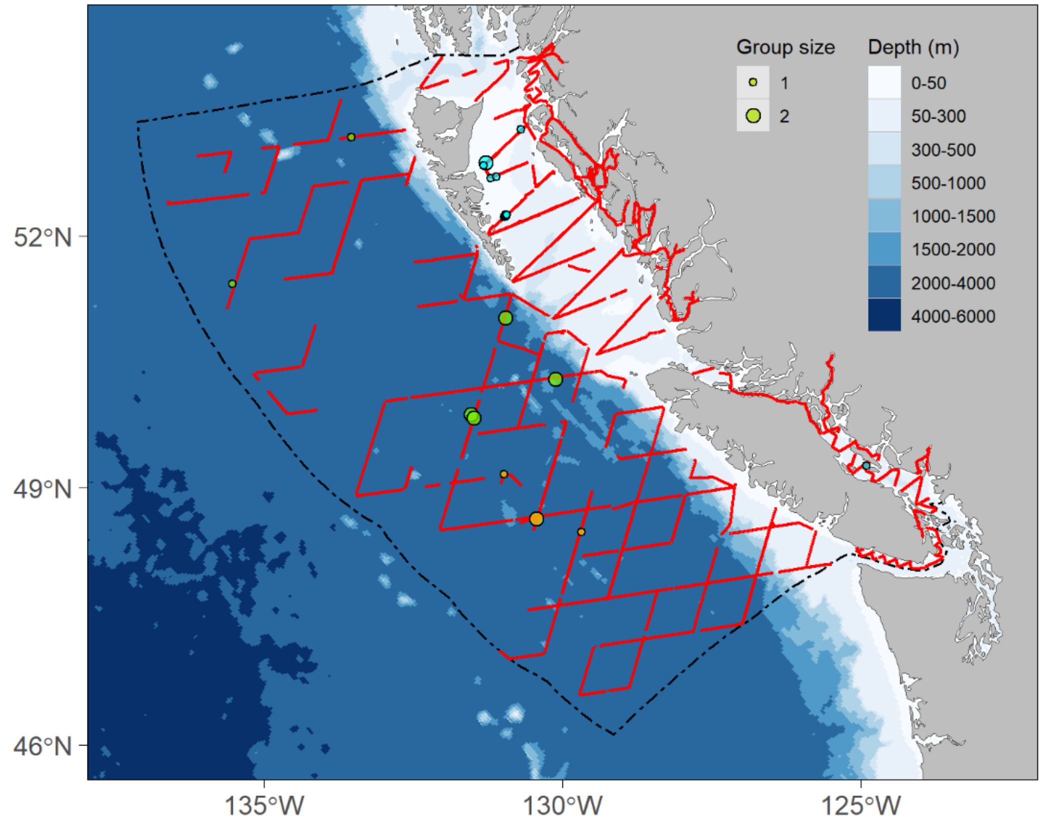

Figure 5. Distribution of other rorqual whale sightings and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size of each sighting for Blue Whales (green circles), Sei Whales (orange circles) and Minke Whales (light blue circles).

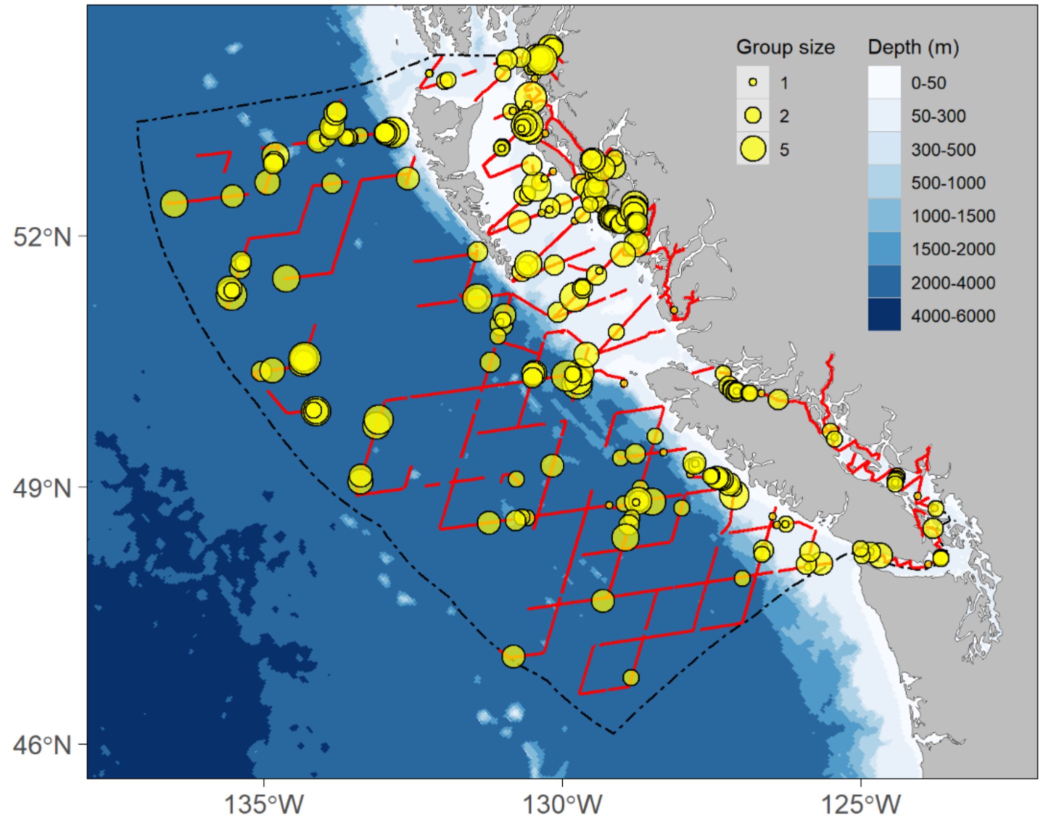

Figure 6. Distribution of Dall's Porpoise sightings (circles) and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size for each sighting.

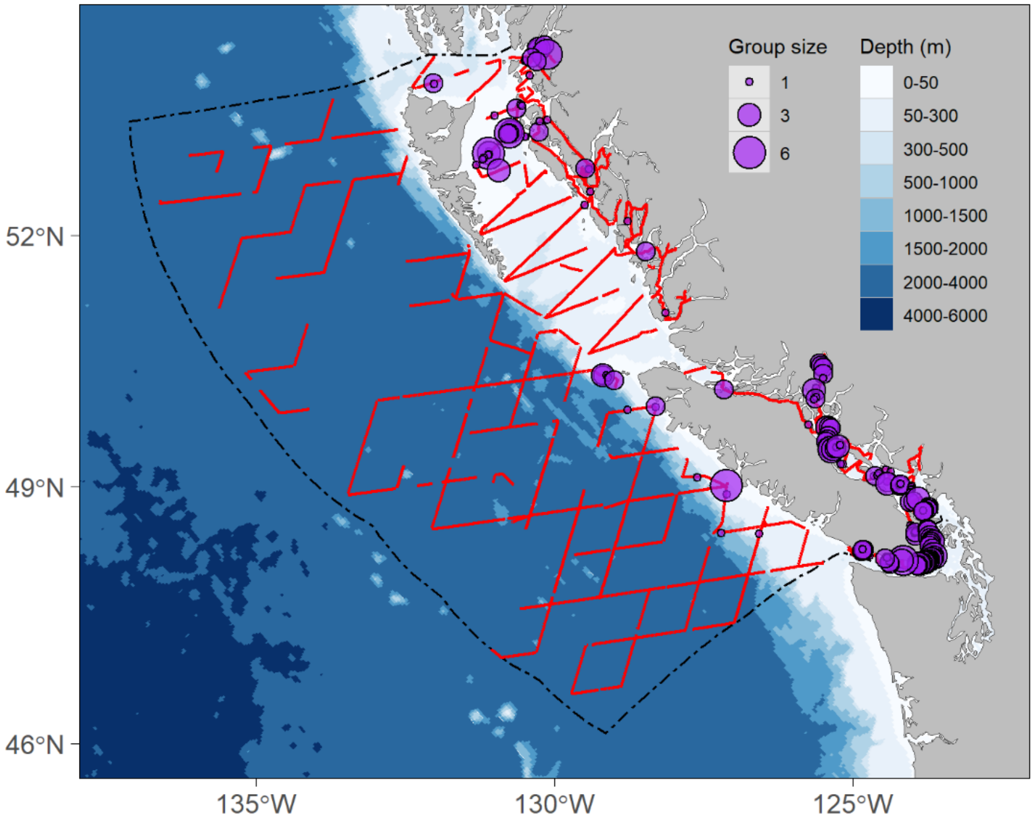

Figure 7. Distribution of Harbour Porpoise sightings (circles) and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size for each sighting.

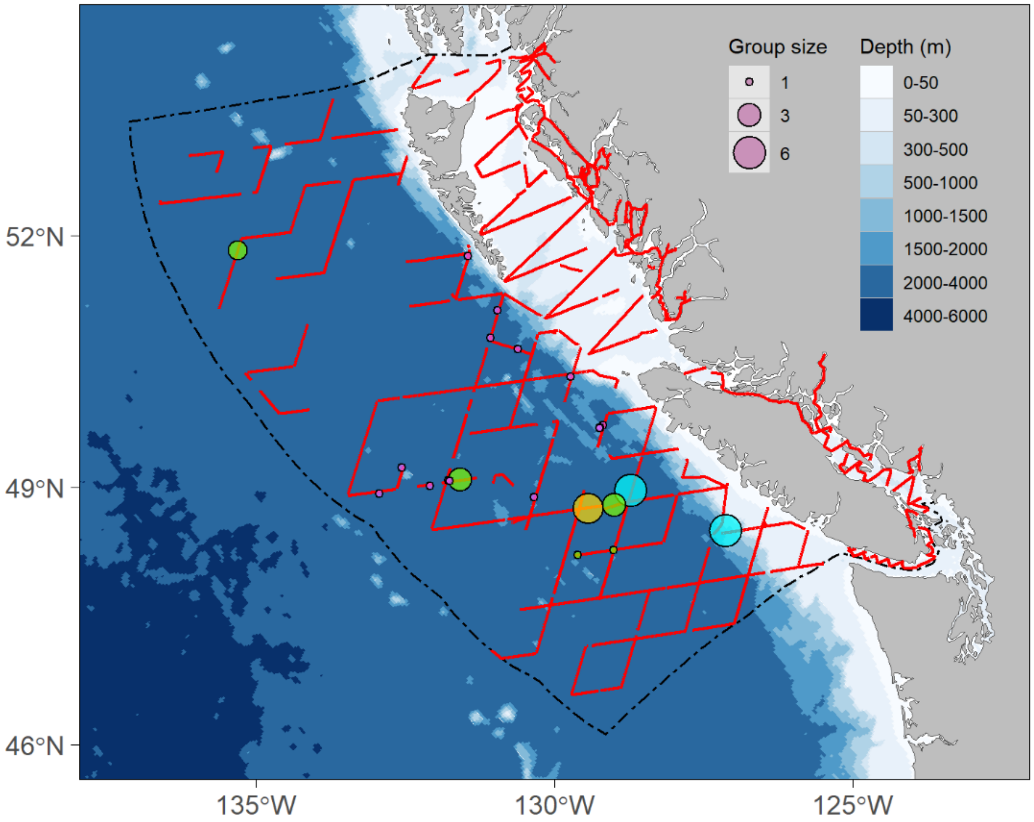

Figure 8. Distribution of sightings of deep-diving odontocete species and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size of each sighting for Sperm Whales (pink circles), Cuvier's Beaked Whales (yellow circles), Baird's Beaked Whales (light blue circles) and unidentified beaked whales (green circles).

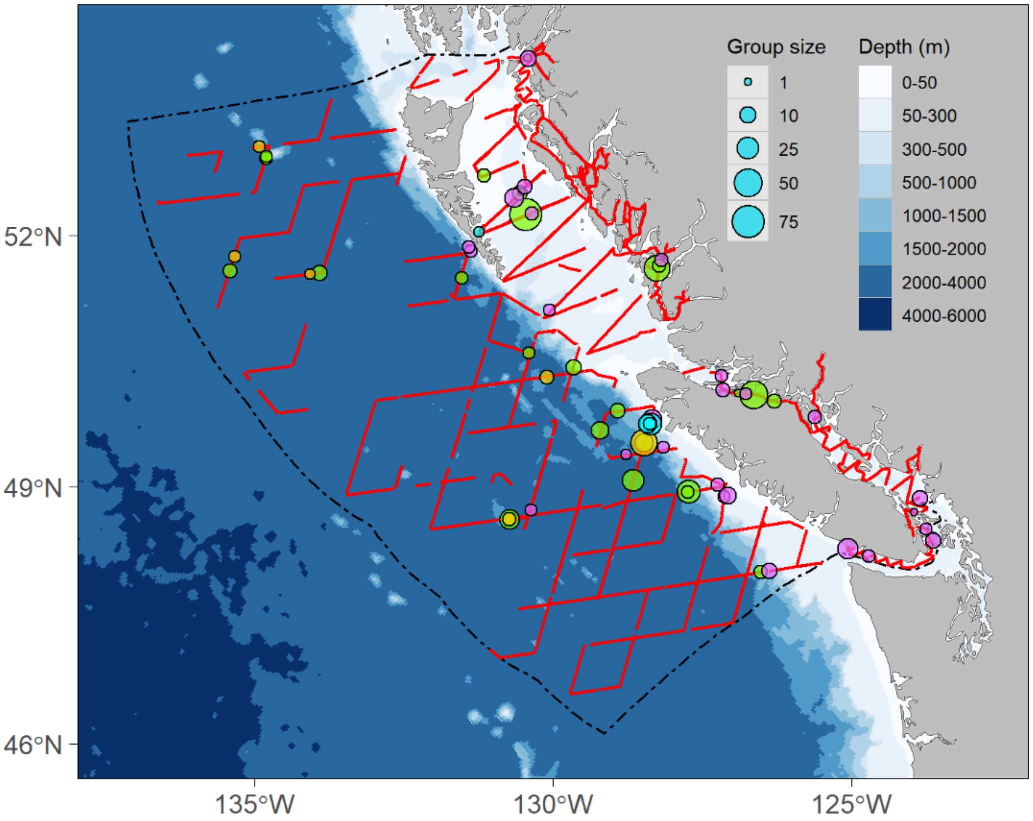

Figure 9. Distribution of sightings of delphinid species and realized visual on-effort survey tracklines (red lines). Relative circle size indicates the group size of each sighting for Killer Whales (pink circles), Pacific White-sided Dolphins (green circles), Northern Right Whale Dolphins (yellow circles) and Risso's Dolphins (light blue circles).

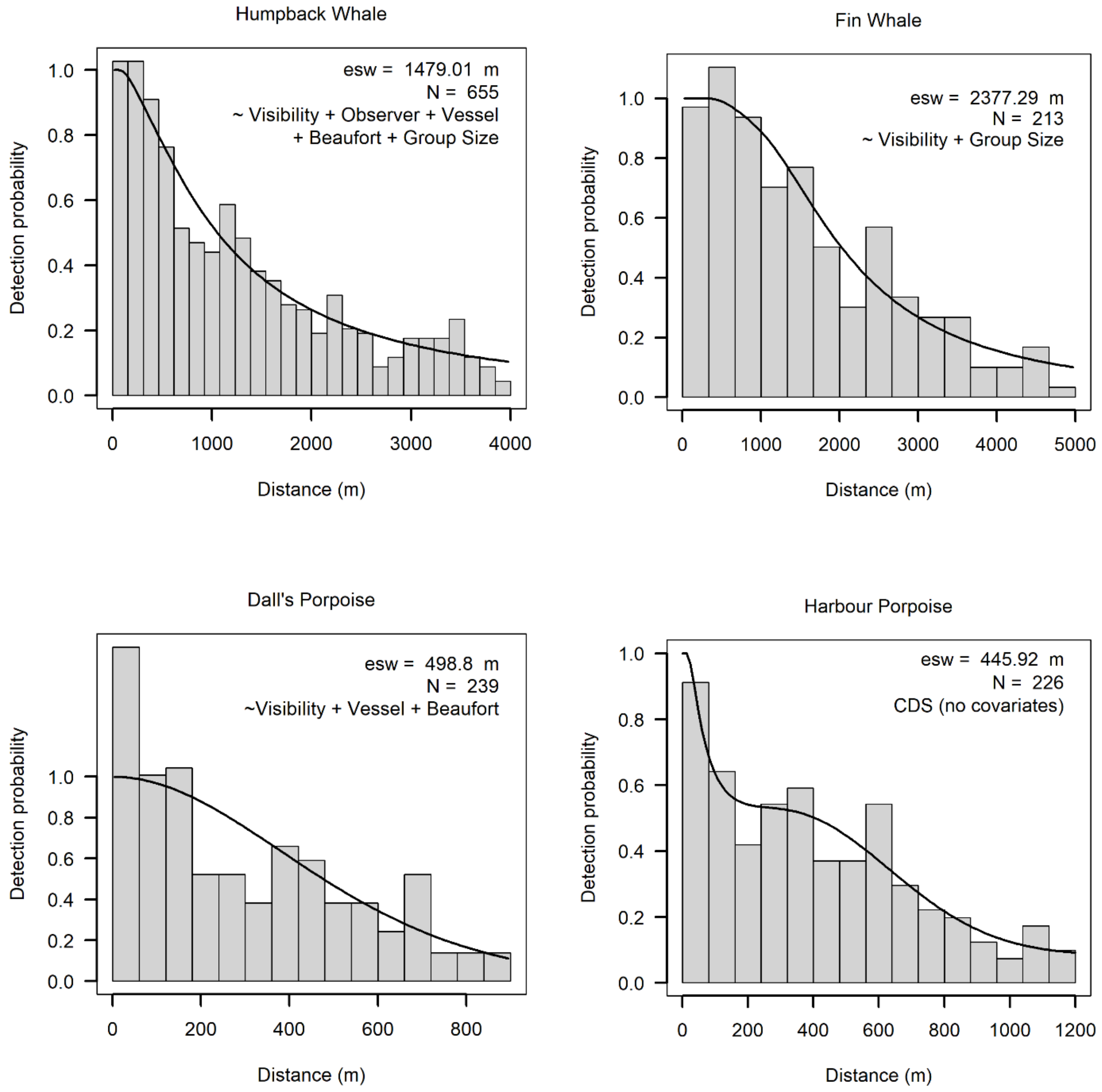

Figure 10. Histograms of observed perpendicular distances and fitted detection functions for Humpback Whale, Fin Whale, Dall's Porpoise and Harbour Porpoise sightings. All detection functions were fit using the hazard-rate key except for the Dall's Porpoise detection function, which used the half-normal key to compensate for the impact of the attractive behaviour of this species to the survey vessel (bow-riding). The effective strip-(half)width (esw), number of sightings (N, after right-truncation), and the formula (covariates) of the best-fit DF model are indicated in the top right corner of each plot. Note that the best-fit Harbour Porpoise detection function contained no covariates but did include a cosine(2,3) adjustment term.

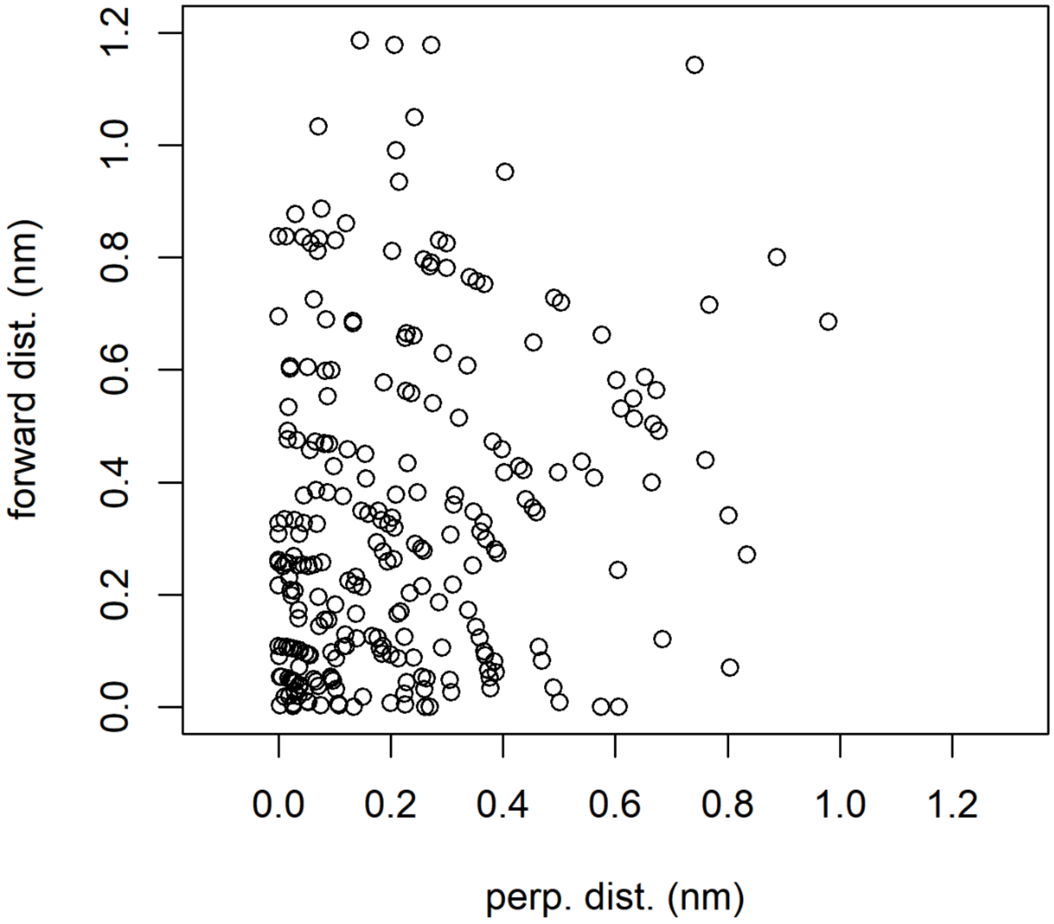

Figure 11. Forward and perpendicular distances of sightings of Dall's Porpoises, measured from the survey vessel. The clustering of sightings very close to the vessel suggests that at least some Dall's Porpoises exhibited a positive movement response to the survey vessel.

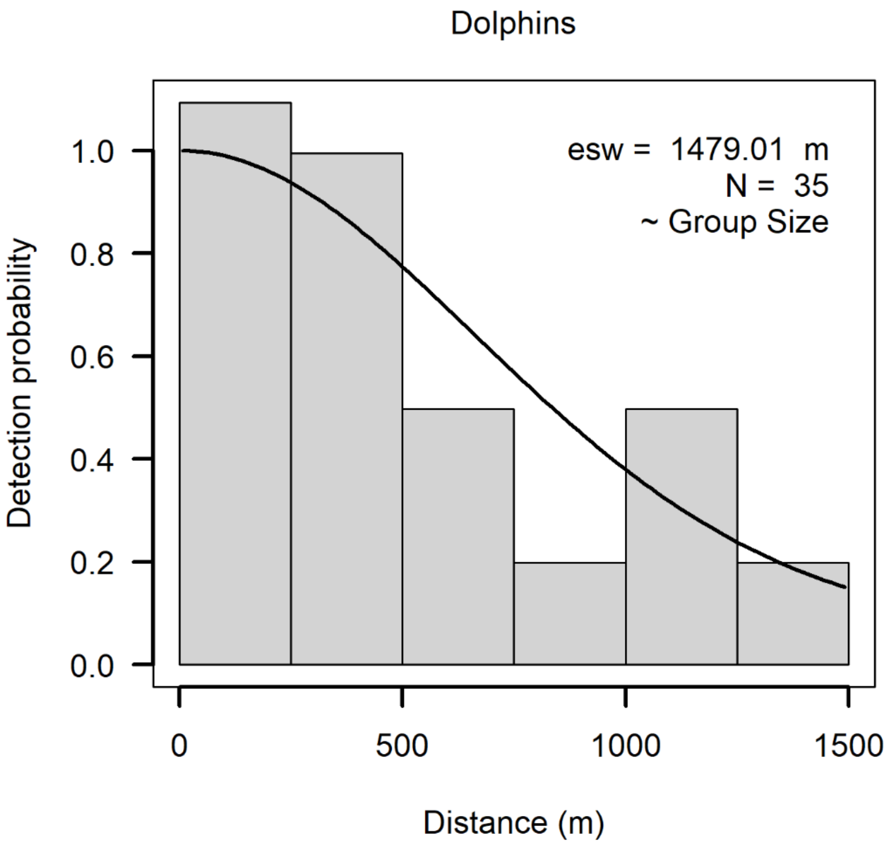

Figure 12. Histogram of observed perpendicular distances and fitted detection functions for dolphin sightings (i.e., Pacific White-sided, Risso's and Northern Right Whale Dolphins, as well as unidentified dolphins). The detection function was fit using the half-normal key. The effective strip-(half)width (esw), number of sightings (N, after right-truncation), and the formula (covariates) of the best-fit model are indicated in the top right corner.