Marine Mammals and Debris in Coastal Waters of British Columbia, Canada

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Abstract [150 word limit]

Entanglement in and ingestion of synthetic marine debris is increasingly recognized worldwide as an important stressor for marine wildlife, including marine mammals. Studying its impact on wildlife populations is complicated by the inherently cryptic nature of the problem. The coastal waters of British Columbia (BC), Canada provide important habitat for marine mammal species, many of which have unfavorable conservation status in the US and Canada. As a priority-setting exercise, we used data from systematic line-transect surveys and spatial modeling methods to map at-sea distribution of debris and 11 marine mammal species in BC waters, and to identify areas of overlap. We estimated abundance of 36,000 (CIs: 23,000-56,600) pieces of marine debris in the region. Areas of overlap were often far removed from urban centers, suggesting that the extent of marine mammal-debris interactions would be underestimated from opportunistic sightings and stranding records, and that high-overlap areas should be prioritized by stranding response networks.

Introduction

Marine wildlife entanglement in and ingestion of synthetic marine debris is insidious and cryptic (Laist, 1997). The cryptic nature of the problem is driven by a low probability of actually recovering marine wildlife carcasses intact with evidence of harm caused by plastic ingestion or entanglement. If death from debris entanglement or ingestion occurs at sea, documentation of the event generally requires the carcass to come close to shore to be detected by a person, reported to the competent authority, and subjected to a full necropsy before the carcass decays. From entanglement event to definitive necropsy outcome, there are several processes at work that reduce the likelihood of the event being detected and documented, and that may ultimately bias our perception of the problem if we based it solely on opportunistic observations. Despite these odds, synthetic marine debris, notably plastic, is increasingly recognized worldwide as an important stressor for a variety of marine taxa (Moore, 2008).

A growing number of studies have documented plastic ingestion in seabirds (Laist, 1997), which are considered good indicators of marine ecosystem variability and anthropogenic impacts (Furness and Camphuysen, 1997). Results from these studies suggest the problem is pervasive, with 138 seabird species (Laist, 1997) found with documented evidence of ingestion or entanglement, representing some 40% of seabird species (Moore, 2008). Marine plastic pollution is becoming an issue in remote areas of the world previously thought to be unaffected (i.e., Arctic (Provencher et al., 2010) and Antarctic (Auman et al., 2004) regions). Plastic is widely distributed in northeast Pacific waters (Matsumura and Nasu, 1997), with some regions like the "Great Pacific Garbage Patch", which is an aggregation of debris trapped by the North Pacific central gyre (Moore et al., 2001), becoming synonymous with the issue. In these areas, as well as in areas of lower density, debris interactions have been identified as conservation threats to many marine mammal species (Laist, 1997). Marine debris has been found to pose threats to marine mammals through entanglement (Wallace, 1985; Fowler, 1987; Henderson, 2001), ingestion (Cawthorn, 1985) and both (Laist 1987, 1997). The extent to which this issue causes morbidity, mortality or population-level effects is rarely known. Entanglement has been identified as a potential contributing factor in the population declines of the Hawaiian Monk Seal (*Monachus shauinslandi*) (Derraik, 2002) and Northern Fur Seals (*Callorhinus ursinus*) (Fowler, 1987).

A number of efforts are ongoing to quantify mortality rates due to debris entanglement and ingestion on local, national, and international levels. At the broadest scale, programs such as the United Nations Open-Ended Informal Consultative Process on Oceans (UNICPO) aim to quantify the scope of the debris problem. One of the recurring items on the work plan of the International Whaling Commission's Sub-Committee on Estimation of Bycatch and Other Human-Induced Mortality[1] is the development of methods for estimating human-induced mortalities from ship strikes and marine debris. The National Progress Reports for member nations of the IWC include sections to account for cetacean mortality known to have occurred as a result of debris entanglement and ingestion. Internationally, one of the most important actions to mitigate marine debris is Annex V of the 1978 Protocol to the International Convention for the Prevention of Pollution from ships (MARPOL). Unfortunately, this accord only partially addresses the issue of marine debris because only a relatively small fraction of marine debris comes from ships.

Few studies have attempted to quantify how much of a threat debris interactions may pose to marine mammals in British Columbia (BC), Canada. The coastal waters of BC provide important habitat for migratory and highly mobile marine mammal species, which are of conservation and management concern to both the US and Canada (Williams and Thomas, 2007; Williams, Hall and Winship, 2008). The recently organized BC Marine Mammal Response Network[2] will address the issue of marine debris and associated impacts. This network is coordinated by Fisheries and Oceans Canada (DFO), the lead agency for protecting marine mammals in Canadian waters, but also includes a broad network of other government agencies, individuals and environmental groups. The selection of priority species to respond to is currently influenced by the species' conservation status under Canada's Species at Risk Act (SARA). As a result, records of debris interactions will be underreported for all species – because the problem is inherently cryptic – but we expect that the degree of underreporting may be higher in non-listed species than it is for listed species.

We sought to identify where marine mammals and marine debris overlap by mapping and superimposing the at-sea distribution of both. It is hoped that additional resources can be brought to bear to target the areas of overlap and to determine origins of debris found in the target areas. A similar priority-setting exercise in nearby Washington State waters was used to build a compelling case for removal of ghost nets and other derelict fishing gear by conducting a cost-benefit analysis of cleanup of derelict fishing gear (Gilardi et al., 2010). Our intent is to encourage and support similar initiatives directed at reducing input and mitigating impacts of marine debris in general.

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[1] www.iwcoffice.org

[2] http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especes/mammals-mammiferes/report-signaler-eng.htm#Report_an_incident

Marine mammal species that regularly inhabit coastal waters of BC (Table 1) include, among others: harbor porpoise (*Phocoena phocoena*); Dall's porpoise (*Phocoenoides dalli*); Pacific white-sided dolphin (*Lagenorhynchus obliquidens*); minke whale (*Balaenoptera acutorostrata*); humpback whale (*Megaptera novaeangliae*); fin whale (*Balaenoptera physalus*); [Northern resident] killer whale (*Orcinus orca*); sea otter (*Enhydra lutris*); northern elephant seal (*Mirounga angustirostris*); Steller sea lion (*Eumetopias jubatus*) and harbor seal (*Phoca vitulina*). Marine debris has been identified as a threat to many of these species in anecdotal reports, peer reviewed journals, and status and assessment reports from US and Canadian agencies responsible for marine mammal stock assessment and management. Summarizing the results of a global literature review (Laist, 1997), the US Marine Mammal Commission (2001) notes that 43% of the world's marine mammal species are affected by either entanglement or ingestion of marine debris.

Many marine mammal species become entangled incidentally in marine debris in their environment. The majority of pinniped entanglement in debris seems to affect young animals, which may be curious, or simply naïve feeders (Wallace, 1985; Laist, 1987; Laist, 1997). Once pinnipeds or cetaceans become entangled, various types of debris can restrict feeding to the point of starvation, restrict movement, drown or exhaust the animal, or cause amputation or wounds that leave sites for infection (Laist, 1997; Marine Mammal Commission, 2001). Juvenile seals can be particularly vulnerable to entanglement in plastic debris. Precocious seals insert their heads through plastic loops and then grow into the loop, which can constrict the neck over time even to the point of severing arteries and strangulation (Fowler, 1987; Weisskopf, 1988). If left to decompose without intervention, the plastic is then available for interaction with other marine animals (Mattlin and Cawthorn, 1986; Derraik, 2002).

Alternatively, marine mammals may mistake synthetic debris like Styrofoam or plastic bags with prey species, and ingest them (Baird and Hooker, 2000; Marine Mammal Commission, 2001). Ingestion of debris may cause a physical blockage in the digestive system to the point of starvation, introduce toxic chemicals into the tissues of animals that consume it, or may cause the animal to feel satiated and reduce its foraging effort (Laist, 1997; Derraik, 2002). Typically, cause of death is difficult to identify in marine mammal strandings, and it is additionally difficult to assess where the animal encountered debris.

Some of these incidents are obvious. For example, in 2002, a minke whale washed up in Normandy, France with fragments of 16 plastic bags (totaling ~1kg of plastic) in its stomach, and no food (De Pierrepont et al., 2005). Ingestion of plastic bags and Styrofoam has been identified as the cause of death for even deep-diving and rarely observed species such as beaked whales (Simmond and Nunny, 2002; Gomercic et al., 2006) and pygmy sperm whales (Tarpley and Marwitz, 1993; Stamper et al., 2006). For the most part, though, attributing cause of death to marine debris ingestion or entanglement is difficult (Laist, 1997), and therefore requires the involvement of well-trained pathologists following careful necropsy protocols (Raverty and Gaydos, 2004).

Here we have attempted to estimate the abundance of marine debris and to identify areas where debris may be posing greatest threat to marine mammals in the coastal waters of BC (see Figure 1). These areas were identified by spatially overlaying interpolated densities of marine debris with interpolated densities of marine mammals, based on systematically collected at-sea survey data. Harwood (2000) notes that “risk” is the probability that an undesirable event will occur, and that risk assessments refer to quantitative methods to estimate that probability. For our purposes, the probability of debris entanglement and ingestion in various marine mammal species is a parameter to be estimated, but intuitively, it is expected that proximity between the two objects is one of the key determinants of risk. Relative risk is approximated by multiplying predicted density of animals with predicted density of a stressor (i.e., overlap with debris in this case, but it could be ship strike, anthropogenic noise impacts, or any other anthropogenic stressor). Zacharias and Gregr (2005) note that risk can, in turn, be decomposed into *vulnerability* and *sensitivity*. Using the terms as defined by Zacharias and Gregr (2005) for our purposes, sensitivity is the degree to which each marine mammal species is prone to debris entanglement and ingestion (i.e., which ones tend to consume or get tangled in plastics). Vulnerability can then be thought of as the probability that a marine mammal will be exposed to that stressor (i.e., the probability that a marine mammal and debris would be found in close proximity). Spatial overlap between debris and wildlife obviously does not guarantee entanglement or ingestion, but overlap is a prerequisite for entanglement and ingestion, so this approach strikes us as a useful starting point for discussion. Our goal was to identify areas where problems may be more likely to occur for any given species, and because the majority of British Columbians live along the province’s south coast, we see this as a useful priority-setting exercise. Mapping the overlap of marine mammals and debris can inform planning and allocation of resources by identifying areas to survey for beach-stranded carcasses that are not normally accessible to the general public in BC and to encourage additional prevention and mitigation measures in these areas.

Methods

We designed (Thomas et al., 2007) and conducted (Williams and Thomas, 2007) systematic sighting surveys of BC coastal waters. The survey was designed to dovetail between the waters surveyed by US federal agencies in waters off California, Oregon, Washington and Alaska. Marine mammal abundance from our surveys has been reported elsewhere (Williams and Thomas 2007), so the emphasis in the current study was on estimating distribution, rather than abundance. The survey was completed as designed in 2004 and 2005, which allowed simple analytical methods to be used (i.e., “conventional distance sampling” methods described in Buckland et al., 2001). The field survey could not be completed in its entirety in 2006, which meant that model-based methods had to be used for any analyses that used all three years of data (i.e., “density surface modelling”, details below, which is in the family of “advanced distance sampling” methods described in Buckland et al., 2001).

We used conventional and advanced distance sampling methods to estimate density of marine debris in the study area. Distance sampling is a well-established method for estimating wildlife density (number of objects per unit area), which is converted to abundance by multiplying by the size of the survey region. In a conventional distance sampling framework, marine debris is assumed to be distributed throughout the survey region according to some unknown process. Transect lines are placed according to a randomized or systematic sampling design and surveyed. This survey allows us to sample some estimable fraction of the debris, in which *n* objects are detected. The assumptions about the trackline placement are handled at the survey design step, which has been described elsewhere (Thomas et al., 2007; Williams and Thomas 2007, 2009).

In terms of field protocols, the following assumptions of conventional distance sampling (Buckland et al., 2001) are most important:

1. Objects directly on the line are always detected, (the so-called 'g(0)=1' assumption).
2. Objects are detected at their initial location, prior to any movement in response to the observer.
3. Distances are measured accurately, thereby allowing accurate calculation of the effective strip width.

Advanced methods are available to deal with cases that violate these assumptions (Thomas et al., 2010), but they are not addressed here.

The surveys were completed on 20-21m boats in summers 2004-06 (see Williams and Thomas, 2007 additional details about field methods). A team of six people allowed frequent rotation through the following positions: three observers on the observation platform; one computer operator out of the elements belowdecks; and two rest (break) positions to reduce observer fatigue. The primary observation team consisted of two observers standing on the platform (5m eye height) with 7X50 binoculars, scanning at 90 degrees on either side of the ship’s bow. A data recorder was on the platform with the observers, keeping a backup of GPS positions of each sighting, recording sightings on a data form, and reporting sightings and sighting conditions to the computer operator down below via two-way radio. In addition to recording effort along predetermined tracklines, the team recorded species, number of individuals, behavior, time, position and swim direction. When a sighting was made, the observer and data recorder noted radial distance, radial angle (measured using angle boards), time, location, species or detailed comments about distinguishing features, and number of objects. The field protocols were designed to maximize the chances of satisfying the three assumptions of conventional distance sampling (above), namely: certain trackline detection; no responsive movement; and accurate estimation of perpendicular distances. In the case of marine debris, the data recorder worked together with the observer who made the sighting to record some fine-scale information about the object to allow subsequent classification of the debris into debris composition categories. We did not record an estimate of object size, but had we done so, covariate distance sampling methods exist to evaluate how detection probability varied simultaneously with object size and perpendicular distance from the trackline (Buckland et al., 2001).

In terms of satisfying the underlying assumptions of distance sampling, we instructed observers to overlap search sectors on the trackline by 10 degrees to maximize the probability that all objects on the trackline were detected. Nevertheless, we almost certainly failed at this assumption, which means that subsequent abundance estimates are *minimum* estimates of the number of pieces of debris in the region. Advanced distance sampling methods exist to estimate g(0), but these require two independent platforms, which is difficult to achieve on a small boat. Responsive movement is obviously not a problem with inanimate objects. Accurate distance estimation is difficult at sea, so we set up blind trials for each observer that allowed us to calculate observer-specific correction factors to remove bias in visual estimates (see Williams et al., 2007). The cruise leader (RW) had each observer gauge the distance to 20 fixed objects while he measured true distance using laser rangefinders or radar. Later, the estimated distances were regressed on the true distances (a linear model with variance proportional to mean and a log link), and calculated the slope through the origin. That slope was used to "correct" visual estimates along the survey.

We estimated an “effective strip width” (Buckland et al., 2001) from the histogram of perpendicular distances to estimate the area effectively surveyed for marine debris and wildlife. The survey was designed such that sample density was representative of debris density within each survey stratum (for full details of the survey design, see Thomas et al. (2007)). The survey region was designed to provide representative coverage of four geographic strata (see Figure 1): Queen Charlotte Basin (covering Dixon Entrance, Hecate Strait, Queen Charlotte Sound and Queen Charlotte Strait); Johnstone Strait (the narrow passage off northeastern Vancouver Island); Strait of Georgia (southern Vancouver Island, including Strait of Juan de Fuca); and the “mainland inlet” stratum (which covered five, randomly sampled fjord systems along the mainland coast). In addition to providing an average density within a stratum, the data also provide sufficiently broad coverage to warrant use of spatial modelling methods to interpolate density surface maps across the entire survey region.

Density surface modelling methods were used to create spatially explicit layers representing average distribution of 11 marine mammal species and marine debris at the time the surveys were conducted (described previously in Williams and O’Hara (2010) and Williams et al. (2010)). Density of objects (11 marine mammal species and marine debris) was modeled using the following three-stage approach: (1) fitting a detection function, (2) estimating object abundance in each segment as a function of covariates, and (3) using the descriptive model to predict object density throughout the study region. Detection functions were fitted using Distance 6 (Thomas et al*.,* 2010). Candidate forms for the detection function were the hazard-rate and half-normal models (Buckland et al., 2001). Model selection was guided by AIC and goodness of fit statistics. Trackline detection probability was assumed to be certain (i.e., g(0) was assumed to be 1). The logarithm of school size, ln(*s*), was regressed on the estimated probability of detection at the distance the school was seen. The predicted value of ln(*s*) at zero distance (where detection probability is 1) was then back-transformed to provide the required estimate.

Estimating abundance of floating marine debris

Debris abundance was estimated using conventional distance-sampling analyses of only the 2004 and 2005 debris data, closely following methods described by Williams and Thomas (2007). Perpendicular distance data were right-truncated (Buckland et al., 2001), and several standard detection function models (Buckland *et al.* 2001 p.47) were fitted to the data using Distance (Thomas et al., 2010). Model selection was guided by AIC (Buckland et al., 2001) and goodness-of-fit statistics.

Estimating distribution through density surface modeling of marine debris and marine mammal data

Density surfaces were created by fitting a generalized additive model (GAM) -based spatial model to the effort and sightings data from 2004, 2005 and 2006. This GAM-based approach for creating density surfaces allows us to combine data from non-randomized surveys, surveys in which coverage probabilities vary in complex ways, or when coverage probability varies spatially and temporally (Hedley *et al.* 1999, Williams *et al.* 2006). Effort and sightings data were modelled using the "count" method (Hedley et al., 1999; Williams. Hedley and Hammond, 2006), which has been packaged into the new Density Surface Modelling (DSM) engine in Distance 6 (Thomas et al*.,* 2010). Tracklines were divided into segments approximately 1 nautical mile (n.mile) in length. Start and end locations of the segments were calculated using the Geofunc add-in (developed by Jeff Laake, National Marine Mammal Laboratory) for EXCEL 2000®. Depth of the midpoint of the segment was estimated by overlaying the tracklines on a bathymetry grid in ArcView 3.2®. Probability of encountering an object was modelled [Equation 1] as a tensor-product (te) smooth function of location (lat_i and lon_i denote the midpoint of the i^{th} segment), water depth (*depth*) and area searched (*area* is twice the effective strip half-width [i.e., truncation distance times mean detection probability within the strip] times the length of the segment). The response variable (estimated abundance of objects in the i^{th} segment, $\hat{n}_i$) was modelled as a quasipoisson distribution with a log link, which allowed an overdispersion (common to situations with many zeroes and few ones) parameter to be estimated from the data. The saturated DSM model was of the general form:

$$\hat{n}_i \sim \mathrm{te}(lat_i\,, lon_i) + \mathrm{s}(depth) + \mathrm{offset}\ (area) \qquad [1]$$

This saturated model was used unless a term was not significant at $P<0.05$. In the case of pinnipeds, only observations of animals at sea were used (i.e., animals that were hauled out were excluded from the analysis).

A gridded data set was created, containing a value in every grid cell for each explanatory variable in the model. A square grid size of 2n.mile (3.7 km) on a side (i.e., 4n.mile^2 or 13.7 km^2) was chosen to illustrate the predictions. Values for the explanatory variables (latitude, longitude and depth) were calculated using the value at the midpoint of each grid square. The prediction grid data were passed to the descriptive model selected for each species using the predict.gam function in mgcv included in Distance 6 (Thomas et al*.,* 2010). The output of the model was an estimate of the predicted number of whale schools in each grid cell, based on each cell's latitude, longitude, depth and area. Animal abundance predicted for each cell was calculated by multiplying the predicted density in each cell by expected school size (from the size-bias regression in the detection function modeling step; Buckland et al., 2001) and by the area of each cell (i.e., removing parts of the grid cell that were covered by land). Abundance overall is estimated by simply taking the sum of all grid cells.

Assessing overlap between marine mammals and marine debris

Vulnerability was modeled for each species as the product of the marine mammal density and marine debris density predicted in each cell. Risk was mapped using the "Jenks" or natural breaks methods in GIS, and therefore ranges from relatively low to relatively high. As a result, our relative risk maps can be used to compare spatial patterns within species, but should not be used to compare risk across species. We have used a similar approach to model spatial variability in ship strike risk for fin, humpback and killer whales in the region (Williams and O'Hara, 2010).

Assessing sensitivity of marine mammal species to marine debris interactions

We assessed the sensitivity (Zacharias and Gregr, 2005) of each species to debris interactions in three ways: reviewing both published and grey literature for reports of a species interacting with debris; querying the NOAA Fisheries Human Interaction database[3] for evidence of debris interactions; and conducting interviews with veterinarians and pathologists about their experience with marine mammal-debris interactions. Given our earlier point that recovered carcasses can only underestimate the scale of the problem, we report our list of marine mammal species known to be involved in debris interactions as a minimum (Table 2).

Results

Estimating abundance and distribution of floating marine debris

Search effort and debris sightings from the survey are shown in Figure 2. In total, 119 debris sightings were included in the analysis for abundance, with additional sightings in 2006 only used in density surface modelling. After truncation the sightings at a strip width of 100m, we had 98 sightings (including 4 pieces of debris that were seen off-effort, that is, used for fitting the detection function, but not for abundance estimation). The data were best described using a hazard rate detection function. Overall, objects within 100m either side of the ship's trackline had a mean probability of being sighted of 27%. All sightings were of single objects.

Mean density of debris (objects per km^2) in the study area overall was 1.48. Point estimates of density were lowest in Johnstone Strait (0.91) and highest in the mainland fjords (2.27). Mean debris density was 1.25 in Queen Charlotte Basin, and 2.13 in Strait of Georgia (the area closest to the largest human populations) (Figure 2). Note that these differences are not statistically significantly different from one another. The range was especially large in the mainland fjords, where the CIs for density spanned two orders of magnitude (0.22 to 23.2 objects per km^2) – this reflects the fact that one of the five mainland

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[3] Courtesy Dr Teri Rowles (US Office of Protected Resources)

fjords sampled had very high concentrations of debris, while others had very low density of debris (Figure 2).

The abundance estimate for floating marine debris overall is 36,000 (95% confidence intervals: 23,000-56,600) pieces. Of this, the vast majority of debris was estimated to occur in the Queen Charlotte Basin, (~23,000 pieces), the largest stratum in our study. The lowest amount of debris was estimated to occur in Johnstone Strait (~100 pieces), the smallest stratum in our study.

Debris composition analysis

The most common type of debris by far was Styrofoam (Table 3). This was followed by plastic bottles and plastic bags. Plastic sheeting, packaging and various other types of plastic, including plastic strapping material, were commonly seen. Relatively little fishing debris was seen, other than buoys, which may have come from fishing or tourism activities. Of course, we were only able to see debris floating at the surface, so we are missing much of the derelict fishing gear (Gilardi et al., 2010) if there. Many items observed in our study are considered indicator items suggesting an ocean-based source according to the Ocean Conservancy's National Marine Debris Monitoring Program (Sheavly, 2007), but most could not be assigned unequivocally to either a land-based or ocean-based indicator category.

Overlapping surface model outputs for marine debris and marine mammal data

The predicted density surface for floating marine debris is shown in Figure 2, and the predicted densities for 11 marine mammal species are shown in Figures 3, 4, 5 and 6 (left-hand side). Note that the density gradient (i.e., grey scale, from white to grey to black to show increasing density) for each map has been optimized for that species to show spatial patterns. "Risk maps" (areas predicted to have overlap between marine mammals and marine debris) are shown in the right-hand panels of Figures 3, 4, 5 and 6 (right-hand side) for 11 marine mammal species. Again, the grey scale ranges from white to grey to black to show increasing probability of animals and debris being found within the same grid square. These maps may be used to identify areas of relative importance within a given species, but should not be used to compare across species, because each map has been scaled to accommodate the densities of that particular species. Comparing risk across species will require additional research and coordinated efforts to quantify the different sensitivity of species to entanglement and ingestion, as well as efforts to identify a link function between proximity to debris and mortality rate.

Discussion

Distribution and composition of debris in BC waters

Overall abundance of floating marine debris was estimated to be 36,000 (95% confidence interval: 23,000-56,600) pieces throughout the study area (Figure 2). Of this, the majority of debris was estimated to occur in the largest distinct water body of this study (the Queen Charlotte Basin stratum, ~23,000 pieces). Perhaps most interesting is that the waters off the most heavily populated area, Vancouver, did not contain the highest densities of debris (Figure 2). In fact, the highest densities of debris were found off Victoria, as well as in relatively remote areas off Prince Rupert, western Dixon Entrance (Langara Island), and Cape Scott (Figure 2).

Styrofoam was by far the most common type of debris we observed, followed by plastic bottles and plastic bags (Table 3). Plastic sheeting, packaging and various other types of plastic, including plastic strapping material, were commonly seen. While plastic strapping material was rarely observed, it is highlighted, because it is often reported constricting the necks of pinnipeds (Laist, 1997). Little fishing debris was seen, other than buoys, and because most derelict fishing gear would be below the surface, we encourage additional studies to evaluate the extent of discarded and derelict fishing gear in the region.

Average density of marine debris in the study area overall was estimated to be 1.48 per km^2. Point estimates of density were lowest in Johnstone Strait (0.91 km^{-2}) and highest in the mainland fjords (2.27 km^{-2}). Mean densities were estimated at 1.25 km^{-2} in the Queen Charlotte Basin, and 2.13 km^{-2} in the Strait of Georgia (the area closest to the largest human settlements). Future research will be required to help identify the source of this debris, in particular whether the bulk of the debris is coming from oceanic or land-based sources, in order to guide efforts to reduce the input of marine debris into these waters (Table 3).

Our estimated density of marine debris found along the coast of BC is approximately 35 times greater than densities reported from surveys conducted between 1986 and 1991 by Matsumura and Nasu (1997). Matsumura and Nasu (1997) estimated densities of floating plastic at 0.042 pieces per km^2 (converted from 14.4 pieces per 100 n.mile^2) off northwestern BC, while no plastic was found off the southwestern coast. In contrast, they reported 0.50 pieces per km^2 (170.5 pieces per 100 n.mile^2) in the waters near the Great Pacific Garbage Patch northwest of Hawaii; and a maximum of 9.3 pieces per km^2 (3178.5 pieces per 100 n.mile^2) in waters off southeast Asia. If estimates from both studies were correct, then density of marine debris would have to be increasing at a rate of at least 25% per year to account for the discrepancy. Furthermore, current estimates of densities of floating plastics in BC waters are similar to densities estimated in the Great Pacific Garbage Patch 19-24 years ago. However, densities by Matsumura and Nasu (1997) are based on data collected opportunistically from a variety of survey platforms including research vessels, training ships, fisheries patrol boats, volunteer fishing boats, and cargo vessels. Different methodologies may explain apparently higher densities documented in our study, as observers on an opportunistic survey may easily have missed debris along the trackline. As well, vessels used by Matsumura and Nasu (1997) were generally larger, allowing for surveys in much rougher seas and consequently poorer sighting conditions, and would therefore have missed many of the smaller pieces of debris reported on our small-boat surveys. This highlights the need for standardized methods in field protocols in debris surveys.

Standardized methods for estimating debris density

The difficulty in comparing results between studies points to a general need for standardization of methods and reporting results in a common currency. Distance sampling (Buckland et al., 2001) is a well-established method for estimating density of objects from line transect surveys, and we encourage the collection of data that satisfy the assumptions underlying any distance sampling analysis. Our ability to make inferences about debris and wildlife distribution, density and abundance was assisted by following good principles of survey design and field protocols for line transect surveys in general. For example, approximately 10% of the total budget for the original survey (Williams & Thomas, 2007) was spent on survey design (Thomas et al., 2007). We know that paying close attention to survey design and field protocols will pay off in generating good results. The line-transect and mark-recapture abundance estimates we generated for killer whales during this survey agreed nicely with the true population size known from annual censuses conducted by Fisheries and Oceans Canada (Williams and Thomas, 2009).

Many marine debris researchers (e.g., Ribic et al. 1992; Aliani et al. 2003) have discussed the relative merits of strip transects (in which a constant strip width is assumed) versus line transects (in which perpendicular distances are used to estimate the width of the strip that is effectively searched along the transect). The former is certainly easier to do in the field, but it makes the assumption that all objects within the strip are detected. In contrast, conventional line transect surveys relax this assumption to certain detection on the trackline (and even this can be corrected with double-platform data collection). From our detection function, we estimated that our observers had only a 27% probability of detecting debris within 100m on either side of the trackline, because detection probability fell off steeply as distance from the trackline increased. As a result, our estimates of abundance would have been underestimated by a factor of 3.7 (= 1/0.27) if we had assumed 100m coverage in a strip transect, rather than estimating this parameter from our own perpendicular distance data we collected in the field. This detectability factor will vary from survey to survey, and we strongly encourage the collection of perpendicular distances (or radial distances and angles) when estimating debris density. The additional data collection is not a burden and its affect on the resulting abundance estimate makes it well worth the effort. In fact, debris sightings can be used to train observers on good field protocols and test for bias in visual range estimates, thereby improving surveys of marine mammals and seabirds (Williams et al., 2007); marine debris and marine wildlife surveys can be combined in a complementary, cost-sharing manner (Williams and Thomas, 2007).

Areas of overlap between debris and mammals

Many areas of strong overlap between marine mammals and marine debris were found far from the urban areas where they would be most likely to be seen. To some extent, this reflects the distribution of marine mammals themselves (Figures 3, 4, 5 and 6 – left-hand side panel), many of which are quite discrete in their distribution and show strong habitat preference for north and central coast waters. However, even for species like harbor porpoise and harbor seals, which are found near urban areas off the south coast, the riskiest areas include both urbanized areas off southern Vancouver Island and remote areas including BC's northern mainland fjords (Figures 5, and 6). The highest risk areas for fin whales were found in Dixon Entrance, Gwaii Haanas National Park Reserve, and mainland fjords north of Vancouver Island (Figure 3). These are the same areas identified as places where attention should be paid to entanglement for humpback whales, although relatively high-risk areas for humpback whales also include Cape Scott Provincial Park off northwest Vancouver Island (Figure 3). For northern resident killer whales, the highest risk area was Johnstone Strait (Figure 3), which has been proposed as critical habitat for the population (Fisheries and Oceans Canada 2008a) and includes Robson Bight (Michael Bigg) Ecological Reserve (Figure 1). Incidentally, this is also the site where killer whales are at highest risk of ship strike (Williams and O'Hara 2010) and oil spills (Williams, Lusseau and Hammond, 2009). Although considered "Not at Risk" in Canada's Pacific region, Pacific white-sided dolphins (Figure 4) would gain parenthetically from any mitigation efforts focused on cleaning up the highest-risk areas for humpback and fin whales offshore of Gwaii Haanas National Park Reserve. For Dall's porpoise, the highest risk areas were off southwest Vancouver Island, as well as western Dixon Entrance, Kitimat (north coast fjords) and central coast fjords (Figure 4). For minke whales, the highest-risk area identified was in western Dixon Entrance (Figure 4). Minke whales strike us as a priority species for additional research (through photo-identification and entanglement scarring analyses of live animals and full necropsies of recovered carcasses), because (a) their abundance, biology and ecology in BC are poorly studied (Williams and Thomas 2007), (b) their distribution is generally far removed from urban areas, and (c) elsewhere in the species' range, there is a surprisingly high rate of entanglement in ropes (Northridge et al., 2010). Our surveys did not cover the west coast of Vancouver Island, the preferred habitat for sea otters (Watson et al., 1997), but we found sea otters distributed in two discrete areas off northeastern Vancouver Island and on the central mainland coast. Both of these areas emerged as high-risk areas for overlap with debris (Figure 6). Steller sea lions were predicted to overlap most strongly with marine debris in Gwaii Haanas National Park Reserve (Figure 5), which includes the largest rookery for this species in our study area (Fisheries and Oceans Canada, 2008b). The areas of overlap between elephant seals and debris were predicted to occur in central coast mainland fjords (Figure 5).

Overall, the highest risk areas across all marine mammal species can be summed up in four broad regions: western Dixon Entrance (Langara Island, northwest part of the study area); Prince Rupert (northeast part of the study area); Cape Scott Provincial Park (northwest Vancouver Island, middle west part of the study area); and southwestern Vancouver Island (southwestern part of the study area). Additionally, Gwaii Haanas National Park Reserve (southern Queen Charlotte Islands, middle-west part of the study area) appeared as a high-risk area for humpback whales, fin whales and Pacific white-sided dolphins. In other words, the riskiest areas were quite remote, and in areas recognized for their importance to at-risk species. The areas that we would identify as the regions of highest concern may warrant funding to improve recovery of at-risk species through the creation and informing of initiatives aimed at reducing debris input and providing mitigation of impacts from debris already present in the system. These initiatives, though aimed at recovery of at-risk species, would incidentally help multiple species that depend on the same habitat. Pacific white-sided dolphins and elephant seals occupy the most pelagic and inaccessible of all the highest-risk areas, and we suspect that reporting bias may be particularly strong for these species (Figures 5, and 6).

Need to assess relationship between proximity to debris and rates of ingestion/entanglement

Elevated risk of exposure to floating debris is not evidence of negative interaction, although marine debris is known to pose health threats for most of the species in our study (Table 2). Here, we identify areas where interaction between marine mammals and marine debris is most likely. In other words, our study answers "*Where*?" questions, rather than "*How much*?" questions. A great deal more work would be required to estimate how much, if any, mortality is occurring from marine debris entanglement and ingestion, and whether that mortality exceeds sustainable limits for marine mammal populations based on Canadian management objectives (Williams et al., 2008). Our approach is intended to guide that future work. Our measure of density of floating debris is considered as an index of distributions of debris in the upper water column in general, because it follows that smaller less detectable debris are likely affected by the same processes such as surface currents, winds, and hydrographic features. Furthermore, and perhaps most importantly, debris in the upper water are likely affected by these processes similarly to plankton in that they passively move with currents and wind, and collect near convergent fronts (Moore et al., 2001). The distribution of marine debris documented here is consistent with some of the surface currents described along the BC coast (Freeland et al., 1984; Crawford et al., 1999). Unfortunately, areas of concentrated of marine debris likely overlap with concentrations of higher trophic-level taxa, which are generally attracted to the same areas – processes that concentrate debris also concentrate plankton and nutrients and increase oceanic productivity (Bakun, 1996). Overlapping distributions of marine mammals and floating debris means that these upper-trophic taxa would likely be exposed to the risk of ingesting marine debris either incidentally or intentionally, which is consistent with emerging results from studies on other upper trophic-level taxa used as indices of marine ecosystem health (for example see Moore 2008). Obviously, the likelihood of ingesting debris or becoming entangled is not solely a function of proximity, and not all interactions will result in fatalities. We welcome the news that the Canadian Department of Fisheries and Oceans is leading a coordinated marine mammal stranding response network, and hope that our analyses can help that effort to identify areas that may need additional resources to conduct surveys for beach-cast carcasses.

Several lessons emerged from our attempt to survey both published and grey literature, query the NOAA Fisheries Human Interaction database[4] for evidence of debris interactions, and interview veterinarians and pathologists about their experience with marine mammal-debris interactions (summarized in Table 2). Overall, we conclude that entanglement is likely to be a bigger problem than ingestion for most species in our study area, but that both issues warrant closer attention. For example, some of the species that are most sensitive to ingestion do not occur in our sightings database, although they are known to occur in BC waters. Sperm whales, which regularly depredate fishing lines and are exposed to human generated plastic debris from fishing vessels, were hunted historically in BC off the west coasts of Vancouver Island and Haida Gwaii, but are now poorly studied in BC. Dr Frances Gulland (The Marine Mammal Center in California) performed necropsies on two sperm whales and found that

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[4] Courtesy Dr Teri Rowles (US Office of Protected Resources)

stomachs contained fishing gear and other plastic debris; gastric impaction was named as the likely cause of death in both cases (Jacobsen et al., 2010).

Two lessons emerged from our literature review in terms of guiding future research priorities. First, the two species that are most likely to consume Styrofoam (the debris type most commonly seen in our survey) are Steller sea lions and northern elephant seals (Table 2). Neither of these species would be a high priority for necropsy if a marine mammal response program were guided solely by endangered species listing status (Table 1). We are not claiming that debris ingestion is causing population-level effects in either case; however, if debris were ever to be considered a conservation threat to these two populations, we would be unlikely to find that out without a plan to necropsy stranded pinnipeds as a matter of course. Secondly, among cetaceans, at least five species are known to ingest plastic bags (Table 2): harbor and Dall's porpoise, Pacific white-sided dolphins, and minke and humpback whales. Among these, only harbor porpoise and humpback whales have any at-risk status under SARA. Again, if the status of one of these other species needed to be re-evaluated, it would be difficult to identify that debris entanglement or ingestion was causing mortality unless these species were routinely incorporated into standard necropsy protocols. At present, stranded large whales generally would be necropsied, but small cetaceans might not be, depending on accessibility and capacity. Existing abundance estimates for harbor and Dall's porpoise and minke whales in BC coastal waters are coarse (Williams and Thomas 2007, Williams et al., 2008), and we are unlikely to detect population decline from a series of imprecise abundance estimates (Taylor et al., 2007).

Need for centralized database

The US National Marine Fisheries Service's Marine Mammal Health and Stranding Program is currently compiling a national database for marine mammal-human interactions. Some regions are farther along in that process than others. Canada's Pacific Region is also compiling decades' worth of paper records into a centralized database for DFO (Lisa Spaven, pers. comm.). One lesson to emerge from our interviews is that detailed necropsy results may not get fed back into the human interactions database, and that some data are proprietary. If a necropsy reveals plastic in a marine mammal's stomach, for example, that may not trigger a stranding to be reclassified as a human interaction. In Canada, each fisheries region collects its own data, and to the best of our knowledge, no national database on marine mammal-debris interactions yet exists. Centralized repositories for cetacean necropsy reports are being developed, but the scale of debris interactions will be underestimated in any database as long as full necropsies are more commonly conducted on endangered cetaceans than non-endangered pinnipeds. On a global scale, IWC is compiling a large-whale ship strike database, which could store information on debris entanglement and ingestion in large whales, but not for pinnipeds, otters or small cetaceans. We encourage regional data sharing and transboundary cooperation on this issue wherever possible.

Ultimately, there are many oceanographic and biological factors beyond our control that cause us to underestimate mortality due to debris interactions: e.g., the carcass does not make it ashore; it does not get reported; it does not get necropsied; it gets necropsied after the evidence has decayed. It is important to identify those factors that are within our control to ensure that those few cases that are detected get reported accurately, namely by conducting necropsies on as many animals as possible or from as representative a sample as possible. When we find information on cause of death, it is essential to ensure that that information is put back into a central database that can assist other pathologists dealing with ambiguous cases. One participant in our interviews noted that it may be as important to report cause of death in cases that are natural as those that are anthropogenic – in many cases, cause of death is not assigned with certainty, but rather through a process of elimination, so any information that can narrow down the field may be helpful to future necropsies.

Recovered carcasses tell an interesting, but inherently incomplete story

In a perfect world, mortality rate from some representative sample of observed mortality events could be used to make inference about the number of mortalities that went undetected at sea. Ideally, we would have an estimate of debris mortality rate in the way that we aspire to do for fisheries bycatch, namely by estimating bycatch rate from some representative sample of observer coverage data (see discussions in Julian and Beeson 1998, Babcock et al. 2003). The cryptic and accidental nature of the debris entanglement and ingestion problem precludes a randomized observer coverage problem, but we see several options. The first is to acknowledge that our view of the problems posed by marine plastic pollution emerges from a negatively biased (by its nature, it can only underestimate the scale of the problem) and opportunistic sample (we work with what we have). One option to minimize bias is to ensure adequate funding for stranding programs, such that carcasses can be recovered from and full necropsies performed on as representative a sample (spatially, temporally and taxonomically) of marine mammal mortalities as possible. Again, the ideal situation would be one in which carcasses of all species and in all places have equal probability of being detected and necropsied to estimate the minimum number of marine mammals harmed or killed by debris entanglement or ingestion. The likelihood of reaching that goal is a function of logistics and funding, but the goal should be representativeness if we want to use the sample for inference.

We see a strong need to develop new analytical tools that would allow us to “scale up” from opportunistically recovered carcasses and observations of entangled marine mammals to try to estimate total number of animals affected each year at sea, but never observed. It is this estimate of total annual mortality, rather than the minimum counts that happen to come to our attention, that should be compared to the sustainable mortality limits that the population is thought to be able to withstand (Wade, 1998; Williams et al., 2008). We have reason to believe that underestimation of the problem could be substantial. In the well-studied killer whales in BC, only 7% of animals known from annual censuses to have died over the last 30 years have resulted in a recovered carcass (Fisheries and Oceans Canada, 2008a). We suspect that our perception of the debris problem would be altered if our scientific advice made a more concerted effort to account, statistically, for the very low probability of detecting the problem in the first place.

It is unknown whether marine mammals are likely to strand close to where an interaction occurred. Animals that interact with marine debris may not die immediately (Laist, 1997). When entangled, some pinnipeds may come ashore to facilitate breathing, and then starve slowly; others (and presumably most cetaceans) may die at sea where carcasses sink or are scavenged and go undetected. As a result, our overlap analyses may indicate where interactions may occur, but not where highly mobile species like marine mammals may eventually strand as a result of an interaction, especially when most interactions are likely to result in chronic rather than acute injury or mortality (Laist, 1997). All of these confounding factors make it essential for regulatory agencies to fund programs that obtain the best spatial, temporal and taxonomic coverage for necropsies as possible, notwithstanding the logistical and funding restraints. Furthermore, we limit our discussion to acute effects resulting from interactions between marine mammals and debris yet fully recognize that there must be a suite of sub-acute affects that could still have profound population-level implications (for e.g., reduced fecundity).

That said, economic realities and logistical constraints ensure that full necropsies cannot always be performed. In some jurisdictions, there may be a need for better training for first responders to prioritize collection of data that may indicate entanglement in, and/or ingestion of, marine debris, in those cases where time or resources are lacking to conduct a full necropsy.

Conclusion

We do not yet have sufficient data to estimate mortality rate due to debris entanglement and ingestion from opportunistic samples, and encourage methodological development that allow us to do so. Our primary intent is to provide results in spatial form so that (a) the density layers can feed into ongoing marine spatial planning processes in the region; and (b) the risk layers can be incorporated into stranding response programs. We see broad benefit to the 3-stage approach we used: collect data from systematic line-transect surveys; use spatial modeling methods to map at-sea distribution of debris and marine mammal species; and identify areas of overlap that could be targeted for future work. We encourage managers to allocate sufficient resources to stranding response programs to search for carcasses in areas that are close to and far from human settlements, as well as necropsying endangered and non-endangered species for signs of debris entanglement or ingestion. We encourage the collection of new field data in marine mammal stranding programs around the world to evaluate whether even abundant and seemingly healthy populations of marine mammals are impacted by debris. Mitigating impacts before populations become threatened will be easier than waiting for population decline to be detected, identifying causal factors, and then trying to reverse it (Taylor et al., 2007).

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References

Aliani, S., Griffa, A., Molcard, A., 2003. Floating debris in the Ligurian Sea, north-western Mediterranean. Mar. Pollut. Bull. 46, 1142–1149.

Auman H.J., Woehler E.J., Riddle M.J., Burton H., 2004. First evidence of ingestion of plastic debris by seabirds at sub-Antarctic Heard Island. Mar. Ornithol. 32, 105-106.

Babcock, E.A., Pikitch, E.K., Hudson, C.G., 2003. How much observer coverage is enough to adequately estimate bycatch? Available from Oceana: http://na.oceana.org/sites/default/files/o/uploads/BabcockPikitchGray2003FinalReport.pdf

Baird, R.W., Hooker, S.K., 2000. Ingestion of plastic and unusual prey by a juvenile harbour porpoise. Mar. Pollut. Bull. 40, 719-720.

Bakun, A., 1996. Patterns in the ocean: ocean processes and marine population dynamics. Centro de Investigaciones Biologicas del Noroeste, La Paz, BCS, Mexico.

Buckland, S., Anderson, D. R. Burnham, K. P. Laake, J., Borchers, D., Thomas, L., 2001. Introduction to distance sampling: estimating abundance of biological populations. Oxford University Press, Oxford, UK.

Cawthorn, M.W., 1985. Entanglement in, and ingestion of, plastic litter by marine mammals, sharks, and turtles, in New Zealand waters. Pp. 336-343. In: Shomura, R.S. and O.H. Yoshida (eds.). Proceedings of the Workshop on the Fate and Impact of Marine Debris, 27-29 November, 1984, Honolulu, Hawaii. US Dept. Commerce, NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFS-54. NOAA, Silver Spring, Maryland.

Crawford, W.R., Cherniawsky, J.Y., Cummins, P., 1999. Surface currents in British Columbia coastal waters: comparison of observations and model predictions. Atmosphere-Ocean 37, 255-280.

De Pierrepont, J.F., Dubois, B., Desormonts, S., Santos, M.B., Robin, J.P., 2005. Stomach contents of English Channel cetaceans stranded on the coast of Normandy. Journal of the Marine Biological Association of the UK 85, 1539-1546.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.

Dufault, S., Whitehead, H., 1994. Floating marine pollution in "the Gully' on the continental slope, Nova Scotia, Canada. Mar. Pollut. Bull. 28, 489-493.

Fisheries and Oceans Canada, 2008a. Recovery Strategy for the Northern and Southern Resident Killer Whales (*Orcinus orca*) in Canada. *Species at Risk Act* Recovery Strategy Series, Fisheries and Oceans Canada, Ottawa, ix+81 pp.

Fisheries and Oceans Canada, 2008b. Management Plan for the Steller Sea Lion (*Eumetopias jubatus*) in Canada [Draft]. *Species at Risk Act* Management Plan Series. Fisheries and Oceans Canada, Ottawa. vii + 70 pp.

Fowler, C.W., 1987. Marine debris and northern fur seals: a case study. Mar. Pollut. Bull. 18, 326–335.

Freeland, H. J., Crawford, W.R., Thomson, R.E., 1984. Currents along the pacific coast of Canada. Atmosphere-Ocean 22, 151-172.

Furness, R.W., Camphuysen, K.C.J., 1997. Seabirds as monitors of the marine environment. ICES J. Mar. Sci. 54, 726-737.

Gilardi, K.V.K., D. Carlson-Bremer, J.A. June, K. Antonelis, G. Broadhurst, T. Cowan., 2010. Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. Mar. Pollut. Bull. 60, 376–382.

Gomercic, H., M.D. Gomercic, T. Gomercic, H. Lucic, M. Dalebout, A. Galov, D. Skrtic, S. Curkovic. 2006. Biological aspects of Cuvier's beaked whale (*Ziphius cavirostris*) recorded in the Croatioan part of the Adriatic Sea. European Journal of Wildlife Research 52, 182-187.

Harwood, J., 2000. Risk assessment and decision analysis in conservation. Biol. Conserv. 95, 219-226.

Henderson, J.R., 2001. A Pre- and Post-MARPOL Annex V Summary of Hawaiian Monk Seal Entanglements and Marine Debris Accumulation in the Northwestern Hawaiian Islands, 1982–1998. Mar. Poll. Bull. 42, 584-589.

Jacobsen, J.K., Massey, L., Gulland, F., 2010. Fatal ingestion of floating net debris by two sperm whales (*Physeter macrocephalus*). Mar. Poll. Bull. 60, 765-767.

Johnston, D.W., Meisenheimmer, P., and Lavigne, D.M., 2000. An evaluation of management objectives for Canada‘s commercial harp seal hunt, 1996 – 1998. Conserv. Biol. 14, 729-737.

Laist, D.W., 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. Mar. Poll. Bull. 18, 319-326.

Laist, D.W., 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records, in Coe, J. M., Rogers, D. B. (Eds*.)* Marine Debris: Sources, Impacts, and Solutions. Springer, New York, pp. 99-139.

Marine Mammal Commission, 2001. Annual Report to Congress, 2000. Marine Mammal Commission, Bethesda, Maryland.

Mattlin, R.H., Cawthorn, M.W., 1986. Marine debris—an international problem. New Zealand Environment 51, 3–6.

Matsumura, S., Nasu, K., 1997. Distribution of floating debris in the North Pacific Ocean: Sighting surveys 1986-1991, in Coe, J. M., Rogers, D. B. (Eds.) Marine Debris: Sources, Impacts, and Solutions. Springer, New York, pp. 15-24.

Moore, C.J., 2008. Synthetic polymers in the marine environment: A rapidly increasing, long-term threat. Environ. Res. 108, 131-139.

Moore, C.J., Moore, S.L., Leecaster, M.K., Weisberg, S.B., 2001. A Comparison of Plastic and Plankton in the North Pacific Central Gyre. Mar. Poll. Bull. 42, 1297-1300.

Northridge, S., Cargill, A., Coram, A., Mandleberg, L., Calderan, S., Reid, B., 2010. Entanglement of minke whales in Scottish waters; an investigation into occurrence, causes and mitigation. Final Report to Scottish Government CR/2007/49, 57 pp. Available from http://www.smru.st-andrews.ac.uk/

Rago, P.J., Wigley, S.E., Fogarty, M.J., 2005. Northeast Fisheries Science Center bycatch estimation methodology: allocation, precision, and accuracy. U.S. Dep. Commer., Northeast Fish. Sci. Cent. Ref. Doc. 05-09; 44 p. Available from National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026.

Raverty, S.A., Gaydos, J.K., 2004. Killer Whale Necropsy Protocol. Unpublished report available from http://www.seadocsociety.org/publications.

Ribic, C.A., Dixon, T.R., Vining, I., 1992. Marine debris survey manual. NOAA Technical Report NMFS 108, NOAA National Marine Fisheries Service, Seattle, WA. 92pp.

Stamper, M.A., Whitaker, B.R., Schofield, T.D., 2006. Case study: morbidity in a pygmy sperm whale *Kogia breviceps* due to ocean-bourne plastic. Mar. Mamm. Sci. 22, 719-722.

Sheavly, S.B., 2007. National Marine Debris Monitoring Program: Final Program Report, Data Analysis and Summary. Prepared for U.S. Environmental Protection Agency by Ocean Conservancy, Grant Number X83053401-02, 76 pp.

Tarpley, R.J., Marwitz, S., 1993. Plastic debris ingestion by cetaceans along the Texas coast: Two case reports. Aquat. Mamm. 19, 93-98.

Taylor, B.L., Martinez, M., Gerrodette, T., Barlow, J., Hrovat, Y.N., 2007. Lessons from monitoring trends in abundance of marine mammals. Mar. Mamm. Sci. 23, 157-175.

Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R., Marques, T.A., Burnham, K.P., 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. J. Appl. Ecol. 47, 5–14.

Thomas, L., Williams, R., Sandilands, D., 2007. Designing line transect surveys for complex survey regions. J. Cetac. Res. Manage. 9***,*** 1-13.

Wade, P.R., 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. Mar. Mamm. Sci. 14, 1–37.

Wallace, N., 1985. Debris entanglement in the marine environment: a review. Pp. 259-277. In: Shomura, R.S. and O.H. Yoshida (eds.). Proceedings of the Workshop on the Fate and Impact of Marine Debris, 27-29 November, 1984, Honolulu, Hawaii. US Dept. Commerce, NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFS-54. NOAA, Silver Spring, Maryland.

Watson, J.C., Ellis, G.M., Smith, T.G., Ford, J.K.B., 1997. Updated status of the sea otter, *Enhydra lutris*, in Canada. Can. Field-Nat. 111, 277-286.

Weisskopf, M., 1988. Plastic reaps a grim harvest in the oceans of the world (plastic trash kills and maims marine life). Smithsonian 18, 58.

Williams, R., Hedley, S.L., Hammond, P.S., 2006. Modeling distribution and abundance of Antarctic baleen whales using ships of opportunity. Ecology and Society 11, 1. [online] URL: http://www.ecologyandsociety.org/vol11/iss1/art1/

Williams, R., Thomas, L., 2007. Distribution and abundance of marine mammals in the coastal waters of BC, Canada. J. Cetacean Res. Manage. 9, 15-28*.*

Williams, R., Leaper, R., Zerbini, A., Hammond, P.S., 2007. Methods for investigating measurement error in cetacean line transect surveys. J. Mar. Biol. Assoc. U.K.87, 313-320.

Williams, R., Hall, A., Winship, A., 2008. Potential limits to anthropogenic mortality of small cetaceans in coastal waters of British Columbia. Can. J. Fish. Aquat. Sci. 65, 1867-1878.

Williams, R., Thomas, L., 2009. Cost-effective abundance estimation of rare animals: Testing performance of small-boat surveys for killer whales in British Columbia. *Biological Conservation* 142:1542-1547.

Williams, R., O'Hara, P., 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. J. Cetacean Res. Manage., 11, 1-8.

Williams, R., Okey, T.A., Wallace, S.S., Gallucci, V.F., 2010. Shark aggregation in coastal waters of British Columbia. Mar. Ecol. Prog. Ser. 414, 249-256

Zacharias, M.A. and Gregr, E.J., 2005. Sensitivity and vulnerability in marine environments: an approach to identifying vulnerable marine areas. Conserv. Biol. 19, 86-97.

Species	Conservation Status by Region or Agency							
	COSEWIC	**SARA**	**BC**	**ESA**	**MMPA**	**WA**	**AK**	**IUCN**
Harbor seal	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower
Elephant seal	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower
Steller sea lion	Special Concern	Special Concern	Imperiled	Endangered	Threatened	Threatened	Threatened	Endang
Dall's porpoise	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower
Harbor porpoise	Special Concern	Special Concern	Vulnerable	Not Endangered	Not depleted	Candidate for Listing	Not Threatened	Threate
Fin whale	Under Consideration	Threatened	Critically Imperiled	Endangered	Depleted	Endangered	Endangered	Endang
Minke whale	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower
Humpback whale	Threatened	Threatened	Critically Imperiled	Endangered	Depleted	Endangered	Endangered	Vulner
Killer whale *northern resident*	Threatened	Threatened	Imperiled	Endangered	Threatened	Endangered	Not Threatened	Lower
Pacific white-sided dolphin	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower
Sea otter	Threatened	Special Concern	Imperiled	Threatened		Endangered	Threatened	Endang

Table 1: Conservation status for marine mammal species observed on Inside Passage surveys. The table includes conservation status as recognized by: Canada's Committee on Status of Endangered Wildlife in Canada (COSEWIC), Canada's Species at Risk Act (SARA), British Columbia's Wildlife Act (BC), US Federal Endangered Species Act (ESA), US Marine Mammal Protection Act (MMPA), Washington State Department of Fish and Wildlife Endangered Species list (WA), State of Alaska Department of Fish and Game (AK), and the International Union for the Conservation of Nature (IUCN).

Species	Entanglement	Ingestion	Debris Type	Reference
Harbor seal	Yes	Unlikely	strapping bands and other	a,b
Elephant seal	Yes	Yes	Styrofoam, monofilament line, strapping bands, trawl net, gill net	A,g
Steller sea lion	Yes	Yes	Styrofoam, trawl net, rope, strapping bands	A,b,c,e,i,j
Dall's porpoise	Yes	Yes	fishing gear, plastic bags & sheeting, plastic straw, cardboard, bottle-cap	A
Harbor porpoise	Yes	Yes	fishing gear, plastic bags, cloth	A,b,d,e
Fin whale	Yes	Yes	fishing gear, general debris	B
Minke whale	Yes	Yes	polyethylene bag, plastic sheeting, plastic bag, ropes	A,k,l
Humpback whale	Yes	Yes	fishing gear, plastic bags	A,b,j,m
Killer whale	Yes	Yes	ropes and floats	A,b,e,f
Pacific white-sided dolphin	Yes	Yes	plastic, plastic bags, plastic bottle caps, waxed paper, fish hooks	A,b
Sea otter	Yes	Yes	fishing nets	H

Table 2: A partial list of reports of entanglement or ingestion of marine debris for target species. Sources: (a) Laist 1997 ; (b) pers. comm. Dr Teri Rowles (US Office of Protected Resources) 2008 (from a query of the NMFS Marine Mammal-Human Interaction strandings database); (c) May 19, 2004. "A Deadly Meal". Laguna Beach, CA www.pacificmmc.org ; (d) COSEWIC 2003; (e) Baird and Hooker 2000; (f) National Marine Fisheries Service 2008. Southern Resident Killer Whale Recovery Plan; (g) Stock Assessment Report Northern Elephant Seal. 2007. po.2007.SENE-CA.pdf; (h) pers. comm. Dr Frances Gulland 2008; (i) pers. comm. Dr Todd O'Hara (North Slope Borough) 2008; (j) pers. comm. Jackie Hildering (marine educator in Johnstone Strait, www.earthlingenterprises.ca); (k) Tarpley and Marwitz 1993; (l) Northridge et al. 2010; (m) "Biologists Cite Plastic Bag in Whale Death," February 28, 1992. New York Times, (Okeanos Ocean Research Foundation performed the necropsy).

Debris type	Indicator *	Frequency	Percentage
styrofoam	unknown	163	48.8
plastic bottles	general	49	14.7
plastic bags (grocery)	general	35	10.5
fishing gear	ocean	21	6.3
plastic (various)	general	19	5.7
plastic food containers	general	13	3.9
buoy	ocean	4	1.2
cardboard	unknown	4	1.2
food wrappers	general	4	1.2
oil container (1-20L)	land and ocean	4	1.2
plastic sheeting and wrap	ocean	4	1.2
safety equipment (life jacket, life ring, oil spill kit)	ocean	3	0.9
aluminum can	land	2	0.6
rubber gloves, lids	ocean, general	2	0.6
carpet	unknown	1	0.3
oil drum	ocean	1	0.3
drywall (construction materials)	unknown	1	0.3
glass bottle	unknown	1	0.3
plastic packing strip	general	1	0.3
paper	unknown	1	0.3
rope	ocean	1	0.3

* after (Sheavly, 2007, p. 25)

Table 3. Composition of debris observed during the survey (“Debris type”), expressed as count and (density surface modelling; details below) percentage of total. Less than half of the categories of debris seen during the survey are considered to be unequivocal “indicators” of either ocean-based sources or land-based sources (Sheavly, 2007, p. 25).

Figure 1:

Coastal British Columbia and territorial waters (Canadian Exclusive Economic Zone). All place names in text are included in these figures. Queen Charlotte Basin (right panel) includes Dixon Entrance, Hecate Strait, Queen Charlotte Sound, and Queen Charlotte Strait. The survey randomly selected 5 of 32 mainland fjords, and conducted systematic surveys within each (see Thomas et al., 2007) for details, and Figure 2 for trackline effort.

Figure 2:

Study area and the predicted relative distribution of marine debris, including survey transects and locations of observed marine debris.

Figure 3:

Relative predicted density (left panels) and relative predicted whale-marine debris interactions (right panels) for fin whales (top row), humpback whales (middle row), and killer whales (bottom row).

Figure 4:

Relative predicted density (left panels) and relative predicted animal-marine debris interactions (right panels) for minke whales (top row), Dall's porpoise (middle row), and Pacific white-sided dolphin (bottom row).

Figure 5:

Relative predicted density (left panels) and relative predicted animal-marine debris interactions (right panels) for harbour porpoise (top row), Steller sea lions (middle row), and elephant seals (bottom row).

Figure 6:

Relative predicted density (left panels) and relative predicted animal-marine debris interactions (right panels) for harbour seals (top row), and sea otters (bottom row).

Figure 1 - high res

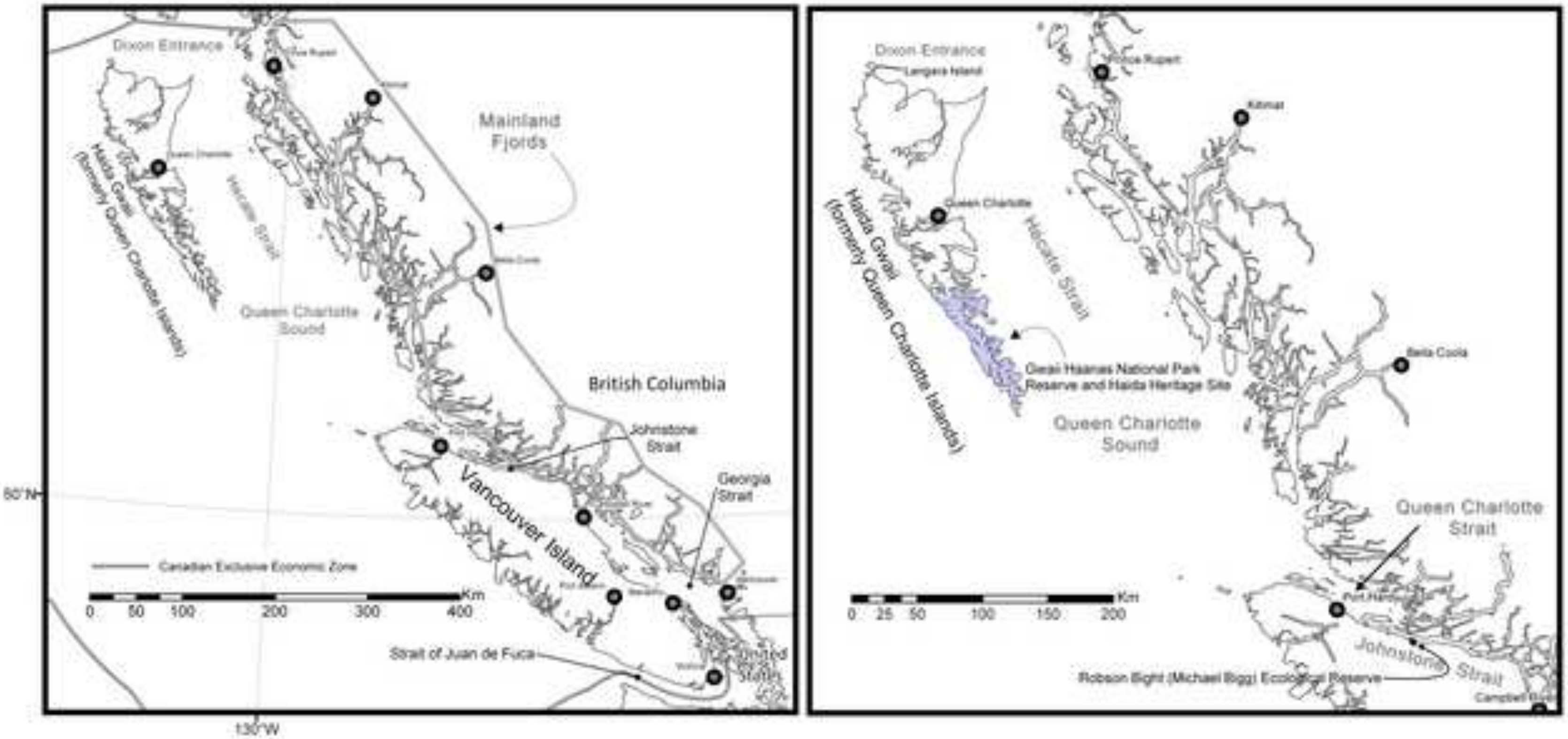

Figure 2 - high res

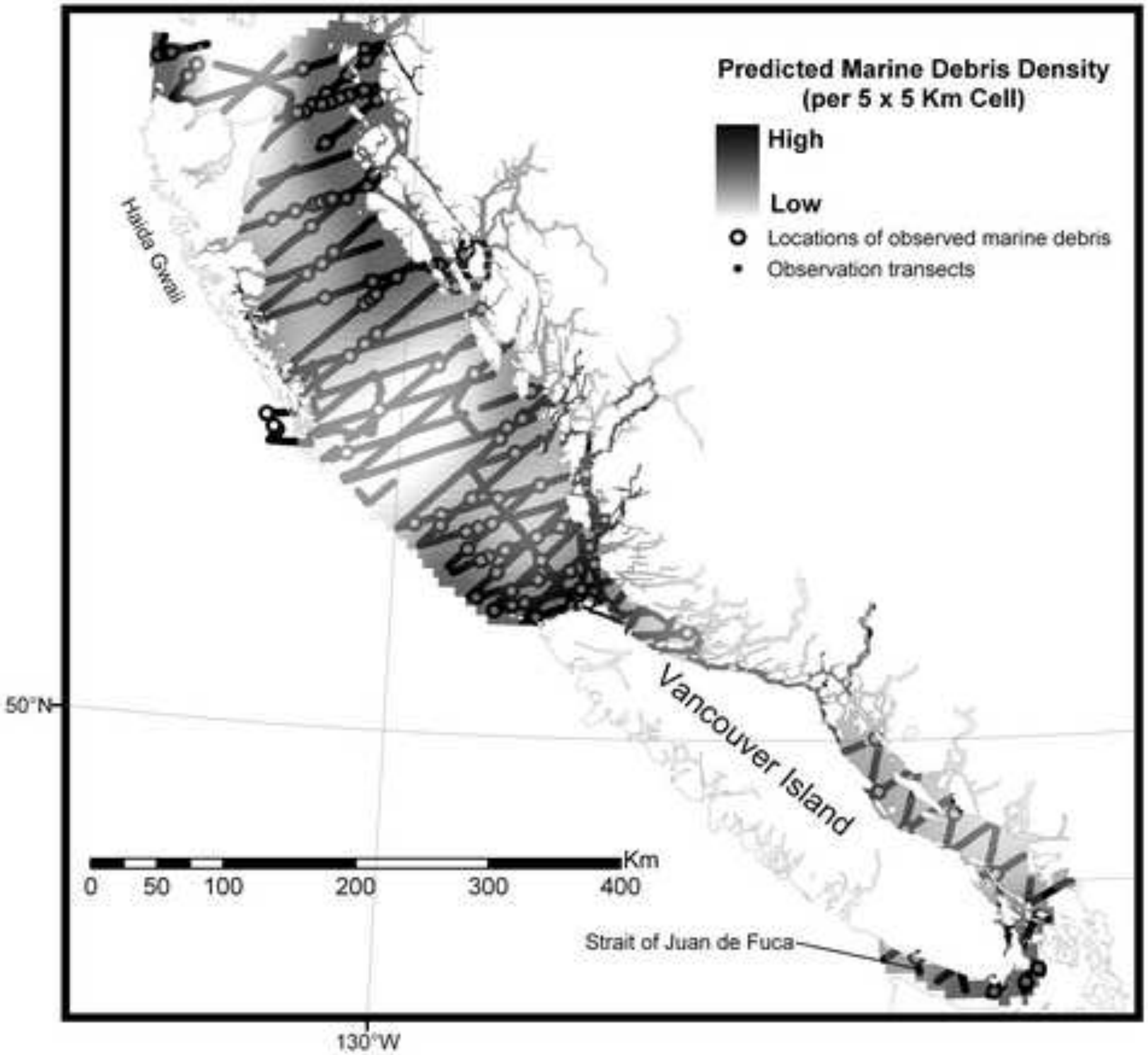

Figure 3 - high res

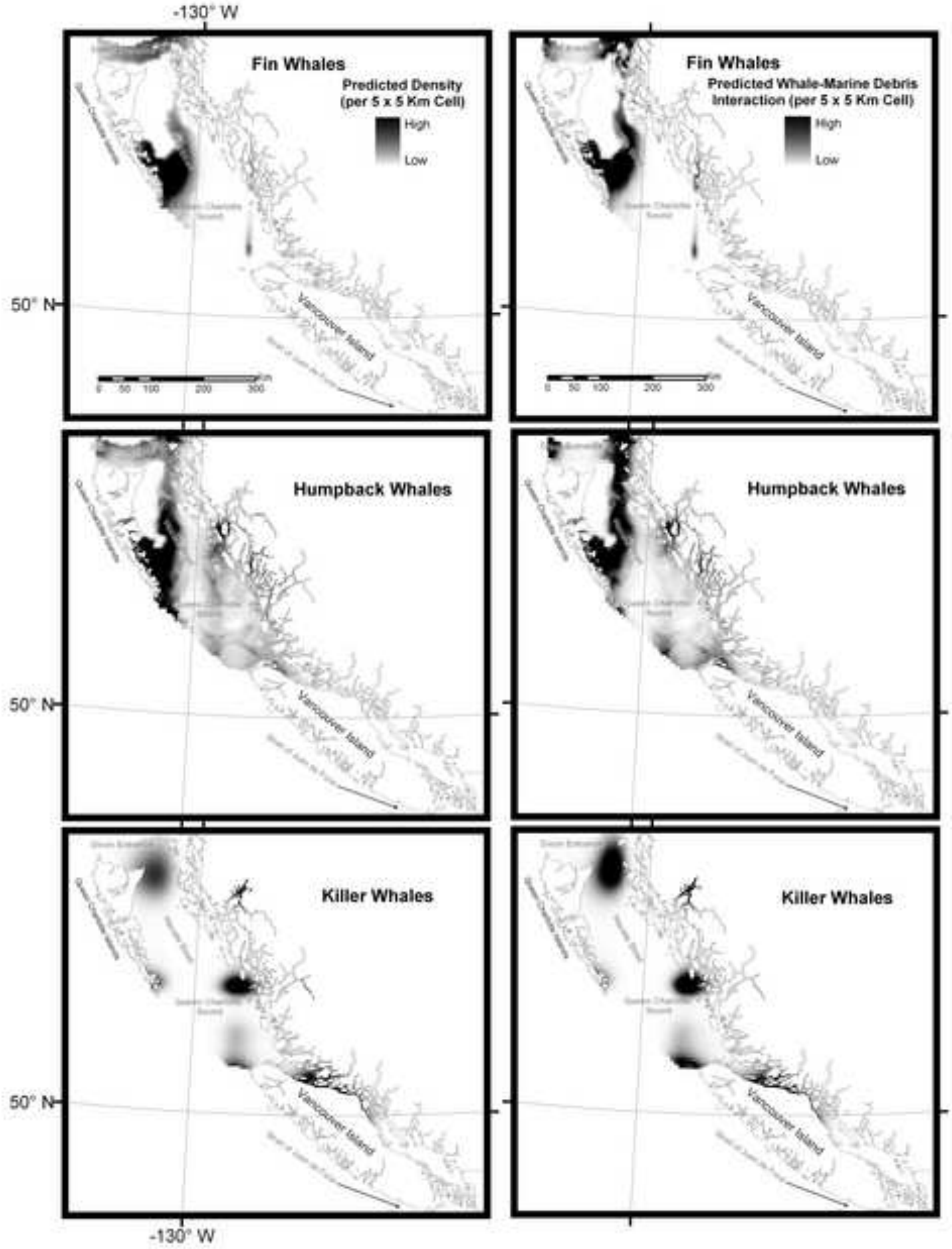

Figure 4 - high res

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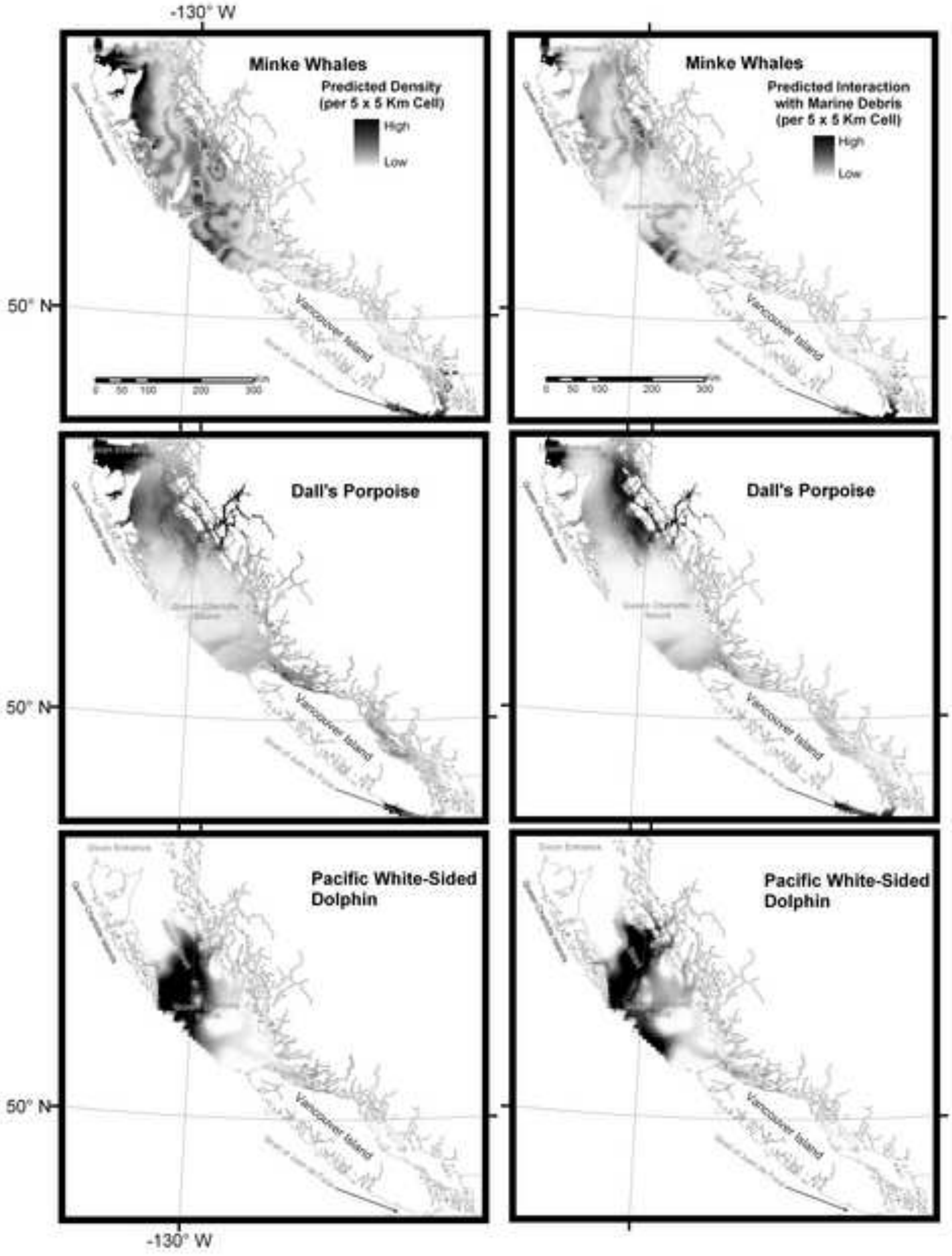

Figure 5 - high res

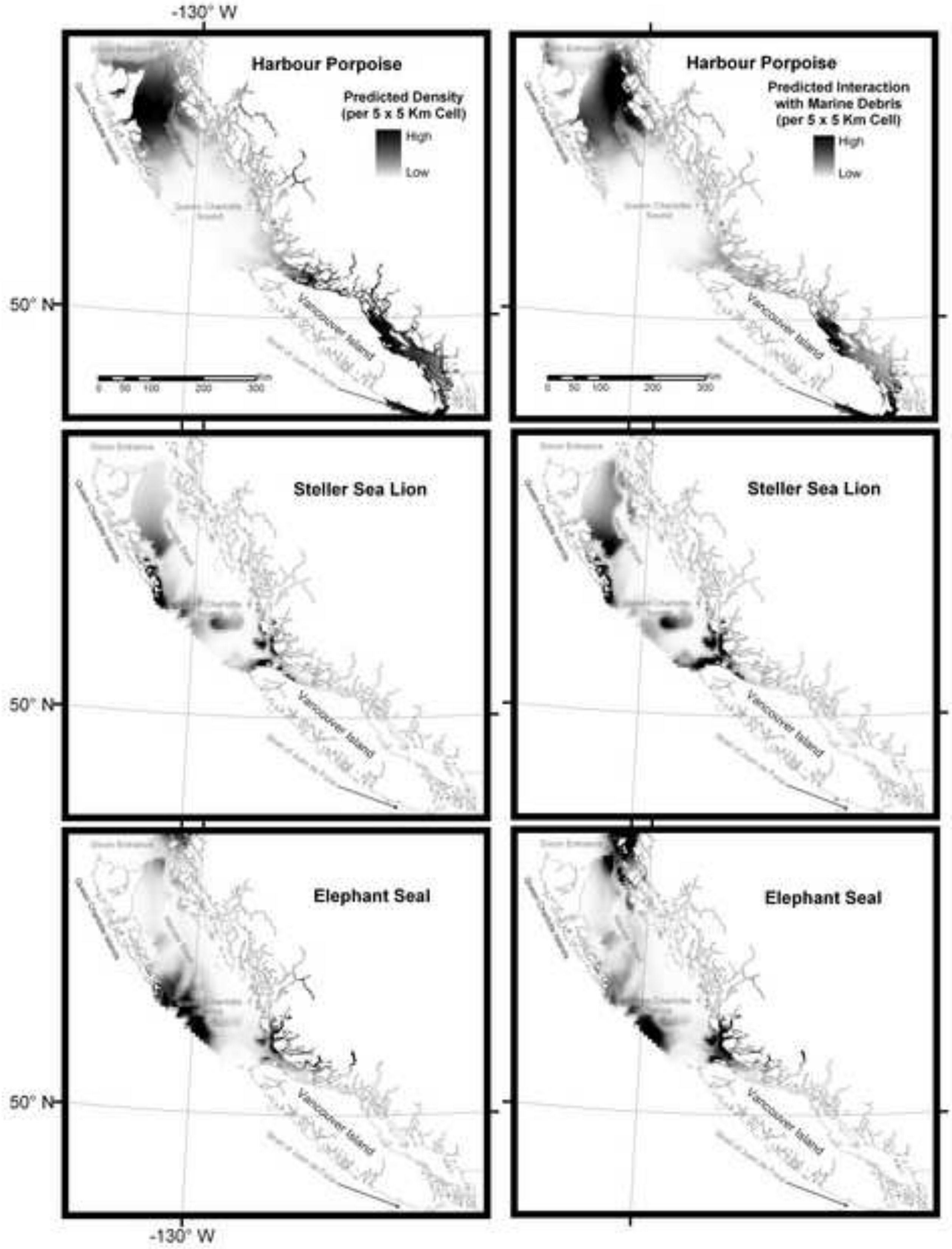

Figure 6 - high res