Marine Mammals and Debris in the Inside Passage, British Columbia, Canada

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Introduction

Entanglement in and ingestion of synthetic marine debris is insidious and cryptic (Laist 1997). Synthetic marine debris, notably plastic, is widely distributed in northeast Pacific waters (Matsumura and Nasu 1997). High-profile regions like the so-called "Great Pacific Garbage Patch," an aggregation of debris trapped by the North Pacific Gyre, are well known (Moore *et al.* 2001). In areas of lower density, debris interactions have been identified as potential conservation threats to many marine mammal species. Marine debris may pose threats to marine mammals in two ways: entanglement and ingestion (Marine Mammal Commission 2001). However the extent to which this issue causes morbidity, mortality or population-level effects 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, regional 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 the 1978 Protocol to the International Convention for the Prevention of Pollution from ships (MARPOL). Annex V of MARPOL is the primary international authority for regulation of marine debris sources.

Few studies have attempted to quantify how much of a threat debris interactions may pose to marine mammals in British Columbia (BC). The coastal waters of British Columbia (BC), Canada 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 region has a well-established program to clean marine debris from beaches[2], but existing cleanup efforts are volunteer-driven and therefore

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[1] www.iwcoffice.org

[2] http://shorelinecleanup.ca/

influenced by proximity to places where people leave. This would be entirely appropriate if all marine debris were derived from nearby terrestrial sources – cleanup efforts would simply mirror distribution of human populations. But if BC waters are serving as a sink for marine-derived, pelagic sources of marine debris, then it is problematic that remote parts of BC have low probability of being cleaned. We believe that a spatially explicit analysis of marine debris can help to identify priority areas for cleanup, and could be used to trigger funding mechanisms for efforts like the Great Canadian Shoreline Cleanup to mobilize teams to target high-priority, remote areas. Similarly, a newly formed BC Marine Mammal Response Network[3], has been initiated for Canada's Pacific Region. The BC Marine Mammal Response 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 will be influenced by each 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 the degree of underreporting should be higher in non-listed species than listed species. We sought to inform these and other ongoing efforts to monitor debris-wildlife interactions by mapping at-sea distribution of debris and marine mammals in BC coastal waters, in order to identify areas where marine mammals and debris is expected to occur commonly. If our analyses can identify areas where debris and wildlife overlap, it is our hope that additional resources can be brought to bear to target these 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 (Gilardi et al. 2010).

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. In a global literature review, the US Marine Mammal Commission (2001) note 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 (Marine Mammal Commission 2001). Once

[3] Lisa Spaven, DFO, Personal Communication (July 2008). Contact Marine Mammal Incident Reporting Hotline: 1 800 465 4336

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 (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 plastic 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 & 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 (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.

Occasionally, some of these incidents are obvious. For example, in 2002, a minke whale washed up in Normandy, France with fragments of 16 plastic bags (totalling ~1kg of plastic) in its stomach, and no food[4]. 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 & Nunny 2002) and pygmy sperm whales (Tarpley & Marwitz 1993). For the most part, though, attributing cause of death to marine debris ingestion or entanglement is difficult, and requires the involvement of well-trained pathologists following careful necropsy protocols (Raverty and Gaydos 2004).

Here we have attempted to identify areas where debris may be posing greatest threat to marine mammals in BC. Our goal was to identify areas where problems may be more likely to occur for any given species. This is a useful priority-setting exercise, because the majority of British Columbians live along the province's south coast, and a mapping exercise such as this can identify areas in which additional resources should be allocated to surveys for beach-stranded carcasses and mitigation measures.

Methods

Estimating abundance of floating marine debris

Conventional distance sampling analysis

[4] http://www.dailymail.co.uk/news/article-519832/Banish-bags-The-amazing-picture-2lb-plastic-poison-whales-stomach.html

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 agencies in California, Oregon, Washington and Alaska. Spatial modeling methods were used to interpolate density of marine mammals and marine debris, and to identify areas of overlap.

We generated a conventional distance sampling estimate of the abundance of floating marine debris observed during systematic surveys in summers 2004 and 2005. (Inclusion of the data from the partially-completed survey in August 2006 required the use of model-based abundance estimators, below.) The conventional distance sampling analysis methods closely followed those described by Williams and Thomas (2007). Objects seen during transit legs (i.e., off-trackline, but 'on-effort') were included in detection function modeling, but were not used in calculating encounter rate. 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 5.0 (Thomas *et al.* 2006a). Model selection was guided by AIC (Buckland *et al.* 2001) and goodness-of-fit statistics.

Debris composition analysis

Ocean Conservancy's National Marine Debris Monitoring Programrecommendations was followed for putting debris sightings data into fine-scale categories that could be combined later into broader groupings. This approach allowed for ease of cross-study comparisons, without losing the detail that may be important to local issues.

Density surface modeling for marine debris and marine mammal data

Interpolating object density between tracklines

A systematic sightings survey was conducted in BC coastal waters in summers (June-August) 2004 and 2005, but only partly completed in summer (August) 2006 due to time and funding constraints. Spatial analyses using generalized additive models (GAMs) allow 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). A GAM-based spatial model was fitted to the effort and sightings data collected in 2004, 2005 and 2006. This model was used to interpolate density between tracklines and to fit a smooth surface through the observed object density measurements. This approach can be used to estimate abundance, although our primary purpose was to illustrate spatial patterns in density data.

Object (either a marine mammal or a piece of marine debris) density was modeled using the following three-stage approach (after Thomas *et al.* 2006b): (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 6.0. Beta 3 (Thomas *et al.* 2006b). 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.

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 6.0 Beta 3 (Thomas *et al.* 2006b). Tracklines were divided into segments approximately 1 nautical mile (nm) in length. Start and end locations of the segments were calculated using the Geofunc add-in (courtesy 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 as a function of location, water depth and area searched (twice the effective strip half-width times the length of the segment). The response variable (abundance, N) was modelled as a quasipoisson distribution with a log link, which allowed 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:

$$N \sim te(\text{longitude}, \text{latitude}) + s(\text{depth}) + \text{offset}(\text{area})$$

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 in this model. (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 2nm on a side (i.e., $4nm^2$) was chosen for prediction. Values for the explanatory variables (latitude, longitude, depth, and distance offshore) 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. 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 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, and taking the sum of all values in the grid.

Assessing overlap between marine mammals and marine debris

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. Spatial overlap between debris and wildlife does not mean entanglement or ingestion, but overlap is obviously required for entanglement and ingestion, so this approach strikes us as a useful starting point for discussion.

Animal distribution was predicted from the density surface model. Relative risk is approximated by multiplying predicted density of animals with predicted density of a stressor (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 be decomposed into two components, which they term 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 entanglement and ingestion. Vulnerability can then be thought of as the probability that a marine mammal will be exposed to that stressor (in this case, the probability that a marine mammal and debris would be found in close proximity). Vulnerability was modelled 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 cannot be used to assess 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).

Results

Estimating abundance of floating marine debris

Conventional distance sampling analysis

Search effort from the entire survey is shown in Figure 1, and sightings of debris are shown in Figure 2. In total, 119 sightings were included in the analysis. 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 (Figure 3). Overall, objects had a mean probability of being sighted of 27%, with objects directly on the trackline assumed to be detected with certainty (the so-called g(0)=1 assumption). 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). Note that these differences are not statistically significantly different from one another. The range was especially large in the mainland inlets, 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 5 inlets sampled had very high concentrations of debris, while others had very low density of debris.

Multiplying the density by the size of the study area provides estimates of debris abundance. Abundance of floating marine debris overall was 36,000 (CIs: 23,000-56,600). Of this, the vast majority of debris was estimated to occur in the largest stratum (Queen Charlotte Basin, ~23,000 pieces). The lowest amount of debris was estimated to occur in the smallest stratum (Johnstone Strait, ~100 pieces).

Debris composition analysis

The most common type of debris by far was Styrofoam (Figure 4). 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 arisen 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).

Density surface modelling for marine debris and marine mammal data

Modelling marine mammal density surfaces and overlap with marine debris

Predicted density surfaces for floating marine debris, and for 11 marine mammal species, are shown in Figures 5 and Figures 6-9 (left hand side), respectively. 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. As a result, each map can be used to infer spatial variability in density within species in BC coastal waters, but the maps cannot be used to compare density across species. "Risk maps" (areas predicted to have overlap between marine mammals and marine debris) are shown in the right-hand panal of figures 6-9 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 for any 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

This study accomplished its two primary objectives, namely to estimate abundance, distribution and composition of floating marine debris in BC coastal waters, and to identify priority areas for cleanup where the potential exists for overlap between debris and marine mammals.

Distribution and composition of debris

Overall abundance of floating marine debris was estimated to be 36,000 (95% CIs: 23,000-56,600) pieces. Of this, the majority of debris was estimated to occur in the largest stratum (Queen Charlotte Basin, ~23,000 pieces). What was most interesting to us is that the waters off the most heavily populated area, Vancouver, did not contain the highest densities of debris. 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 5). Not surprisingly, very few beach cleanup sites have been identified in these remote areas in the Great Canadian Shoreline Cleanup[5], due to the difficulty in accessing these regions. One

[5] http://www.vanaqua.org/cleanup/

recommendation from this analysis is that the GCSC and other programs be allocated sufficient resources to target these high-priority regions for cleanup. The degree to which these may indicate debris sinks (or some local or maritime traffic source that is not immediately obvious) should be evaluated with future, dedicated research. Recall that the majority of search effort took place in Queen Charlotte Basin, which is a fairly remote area (the center of which is hundreds of miles from Vancouver). The main industries here are fishing, logging (along the coast, of course), and tourism (cruise ships and ferries routinely transit this area). It is unclear how much of this debris originates from local vessel traffic or land sources, and how much is accumulated by oceanic currents. The most common type of debris by far was Styrofoam (Figure 4). This was followed by plastic bottles and plastic bags.

Comparison of BC waters with other regions

Average density (objects per km^2) of marine debris in the study area overall was estimated to be 1.48. Point estimates of density were lowest in Johnstone Strait (0.91) and highest in the mainland fjords (2.27). Mean density was 1.25 in Queen Charlotte Basin, and 2.13 in Strait of Georgia (the area closest to the largest human settlements). Note that these differences are not statistically significantly different from one another: the 95% confidence intervals (CIs) all overlapped. The range was especially large in the mainland inlets, 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 5 inlets sampled had very high density of debris, while others had very low density. Some of this variation could be due to chance alone, because the difference between seeing either one or two pieces of garbage along a trackline in any particular inlet will result in proportionately large differences in encounter rate and density.

Matsumura and Nasu (1997) analysed data collected between 1986 and 1991 from a variety of survey platforms, including research vessels, training ships, fisheries patrol boats, volunteer fishing boats, and cargo vessels. They estimated that 0.042 pieces per km^2 (converted from 14.4 pieces per 100 nautical $miles^2$) of floating plastic products could be found off northwestern BC waters, and 0 pieces per km^2 were found off southern BC waters. In contrast, they found 0.50 pieces per km^2 (170.5 pieces per 100 square nautical miles) 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 square nautical miles) in waters off southeast Asia. The average density of debris that we found in our study was about 35 times that reported for BC north coast waters by Matsumura and Nasu (1997). Taking the average density reported by Matsumura and Nasu (1997) for BC north and south coast waters, we find that our average density was about 70 times that reported previously. One way to interpret the vast disparity between our results and those of Matsumura and Nasu (1997) is that the density of plastic has increased dramatically since the 1986-1991 surveys. While this may be true, we have two reasons to suspect that density was also underestimated in the earlier survey to a greater extent than it was in our 2004-6 survey. Trackline detection probability was likely lower in the earlier survey because it was essentially a platform-of-opportunity survey that combined data from a variety of vessels. Secondly, the large ships used in the earlier survey could conduct surveys in much rougher seas (and consequently poorer sighting conditions) than the Williams and Thomas (2007) small-boat

survey. If both point estimates were accurate, then density of marine debris would have to be increasing at a rate of at least 25% per year to account for such a substantial increase over a 15-year period.

Areas of overlap between debris and mammals

Perhaps the most surprising result to emerge from our spatial analyses is that areas of overlap between marine mammals and marine debris were generally found far from Vancouver, the largest city in the region. To some extent, this reflects the distribution of marine mammals themselves (Figures 6-9), many of which are quite discrete in their distribution and show strong habitat preference for north and central waters. However, even for species like harbor porpoise and harbor seals, which are found near urban areas off the south coast, the riskiest areas are still predicted to occur in relatively remote inlets. The highest risk areas for fin whales were found in Dixon Entrance, Gwaii Haanas National Park Reserve, and the central coast mainland inlets. 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. For northern resident killer whales, the highest risk area was Johnstone Strait, which has been proposed as critical habitat for the population (Fisheries and Oceans Canada 2008a) and includes Robson Bight (Michael Bigg) Ecological Reserve. (Incidentally, this is also the site where killer whales are at highest risk of ship strike (Williams and O'Hara 2010); oil spill (Williams, Lusseau and Hammond 2009); and highest ambient noise levels (Williams, Ashe and Clark, unpublished).) Pacific white-sided dolphins are "Not at Risk" in Canada's Pacific region, but if one were cleaning up the highest-risk areas for humpback and fin whales, one would clean up important areas for these dolphins parenthetically. For Dall's porpoise, the highest risk areas were off southwest Vancouver Island, as well as western Dixon Entrance, Kitimat (north coast inlets) and central coast inlets. For minke whales, the highest-risk area identified was in western Dixon Entrance. Sea otters are distributed quite discretely in our study area off north-eastern Vancouver Island (because we did not survey the west coast of Vancouver Island) and on the central mainland coast. Consequently, these two areas were identified as the only high-risk areas for overlap between sea otters and debris. Steller sea lions were predicted to overlap most strongly with marine debris in Gwaii Haanas National Park Reserve, 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 inlets.

Overall, the highest risk areas across all species are found 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 (and in many cases, protected) for their importance to at-risk species. The areas that we would identify as the highest priority regions to target for cleanup are areas that are

unlikely to have much participation in the Great Canadian Shoreline Cleanup[6] or other volunteer-led efforts, because few people live near the areas and they are relatively difficult to access. We strongly encourage providing support to programs like GCSC to allocate cleanup efforts strategically for targeting these areas. A strategic approach to prioritising areas and targeting them in a cost-benefit framework has been used successfully to tackle the problem of derelict fishing gear in nearby Puget Sound (Gilardi et al. 2010), and we see that as a model for developing a strategy for dealing with marine debris in BC on a priority-setting basis.

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

Our analyses identify where to look for potential problems. This does not provide evidence that there are problems, although marine debris is known to pose health threats for most of the species in our study (Table 2). 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 DFO 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.

In addition to reviewing published and grey literature and querying the NOAA Fisheries Human Interaction database[7] for evidence of debris interactions, we interviewed veterinarians and pathologists about their experience with marine mammal-debris interactions. Dr Frances Gulland (The Marine Mammal Center) offered a summary of her experience necropsying many of these species (Table 2). Gulland noted that 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. For example, Gulland has recently participated in necropsies of two sperm whales that were found to have derelict fishing gear in their guts. Gulland noted that *Kogia* have been found with evidence of ingesting various kinds of plastic, including plastic bags, plastic sheeting and various packaging material. *Kogia* are rarely seen in BC waters, but sperm whales regularly depredate fishing lines and may be exposed to human generated plastic debris from fishing vessels, and one specimen of *Kogia* has stranded in Johnstone Strait in recent years[8].

Gulland notes that pinnipeds frequently strand with evidence of debris entanglement and ingestion. California sea lions, Northern fur seals and Guadalupe fur seals have all presented entangled in plastic packing straps and Mylar balloon strings. One California sea lion was found with a broken bottleneck lodged in its intestine. Overall, Gulland finds entanglement to be a far more common occurrence than ingestion. Elephant seals strand regularly, but signs of ingestion of debris are exceedingly rare in her experience. Generally the stomachs of elephant seals that are brought to The Marine Mammal Center are empty, because they are juveniles

[6] http://www.vanaqua.org/cleanup/

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

[8] www.killerwhalecentre.org

and have not yet begun to feed. (The elephant seals typically seen in BC coastal waters are adults, and their foraging activity may lend them sensitive to debris ingestion when in this region.) Similarly, Gulland has necropsied many porpoise and Pacific white-sided dolphins, none of which has had plastic in its stomach.

Dr Todd O'Hara (North Slope Borough) also notes that, in his experience, ingestion of marine debris by marine mammals is rare in the region where he works. Although O'Hara has necropsied large numbers of marine mammals, he has never observed Styrofoam in an animal's stomach, and generally only sees plastics in the stomachs of polar bears that scavenge for food near landfills.

Dr Stephen Raverty is a veterinary pathologist with the Animal Health Centre of BC's Ministry of Agriculture and Lands. Dr Raverty has necropsied countless pinnipeds and cetaceans in BC, and has developed, with Dr Joe Gaydos, the global standard for killer whale necropsy protocols. He notes that throughout his career, he has never detected Styrofoam in the oral cavities or stomach of any stranded and necropsied animal.

Overall, we conclude that entanglement is likely to be a bigger problem than ingestion for most species in our study area (Table 2), but that both issues warrant closer attention in BC.

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 elephant seals (Table 2). It should be noted that neither of these species is likely to be a high priority for necropsy if a marine mammal response program is guided solely by SARA status (Table 1). We are not claiming that debris ingestion is causing population-level effects in either case; however, if debris were ever to cause 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. 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 series of imprecise abundance estimates (Taylor *et al.* 2007).

Allocation of scarce resources and identification of debris sources and sinks

Despite low human population density, the waters off the Queen Charlotte Islands (Haida Gwaii) and BC north coast waters have relatively high concentrations of marine debris. These regions also host high densities of marine mammals. This information can be used in a priority-

setting exercise, so that people are sent to places where their help is most needed, and where their clean-up efforts would do the most good. The Vancouver Aquarium's Great Canadian Shoreline Cleanup program lead, Dr. Angela Griffiths, has expressed willingness to use our results to choose priority cleanup sites, if funding were available to do so. The fact that high densities of debris are found far from human settlements may indicate an at-sea source of debris, or provide evidence that such regions serve as collection or aggregation sites that accumulate debris. Dr O'Hara noted that in Mekoryuk, Alaska, NOAA provides funds to clean up a very remote but important "sink" for debris. We believe that our analyses can be used in a similar priority-setting exercise to identify gyres and other areas that accumulate debris, and to promote removal before debris washes ashore or poses threats to marine wildlife. Communities on Haida Gwaii, northern Vancouver Island, and the north and central mainland coasts would make obvious sites for allocation of resources to turn BC's debris cleanup programs from a passive (grassroots) process to a proactive, targeted site-selection approach.

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 regional offices 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 office collects its own data, and to the best of our knowledge, no national database on marine mammal-debris interactions yet exists in Canada. The new BC Marine Mammal Response Network will provide a centralized repository for regional cetacean necropsy reports, but we hope that this process does not become biased toward SARA-listed species and will probably include few data on pinnipeds. On a global scale, IWC is compiling a large-whale ship strike database. The IWC may be interested in a similar database for debris entanglement and ingestion, but not for pinnipeds, otters or small cetaceans. We encourage regional data sharing and transboundary cooperation on this issue wherever possible.

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,e,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	a,k
Humpback whale	Yes	Yes	fishing gear, plastic bags	a,b,j,l
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: An initial, cumulative record of whether entanglement or ingestion of marine debris has been reported for given species. If so, the type(s) of debris observed is also reported. Sources: (a) Laist 1997 ; (b) pers. comm. Dr Teri Rowles 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 2008; (j) Jackie Hildering (marine educator in Johnstone Strait area who compiles local records on marine debris / marine mammals interactions; www.earthlingenterprises.ca); (k) Tarpley and Marwitz 1993; (l) "Biologists Cite Plastic Bag in Whale Death," February 28, 1992. New York Times, (Okeanos Ocean Research Foundation performed the necropsy).

Summary

We do not yet have sufficient data to estimate mortality rate due to debris entanglement and ingestion in BC, and are seeking guidance about how to do so. Our primary intent is to provide the results in spatial form so that the risk areas can be incorporated into the early planning stages of Canada's new BC Marine Mammal Response Program. We hope that that program can be given sufficient resources to search for stranded animals in areas that are far removed from human settlements, and for non-SARA-listed species to be included in some of the necropsy protocols (or at least a cursory look for external signs of debris entanglement). We encourage the collection of new field data 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, and then trying to reverse it (Taylor *et al.* 2007).

Acknowledgements

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Figure Captions and Tables

Species	Conservation Status							
	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 Risk
Elephant seal	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower Risk
Steller sea lion	Special Concern	Special Concern	Imperiled	Endangered	Threatened	Threatened	Threatened	Endangered
Dall's porpoise	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower Risk
Harbor porpoise	Special Concern	Special Concern	Vulnerable	Not Endangered	Not depleted	Candidate for Listing	Not Threatened	Threatened
Fin whale	Under Consideration	Threatened	Critically Imperiled	Endangered	Depleted	Endangered	Endangered	Endangered
Minke whale	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower Risk
Humpback whale	Threatened	Threatened	Critically Imperiled	Endangered	Depleted	Endangered	Endangered	Vulnerable
Killer whale *northern resident*	Threatened	Threatened	Imperiled	Endangered	Threatened	Endangered	Not Threatened	Lower Risk
Pacific white-sided dolphin	Not at Risk	Not at Risk		Not Endangered	Not depleted	Not Threatened	Not Threatened	Lower Risk
Sea otter	Threatened	Special Concern	Imperiled	Threatened		Endangered	Threatened	Endangered

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).

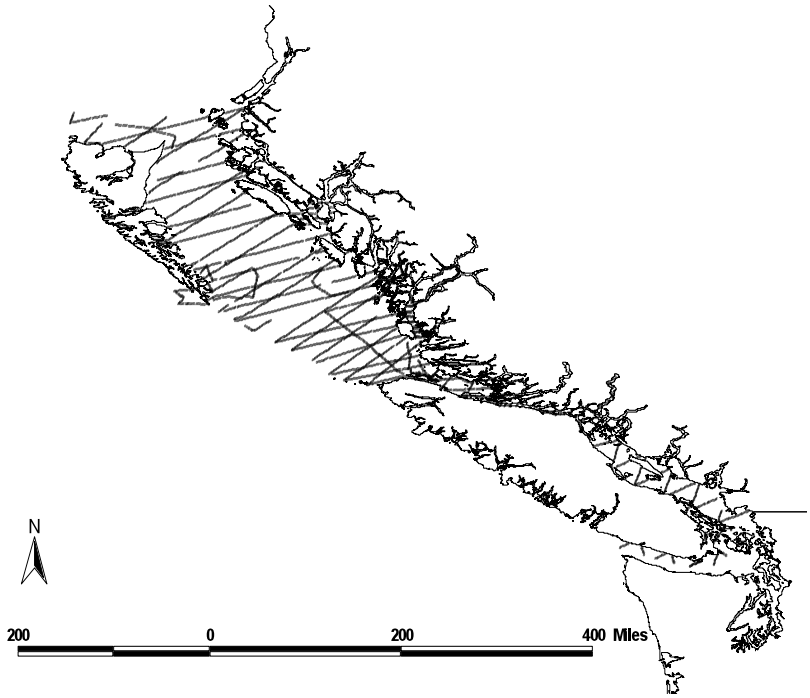


Figure 1. Search effort (on-effort segments of trackline included in density surface fitting model).

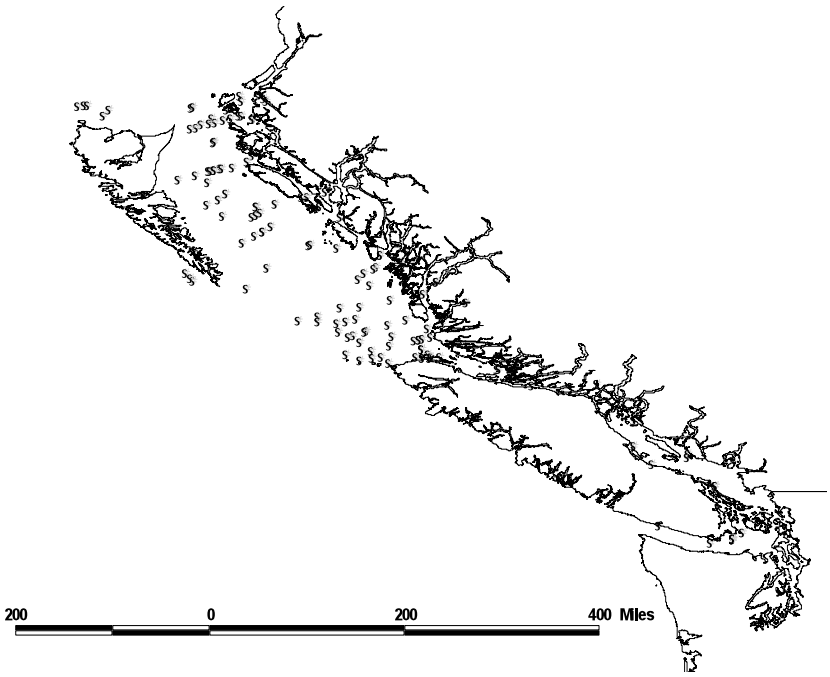


Figure 2. All marine debris sightings (2004-6).

Figure 5. Predicted density surface for floating marine debris. White areas are expected to have low densities, black areas are expected to have high densities and grey areas are expected to have intermediate densities.

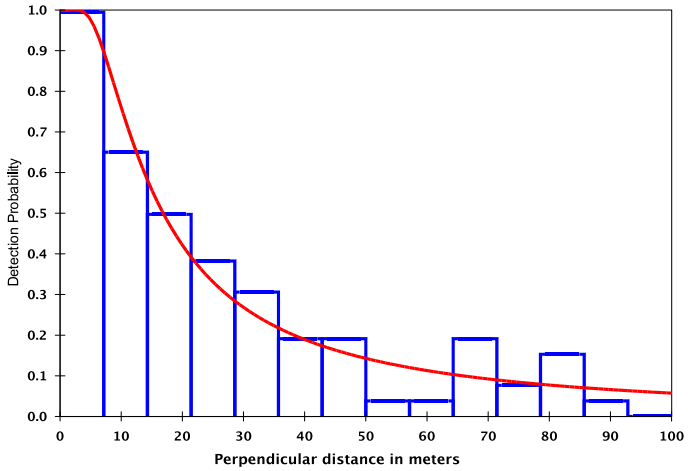


Figure 3. The selected detection function, showing probability of debris detection as a function of perpendicular distance from the trackline (in meters).

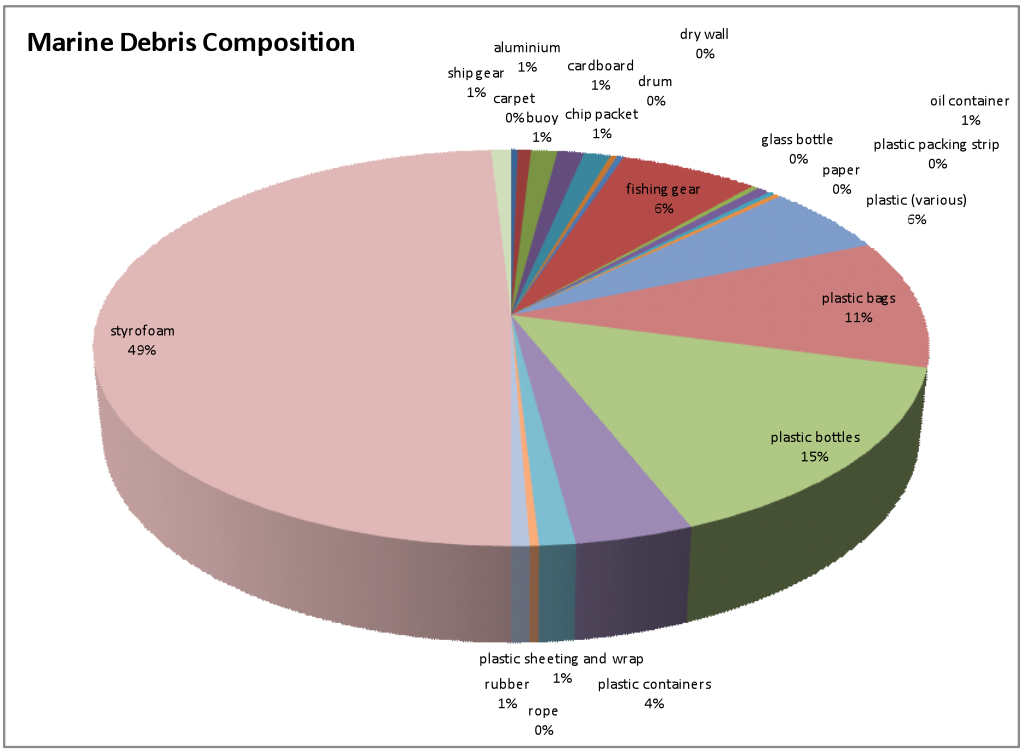
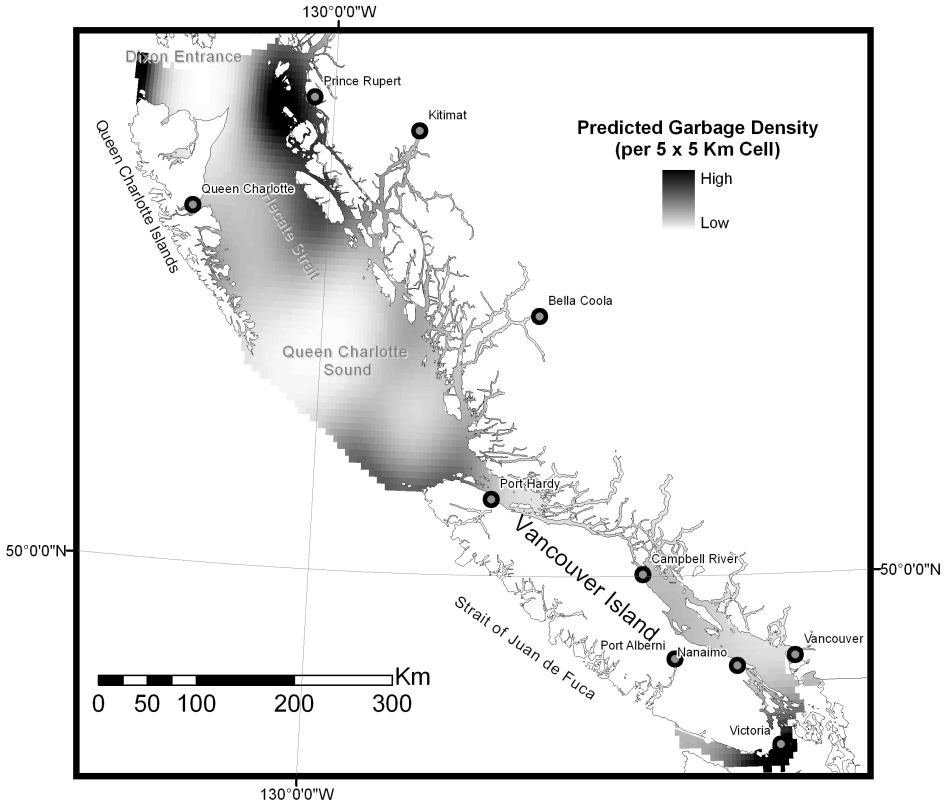
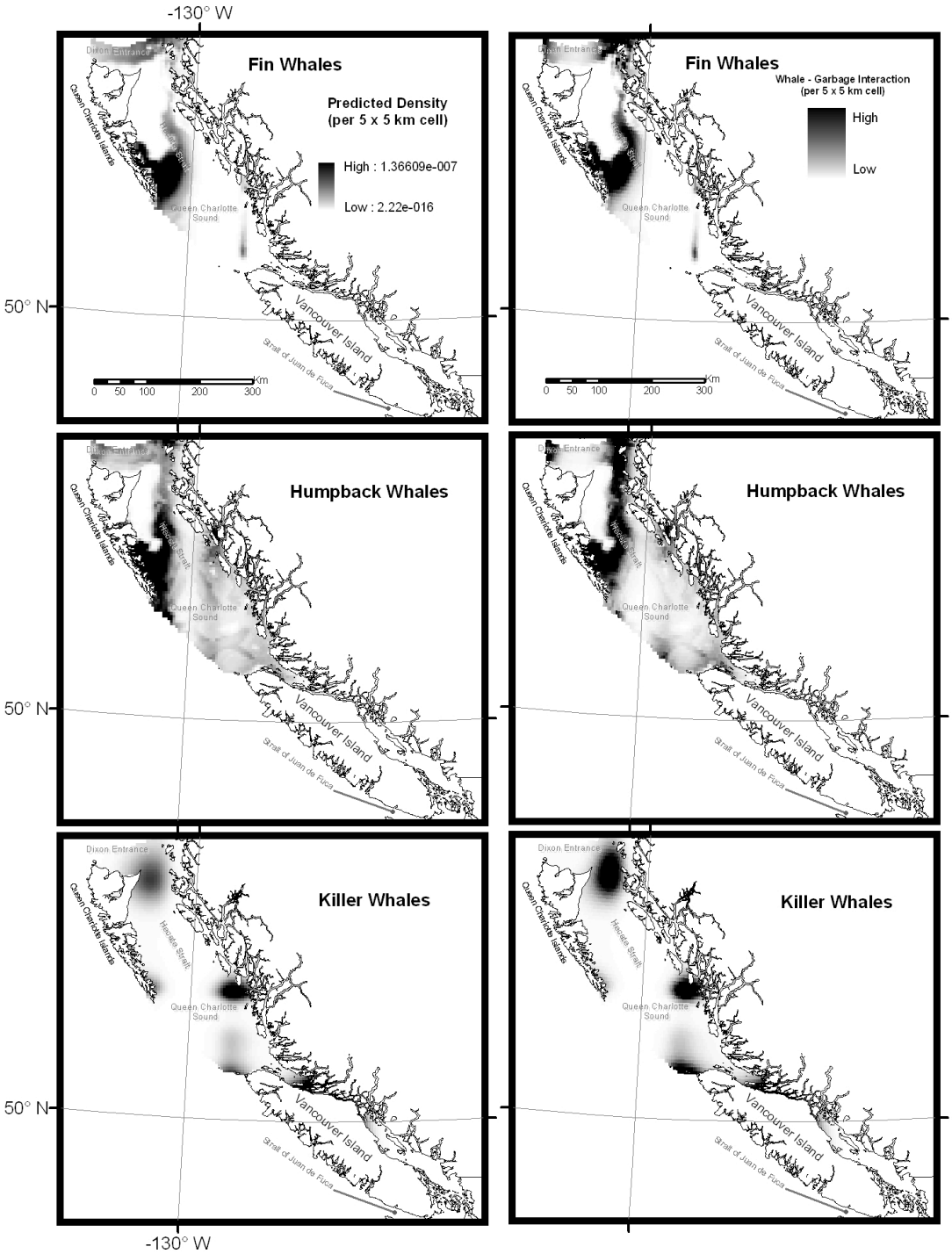


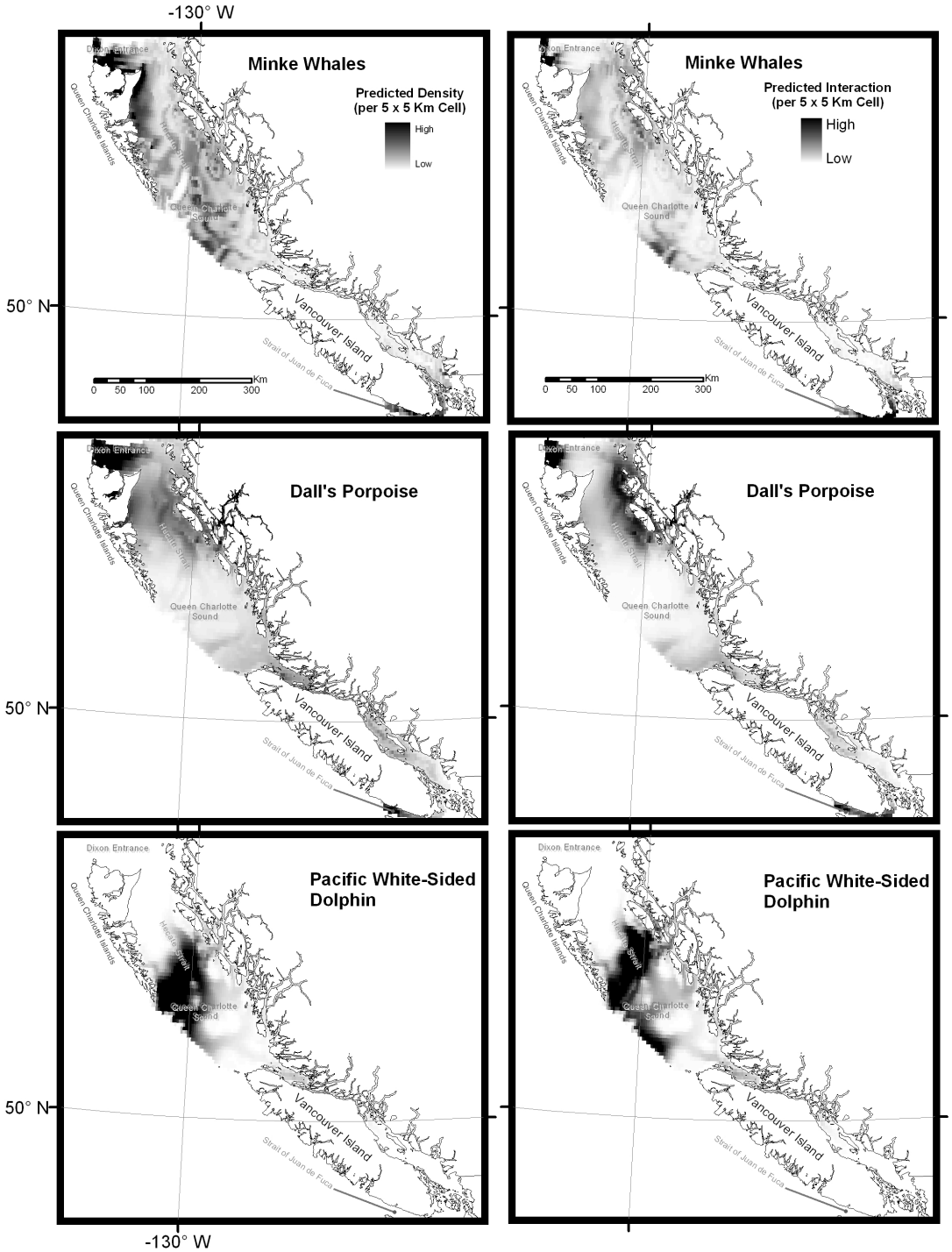
Figure 4. Kinds of marine debris (in fine-scale categories used by Ocean Conservancy's National Marine Debris Monitoring Program), and their frequency of occurrence, observed during our study. Proportions are rounded to the nearest percentage.

674

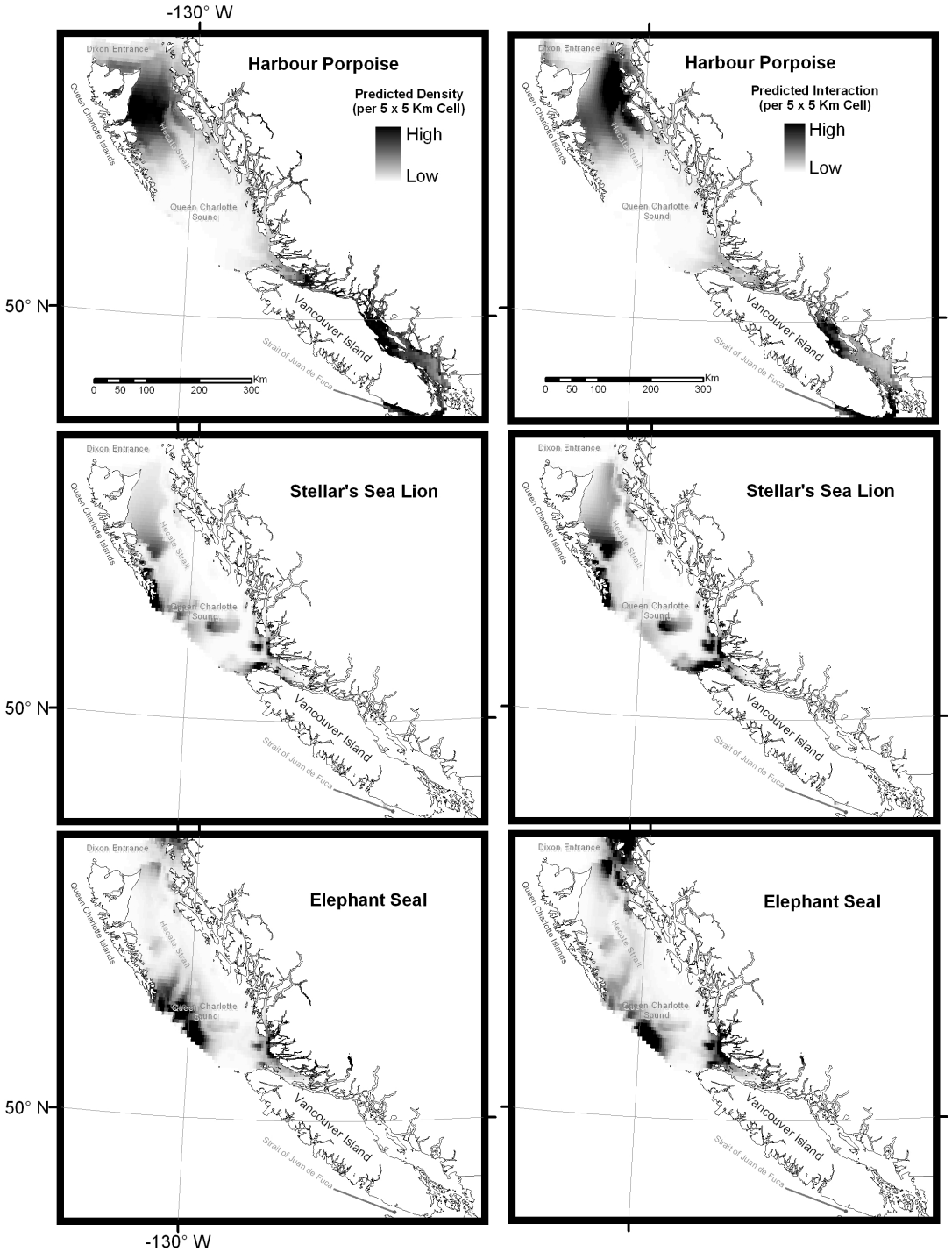

130°0'0"W
Dixon Entrance
Prince Rupert
Kitimat
Predicted Garbage Density
(per 5 x 5 Km Cell)
High
Low
Queen Charlotte Islands
Queen Charlotte
Hecate Strait
Bella Coola
Queen Charlotte
Sound
Port Hardy
Vancouver Island
50°0'0"N
Campbell River
50°0'0"N
Strait of Juan de Fuca
Port Alberni
Nanaimo
Vancouver
Km
0 50 100 200 300
Victoria
130°0'0"W

675

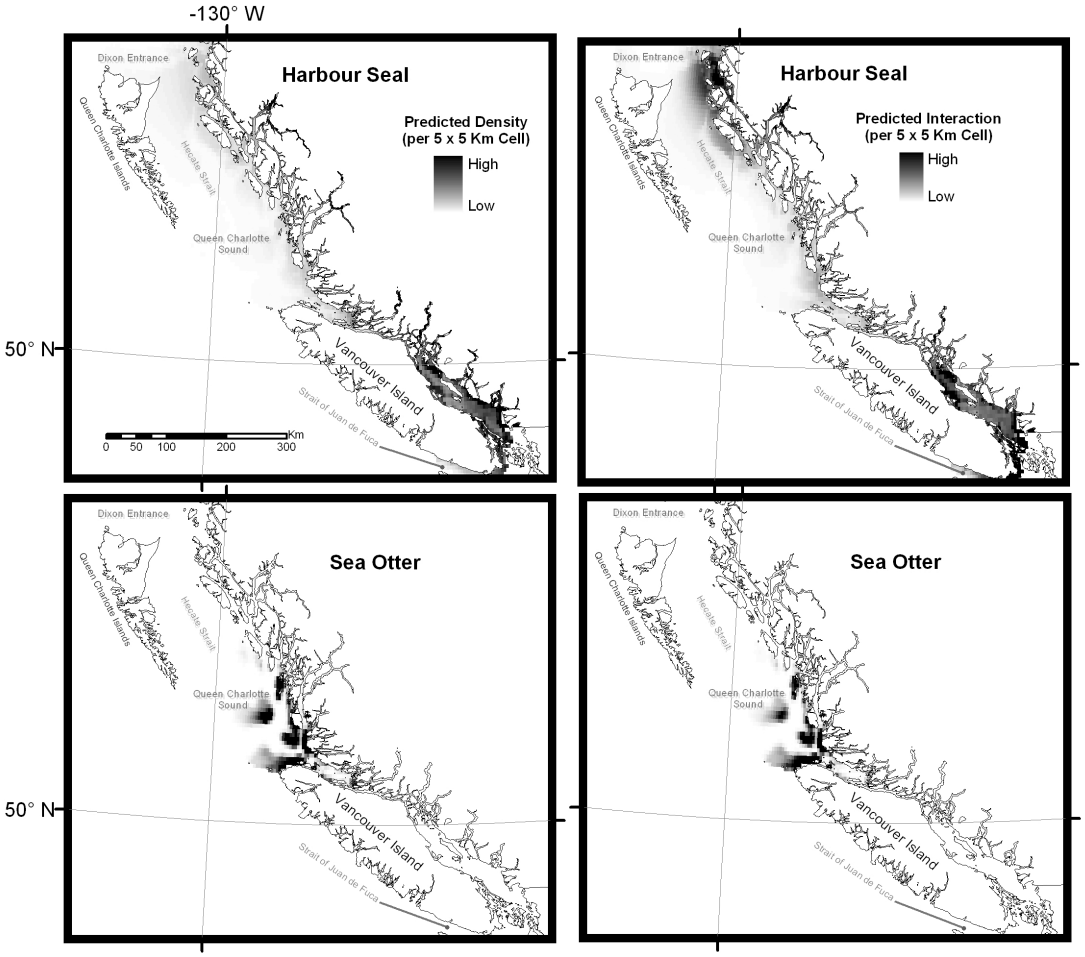

-130° W
50° N
Fin Whales
Predicted Density
(per 5 x 5 km cell)
High : 1.36609e-007
Low : 2.22e-016
Fin Whales
Whale - Garbage Interaction
(per 5 x 5 km cell)
High
Low
Humpback Whales
Humpback Whales
Killer Whales
Killer Whales
Dixon Entrance
Queen Charlotte Islands
Hecate Strait
Queen Charlotte Sound
Vancouver Island
Strait of Juan de Fuca
0 50 100 200 300 Km


-130° W
50° N
Minke Whales
Predicted Density
(per 5 x 5 Km Cell)
High
Low
Minke Whales
Predicted Interaction
(per 5 x 5 Km Cell)
High
Low
Dall's Porpoise
Dall's Porpoise
Pacific White-Sided Dolphin
Pacific White-Sided Dolphin
Dixon Entrance
Queen Charlotte Islands
Hecate Strait
Queen Charlotte Sound
Vancouver Island
Strait of Juan de Fuca
0 50 100 200 300 Km

678


-130° W
50° N
Harbour Porpoise
Predicted Density
(per 5 x 5 Km Cell)
High
Low
Harbour Porpoise
Predicted Interaction
(per 5 x 5 Km Cell)
High
Low
Stellar's Sea Lion
Stellar's Sea Lion
Elephant Seal
Elephant Seal
Dixon Entrance
Queen Charlotte Islands
Hecate Strait
Queen Charlotte Sound
Vancouver Island
Strait of Juan de Fuca
0 50 100 200 300 Km

679


-130° W
50° N
Harbour Seal
Predicted Density
(per 5 x 5 Km Cell)
High
Low
Harbour Seal
Predicted Interaction
(per 5 x 5 Km Cell)
High
Low
Sea Otter
Sea Otter
Dixon Entrance
Queen Charlotte Islands
Hecate Strait
Queen Charlotte Sound
Vancouver Island
Strait of Juan de Fuca
0 50 100 200 300
Km

680