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SPECIAL ISSUE: OCEAN SPILLS AND ACCIDENTS

Oil Spills and Marine Mammals in British Columbia, Canada: Development and Application of a Risk-Based Conceptual Framework

Adrianne L. Jarvela Rosenberger[1] · **Misty MacDuffee**[1] · **Andrew G. J. Rosenberger**[1] · **Peter S. Ross**[2]

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Abstract Marine mammals are inherently vulnerable to oil spills. We developed a conceptual framework to evaluate the impacts of potential oil exposure on marine mammals and applied it to 21 species inhabiting coastal British Columbia (BC), Canada. Oil spill vulnerability was determined by examining both the likelihood of species-specific (individual) oil exposure and the consequent likelihood of population-level effects. Oil exposure pathways, ecology, and physiological characteristics were first used to assign species—specific vulnerability rankings. Baleen whales were found to be highly vulnerable due to blowhole breathing, surface filter feeding, and invertebrate prey. Sea otters (*Enhydra lutris*) were ranked as highly vulnerable due to their time spent at the ocean surface, dense pelage, and benthic feeding techniques. Species-specific vulnerabilities were considered to estimate the likelihood of population-level effects occurring after oil exposure. Killer whale (*Orcinus orca*) populations were deemed at highest risk due to small population sizes, complex social structure, long lives, slow reproductive turnover, and dietary specialization. Finally, we related the species–specific and population-level vulnerabilities. In BC, vulnerability was deemed highest for Northern and Southern Resident killer whales and sea otters, followed by Bigg's killer whales and Steller sea lions (*Eumetopias jubatus*). Our findings challenge the typical "indicator species" approach routinely used and underscore the need to examine marine mammals at a species and population level for risk-based oil spill predictions. This conceptual framework can be combined with spill probabilities and volumes to develop more robust risk assessments and may be applied elsewhere to identify vulnerability themes for marine mammals.

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✉ Peter S. Ross
Peter.Ross@vanaqua.org

1 Raincoast Conservation Foundation, P.O. Box 2429, Sidney, BC V8L 3Y3, Canada

2 Ocean Pollution Research Program, Vancouver Aquarium Marine Science Centre, P.O. Box 3232, Vancouver, BC V6B 3X8, Canada

Accidents resulting from fossil fuel extraction and transportation have caused spills in the marine environment. Although many spills are small and/or unreported (contributing to chronic oiling in industrial areas), large reported oil spills have impacted marine mammals. These accidents range from large and highly publicized events, such as the *Exxon Valdez* oil spill (1989) and the *Deepwater Horizon* oil spill (2010), to much smaller regionally localized events, such as the 2007 Robson Bight diesel fuel spill at a killer whale sanctuary in Johnstone Strait, British Columbia (BC), Canada.

Long-term impacts associated with the *Exxon Valdez* oil spill were observed in two killer whale populations in Alaska resulting in population depression in one, and the loss of all potentially reproducing individuals, leaving the group functionally extinct, in the other (Matkin et al. 2008, 2012). In addition, several thousand sea otters and several hundred harbour seals (*Phoca vitulina*) died in the immediate aftermath of the accident. Chronic oiling from submerged oil in shoreline sediments have been associated with long-term impacts to sea otters (Ballachey et al. 1994, 2013).

After the *Deepwater Horizon* oil spill, significant adverse effects were observed in northern Gulf of Mexico bottlenose dolphins (*Tursiops truncatus*) and other cetaceans, with mortalities estimated to be in the thousands (Venn-Watson et al. 2015; Schwacke et al. 2014; Carmichael et al. 2012; Williams et al. 2011). Natural Resource Damage Assessment Trustees on the *Deepwater Horizon* oil spill examined more than 30 populations of whales and dolphins within the oil spill footprint area for damages. The trustees concluded that nearly all marine mammal populations that overlapped with the oil spill footprint had demonstrable, quantifiable impacts. In total, 21 of the most severely impacted whale and dolphin populations experienced long-term population level consequences from the *Deepwater Horizon* oil spill, with most species requiring decades to recover (DWH NRDAT 2016).

Small, localized spills can also expose marine mammals to the adverse effects of oil spills. For example, the 2007 sinking of the LeRoy Trucking barge released approximately 10,000 litres of diesel fuel in a killer whale sanctuary in Robson Bight, BC. Estimates suggest that as many as 25% of the northern resident killer whale population passed through the oil and would have inhaled toxic vapors for a period of hours to days (Williams et al. 2009).

Before the *Exxon Valdez* oil spill, the few case reports and investigations where marine mammal mortality was attributed to petroleum spills rarely had conclusive evidence (Geraci and St. Aubin 1990). During the *Exxon Valdez,* known individuals (i.e., killer whales) are presumed to have died as a result of exposure; however, the lack of carcass recovery or their decomposed state has limited causal information and rendered weight of evidence arguments vulnerable to attack (for example Fraker 2013). Even today, oil spills generally impact populations with limited population information and the victims disappear unnoticed (most carcasses sink, Williams et al. 2011). Following the *Deepwater Horizon* oil spill, considerable effort was made to determine the cause of reproductive failure, adverse health effects, and mortality observed in cetaceans in the northern Gulf of Mexico. The resulting attribution of lethal and sublethal effects to oil exposure from the *Deepwater Horizon* oil spill has increased the body of forensic evidence linking cause and effect (Venn-Watson et al. 2015; DWH NRDAT 2016).

Furthermore, oil spills often occur in habitats where ecosystem components, processes, and structures are previously compromised by human activities. As such, when mortality or other evidence is available, preexisting stressors can confound ascribing the role of oil, dismissing spill concerns. A final constraint on evidence linking exposure and response, especially in cetaceans, are the logistical and ethical constraints associated with experimental testing of petroleum effects. While a small number of controlled exposure studies using captive marine mammals were conducted before the 1990s, information on the effects of petroleum on marine mammals has come principally from spills themselves. Table 1 in the Supplementary Materials summarizes oil spill studies that have linked oil exposure to individual or population consequences.

The ability to assess and categorize species' oil spill vulnerability is a critical part of being able to evaluate risks from fossil fuel exports and informing spill response planning. Oil spill modeling attempts to predict the fate and behavior of spilled oil, and oil spill risk is determined by examining the likelihood (i.e., probability) of spills occurring multiplied by the consequence of those incidents (French-McCay 2004; French-McCkay et al. 2009; Reich et al. 2014). Some small-scale models have been developed to assess oil spill risk to specific marine mammal populations. These models combine oil spill trajectories and fate with species biological information (Reed et al. 1989; Jayko et al. 1990), such as time spent at the surface, species aggregation, physiology, and feeding specificity (Reich et al. 2014). Few risk models quantitatively address biological consequences of oil spills in aquatic environments (French-McCkay et al. 2009).

In the absence of species-specific physiological thresholds for oil exposure, we offer a conceptual framework to provide a general approach to identifying and ranking the vulnerability of marine mammals to oil spills. The foundation for this risk-based framework lies on the premise that species-specific biology and ecology positions certain marine mammals to be more vulnerable to the adverse effects of oil exposure than others. This "consequence" component can be combined with a separate probability for spill occurrence to provide a more complete assessment of oil spill "risk" in the conventional sense. Site and incident-specific factors, such as the type of oil product spilled, spill size, meteorological and oceanographic conditions, and the nature of the adjacent shoreline, will all be factors in exposure pathways and will ultimately determine the impacts to any given group of marine mammals.

Methods

Conventional biological categorization places marine mammals into two groups: fully aquatic (cetaceans) and semi-aquatic (pinnipeds and sea otters). A third group of semi-aquatic maritime mammals that live and feed in coastal environments include species, such as bears, wolves, and river otters. While still at risk from oil exposure in the event of a spill, this third group is outside the scope of this paper.

Our approach to scoring marine mammal sensitivity based on vulnerability themes is consistent with approaches taken by others (Reich et al. 2014) but considers more in-depth details that are specific to marine mammal species in question. We first consider the biological and ecological traits that allow us to rank the likelihood and severity of oil exposure consequences at a species level. We then consider this with population demographics and life-history traits to score the likelihood of population-level consequences. Combined, these measures provide an overall likelihood of species that will suffer immediate and long-term effects of an episodic oil spill.

Estimating the Likelihood of Oil Exposure

Oil products transported by ship can range from ultra-light oil condensates to heavy crude oils and bitumen products. Most oils will form surface slicks when spilled into the marine environment, where volatile components immediately begin to evaporate at a rate that is dependent upon both the oil's specific chemistry and environmental conditions (Lee et al. 2015). During this period, marine mammals are at acute risk of oil exposure through oil inhalation, contact, and ingestion (directly or via contaminated prey) during their normal surface behaviors of breathing, resting, socializing, feeding, and travelling (Harris et al. 2011). While some marine mammals may possess the ability to detect oil, avoidance of surface slicks, contaminated waters, or oiled shorelines is not typical (Sorensen et al. 1984; Smultea and Wursig 1995; Engelhardt 1983; Matkin et al. 2008; Geraci and St. Aubin 1990; Siniff et al. 1982).

In many cases, spilled oil will move from the surface into the water column, affecting marine mammals through contact or ingestion. In near-shore areas, oil stranded on shorelines can foul marine mammals on haul-out sites, on rookeries, and in foraging areas (Neff 1990). Oil also can sink, depending on oil-water densities, weathering processes, environmental conditions, and/or sediment aggregation. Once in sediments, oil can become a persistent source of hydrocarbon toxicity to the marine environment (Lee et al. 2015; Harris et al. 2011).

These pathways of exposure can cause acute or chronic exposures leading to sublethal or lethal effects (Bodkin et al. 2002, 2012; Peterson et al. 2003; Monson et al. 2011; Ballachey et al. 2013; Venn-Watson et al. 2015). We considered known behavioral and physiological characteristics with the following five exposure pathways to estimate the likelihood of a given marine mammal being exposed to oil in the event of an oil spill (Table 1).

Exposure Pathways

Contact Due to their time spent at or near the water's surface, marine mammals are inherently vulnerable to spilled oil, water-in-oil emulsions, and tar balls as they breath, swim, feed, and/or rest (Neff 1990). Prolonged contact with oil can lead to long-term coating that may interfere with swimming ability in seals, filtering capacity in baleen whales, and thermoregulation in furred mammals (Engelhardt 1983). Oiling has been linked to hypothermia, reduced feeding, cessation of breathing ability, inhalation of toxic vapors, behavioral changes, absorption and irritation to skin and mucous membranes, decreased mobility, and mortality (Geraci and St. Aubin 1990; Peterson 2001).

While spilled oil partitions between air, surface, and subsurface components of marine habitat, the risk of exposure typically increases with time spent at the surface or hauled out on affected shorelines (Peterson 2001). Thus, the time a species typically spends at the surface was used to estimate contact likelihood, with the feeding ecology of each marine mammal used as a proxy for time spent on the surface. Prey type and feeding behavior informed the time spent at the surface. Marine mammals feeding on prey that live near the surface were given a higher likelihood of encountering surface oil than those that feed on deeper prey. Species spending time hauled-out on shore also were assigned a higher likelihood of oil contact.

Adhesion While the duration of oil exposure is important, so is the strength of its adhesion to the animal. Generally, the degree of skin damage and the amount of absorption into the body can be attributed to the nature and duration of hydrocarbon adhesion (Geraci and St. Aubin 1990). Adhesion ultimately depends on three factors: the texture of the exposed surface, the frequency and duration of exposure, and the characteristics of the oil (Engelhardt 1983). Exposure duration and oil properties are somewhat incident-dependent, so we characterised adhesion differences in fur and skin texture of different marine mammals, and scored according to their texture.

Because many furred marine mammals rely on the integrity of their pelage for thermoregulation, oiling can cause a loss of insulating capacity and can lead to death from hypothermia, smothering, drowning, and starvation due to an increased metabolic response (Peterson et al. 2003; Costa and Kooyman 1981). As such, species with fur are at very high risk of oil adhesion and were placed in the highest risk category. In terms of skin texture, rough skin surfaces of certain cetaceans, such as grey whales with barnacles and right whales with callosities, have been associated with increased risk of oil adhesion and were thus given a higher likelihood of prolonged adhesion than smooth skin (Engelhardt 1983).

Table 1 Physiological and behavioral criteria of marine mammal species used to determine likelihood of individual exposure to oil through five known exposure pathways. Risk was categorized as low, medium, and high based on the criteria examined for each exposure pathway

Exposure pathway	Criteria examined	Score		
		Low (1)	Medium (2)	High (3)
Contact	Time spent at surface approximated using feeding ecology Other factors if known i.e. dive time/depth Time spent hauled out on shore	A score of LOW was not assigned, as all marine mammals must breathe air at the surface	Feed on benthic prey Long/deep dive duration	Surface feeders Feed on epi- or mesopelagic species Known behaviours at surface and/or on shore
Adhesion	Skin texture	Smooth	Rough patches Short fur	Presence of true fur
Inhalation	Time spent breathing at the air/water interface Breathing physiology Grooming behaviour	A score of LOW was not assigned, as all marine mammals must breathe air at the surface	No blowhole OR Spends time away from surface	Blowhole Spends extended time at surface Grooming behaviour
Direct Ingestion	Feeding mechanism Other behaviours known to increase contact with oil	Teeth	Baleen plates OR Benthic Feeding	Baleen plates AND Benthic Feeding Grooming
Ingestion through contaminated prey	Physiological ability of prey to metabolize oil products	Fish and other vertebrates	Fish and invertebrates	Invertebrates

Inhalation After an oil spill, the highest concentrations of volatile monoaromatic hydrocarbons are typically found at the air-water interface (Colegrove et al. 2013). This interface is where marine mammals encountering fresh oil are likely to inhale volatile and toxic hydrocarbons evaporating from the surface slick (Matkin et al. 2008; Neff 1990). Inhalation and aspiration of oil and its primary and secondary aerosol products can cause effects, including inflammation and lesions in respiratory membranes. These can lead to lung disease and bacterial pneumonia, adrenal disease, absorption of hydrocarbons into the bloodstream, neurological damage, and liver disorders (Venn-Watson et al. 2015; Geraci and St. Aubin 1990) and ultimately can cause organ failure, reproductive failure, and mortality (Venn-Watson et al. 2015). If fumes themselves are not directly lethal, they can result in a narcosis response causing drowning (Matkin et al. 2008).

All exposed marine mammals have a high likelihood of inhaling toxic fumes from an oil spill due to the need to breath, rest, socialize, and travel at the ocean's surface. We ranked this likelihood by examining time spent at the surface as well as the breathing physiology of each species. As obligatory surface breathers, cetaceans begin to exhale before surfacing and thus are committed to inhaling before toxic vapours can be detected (Matkin et al. 2008). Killer whales, for example, have been identified as being at an increased risk from airborne pollutants due to this method of breathing (Lachmuth et al. 2011). Oil vapour and particulates could therefore be inhaled through normal breathing patterns. As such, species with a blowhole were scored as having a higher likelihood of oil exposure.

Direct Ingestion Most marine mammals do not ingest large quantities of seawater, which limits their ingestion of large quantities of oil (McLaren 1990; Neff 1990). However, some physiological and lifestyle characteristics can predispose individuals to oil ingestion. The consequences of ingested oil range from acute and delayed mortality to sublethal progressive organ damage through the destruction of cells and formation of lesions (Geraci and St. Aubin 1990; Matkin et al. 2008; Bodkin et al. 2012). We identified three biological features that could lead to an increased likelihood of direct ingestion of spilled oil: (1) Filter feeding species could trap oil in their baleen plates, which would lead to ingestion of residual amounts of oil (Engelhardt 1983); (2) Benthic feeders can ingest sunken oil while feeding in areas of contaminated sediment. Following the *Exxon Valdez* oil spill, repeated exposure of sea otters to oil through their benthic foraging behaviour has been identified as the cause for protracted recovery and chronic mortality (Bodkin et al. 2002, 2012); and (3) Fur-bearing mammals, notably sea otters, can ingest large quantities of oil during grooming and are therefore at a much higher risk for oil-related injury (Peterson 2001).

Indirect Ingestion Marine mammals also can ingest oil products through the consumption of prey that accumulate PAHs (Geraci and St. Aubin 1990). Indirect ingestion of oil can occur through consumption of invertebrates—amphipods, crab larvae, mysiids, crustaceans, bivalves, and cephalopods—that do not readily metabolize PAHs, and can accumulate the PAHs contained in oil (Peterson 2001; Nakata et al. 2003; Wursig 1990; Geraci and St. Aubin 1990). Hydrocarbons that bioaccumulate in these invertebrates can be passed on to their predators (Harris et al. 2011; Peterson 2001; Wursig 1990). In vertebrates, detoxification enzymes (from the cytochrome 450 group) enable fish to degrade and eliminate PAHs to a greater extent, thereby reducing risk of exposure in their predators (Neff 1990; Baussant et al. 2001). We estimated the likelihood of oil exposure through this indirect pathway by reviewing the known diets of marine mammals and assigning a higher risk to those with diets that include prey species that do not readily metabolize PAHs.

Determining Oil Exposure Risk Scores for Individual Species

Table 1 summarizes the five exposure pathways, the physiological and behavioural characteristics examined, and the criteria used to rank each characteristic as low, medium, or high risk of exposure. A score was assigned to each risk level: low = 1; medium = 2; and high = 3. For each marine mammal species assessed, these scores were summed to provide the likelihood of individual exposure to oil for each marine mammal species relative to the other species assessed.

Estimating the Likelihood of Population-Level Effects from Oil Exposure

The impacts associated with oil exposure can range from short-term localized injury of individuals to long-term population changes (Peterson et al. 2003; Matkin et al. 2012; DWH NRDAT 2016). To identify the likelihood of population-level effects given an oil spill, we examined eight species-specific biological, ecological, and demographic characteristics (population, distribution, group size, habitat, reproduction, life history, diversity of diet, and prey susceptibility to decline) that could potentially increase the chance of population-level consequences from exposure to an episodic oil spill. The best available information for each characteristic was identified and ranked according to its ability to increase or decrease the likelihood of population level effects. The following criteria were used to characterise each species examined.

Population Population size, provincial or federal conservation status, and/or trend was used, as available, as an indication of the overall robustness of the population and the significance of the potential loss of individuals. The likelihood of population-level effects occuring was ranked higher in small populations, in those with *at-risk* status (i.e., existing conservation concerns) and in those with declining population trends.

Distribution When considering species distribution, those with year-round residency were ranked as having a high likelihood of encountering an oil spill in the study area.

Group Size Marine mammals can be found as solitary individuals, pairs, pods, colonies, or in groups numbering in the hundreds. Groups can be based on family units, sex-segregated, breeding or nonbreeding, or large aggregates of mixed sexes and age classes. The potential for an oil spill to affect individuals or aggregates was ranked according to average group size. Those with large average group sizes were ranked as having a higher likelihood of population-level effects as more individuals would be affected. In species where groups travel, feed, and/or socialize together, it only takes one poorly timed event to have catastrophic population consequences (Williams et al. 2009).

Habitat The presence of habitat important to the long-term viability of a marine mammal species was used as criteria for determining the likelihood of population-level effects. Areas that are legally identified as "critical" and areas documented to which high site fidelity has been shown were designated as having high potential for population-level effects.

Reproduction Many species have known habitats that are essential for life processes, such as breeding and calving. A higher ranking was assigned to those species who undertake these essential activities within study area waters.

Life History Long-lived species with low reproductive rates were ranked as having an increased likelihood of experiencing population-level effects due to long recovery times from population pertebations.

Diversity of Diet Species with more diverse diets were assumed to have a lower likelihood of population effects from decreased prey abundance than those with a selective diet. Thus, species with restricted diets were ranked as having higher likelihood of effects from an oil spill scenario.

Prey Susceptible to Decline Marine mammals can consume prey (invertebrates, fish, or other mammals) that is itself vulnerable to declines from oil exposure. Given a spill scenario, a population could become food limited by declines in prey availability. Marine mammal species that rely on spill-vulnerable prey were scored as having a higher likelihood of population-level effects.

Determining Oil Spill Risk Scores at the Population Level

Table 2 summarizes the biological, ecological, and demographic features of marine mammal species and the criteria for ranking each as low, medium, or high likelihood of population level effects. To calculate the likelihood of population-level effects, a score was applied to each risk level: low = 1; medium = 2; and high = 3. The scores were summed to give the ranking for likelihood of population-level effects for each species relative to the other species assessed.

Identifying Species at Greatest Risk from an Oil Spill

By relating the individual scores with population level scores through the application of this framework, we can identify marine mammal species that are at an overall increased risk of consequence from oil exposure and its related effects.

As a real-world application of our conceptual framework, we examined the biological, physiological, and ecological characteristics of 21 BC marine mammal species and applied our oil spill vulnerability framework to identify species that are at high risk of adverse effects from a hypothetical episodic oil spill.

As a case study, we demonstrated how our framework could be applied to determine oil spill risk (i.e., consequence x probability) to Southern Resident killer whales. We digitized and georeferenced a hypothetical modelled oil spill from stochastic simulations that were created using SPILLCALC and H3D software (EBA 2013) 15 days following a 15,000 m^3 release of diluted bitumen at Arachne Reef in northern Haro Strait, BC. We then mapped the overlap with the designated critical habitat for Southern Resident killer whales in both Canada and the United States (DFO 2011a; NMFS 2008). The overlap area between Critical Habitat and the probability of oil presence was determined using an intersect function to give an overlap area (km^2) for each probability category. The percent of the critical habitat was then calculated by taking the area in each category and dividing by the total area of critical habitat (Table 6). We then took these modelled spill probabilities and overlaid them with the critical habitat of Southern Resident killer whales.

Results and Discussion

Marine Mammals of Coastal British Columbia, Canada

Characterizing spill vulnerability of marine mammals requires context. In BC, most marine mammals were exploited extensively in the nineteenth and twentieth centuries (Bigg 1985; Olesiuk et al. 1990; Gregr et al. 2000; Nichol et al. 2002, 2009a). With the cessation of these activities through domestic legislation (1970) and international treaty (1982), many populations are returning to their historic feeding grounds, migration routes, and ranges (Olesiuk 1999; Nichol et al. 2009b; Williams and Thomas 2007; Best et al. 2015). Nevertheless, some species remain at critically low numbers, reflecting their long lifespans and low reproductive turnover. Consequently, high mortality can be biologically perturbing and recovery from significant population reductions can take decades, if not longer. Blue whales, sei whales, and fin whales have still not recovered despite 50 years since whaling ceased in BC waters, and there is little evidence of recovery for North Pacific right whales.

The long-term consequences of perturbations are reflected in the high number of BC marine mammals listed under Canada's Species at Risk Act (SARA) and/or the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Of more than 20 species of marine mammals that can be found in BC waters, 14 are listed as *Endangered, Threatened*, or of *Special Concern*. These *at risk* species, and their identification (or not) as vulnerable to oil spills in recovery plans, are listed in Table 3. BC maritime mammals at potential risk from oil spills are listed in Supplementary Materials (Table 2).

Likelihood of Individual Exposure

All marine mammals have an inherent likelihood of exposure to spilled oil because of their existence at the air-surface interface. Despite many shared features, marine mammals also exhibit some remarkable biological and ecological dissimilarities that have the potential to predispose certain species to increased oil vulnerability. An assessment of the likelihood of oil-spill exposure for BC marine mammals species is shown in Table 4. An understanding of both the shared features and the species-specific features that dictate the relative vulnerability of marine mammals served as the basis for the framework development here.

As a group, BC marine mammals were found to be at moderate risk to individual oil exposure given a spill

Table 2 Species-specific biological, ecological, and demographic features of marine mammal species that could increase the likelihood of population-level consequences in the event of an oil spill. Risk was categorized as low, medium, and high based on the criteria examined for each characteristic

Characteristic	Criteria examined	Score		
		Low (1)	Medium (2)	High (3)
Population	Size of the population that inhabits the study area, population trends	Large, stable population	Presence of small subpopulations	Small and/or declining populations
Distribution	Spatial and temporal use of habitat in study area	Only present in study area for a small portion of the year	Observed in study area for half of the year	Observed in study area at all times throughout year
Group size	Average size of aggregations	Small group size	Small segregated groups (age class or sex)	Large groups
Habitat	Habitat designated as critical for population survival or high site fidelity observed	No critical habitat or site fidelity within study area	Areas identified that may be critical for the survival of the population	Critical habitat or high site fidelity has been defined in study area
Reproduction	Habitat that is essential to life processes	Calving and breeding take place outside study area	Study area historically important to calving or breeding	Calving or breeding known to occur within the study area
Life history	Reproductive rates and age at sexual maturity	Low age at sexual maturity High reproductive rate	High age at sexual maturity OR Low reproductive rate	High age at sexual maturity AND Low reproductive rate
Diversity of diet	Species is a generalist or obligate to one prey type	Opportunistic feeders that consume a wide variety of prey	Diets limited to a certain class or trophic level	Highly specialized diets limited to one or a few prey species
Prey susceptibility to decline	The ability of prey species to maintain population numbers in the case of an oil spill	Feed on prey that are not susceptible to decline	Feed both on prey that are susceptible and resistant to decline	Feed on prey susceptible to decline

scenario in BC waters. Based on their need to interact with the air/surface interface, and in some cases with the land/water interface, they are inherently vulnerable to coastal oil spills.

Baleen whales were found to exhibit many behavioural and physiological characteristics that increase their likelihood of exposure to spilled oil. These include exposure to oil at the surface where they are often present, oil adhesion to rough skin surfaces, inhalation from obligatory surface breathing, oil ingestion directly through surface feeding activities, fouling of baleen plates, and indirectly through consuming invertebrate prey. Baleen whales as a group have not typically been associated with oil spill mortality, but carcass sinkage following an oil spill may have confounded this observation in previous incidents (Williams et al. 2011).

Harbour porpoise were scored as having a higher risk than other similar species due to their increased likelihood of ingesting oil via contaminated squid (a large portion of their diet). This illustrates how one behaviour or preference can increase a species' likelihood of oil exposure. It also reveals the shortcomings of grouping similar species in risk assessments, as this can potentially overlook species-specific traits that increase vulnerability (Fig. 1).

As expected, sea otters were ranked as having a high likelihood of oil exposure in every category. Their extremely dense pelage (100,000 hairs/cm^2), their intense grooming behaviors (2–4 h/day), their benthic foraging methods, and their consumption of benthic prey place them at high vulnerability to oil exposure. Acute losses in previous oil spills reinforce their high sensitivity (Ballachey et al. 1994).

Likelihood of Population-Level Effects from Oil Exposure

The majority of marine mammals examined were found to have a high likelihood of suffering population-level effects in the event of an oil spill. The review of species-specific likelihood of population-level effects for BC marine mammals is shown in Table 5.

Of the 21 BC marine mammals examined, only the sperm whale, Northern elephant seal, and California sea lion were found to have a moderate risk of suffering population level effects from an oil spill (Fig. 2). Both the sperm whale and Northern elephant seal have relatively large populations, only spend a small amount of time in BC waters, and are typically sighted alone or in small groups.

Table 3 Marine mammal species in British Columbia waters, their status under the Species at Risk Act (SARA) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), and their vulnerability to oil spills as defined in Federal Government Recovery and Management Plans

Species	Designation	Oil risk outlined in recovery/management plan
Harbour porpoise *Phocena phocena*	Special concern (COSEWIC 2003a); Special concern (SARA)	Toxic spill rated as high level of concern to survival, prey availability and reproductive rate; management plan (Fisheries and Oceans Canada (DFO) 2009)
Dall's porpoise *Phocoenoides dalli*	Not at risk	n/a
Pacific white-sided dolphin *Lagenorhynchus obliquidens*	Not at risk	n/a
Northern Resident killer whale *Orcinus orca*	Threatened (COSEWIC 2008, SARA)	Recovery strategy indicates oil spill a low risk but potentially catastrophic (DFO 2011a)
Southern Resident killer whale *Orcinus orca*	Endangered (COSEWIC 2008, SARA)	Recovery strategy indicates oil spill a low risk but potentially catastrophic (DFO 2011a)
Transient (Bigg's) killer whale *Orcinus orca*	Threatened (COSEWIC 2008, SARA)	Toxic spill rated as high level of concern (DFO 2007)
Offshore killer whale *Orcinus orca*	Threatened (COSEWIC 2008, SARA)	Unknown
Minke whale *Balaenoptera acutorostrata*	Not at risk	n/a
Humpback whale *Megaptera novaeangliae*	Special concern (COSEWIC 2011); Threatened (SARA)	Toxic spills seen as threat with moderate level of concern in recovery strategy (DFO 2013)
Grey whale *Eschrichtius robustus*	Special concern (COSEWIC 2004a, SARA)	Toxic spill seen as low-medium threat for population and high level threat in management plan (DFO 2010a)
Sei whale *Balaenoptera borealis*	Endangered (COSEWIC 2013, SARA)	Oil spill not designated a "risk of note" in recovery plan (Gregr et al. 2006)
Fin whale *Balaenoptera physalus*	Threatened (COSEWIC 2005, SARA)	Oil spills deemed a "poorly understood threat"(Gregr et al. 2006)
Blue whale *Balaenoptera musculus*	Endangered (COSEWIC 2012, SARA)	Oil spill not deemed a risk in recovery plan (Gregr et al. 2006)
North Pacific Right whale *Eubalena glacialis*	Endangered (COSEWIC 2004b, SARA)	Risk of contact with oil spill in shipping zones as well as prey a threat to recovery (DFO 2011b)
Sperm whale *Physeter macrocephalus*	Not at risk	n/a
Harbour seal *Phoca vitulina*	Not at risk	Status report identifies oil spills as threat to the species (Baird 2001)
Northern fur seal *Callorhinus ursinus*	Threatened (COSEWIC 2010); NO SARA STATUS	Oil spill a threat to migrating and feeding fur seals (COSEWIC 2010)
Steller sea lion *Eumetopias jubatus*	Special concern (COSEWIC 2003b, SARA)	Toxic spills rated as low-medium level of concern in management plan (DFO 2010b)
California sea lion *Zalophus californianus*	Not at risk	n/a
Northern elephant seal *Mirounga angustirostris*	Not at risk	n/a
Sea otter *Enhydra lutris*	Special concern (COSEWIC 2007, SARA)	Oil spill rated as high level of concern in management plan (DFO 2014a)

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Table 4 Likelihood of oil exposure for common BC marine mammals were based on their biological and ecological characteristics. Five oil exposure pathways were examined and the likelihood of oil exposure was scored as low, medium, or high, as defined in Table 2

Species	Contact	Adhesion	Inhalation	Direct ingestion	ingestion through contaminated prey
Harbour porpoise	HIGH epi/meso pelagic prey[1]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	HIGH market squid most important prey[5]
Dall's porpoise	MED deeper feeding, long dive duration[6]	LOW smooth skin[2]	HIGH known surface behaviours[7] blowhole[3]	LOW do not ingest large quantities of seawater[4]	LOW mainly small schooling fish[6]
Pacific White-Sided dolphin	HIGH surface feeding, short dive duration[8]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	MED Small schooling fish and squid[8]
Northern Resident killer whale	HIGH majority of time spent at surface[9]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	MED Chinook salmon, chum[10], small percentage of cephalopods[11]
Southern Resident killer whale	HIGH majority of time spent at surface[9]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	MED Chinook salmon[12], small percentage of cephalopods[11]
Transient (Bigg's) killer whale	HIGH captures prey at surface and coastline[13]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	MED marine mammals[10,14,15]
Offshore killer whale	HIGH majority of time spent at surface[9]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	LOW do not ingest large quantities of seawater[4]	LOW Largely unknown, diverse range of fish[16,17,18], sharks[19]
Minke whale	HIGH surface feeding behaviours[20]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	LOW Small schooling fish[21]
Humpback whale	HIGH Surface feeding techniques[22]	MED Tubercles present[22]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	HIGH Euphausiids[23]
Grey whale	MED Benthic feeder[24]	MED Rough skin with barnacles[25]	MED Blowhole[3]	HIGH Baleen plates, bottom feeding[3]	HIGH Planktonic mysiids, benthic invertebrates[24]
Sei whale	HIGH Surface feeding behaviours[26]	MED Infestations of ectoparasitic copepods[27]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	HIGH Calanoid copepods, euphasiids, schooling fish[28]
Fin whale	HIGH Majority of time spent at surface[29]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	HIGH Zooplankton, euphasiids, copepods[28]
Blue whale	HIGH Feed at surface, gulps large quantities of water[30,20]	LOW smooth skin[2]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	HIGH Euphasiids[31]

Table 4 continued

Species	Contact	Adhesion	Inhalation	Direct ingestion	ingestion through contaminated prey
North Pacific right whale	HIGH Surface feeding[32]	MED Callosites[32]	HIGH Extended time near surface; blowhole[3]	MED Baleen plates[3]	HIGH Copepods, euphasiids[33,34]
Sperm whale	MED Feed in deep water[35]	LOW smooth skin[2]	MED Deep, long dives[36] blowhole[3]	LOW do not ingest large quantities of seawater[4]	HIGH Primarily squid and large fish[28]
Harbour seal	HIGH Feed at surface and haul out[37]	MED Oil and detritus adhesion common[38]	MED Spend some time at or near surface[37]	LOW Risk of direct ingestion negligible[37]	LOW Small fish[39]
Northern fur seal	MED Feed on deep prey species[41] do not haul out in BC[41]	HIGH Oil adheres to fur[38]	MED Spend some time at or near surface[37]	LOW Risk of direct ingestion negligible[37]	MED Small fish, squid, crustaceans[40]
Steller sea lion	HIGH Feed at surface and haul out[37]	MED Oil and detritus adhesion common[38]	MED Spend some time at or near surface[37]	LOW Risk of direct ingestion negligible[37]	MED Over 50 species of fish and invertebrates[42]
California sea lion	HIGH Feed at surface and haul out[37]	MED Oil and detritus adhesion common[38]	MED Spend some time at or near surface[37]	LOW Risk of direct ingestion negligible[37]	MED Small schooling fish and cephalopods[43]
Northern elephant Seal	MED Forage constantly during time in BC[44], deep water prey[45]	MED Oil and detritus adhesion common[38]	MED Spend some time at or near surface[37]	MED Bottom foraging[46]	MED Deepwater fish, sharks, and cephalopods[45]
Sea otter	HIGH Present in shallow waters and on shore habitats[47]	HIGH Oil adheres to fur[48]	HIGH Grooming fur[38]	HIGH Grooming fur[38], bottom foraging[46]	HIGH Benthic invertebrates[49,50]

[1] Fisheries and Oceans Canada (DFO) (2009), [2] Engelhardt (1983), [3] Wursig (1990), [4] Neff (1990), [5] COSEWIC (2003a), [6] Walker et al. (1998), [7] Jefferson (1987), [8] Heise (1997a), [9] Ford et al. (2000), [10] Ford et al. (1998), [11] Fisheries (2011a), [12] Hanson et al. (2010), [13] Fisheries (2007), [14] Baird and Dill (1995), [15] Ford et al. (2005), [16] Heise et al. (2003), [17] Jones (2006), [18] Krahn et al. (2007), [19] Ford et al. (2011), [20] Kot et al. (2014), [21] Dorsey et al. (1990), [22] Fisheries and Oceans Canada (2013), [23] Ford et al. (2009), [24] Dunham and Duffus (2001), [25] Fisheries (2010a), [26] Nemoto and Kawamura (1977), [27] Gregr et al. (2006), [28] Flinn et al. (2002), [29] Douglas et al. (2008), [30] Sears and Calambokidis (2002), [31] Calambokidis et al. (2002), [32] Fisheries (2011b), [33] Nichol et al. (2002), [34] NMFS (2006), [35] Watkins et al. (2002), [36] Gaskill (2010), [37] McLaren (1990), [38] Geraci and St. Aubin (1990), [39] Fisheries and Oceans Canada (2010a, b), [40] COSEWIC (2010), [41] Fisheries and Oceans Canada (2012), [42] COSEWIC (2003b), [43] Lowry et al. (1991), [44] Brillinger and Stewart (1998), [45] Condit and LeBoeuf (1984), [46] Peterson et al. (2003), [47] Fisheries and Oceans Canada (2014a), [48] Costa and Kooyman (1981), [49] Estes et al. (2003), [50] COSEWIC (2007)

They are at a low risk of having large numbers exposed to a single spill.

California sea lions also were ranked as moderate in stark contrast to Steller sea lions, whose population was ranked as having the highest risk of suffering adverse oil spill effects. This ranking for Steller sea lions was due to their smaller population size, their presence in large groups, and reliance on a small number of rookeries along the BC coast for vital life processes. BC's Steller sea lion population is federally designated as Special Concern by SARA, but heightened concern exists for its vulnerability to become threatened due to a combination of biological characteristics and identified threats (Fisheries 2010b).

Ranked in the highest risk category are Resident and Biggs (transient) killer whales. They scored "high" in all categories due to their long lives, limited reproductive turnover, very small population sizes, complex social structure, identified critical habitat, and high dietary specialisation. The vulnerability of killer whales to population-level effects from oil spills was documented in

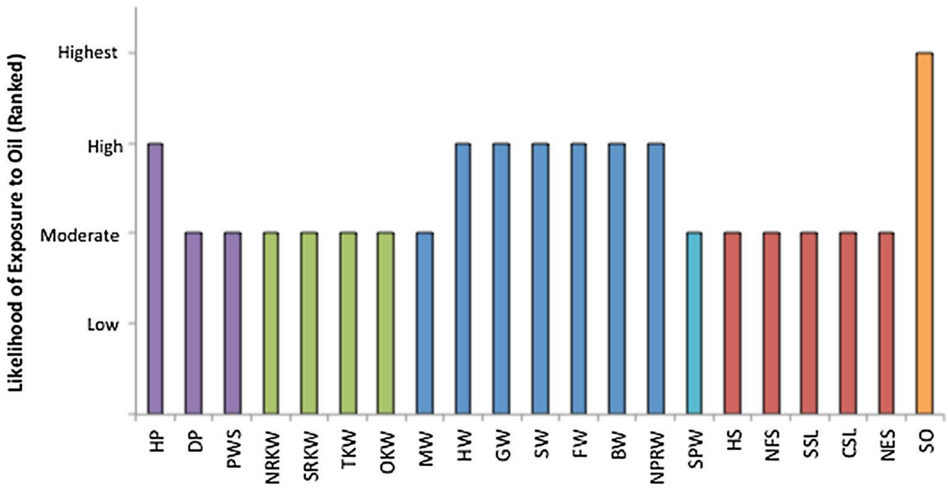

Fig. 1 Likelihood of individual exposure to oil for marine mammals in BC was ranked using four categories: low, moderate, high, and highest, binned using equal intervals from the minimum possible cumulative score to the maximum possible cumulative score (min/max score (5/15), bins low (5–7), moderate (8–10), high (11–13) and highest (14–15). *Purple*: dolphins, porpoises: *HP* harbour porpoise, *DP* Dall's porpoise, *PWS* Pacific white-sided dolphin; *Green*: killer whales: *NRKW* Northern Resident killer whale, *SRKW* Southern Resident killer whale, *TKW* transient killer whale, *OKW* offshore killer whale; *blue*: baleen whales: *MW* minke whale, *HW* humpback whale, *GW* grey whale, *SW* sei whale, *FW* fin whale, *BW* blue whale, *NPRW* North Pacific right whale; *light blue*: SPW: sperm whale; *red*: pinnipeds: *HS* harbour seal, *NFS* Northern fur seal, *SSL* Steller sea lion, *CSL* California sea lion, *NES* Northern elephant seal; *Orange*: *SO* sea otter

Alaska's *Exxon Valdez* spill. Alaska's AB Resident killer whale population remained depressed for more than 20 years following the loss of 13 individuals (33% of the population), and the AT1 Transient group lost 9 individuals (41% of the population), including its remaining reproductive females (Matkin et al. 2008).

Species at Greatest Threat from an Oil Spill

By combining the likelihood of individual exposure with the likelihood of population-level effects, we found the majority of BC marine mammals were at high risk to oil spill impacts (Fig. 3). Only sperm whales and Northern elephant seals, for reasons discussed, were ranked as moderate. At especially high risk are Northern and Southern Resident killer whales and sea otters, followed closely by Bigg's (transient) killer whales, and Steller sea lions. Both killer whales and sea otters experienced high mortality following the *Exxon Valdez* oil spill (Matkin et al. 2008; Ballachey et al. 2013).

Our framework suggests that many of the species and populations deemed to be at the greatest risk for oil spill exposure and impact are also those with a high conservation concern as identified by their legal listing under Canada's *Species at Risk Act*. These include Northern and Southern Resident killer whales, Bigg's (Transient) killer whales, Steller sea lions, and sea otters. The qualitative risk rankings generated through our framework therefore may inform recovery planning for at-risk species or help to identify at-risk species or populations by identifying oil exposure as a major threat.

This risk-based conceptual framework aligns with other qualitative or semiquantitative risk assessments undertaken in Alaska and Canada's east coast (French-McCay 2004; Reich et al. 2014; Lawson and Lesage 2013). However, our framework allows a more in-depth evaluation to identify at-risk species by considering both individual exposure and population variables. The framework was applied in British Columbia but could be equally useful to other areas of the world. Through the application of this framework, species, and/or populations whose ecological and physiological characteristics predispose them to greater injury from an episodic oil spill can be identified. This information can be integrated with oil spill models that predict the likelihood and extent of an oil spill in a given area and create a more robust prediction on a species-specific level. In practical application for this framework, species identified as being at higher risk of adverse effects would warrant more detailed examination or modeling exercises and receive prioritized actions during spill response planning and operations.

Applying the Risk Framework with Modelled Spill Probabilities: A Southern Resident Killer Whale Example

Through the application of our framework, we determined Southern Resident killer whales to be highly vulnerable to

Table 5 Likelihood of population level effects due to oil exposure in common BC marine mammals were evaluated on the basis of their biological and ecological characteristics. Life history traits were examined and scored as having a low, medium, or high likelihood, as defined in Table 2

Species	Population	Distribution	Group size	Habitat	Reproduction	Life history	Diversity of diet	Prey susceptibility to decline
Harbour porpoise	MED Estimated 8000–10,000[1,2] small subpopulations present[3]	HIGH Present year round[4] near shore[2]	LOW Small groups of 1–8 individuals[4]	MED Distribution possibly linked to prey abundance[5]	HIGH Seasonal reproduction[6] in BC waters[4]	MED Short-lived species, 1–2 years between offspring[4]	LOW Diverse diet of small schooling fish and squid[7]	HIGH Prey vulnerable to abundance decrease[8,9,10]
Dall's porpoise	LOW Estimated 4000–6,000[1,2] stable population[11]	HIGH Present year round inshore and offshore[11]	LOW Small groups of < 5 individuals[12]	MED Johnstone Strait suggested as important calving area[12]	HIGH Twice annual reproduction in BC waters[13]	LOW Short-lived species, 1–2 years between offspring[11]	LOW Small schooling fish[7]	HIGH Prey vulnerable to abundance decrease[8,9,10]
Pacific White-Sided dolphin	LOW Large stable population Estimated 22,000–26,000[1,2]	HIGH Present year round inshore and offshore[14]	HIGH Large group size 40–100 individuals[2,14,15]	LOW No defined critical habitat	HIGH Calving in summer in BC waters[16]	HIGH Slow reproduction, high age at sexual maturity and 5 years between offspring[16]	LOW Opportunistic feeder on over 13 different fish species[15,17]	HIGH Prey vulnerable to abundance decrease[8,9,10]
Northern Resident killer whale	HIGH Very small population around 250 individuals[18,19]	HIGH Sighted year round in BC waters[20]	HIGH Large group size 10 to >25 individuals[21] Complex social structure[22,23]	HIGH Critical habitat defined in BC waters[24]	HIGH Calving takes place in BC waters[25]	HIGH Long-lived, Slow reproducing, 15–25 years before fist mating and 5–6 years between offspring[24,25,26]	HIGH Specialized diet Chinook and chum salmon[27], small percentage of cephalopods[24]	HIGH Prey vulnerable to abundance decrease[9,10]
Southern Resident killer whale	HIGH Extremely small declining population around 80 individuals[19]	HIGH Sighted year round in BC waters[25]	HIGH Large groups and complex social structure[22,23]	HIGH Critical habitat defined in BC waters[24], small areas of pod specific high density[28]	HIGH Calving takes place in BC waters[25]	HIGH Long-lived, Slow reproducing, 15–25 years before fist mating and 5–6 years between offspring[24,25,26]	HIGH Specialized diet Chinook salmon, small percentage of cephalopods[25]	HIGH Prey vulnerable to abundance decrease[9,10]

Table 5 continued

Species	Population	Distribution	Group size	Habitat	Reproduction	Life history	Diversity of diet	Prey susceptibility to decline
Transient killer whale	HIGH	HIGH	LOW	HIGH	HIGH	HIGH	LOW	HIGH
	Small, at risk population around 250 individuals[30]	Present year round in BC waters[30]	Small groups of around 3 individuals[31]	Proposed critical habitat along entire BC coast[32]	Calving takes place in BC waters[25]	Long-lived, Slow reproducing, 15–25 years before fist mating and 5–6 years between offspring[24,25,26]	Diverse diet of marine mammals[27,31,33]	Prey vulnerable to abundance decrease[9,34]
Offshore killer whale	HIGH	UNKNOWN	HIGH	UNKNOWN	UNKNOWN	HIGH	LOW	HIGH
	Largely unknown, at least 288 unique individuals[18]	Rarely present in coastal or inshore waters[21]	Large groups 30–60 individuals[21]			Long-lived, Slow reproducing, 15–25 years before fist mating and 5–6 years between offspring[24,25,26]	Largely unknown, diverse diet consisting of a variety of fish and sharks[35,36,37,38]	Prey vulnerable to abundance decrease[9,39,40,41]
Minke whale	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
	Population deemed not at risk[43], estimated 350–550 individuals[1,2]	Present year round in BC waters[43]	Primarily seen alone[44]	Extreme site fidelity to feeding sites in BC waters[43]	Calving areas not identified in BC waters[43]	Long-lived species, 6–9 years at sexual maturity[45]	Diverse diet of small schooling fish[43]	Prey vulnerable to abundance decrease[8,9,10]
Humpback whale	MED	MED	LOW	HIGH	LOW	HIGH	HIGH	HIGH
	North Pacific estimated at 21,808[46], BC population estimates 993–1,200[1,2], and 1970–2331[47], BC subpopulations exist with little interchange[48]	Most present in BC summer months, some reside year round[47]	Small groups <8 individuals[2]	Areas of critical feeding habitat present in BC waters[49], strong site fidelity to summer feeding grounds[48]	Calving areas outside of BC waters[50]	Long-lived species with long calving intervals (1–5 years)[47]	Specialized diet of large zooplankton, euphausiids, crab larve with some small fishes[47,50]	Prey vulnerable to abundance decrease[8,9,60,61]
Grey whale	MED	MED	MED	HIGH	LOW	MED	HIGH	HIGH
	Recovering large population around 20,000[51,52], small subpopulations exist in BC waters (PCFA)	Migrates through BC waters from January to May[54], group of 200 spends summer in BC waters[55]	Small group size (1–5)[56], population is age class segregated when in BC waters[57]	Critical summer feeding grounds in BC waters[51]	Calving and breeding takes place outside BC waters[51]	Long-lived species with calving every two years[58]	Specialized diet of planktonic mysiids, crab larvae, benthic invertebrates[59]	Prey vulnerable to abundance decrease[9,60,61,62]

Table 5 continued

Species	Population	Distribution	Group size	Habitat	Reproduction	Life history	Diversity of diet	Prey susceptibility to decline
Sei whale	HIGH Largely unknown estimated small post-whaling population estimate 126[63,64,65]	LOW Currently few sightings in BC waters[66], historical north-south migration in summer[65]	MED Small group size (1–3)[63,64], age class segregated when travelling through BC waters[66]	MED Critical habitat predicted in offshore BC waters[67]	LOW Calving and breeding takes place outside BC waters[66]	HIGH Long-lived species with calving every two years and age at sexual maturity 5–15 years[66]	LOW Diverse diet of calanoid copepods, euphausiids, amphipods, fish[68]	HIGH Prey vulnerable to abundance decrease[9,60,61,62]
Fin whale	HIGH Small population, partial estimate 300–500 in BC waters[1,2], recovering from exploitation[66]	MED Present in BC waters in summer months[69]	HIGH Larger groups of around 20 individuals[2]	MED Critical habitat predicted in BC waters[67]	LOW Calving and breeding takes place outside BC waters[66]	HIGH Long-lived species with calving every 2–3 years and older age at sexual maturity[69]	LOW Large zooplankton, euphausiids, copepods, small fish, squid[66,68]	HIGH Prey vulnerable to abundance decrease[8,9,10,60,61]
Blue whale	MED Entire North Pacific stock estimated between 2000–3000 of which it is estimated significantly less than 250 use BC waters[70,71]	LOW Sighted very sporadically in BC waters[65,66]	LOW Whales sighted alone in BC waters[56]	MED Critical habitat predicted in BC waters[67]	LOW Calving and breeding takes place outside BC waters[66]	HIGH Long-lived species with calving every 2–3 years and reach sexual maturity between 5–15 years[72]	HIGH Specialized diet of euphasiids[55]	HIGH Prey vulnerable to abundance decrease[9,60,61]
North Pacific right whale	HIGH Extremely small population estimated at 30 individuals[73]	LOW Historically present in BC waters in summer[74]	LOW Largely unknown in BC waters[75]	MED BC may contain historically important feeding ground[76], conditions for prey aggregation found in BC waters[77]	LOW Unknown[78]	HIGH Long-lived species with calving every 4 years[79]	HIGH Specialized diet of copepods and euphausiids[78,80]	HIGH Prey vulnerable to abundance decrease[9,60,61]
Sperm whale	LOW Large North Pacific population estimated at 26,300[81]	LOW Historically sighted in BC waters during summer months[65]	LOW Sighted either singly or in pairs[56]	MED Critical habitat predicted in BC waters[67]	MED Mating and calving historically took place in BC[65]	HIGH Long-lived species with calving every 4–6 years and reach late age at sexual maturity[82,83]	LOW Diverse diet, wide range of prey including squid and fish[68,84]	HIGH Prey vulnerable to abundance decrease[9,10]

Table 5 continued

Species	Population	Distribution	Group size	Habitat	Reproduction	Life history	Diversity of diet	Prey susceptibility to decline
Harbour seal	LOW Large population >100,000[85,86]	HIGH Present in near shore BC waters year round[86]	MED Usually alone or in small groups in water and in medium to large groups when hauled out[86]	MED Strong site fidelity to many haul out sites in BC[86]	HIGH Pupping and breeding take place in BC waters[86]	MED Sexual maturity between 3–6 years and calve annually[87]	MED Semi-diverse diet of small and large fish[86]	HIGH Prey vulnerable to abundance decrease[9]
Northern fur seal	MED Large population (650,000) in drastic decline[88]	MED Migrate through offshore BC waters between Jan and June[89]	HIGH Large age class segregated groups[90]	MED Offshore BC waters important habitat for migrating and overwintering females and sub adults[90]	LOW Pupping and breeding take place outside BC waters[88]	MED Sexual maturity between 4–6 years and calve annually[91]	LOW Opportunistic feeder on small fish, squid, crustaceans[88]	HIGH Prey vulnerable to abundance decrease[8,9,10]
Steller sea lion	MED Population between 20,000–28,000 estimated in BC waters[92]	HIGH Present in BC waters year round[93,94]	HIGH Large group size (15–300) at sea and on land at rookeries and haul-out sites[2,95]	HIGH Strong site fidelity to four known breeding sites in BC[95,96]	HIGH Pupping and breeding takes place inside BC waters[95]	MED Slow reproductive rate, sexual maturity 3–6 years[95]	LOW Diverse diet of over 50 species of fish and invertebrates[94]	HIGH Prey vulnerable to abundance decrease[9]
California sea lion	LOW Population estimated at 153,000[97]	MED Present in BC waters fall, winter, spring[98]	HIGH Large groups concentrated at haul out sites[98]	MED Haul out sites in BC waters[98]	LOW Breeding and calving outside BC waters[98]	MED Sexual maturity at 4–5 years[99], calve yearly[100]	LOW Diverse diet of small schooling fish and cephalopods[101]	HIGH Prey vulnerable to abundance decrease[8,9,10]
Northern elephant seal	LOW Population estimated at 175,000[102]	LOW Present sporadically in BC waters[103]	LOW Sighted alone in BC waters[2]	MED Forage constantly during migration through BC waters[104]	LOW Breeding and calving outside BC waters[103]	LOW Sexual maturity at 2–6 years, calve annually[105]	MED Deepwater fish, sharks, cephalopods[106]	HIGH Prey vulnerable to abundance decrease[7,8,9]

Table 5 continued

Species	Population	Distribution	Group size	Habitat	Reproduction	Life history	Diversity of diet	Prey susceptibility to decline
Sea otter	MED	HIGH	HIGH	HIGH	HIGH	LOW	HIGH	LOW
	Population increasing, BC estimate 4700[107,108]	Present year round in BC coastal areas[109]	Large, sexually segregated groups on shore and rafts in water[107]	Strong site fidelity to breeding sites on BC coast[107]	Breeding and calving inside BC waters[107]	Sexual maturity at 2–6 years, calve annually[110]	Specialize in benthic invertebrates[109,111]	Prey not susceptible to decrease in abundance[34]

[1] Williams and Thomas (2007), [2] Best et al. (2015), [3] Chivers et al. (2002), [4] COSEWIC (2003a), [5] Raum-Suryan and Harvey (1998), [6] Baird and Guenther (1995), [7] Walker et al. (1998), [8] Incardona et al. (2012), [9] Peterson (2001), [10] McCay et al. (2004), [11] Jefferson (1990), [12] Jefferson (1987), [13] Jefferson (1989), [14] Stacey and Baird (1991), [15] Heise (1997a), [16] Heise (1997b), [17] Morton (2000), [18] COSEWIC (2008), [19] (Fisheries 2014b), [20] Nichol and Shackleton (1996), [21] Ford et al. (2000), [22] Williams and Lusseau (2006), [23] Barrett-Lennard and Ellis (2001), [24] Fisheries (2011a), [25] Olesiuk et al. (1990), [26] Barrett-Lennard (2000), [27] Ford et al. (1998), [28] Hauser et al. (2007), [29] Hanson et al. (2010), [30] Fisheries (2007), [31] Baird and Dill (1996), [32] Ford et al. (2013), [33] Ford et al. (2005), [34] Peterson et al. (2003), [35] Heise et al. (2003), [36] Jones (2006), [37] Krahn et al. (2007), [38] Ford et al. (2011), [39] Muhling et al. (2012), [40] Gaskill (2010), [41] Walker (2011), [42] COSEWIC (2006), [43] Dorsey et al. (1990), [44] Dorsey (1981), [45] Ohsumi and Masaki (1975), [46] Barlow et al. (2011), [47] Calambokidis et al. (2001), [48] Ford et al. (2009), [49] Nichol et al. (2009b), [50] Fisheries (2013), [51] Fisheries (2010a), [52] Punt and Wade (2012), [53] Frasier et al. (2011), [54] Rugh et al. (2005), [55] Calambokidis et al. (2002), [56] Ford et al. (2010), [57] Wursig (1990), [58] Jones (1990), [59] Dunham and Duffus (2001), [60] Neff (1990), [61] Suchanek (1993), [62] Nikitik and Robinson (2003), [63] Forney (2007), [64] Barlow (2010), [65] Gregr et al. (2000), [66] Gregr et al. (2006), [67] Gregr and Trites (2001), [68] Flinn et al. (2002), [69] COSEWIC (2005), [70] Calambokidis et al. (2009), [71] COSEWIC (2012), [72] Sears and Calambokidis (2002), [73] Wade et al. (2011), [74] Clapham et al. (2004), [75] Fisheries (2011b), [76] Brownell et al. (2001), [77] Gregr and Coyle (2009), [78] NMFS (2006), [79] Knowlton et al. (1994), [80] Nichol et al. (2002), [81] Barlow and Taylor (2005), [82] Best et al. (1984), [83] Kasuya (1991), [84] Miller et al. (2004), [85] Olesiuk (1999), [86] DFO (2010), [87] Baird (2001), [88] COSEWIC (2010), [89] Baird and Hanson (1997), [90] Bigg (1990), [91] DFO (2012), [92] DFO (2008), [93] Merrick and Loughlin (1997), [94] COSEWIC (2003b), [95]Fisheries (2010b), [96]Raum-Suryan et al. (2002), [97] NOAA (2011), [98] Bigg (1985), [99] Mate (1978), [100] Hernandez-Camacho et al. (2008), [101] Lowry et al. (1991), [102] Weber et al. (2000), [103] Stewart and DeLong (1995), [104] Brillinger and Stewart (1998), [105] Reiter and LeBeouf (1991), [106] Condit and LeBoeuf (1984), [107] Fisheries (2014a), [108] Nichol et al. (2009a), [109] COSEWIC (2007), [110] Jameson and Johnson (1993), [111] Estes et al. (2003)

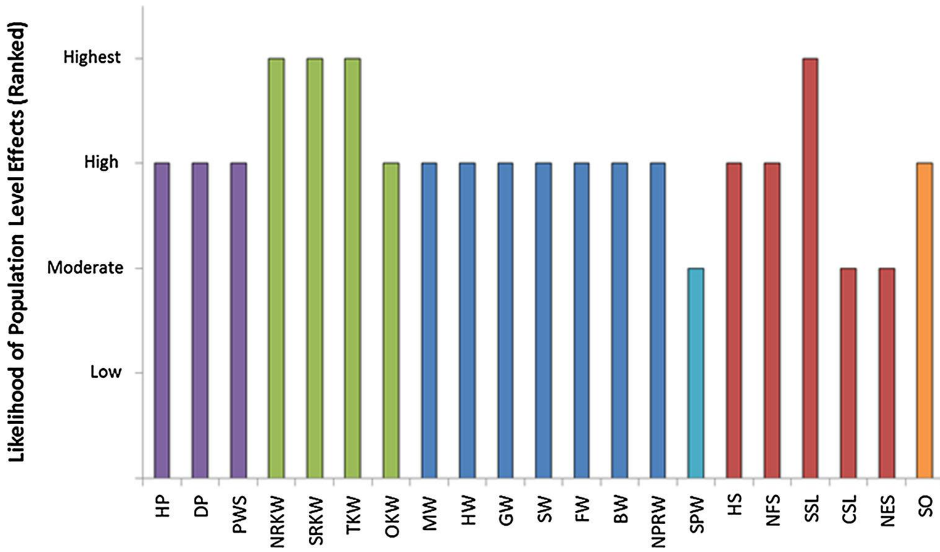

Fig. 2 Likelihood of population-level effects is depicted here in the event of an oil spill for marine mammals in BC ranked. Four categories are scored as low, moderate, high, and highest using equal intervals from the minimum possible cumulative score to the maximum possible cumulative score as follows: (min/max score (8/24), with bins for low (8–11), moderate (12–15), high (16–20) and highest (21–24). *Purple*: dolphins, porpoises: *HP* harbour porpoise, *DP* Dall's porpoise, *PWS* Pacific white-sided dolphin; *green*: killer whales: *NRKW* Northern Resident killer whale, *SRKW* Southern Resident killer whale, *TKW* transient killer whale, *OKW* offshore killer whale; *blue*: baleen whales: *MW* minke whale, *HW* humpback whale, *GW* grey whale, *SW* sei whale, *FW* fin whale, *BW* blue whale, *NPRW* North Pacific right whale; *light blue*: *SPW* sperm whale; *red*: pinnipeds: *HS* harbour seal, *NFS* Northern fur seal, *SSL* Steller sea lion, *CSL* California sea lion, *NES* Northern elephant seal; *orange*: *SO* sea otter

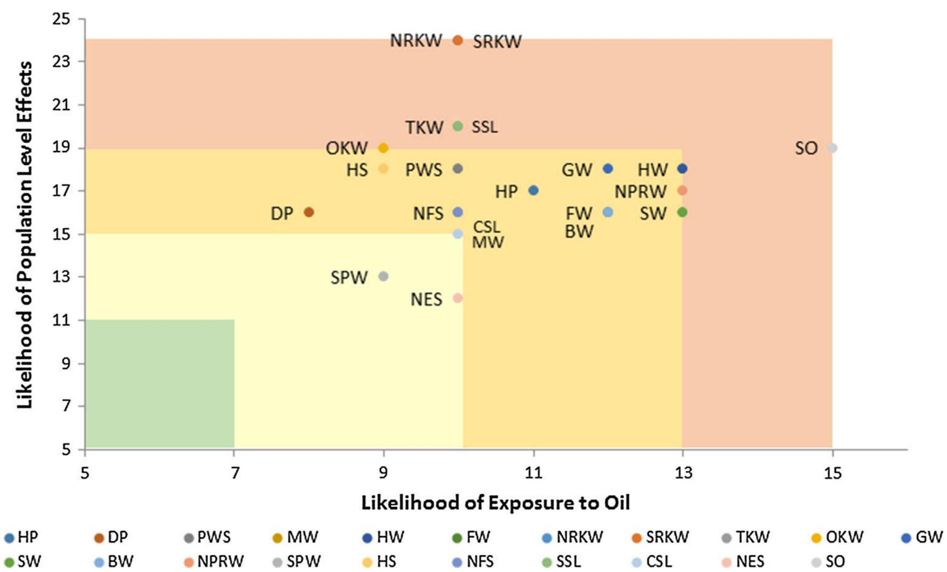

Fig. 3 Overall risk of marine mammal species to oil spills in British Columbia waters is depicted using species cumulative rankings for likelihood of individual exposure to oil (*x*-axis) and likelihood of population-level effects (*y*-axis) from an oil spill. This figure is broken into four categories. The *green shaded area* represents the lowest combined risk, followed by *yellow* (moderate), then *amber* (high), and then *red* is highest. *HP* harbour porpoise, *DP* Dall's porpoise, *PWS* Pacific white-sided dolphin, *NRKW* Northern Resident killer whale, *SRKW* Southern Resident killer whale, *TKW* transient killer whale, *OKW* offshore killer whale, *MW* minke whale, *HW* humpback whale, *GW* grey whale, *SW* sei whale, *FW* fin whale, *BW* blue whale, *NPRW* North Pacific right whale, *SPW* sperm whale, *HS* harbour seal, *NFS* Northern fur seal, *SSL* Steller sea lion, *CSL* California sea lion, *NES* Northern elephant seal, *SO* sea otter

Table 6 The overlap between a 15,000 m^3 modelled oil spill that originated near Turn Point in Northern Haro Strait (BC and WA) and legally designated Critical Habitat in Canada and the United States for the transboundary Southern Resident killer whales. See *Methods* for details

Probability of oil presence (source: EBA 2013)	Overlap between modelled spill and SRKW critical habitat (km^2)	Percent of SRKW critical habitat affected (%)
0.1	7107	80
0.10	6652	75
0.20	5985	67
0.40	4831	54
0.60	3785	43
0.80	2687	30
0.90	2205	25
0.95	1962	22

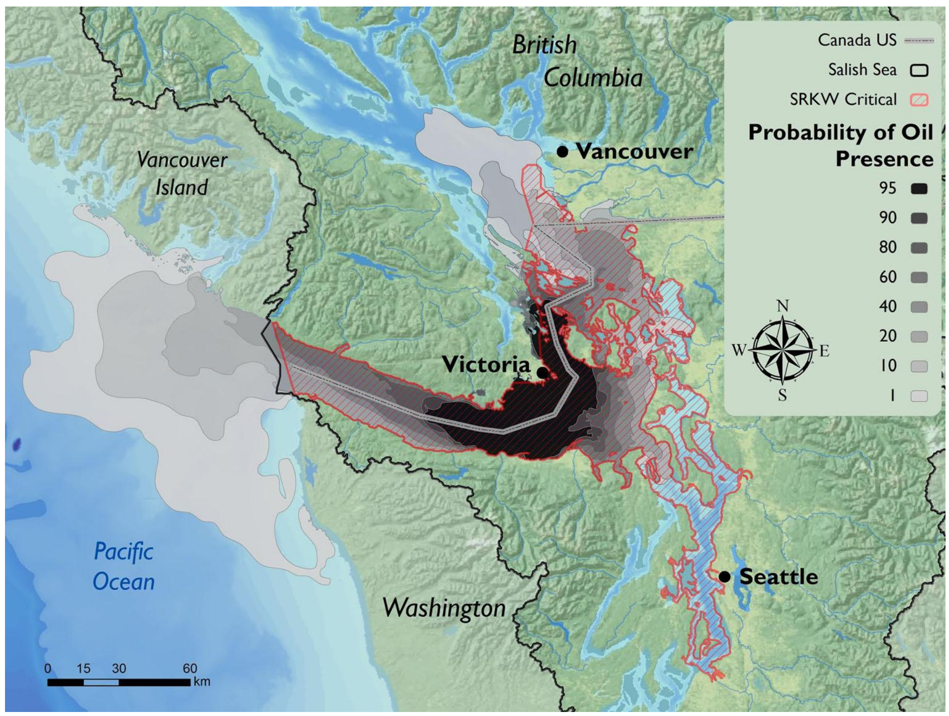

Fig. 4 *Black to grey shading* indicates the probability of oil presence 15 days following a 15,000 m^3 fall release of diluted bitumen at Arachne Reef in northern Haro Strait, BC. The modelled probabilities of oil presence (EBA 2013) are overlaid with the Critical Habitat of Southern Resident killer whales in Canada and the United States

oil spills (Table 6; Figs. 2, 3). A recently modelled, hypothetical episodic oil spill in southern BC (EBA 2013) illustrates the magnitude of risk when combined with the likelihood of adverse effects from exposure as predicted in our framework (Fig. 4). The modeled probability for oil presence (EBA 2013), combined with our calculation for the potential overlap of this spill within critical habitat, shows that between 22 and 80% of designated Southern Resident killer whale *Critical Habitat* would be affected by a spill at this location. This illustrates a real-world example where high-risk identification could inform decisions regarding the approval or rejection of new development.

The application of our framework should allow natural resource managers to assess more effectively and potentially mitigate the impacts to identified high-risk species/populations. Modeling of biological effects of oil spills is generally required in major project applications in Canada. Current methodology in these applications utilizes "indicator" species to represent groups of animals (TERA 2013; Stantec 2010), a standard method for simplifying biological risk assessments. Marine mammals often are examined as a group when assessing oil spill risk, but our findings indicate variable outcomes based on the different biological and ecological vulnerabilities of species. Previous oil spill models have ranked sea otters as high risk, while putting cetaceans, as a group, in a lower-risk category (French-McCay 2004). Our results suggest that certain cetaceans and certain populations of cetaceans (such as the Northern Resident, Southern Resident, and Bigg's killer whales) are highly vulnerable to oil spills. Our framework may help to guide the choice of indicator species in such assessments and may be used to inform on the relative strengths and weaknesses of the indicator species used in a given study area.

Uncertainty around the effects of oil on different marine mammals, or to their prey, hampers a full understanding of oil spill risks. Additional research on individual species characteristics and real-time distribution would help to increase the resolution of this framework to detect relative vulnerabilities at the species and population levels. In summary, this framework should be informative to conservationists and natural resource managers, and with area-specific data, could be scalable and transferable to other regions.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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