APPLICATION OF A FRAMEWORK TO ASSESS VULNERABILITY OF BIOLOGICAL COMPONENTS TO THREE OIL CATEGORIES (DIESEL AND GASOLINE, BUNKER C, AND DILUTED BITUMEN) IN THE MARINE ENVIRONMENT IN THE PACIFIC REGION

Figure 1. Bligh Island Spill - Canadian Coast Guard

Context:

Under Canada's World Class Tanker Safety System Initiative (WCTSS) a national framework was developed to identify marine biological organisms most vulnerable to a ship-source oil spill (Thornborough et al. 2017). The Pacific regional application of this framework (Hannah et al. 2017) and the 2022 update of the Pacific Application (DFO 2023) identified 27 biological groups highly vulnerable to all oil types, with sea grasses, salt marsh grasses/succulents, Sea Otters, and baleen whales being most vulnerable. The previous assessment in the Pacific Region considered all oil types together (Hannah et al. 2017), however, some species are expected to respond differently to different types of oil. It was recommended to further define impacts by assessing vulnerability for individual oil types separately (DFO 2017). This work will refine assessments for species based on different oil types to inform oil spill response relative to each oil type for the initial period of an oil spill when the oil is still fresh and floating. Ongoing funding under Oceans Protection Plan was approved in 2022 to carry out this work.

Under the Fisheries and Oceans Canada (DFO) spill response program initiative, there is a need in the Pacific Region to build on the vulnerability to oil framework to better understand impacts of different products on vulnerable species. At present, the vulnerability framework is the best tool available for Government of Canada Environmental Incident Coordinators (EICs) to prioritize which species or species assemblages are most vulnerable to oil. EICs use the framework as the foundation to prioritize 'resources at risk', and these are then assessed with archaeological, cultural, and socio-economic priorities to recommend areas for protection measures (booms, noise deterrents for marine mammals, etc.).

Fisheries and Oceans Canada Fish and Fish Habitat Protection Program (FFHPP), Ecosystem Management Branch, requested that Science Branch assess which groups of species are most vulnerable to three types of oil (gasoline and diesel, Bunker C, and diluted bitumen) and whether vulnerability may change when considering the fate and behaviour of the three oil types over time and under different environmental conditions. The assessment focused on the acute effects of direct contact with oils. Advice was provided in three separate working papers, which contributed to the advice provided in this document. The assessment and advice arising from this Canadian Science Advisory Secretariat (CSAS) Regional Peer Review (RPR) will be used to inform emergency oil spill responses in the Pacific Region as well as recovery efforts and other marine spatial planning initiatives.

SUMMARY

- Under Canada's World Class Tanker Safety System Initiative (WCTSS) a national framework was developed to identify marine biological organisms most vulnerable to ship-source oil (Thornborough et al. 2017) in the event of an oil spill. The Pacific regional application of this framework (Hannah et al. 2017) and the 2022 update for all oil types (DFO 2023) considered all oil types together and identified 27 highly vulnerable biological groups., However, it was recommended to further define impacts by assessing vulnerability for individual oil types or categories separately for the initial period of an oil spill when the oil is still fresh and floating. Ongoing funding under Oceans Protection Plan was approved in 2022 to carry out this work.
- Criterion definitions and scoring guidance from the Pacific Application of the vulnerability framework (all oil types) (Hannah et al. 2017) were reviewed to determine where adaptations were necessary to capture the vulnerability of Pacific marine species to three different types of oil: diesel and gasoline[1]; Bunker C[2]; and diluted bitumen[2] above. Changes in the definition and guidance for scoring were required for two criteria ('seafloor or vegetation interacting' and 'close association with unconsolidated substrate' were changed to add 'in intertidal areas') to capture that oil floats when fresh.
- This application is only relevant to the spill phase when each oil type is fresh and floating as identified by the Automated Data Inquiry for Oil Spills (ADIOS) model output. Consequently subtidal groups will likely have lower vulnerability.
- Oil fate and behaviour modelling informed timelines and exposure considerations for when the scoring results for individual oil types would be most applicable during the initial period of an oil spill response when the oil is fresh and floating. This period can vary from hours to days depending on oil type and environmental conditions.
- Scoring for individual oil types lowered the total vulnerability score of several subgroups when compared to the scores for all oil types, particularly for diesel and gasoline, which had fifteen fewer subgroups in the high vulnerability category. For both Bunker C and diluted bitumen there were seven fewer subgroups in the high vulnerability category compared to scores for all oil types (DFO 2023). The distribution of vulnerability scores across subgroups was similar to those for all oil types. There was no difference in

[1] St. Germain, C., Herborg, L-M., Punt, M., Jeffery, S., Hannah, L., and Finney, J. In prep. Application of a Framework to Assess Vulnerability of Biological Components to Ship-source Diesel and Gasoline Spills in the Marine Environment in the Pacific Region. Can. Sci. Adv. Res. Doc.

[2] St. Germain, C., Herborg, L-M., Punt, M., Jeffery, S., Hannah, L., and Finney, J. In prep. Application of a Framework to Assess Vulnerability of Biological Components to Ship-source Bunker C and Diluted Bitumen Spills in the Marine Environment in the Pacific Region. Can. Sci. Adv. Res. Doc.
*Bunker C and Diluted Bitumen working papers were combined for publication.

vulnerability scores between Bunker C and diluted bitumen for each subgroup, but for diesel and gasoline several vulnerability scores for the same subgroups were lower. The lower vulnerability scores for diesel and gasoline are due to the mechanical impairment criterion, as light oils are not expected to smother or clog feeding structures, like the heavier and more viscous Bunker C and diluted bitumen.

- Oil weathering models were run using the National Oceanic and Atmospheric Administration's (NOAA) ADIOS tool, to determine weathering timelines for four different weather scenarios. ADIOS model predictions indicated that the majority of weathering is due to evaporation for diesel and gasoline, and both evaporation and dispersion for Bunker C and diluted bitumen. For diluted bitumen there is an initial period of rapid weathering where the diluent is lost through evaporation and then a slower weathering period where dispersion is the main mode of weathering.
- Scoring the chemical sensitivity criterion was challenging using the existing scoring guidance. Consequently, all subgroups were scored a precautionary 1 (indicated as 1*) for this criterion unless sufficient evidence was found to give them a score of 1. Currently, there is not clear guidance for deriving a score of 0.
- Oils vary greatly, even within a specific oil type, and many factors impact how an oil behaves in the environment. Also, individual species within a subgroup can vary in terms of their life history, behaviour, and vulnerability to oil. As such, oil fate and behaviour information and predictions from modelling, as well as expected oil impacts and vulnerability, may not apply to all situations. This framework is one tool used by Fisheries and Oceans' Environmental Incident Coordinators (EICs) in a response scenario. Combining these results with information from other response partners (such as ecological, archaeological, cultural, and socio-economic priorities) provides a strong response strategy.
- Based on ADIOS modelling predictions, the list of highly vulnerable subgroups determined for each oil type is most applicable within the first six to eighteen hours after a diesel spill, the first hour after a gasoline spill, the first two to five days after a Bunker C spill, and the first two to twelve hours after a diluted bitumen spill. When environmental conditions are such that significant weathering is likely, or if a sufficient amount of time has passed, the oil will behave differently, and the list of highly vulnerable subgroups resulting from the 2022 update for all oil types (DFO 2023) would be most applicable.
- For the next revision of the framework, the inclusion of how and whether to include chemical sensitivity should be re-evaluated. If the chemical sensitivity criterion is included, we recommend developing clearer guidance and methods to score chemical sensitivity so that clear sensitivity endpoints are established for each possible score, a consistent evaluation rubric is used to filter studies based on their utility to inform chemical sensitivity, and the weighting of sensitivity is more balanced with life history traits (exposure and recovery criteria) in the framework method.
- Limitations of this application include the binary scoring method and that current scoring guidance does not capture the breadth of effects (e.g., acute, indirect, and cumulative effects) to appropriately delineate differences in vulnerability between oil types. Though limited to considering marine components within DFO's jurisdiction, the method could be applicable for other jurisdictions (e.g., marine birds). Species are not assessed based on their socio-economic status (fishery and conservation status) or cultural value, as this information is provided by other response partners, in particular Indigenous communities. The application assumes floating oil does not reach subtidal areas, however, under rough

conditions wave action may cause oil droplets, oil particulate aggregates, or dissolved oil components to remain in the water column in subtidal areas.

- Limitations of the modelling outputs include: input variables (e.g., salinity, temperature, wind) may not be representative of all areas in the region or of all seasons (e.g,. freshwater input and stratification); and the assumption of a single point-source release means results may not apply in all release situations (e.g., continuous release).

INTRODUCTION

Under Canada's World Class Tanker Safety System Initiative (WCTSS) a national framework was developed to identify marine biological organisms most vulnerable to ship-source oil (Thornborough et al. 2017) in the event of an oil spill. That same year, the framework was applied to the species groups found in the Pacific Region (Hannah et al. 2017) and identified 27 highly vulnerable biological groups, with sea grasses, salt marsh grasses/succulents, Sea Otters, and baleen whales being most vulnerable. The 2017 Pacific Regional Application considered all oil types as one category. In 2022, this Application was updated to incorporate new information related to the vulnerability of species groups to oil in a Science Response (DFO 2023). The history of these publications, as well as the present one, are outlined in Figure 2.

At present, the vulnerability framework is the best tool available for Government of Canada Environmental Incident Coordinators (EICs) to prioritize which species or species assemblages are most vulnerable to oil. EICs use the framework as the foundation to prioritize 'resources at risk' for ecological concerns. These are then assessed along with archaeological, cultural, and socio-economic priorities to recommend areas for protection measures (booms, noise deterrents for marine mammals, etc.). The Pacific Application and 2022 Update considered all oil types at once, and were based on the presumption that together these oils would both float and sink. However, some species are expected to have differing degrees of vulnerability to different types of oil. Consequently, in the Science Advisory Report that accompanied the Pacific Application it was recommended that vulnerability for specific oil types be assessed at a later date.

Given DFO's commitment to ensuring sustainable aquatic ecosystems and the recommendations in the Science Advisory Report in 2017 (DFO 2017) that accompanies Hannah et al. 2017, there is a need to expand on the Pacific application to better understand the vulnerability of species to the different oil products that are commonly transported on our coast; namely to diesel and gasoline, Bunker C, and diluted bitumen. To this end, criteria definitions and scoring guidance from the Pacific Application of the vulnerability framework were reviewed to determine where adaptations were needed for an application to assess the vulnerability of Pacific marine species to these oil types. In this paper we reassess all subgroups for the three oil types and present the results. Oil fate and behaviour modelling was also conducted to inform how the oil types would behave when they were fresh versus weathered. Scoring of the subgroups was based on fresh oil characteristics and is not considered valid once the oil has weathered. The modeling was also used to determine during what timelines and exposure considerations the oils would remain fresh, and the scoring results for individual oil types remain applicable.

The limitations of this framework are outlined in Thornborough et al. (2017) and Hannah et al. (2017).

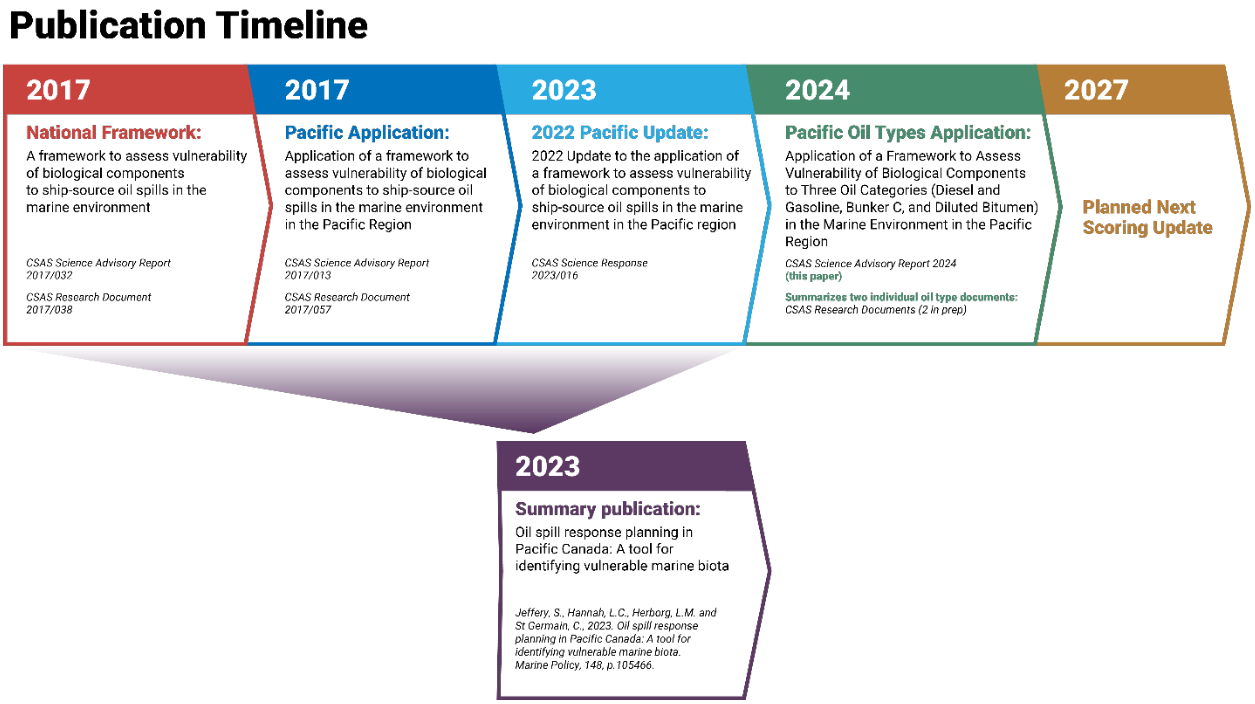

Figure 2. A history of oil vulnerability publications in the Pacific region.

Properties of the oil types assessed

Behaviour on water

When oil is released into the marine environment it undergoes a series of transformations during weathering, such as dispersion, dissolution, biodegradation and emulsification. While the fuel types considered here all have a density less than that of water (1000 kg/m^3) and will therefore float on sea water, the heavier types (Bunker C and diluted bitumen) have a potential of sinking as weathering progresses. Also, there is a potential in high energy environments and conditions, where waves can drive lower density floating oils below the surface, increasing the likelihood of oil exposure in subtidal areas. Another mechanism to make heavier oils negatively buoyant is when particulate matter adheres to oil droplets in the water, forming oil-particulate aggregates, which can sink further into the water column (Niu et al. 2010). In a near shore environment the adhesion of sand can cause heavier oil to sink. Since these conditions likely only occur later in a spill and under specific conditions we considered all oils as floating. In case of sinking oil being a concern, the updated vulnerability framework application of all oils should be used for guidance (DFO 2023).

Oil adhesion, retention and penetration

Generally, the higher the viscosity of an oil the more likely it will adhere to solid materials (e.g., shoreline material, response equipment, coastal infrastructure, plants, animals) and the less likely it will penetrate unconsolidated shoreline material (e.g., sand and cobble) (US EPA 2003). Diesel and Gasoline oils have low adhesion properties primarily due to their low viscosity and, therefore, these oils will not accumulate to a significant thickness on shoreline material (Etkin et al. 2007). As a result, it is expected that diesel and gasoline will readily penetrate most porous shoreline materials. Bunker C and diluted bitumen oils have high adhesion properties, primarily due to their high viscosity and, therefore, these oils can coat shoreline materials and be difficult to remove due to their holding capacity. This is particularly true once the oils weather. Sand beach and marsh areas would be particularly affected. Penetration would be highest for boulder or pebble/cobble beaches or banks and man-made permeable structures, with moderate to very high retention.

Oil toxicity

Polycyclic aromatic hydrocarbons (PAHs) are the compounds of greatest concern with regard to the aquatic toxicity of crude and refined petroleum products. In the case of diesel and gasoline, their PAH composition consists entirely of low molecular weight compounds, which are usually the most water soluble and bioavailable (Neff et al. 2005; Patel et al. 2020). The PAH content of diluted bitumen consists of both low and high molecular weight compounds, although it generally has a lower proportion of low molecular weight PAH compared to conventional crude oils. The PAH content of Bunker C also consists of both low and high molecular weight compounds, and it tends to have a greater PAH content than diluted bitumen.

Weathering scenarios

We developed scenarios for the expected fate and behaviour of diesel and gasoline, Bunker C, and diluted bitumen in four different environmental conditions (involving summer versus winter water temperatures and calm versus rough water and wind conditions). These results informed the oil type application process in two ways:

1. Determining what behaviour could be expected from each oil type when fresh so that criteria and scoring could be adapted appropriately; and
2. Determining the length of time each oil would retain its original characteristics before becoming weathered as this informs the period of time that the results from this application are valid; after the oils are weathered responders should revert to using results from the updated vulnerability framework application of all oils (DFO 2023).

ASSESSMENT

Methods

Method development

In the Pacific vulnerability framework (Hannah et al. 2017) marine organisms with similar characteristics and life histories were organized into subgroups that would be similarly vulnerable to all oil types. There were five major taxonomic groupings: Marine Plants and Algae, Marine Invertebrates, Marine Fishes, Marine Reptiles, and Marine Mammals, within which subgroups were further broken down by life history traits, habitat, and taxonomy. Each subgroup was then scored for three categories of vulnerability criteria: exposure, sensitivity, and recovery, each broken down into further specific criteria. To assess vulnerability, every subgroup received a score of either 0 (does not fulfill the specific criterion) or 1 (fulfills the specific criterion) for each of the criteria for a total of 10. Subgroups were then ranked based on their total vulnerability score into categories of high (7–10), medium (4–6) and low vulnerability (0–3). For more detail see Hannah et al. (2017) and Figure 3.

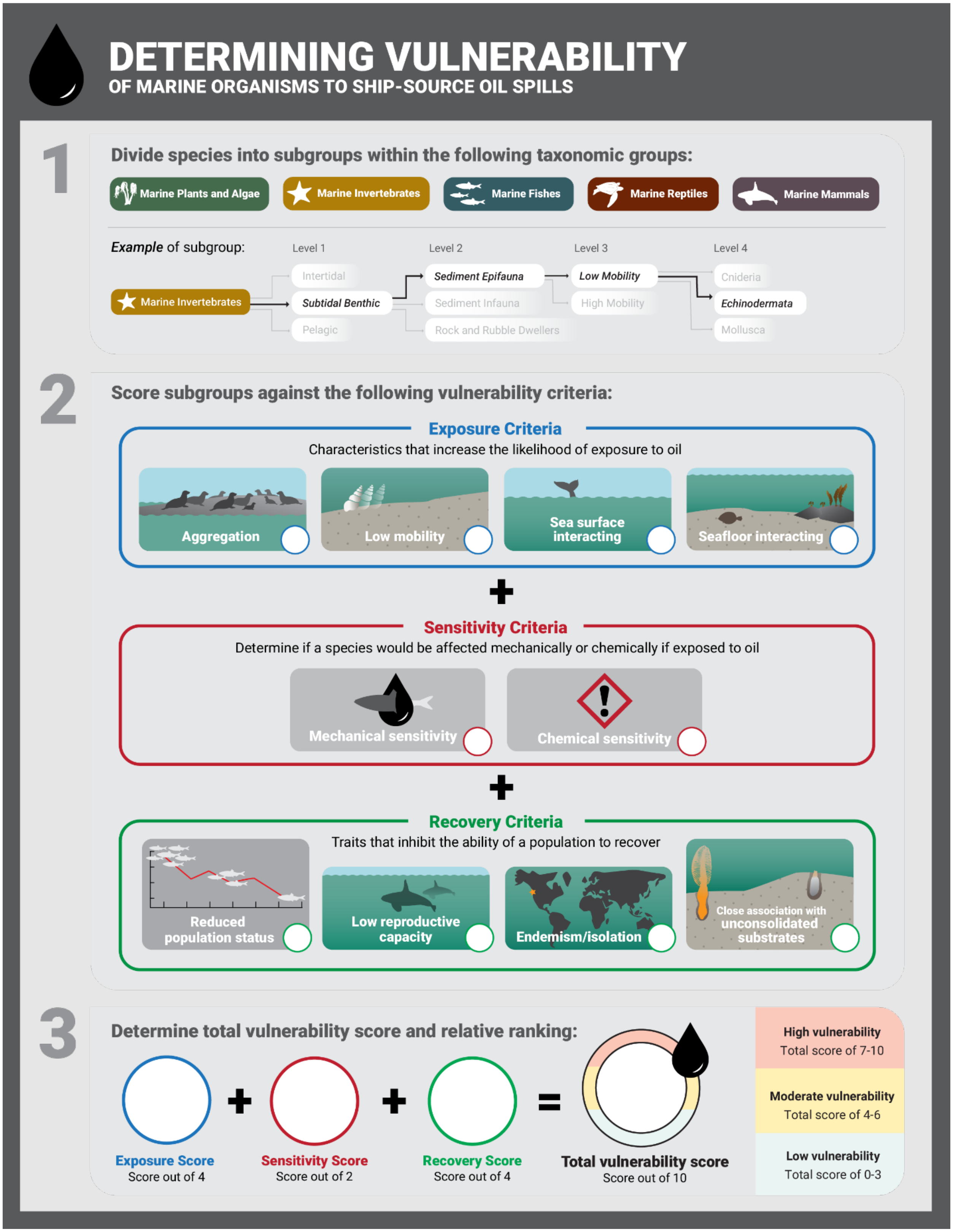

Figure 3. Overview of framework to identify vulnerable biological components (Jeffery et al. 2023).

As part of the review and update of Hannah et al. (2017) the last five years of literature was incorporated to update the Pacific vulnerability framework for all oil types (DFO 2023). A comparison of the scores for all oil types versus the scores for the three oil types assessed here is in Figures 4–8.

The subgroups for the work presented here and in 2022 (DFO 2023) were updated so that marine mammals were scored at the species/distinct ecotype level. The reason was the high concern associated with impacts to marine mammals during spills in addition to the relatively few (25) distinct ecotypes and species present the Pacific Region.

Vulnerability criteria

Two of the ten criteria used in Hannah et al. (2017) required adaptation to capture the tendency for diesel and gasoline, Bunker C, and diluted bitumen to float when fresh (Table 1). These two criteria are:

- Seafloor or Vegetation Interacting
    - Updated criterion name to include “in intertidal areas” making it “Seafloor or Vegetation Interacting in intertidal areas”. The oil types considered here float when fresh, thus only seafloor and vegetation in the intertidal would be fouled.
- Close association with unconsolidated substrates
    - Updated criterion name to include “in intertidal areas” making it “Close association with unconsolidated substrates in intertidal areas”. The oil types considered here float when fresh, thus only substrates in the intertidal would be fouled.

Scores were updated to reflect these changes. In addition, a literature review was undertaken for the two sensitivity criteria to look for information on the specific effects of diesel and gasoline, Bunker C, and diluted bitumen pertaining to:

- Reduction of feeding/photosynthesis or Loss of insulation; and
- Impairment due to toxicity

The other six criteria relate to organism life history and behaviour, so did not require updating for the differing oil types (Table 1).

Table 1. Criteria definitions and description changes from Hannah et al. 2017.

Pacific Framework Application criterion	Changes and guidance for Pacific diesel and gasoline, Bunker C, and diluted bitumen applications
Seafloor or Vegetation Interacting: Does the subgroup contain species that interact regularly with the seafloor and/or marine plants and algae? Direct exposure due to presence of oil on the seabed and/or vegetation. Contaminated seabed substrates can expose associated individuals in a population for as long as the oil persists. Persistent oil has the opportunity to impact a greater proportion of the population through direct contact over time.	Update criterion name to include “in intertidal areas”: Seafloor or Vegetation Interacting in intertidal areas. Adjust scores to reflect this change. These oil types float when fresh, thus only seafloor and vegetation in the intertidal would be fouled.
Reduction of feeding/photosynthesis or Loss of insulation: Does direct contact with oil result in the mechanical impairment of structures that can impact energetics of species in the subgroup? Fouling of feeding structures by oil may reduce the ability of organisms to feed, reducing body condition and reproductive capacity, and increasing time spent feeding (Reich et al. 2014). Smothering can reduce photosynthesis, and oil causes a substantial decrease in the insulative value of fur, inhibiting the ability of affected organisms to thermoregulate (Reich et al. 2014).	Review scores: include information for specific oil type and timelines for fouling where available.
Impairment due to toxicity: Does direct contact with oil result in severe, irreversible effects or death for species in the subgroup? Organisms that are more sensitive to toxic effects of oil are more likely to experience irreversible effects or death.	Review scores: include information for specific oil type and timelines for toxicity where available.
Close association with unconsolidated substrates: Does the subgroup contain species that are closely associated with unconsolidated substrates? Significant amounts of spilled oil deposited in benthic substrates can persist sub-surface (5–18 cm deep) for over 20 years after a spill, and retain its original toxicity (Exxon Valdez Oil Spill Trustee Council 2009). This persistent oil will expose associated organisms for decades after a spill, and hinder their recovery (Gunster et al. 1993; Kennish 1996). Highest oil concentrations are found in fine-grained substrates (D’Ozouville et al. 1979).	Update criterion name to include intertidal areas only: Close association with unconsolidated substrates in intertidal areas; adjust scores to reflect this change: these oil types float when fresh, thus only substrates in intertidal would be fouled.

Long-term impacts studies

Efforts were made to score based on immediate impacts of direct contact with oil. However, there were several studies of oil spill impacts and recovery several months or years after the initial spill which were included in the justifications sections of the scoring tables for additional information.

Fate and behaviour scenarios

Scenario descriptions

The weathering of the different fuel types (diesel and gasoline, Bunker C, and diluted bitumen) in four environmental conditions was modelled using the National Oceanic and Atmospheric Administration’s (NOAA’s) Automated Data Inquiry for Oil Spills (ADIOS) oil weathering model (NOAA, no date). The model uses the spill and climatic conditions to predict changes in the oil’s density, viscosity, and the rate of weathering over time.

The scenarios and the environmental conditions used in the ADIOS model are outlined in Table 2. The volume of oil released for the scenarios was chosen as 25 m^3 as this is in the midrange of the volumes of recent west coast oil spills (Punt 2020). For the ADIOS model, it was assumed that this volume of oil was released instantaneously.

The specific oil types selected from the ADIOS database for the scenarios were:

- Diesel Fuel Oil (Canada), ADIOS Oil ID: AD02082, API: 39.4°
- Gasoline (Shell unleaded), ADIOS Oil ID: AD02153, API: 57.2°
- Bunker C Fuel Oil, Adios Oil ID: AD02051, API: 12.3°
- Diluted Bitumen Cold Lake Blend, Adios Oil ID: AD02070, API: 22.6°

Table 2. Oil spill environmental condition scenarios.

Scenario	Air Temperature	Water Temperature	Wave Height	Wind Speed
Scenario 1: 25 m^3 oil spilled at noon on August 3rd	Summer 19°C	Warm water 15°C (32 ppt salinity)	Calm 0.1 m	Little wind 8.5 km/hr (5 knots)
Scenario 2: 25 m^3 oil spilled at noon on August 3rd	Summer 19°C	Warm water 15°C (32 ppt salinity)	Rough 3.0 m	Windy 46 km/hr (25 knots)
Scenario 3: 25 m^3 oil spilled at noon on February 3rd	Winter 3°C	Cold water 8°C (32 ppt salinity)	Calm 0.1 m	Little wind 8.5 km/hr (5 knots)
Scenario 4: 25 m^3 oil spilled at noon on February 3rd	Winter 3°C	Cold water 8°C (32 ppt salinity)	Rough 3.0 m	Windy/exposed 46 km/hr (25 knots)

Results and Discussion

Total vulnerability scores

Total vulnerability scores for subgroups scored for specific oil types were either unchanged, or one to three points (out of 10) lower compared to those in the 2022 update for all oil types (DFO 2023) (Figures 4–8). In many cases, scores were lower as a result of the adaptations made to the two criteria capturing the fact that the oil types assessed here float in the early stages of a spill. Many subgroups received lower scores for specific oil types because they contain species that only occur in subtidal areas. Thus, in this application they did not score for the seafloor or vegetation interaction criterion, or close association with unconsolidated substrates criterion as their subtidal location makes them less vulnerable to floating oils, which mostly contaminate the seafloor, vegetation, and unconsolidated substrates in intertidal areas.

For both the Bunker C and diluted bitumen applications, 38% of subgroups had lower total vulnerability scores (45 of 118) compared to the 2022 update for all oil types date (DFO 2023). For the diesel and gasoline application, the majority of subgroups (87 out of 118, 74%) had lower total vulnerability scores than for the 2022 update for all oil types (DFO 2023). The greater number of subgroups with lower total vulnerability scores in the diesel and gasoline application is due to differences in how the mechanical sensitivity criterion was scored for this oil type. Feeding or respiratory structures, and fur for insulation, are likely to become fouled by more viscous oils such as Bunker C and diluted bitumen, but this is not the case for the less viscous diesel and gasoline oil types, which would not be expected to foul feeding and respiratory structures or fur.

Total vulnerability scores for the 118 subgroups ranged from 1–9 out of a maximum possible score of 10 (ten criteria with a maximum score of 1 for each). For diesel and gasoline, the most vulnerable subgroup (scoring 9 out of 10) was Sea Otters (Mustelids). For Bunker C and diluted bitumen applications, seven subgroups scored 9 out of 10: three Marine Plants and Algae subgroups (seagrasses, salt marsh grasses and salt marsh succulents); two Marine Invertebrate subgroups (low mobility intertidal epifaunal echinoderms and infaunal worms); and two Marine Mammal subgroups (Mustelids and Discrete Baleen Whales). All of these subgroups also scored the highest for vulnerability in the 2022 update for all oil types (DFO 2023).

Four subgroups received the lowest vulnerability score of 1 out of 10 for all three oil types. All four subgroups were Marine Fishes. Despite the lower total vulnerability scores in these subgroups, they remained in the same vulnerability category (low) as in the 2022 update for all oil types (DFO 2023).

Scoring for the three oil type applications resulted in fifteen fewer subgroups in the high vulnerability category for diesel and gasoline, and seven fewer for Bunker C and diluted bitumen, as compared to the 2022 update for all oil types (DFO 2023) (Table 3). These scoring differences have direct implications for oil spill response, as the high vulnerability category is used together with species of conservation concern, culturally important species and areas, and other socio-economic priorities to inform EICs of the resources at risk during an oil spill emergency. For the subgroups that are operationally different under the three oil type applications (classified as medium rather than high), responders may wish to use the scores from the 2022 update for all oil types (DFO 2023), and consider these groups as highly vulnerable if a high degree of weathering is expected.

While Bunker C and diluted bitumen scored the same for all subgroups, there were sixty-two scoring differences between these two oil types and diesel and gasoline (Figures 4–8). Again, these differences were because diesel and gasoline are not expected cause mechanical impairment, such as clogging of feeding or respiratory structures, or fouling of fur, while Bunker C and diluted bitumen are. There may be more differences between the three oil types for other subgroups, but the methodology is currently limited in its ability to detect them. For example, for the mechanical and chemical sensitivity criteria, many or all subgroups received precautionary1* due to a lack of oil type-specific information in the literature. Because of this, the mechanical sensitivity criterion did not distinguish differences between oil types well, and the chemical sensitivity criterion did not distinguish at all. However, despite the minimal, or lack of, differentiation, the oil type-specific information collected for the scoring process remains as useful reference information for EICs. It would be helpful for future updates of the vulnerability framework to develop clearer guidance and methods to score sensitivity so that clear sensitivity endpoints are established for each possible score, a consistent evaluation rubric is used to filter studies based on their utility to inform chemical sensitivity, and the weighting of sensitivity is more balanced with exposure and recovery in the framework method.

VULNERABILITY OF MARINE ORGANISMS TO OIL SPILLS IN THE CANADIAN PACIFIC

MARINE PLANTS & ALGAE

High vulnerability (scores of 7-10)
Moderate vulnerability (scores of 4-6)
Low vulnerability (scores of 0-3)
* indicatesa low likelihood of exposure

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Intertidal	Vascular plants	Moderate to low energy unconsolidated habitat	Seagrasses	e.g. *Zostera marina*; e.g. *Zostera japonica*	8	9	9	9
			Salt marsh grasses	e.g. Lyngbye's Sedge; e.g. Dune Grass				
			Salt marsh succulents	e.g. Sea Asparagus; e.g. Sea Milkwort				
		High energy, rocky habitat	Seagrasses	e.g. *Phyllospadix scouleri, P. torreyi, P. serrulatus*	7	8	8	8
	Understory/turf algae	High energy, rocky habitat		e.g. Sea Palm Kelp	6	7	7	7
		Moderate to low energy, rocky habitat		e.g. *Fucus gardneri, Desmarestia* sp., *Laminaria saccharina*	5	6	6	6
	Encrusting algae	Rocky habitat		e.g. *Codium setchellii*, coralline algae	4	5	5	5
	Canopy algae			e.g. Feather Boa Kelp	4	5	5	5

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*Figure 4a. Comparison of total vulnerability scores across the three oil types (diesel and gasoline, Bunker C, diluted bitumen) and with the 2022 update for all oil types (DFO 2023) (All oil types column). Subgroups classified as Highly vulnerable (scores of 7–9) are coloured pink, Moderately vulnerable subgroups (scores of 4–6) are coloured orange, and Low vulnerability subgroups (scores of 0–3) are coloured green. Subgroups having an exposure category score of 1 or less, indicating a low likelihood of exposure, are identified with a *. Species subgroups are read as rows across the figure from left to right, and are comprised of 4 hierarchical levels (e.g., Intertidal | Vascular plants | High energy, rocky habitat | Seagrasses). Contiguous rows sharing the same hierarchical level are merged.*

MARINE PLANTS AND ALGAE *continued from previous page*

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Subtidal	Canopy algae	Moderate to low energy, rocky habitat		e.g. Giant Kelp	6	7	7	7
	Canopy algae	High energy, rocky habitat		e.g. Bull Kelp, Feather Boa Kelp	5	6	6	6
	Understory algae	Rocky habitat	With tall, woody stipes, or floats	e.g. *Pterygophera californica, Sargassum muticum*	5	6	6	6
	Understory algae	Rocky habitat	Without tall, woody stipes, or floats	e.g. *Desmarestia* sp, *Agarum fimbriatum*, *Laminaria* sp.	2 *	3 *	3 *	4
	Turf algae	Rocky habitat		e.g. *Callophyllis* sp., *Dictyota binghamiae*	2 *	3 *	3 *	4
	Encrusting algae			e.g. coralline algal crusts, *Hildenbrandia* sp.				
Pelagic				Phytoplankton	4	4	4	4

Figure 4b. A continuation of Figure 4a, marine plants and algae, showing subtidal and pelagic zones.

VULNERABILITY OF MARINE ORGANISMS TO OIL SPILLS IN THE CANADIAN PACIFIC

MARINE INVERTEBRATES

High vulnerability (scores of 7-10)
Moderate vulnerability (scores of 4-6)
Low vulnerability (scores of 0-3)
★ indicates a low likelihood of exposure

Subgroups					Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4	Pacific species examples	Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Intertidal	Sediment epifauna	Low mobility	Echinodermata	e.g. Bat Star	7	8	8	8
			Mollusca	e.g. Whelks	7	8	8	8
			Cnidaria	e.g. Stubby Rose Anemone				
		High mobility	Arthropoda	e.g. Dungeness Crab	5	5	5	5
	Sediment infauna	Low mobility	Worms	e.g. burrowing polychaete worms	8	9	9	9
			Arthropoda	e.g. Ghost Shrimp	7	8	8	8
			Mollusca	e.g. Littleneck Clams, Razor Clam; e.g. Olive Snails	6	7	7	7
			Lophophorata	e.g. Horseshoe Worms				
	Rock and rubble dwellers	Sessile (attached to hard substrate)	Porifera	e.g. encrusting sponges	7	8	8	8
			Mollusca	e.g. Pacific Oyster; e.g. California Mussel	6	7	7	7
			Cnidaria	e.g. Red Soft Coral	5	6	6	6
			Arthropoda	e.g. Acorn Barnacle				
			Worms	e.g. tube worms				
			Urochordata	e.g. Horseshoe Tunicate				
			Lophophorata	e.g. encrusting bryozoans				

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*Figure 5a. Comparison of total vulnerability scores across the three oil types (diesel and gasoline, Bunker C, diluted bitumen) and with the 2022 update for all oil types (DFO 2023) (All oil types column). Subgroups classified as Highly vulnerable (scores of 7–9) are coloured pink, Moderately vulnerable subgroups (scores of 4–6) are coloured orange, and Low vulnerability subgroups (scores of 0–3) are coloured green. Subgroups having an exposure category score of 1 or less, indicating a low likelihood of exposure, are identified with a *. Species subgroups are read as rows across the figure from left to right, and are comprised of 4 hierarchical levels (e.g., Intertidal | Vascular plants | High energy, rocky habitat | Seagrasses). Contiguous rows sharing the same hierarchical level are merged.*

MARINE INVERTEBRATES *continued from previous page*

Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4	Pacific species examples	Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Intertidal	Rock and rubble dwellers	Low mobility	Echinodermata	e.g. Purple Urchin; e.g. Orange Sea Cucumber; e.g. Purple Ochre Star	6	7	7	7
			Arthropoda	e.g. Rockweed Isopod	5	5	5	6
			Cnidaria	e.g. Green Surf Anemone				
			Worms	e.g. peanut worms, ribbon worms	5	5	5	5
			Mollusca	e.g. Gumboot Chiton, Turban Snail				
		High mobility	Mollusca	e.g. Giant Pacific Octopus	4	5	5	5
			Arthropoda (filter feeders)	e.g. Porcelain Crabs	5			
			Arthropoda (other)	e.g. Red Rock Crab	4	4	4	4
Subtidal benthic	Sediment epifauna	Low mobility	Echinodermata	e.g. Sand Star	4	5	5	7
			Cnidaria	e.g. Orange Sea Pen	4	5	5	7
			Mollusca	e.g. Whelks	3	4	4	6
		High mobility	Arthropoda	e.g. Dungeness Crab	2 *	2 *	2 *	4
	Sediment infauna	Low mobility	Mollusca	e.g. Butter Clam	4	5	5	7
			Worms	e.g. burrowing polychaete worms	3	4	4	6
			Lophophorata	e.g. horseshoe worms; lampshells				
	Rock and rubble dwellers	Sessile (attached to hard substrate)	Porifera	e.g. glass sponges (boot sponge, cloud sponge)	5	6	6	7
			Cnidaria	e.g. cup coral, bubblegum coral				
			Arthropoda	e.g. Giant Barnacle	4	5	5	6
			Urochordata	e.g. Sea Peach Tunicate				
			Mollusca	e.g. Rock Scallop	3	4	4	5
			Worms	e.g. feather duster worms				
			Lophophorata	e.g.bryozoans, lampshells				

Vulnerability Score (0-10)

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Figure 5b. A continuation of Figure 5a, marine invertebrates, showing intertidal and subtidal benthic zones.

MARINE INVERTEBRATES *continued from previous page*

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Subtidal benthic	Rock and rubble dwellers	Low mobility	Echinodermata	e.g. Red Sea Urchin; e.g. Sunflower Star	5	6	6	7
			Worms	e.g. scale worms	3	4	4	5
			Cnidaria	e.g. fish-eating anemone				
			Mollusca	e.g. Hairy Triton Snail	4	4	4	5
		High mobility	Mollusca	e.g. Giant Pacific Octopus	3 *	3 *	3 *	4
			Arthropoda	e.g. Red Rock Crab	2 *	2 *	2 *	3
Pelagic	Larvae		Echinodermata		5	6	6	6
			Mollusca					
			Cnidaria		4	5	5	5
			Worms					
			Arthropoda					
			Lophophorata					
			Porifera		4	4	4	4
			Chordata					
	Low mobility		Zooplankton (other than larvae)		4	5	5	5
			Cnidaria	e.g. Moon Jellyfish, Fried Egg Jellyfish				
	High mobility		Mollusca	e.g. Opalescent Squid	3	3	3	3

Figure 5c. A continuation of Figure 5b, marine invertebrates, showing subtidal benthic and pelagic zones.

VULNERABILITY OF MARINE ORGANISMS TO OIL SPILLS IN THE CANADIAN PACIFIC

MARINE FISHES

High vulnerability (scores of 7-10)
Moderate vulnerability (scores of 4-6)
Low vulnerability (scores of 0-3)
* indicates a low likelihood of exposure

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Estuarine	Transient		Salmonids	e.g. juvenile and adult salmon, Steelhead	6	7	7	8
			Sturgeon	e.g. Green Sturgeon, White Sturgeon	5	5	5	7
			Smelts	e.g. Eulachon	5	5	5	5
			Sticklebacks	e.g. Threespine Stickleback	3	3	3	4
			Lampreys	e.g. river & Pacific Lamprey	2 *	2 *	2 *	3
			Sculpins	e.g. Prickly Sculpin	1 *	1 *	1 *	3 *
			Flatfishes	e.g. Starry Flounder				
			Cod	e.g. Pacific Tomcod, Walleye Pollock (juveniles)	1 *	1 *	1 *	1 *
	Resident		Surfperches	e.g. Shiner Perch	4	4	4	5
			Sculpins	e.g. Staghorn Sculpin	1 *	1 *	1 *	3 *
			Salmonids	e.g. Cutthroat Trout, Dolly Varden	2 *	2 *	2 *	3
Intertidal	Benthic	Associated with unconsolidated substrates (Silt, Sand, Gravel) (including eelgrass environments)	Salmonids (juvenile)	e.g. Pink, Chum, Coho, Chinook Salmon	7	8	8	8
			Herring	e.g. Pacific Herring	6	7	7	7
			Smelts and sand lance	e.g. Pacific Sand Lance, Surf Smelt	6	6	6	6
			Other species (e.g. sculpins, gobies)	e.g. Staghorn Sculpin, Plainfin Midshipmen	5	5	5	5

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*Figure 6a. Comparison of total vulnerability scores across the three oil types (diesel and gasoline, Bunker C, diluted bitumen) and with the 2022 update for all oil types (DFO 2023) (All oil types column). Subgroups classified as Highly vulnerable (scores of 7–9) are coloured pink, Moderately vulnerable subgroups (scores of 4–6) are coloured orange, and Low vulnerability subgroups (scores of 0–3) are coloured green. Subgroups having an exposure category score of 1 or less, indicating a low likelihood of exposure, are identified with a *. Species subgroups are read as rows across the figure from left to right, and are comprised of 4 hierarchical levels (e.g., Intertidal | Vascular plants | High energy, rocky habitat | Seagrasses). Contiguous rows sharing the same hierarchical level are merged.*

MARINE FISHES *continued from previous page*

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Intertidal	Benthic	Associated with unconsolidated substrates (Silt, Sand, Gravel) (including eelgrass environments)	Pipefish	e.g. Bay Pipefish	4	4	4	4
			Greenlings	e.g. Lingcod - juvenile	4 *	4 *	4 *	4 *
			Flatfishes (juvenile)	e.g. English Sole, Starry Flounder	3 *	3 *	3 *	3 *
		Associated with consolidated substrates (cobble, boulder, bedrock)	Snailfishes	e.g. Tidepool Snailfish	4	4	4	4
			Clingfishes	e.g. Northern Clingfish				
			Blennies	e.g. Penpoint Gunnel, Crescent Gunnel, High Cockscomb				
	Non-benthic (pelagic and demersal)		Rockfishes (juvenile)	e.g. Black Rockfish, Copper Rockfish	4 *	4 *	4 *	4 *
			Surfperches	e.g. Shiner Perch, Striped Perch, Pile Perch	4	4	4	4
Subtidal	Benthic	Associated with unconsolidated substrates (Silt, Sand, Gravel)	Elasmobranchs	e.g. Big Skate	4 *	4 *	4 *	6
			Rockfishes	e.g. Dark-blotched Rockfish, Canary Rockfish	3 *	3 *	3 *	5 *
			Hagfishes	e.g. Pacific Hagfish	3 *	3 *	3 *	5
			Flatfishes	e.g. English Sole, Starry Flounder, Pacific Halibut	2 *	2 *	2 *	4
		Associated with consolidated substrates (cobble, boulder, bedrock)	Rockfishes	e.g. Quillback, Yelloweye, Tiger & China Rockfishes	4 *	4 *	4 *	5
			Wolf fish	e.g. Wolf-eel	3 *	3 *	3 *	4
			Greenlings & Sculpins	e.g. Lingcod (adult), Cabezon				
	Non-benthic (pelagic, midwater, demersal)		Rockfishes	e.g. Yellowtail, Blue, Widow Rockfishes, Bocaccio	5	5	5	5
			Elasmobranchs (other)	e.g. Spiny Dogfish, Sixgill Shark				
			Elasmobranchs (filter feeders)	e.g. Basking Shark	4 *	5 *	5 *	5 *
			Ratfish	e.g. Spotted Ratfish	3 *	3 *	3 *	5
			Sand lance	e.g. Pacific Sand Lance	2 *	2 *	2 *	4
			Anchovy	e.g. Northern Anchovy	3	4	4	
			Ocean sunfishes	e.g. Ocean Sunfish	3 *	3 *	3 *	3 *
			Other species	e.g. Sablefish, salmon, surfperch, herring				
			Cod	e.g. Pacific Cod, Hake, Pacific Tomcod	2 *	2 *	2 *	3
			Mackerels & Tunas	e.g. Pacific Chub Mackerel	2 *	2 *	2 *	2 *

Figure 6b. A continuation of Figure 6a, marine fishes, showing intertidal and subtidal zones.

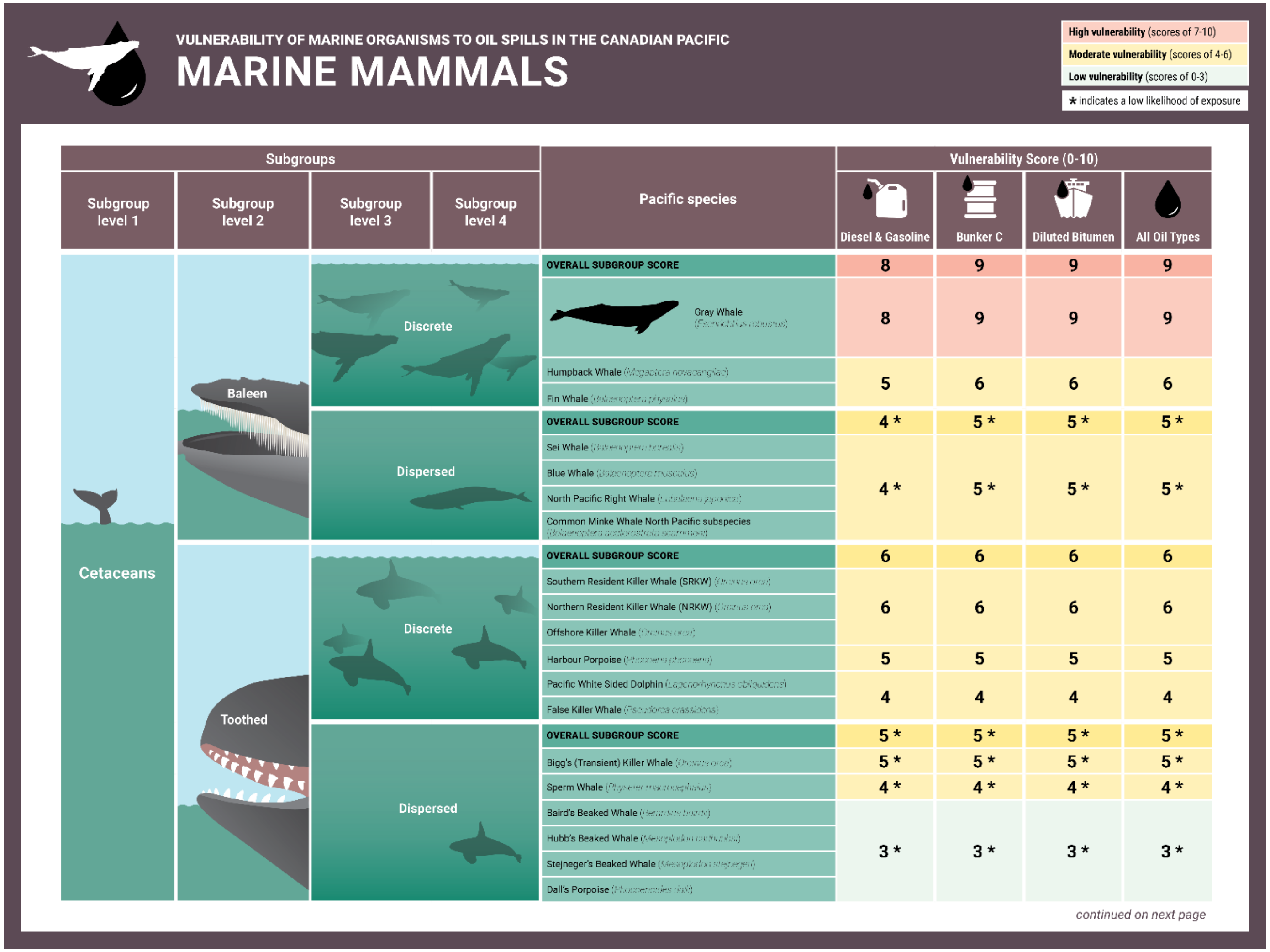
VULNERABILITY OF MARINE ORGANISMS TO OIL SPILLS IN THE CANADIAN PACIFIC

MARINE REPTILES

High vulnerability (scores of 7-10)
Moderate vulnerability (scores of 4-6)
Low vulnerability (scores of 0-3)
* indicates a low likelihood of exposure

Subgroups				Pacific species examples	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Sea Turtles				e.g. Leatherback Sea Turtle; Green Sea Turtle, Olive Ridley	4 *	4 *	4 *	4 *

*Figure 7. Comparison of total vulnerability scores across the three oil types (diesel and gasoline, Bunker C, diluted bitumen) and with the 2022 update for all oil types (DFO 2023) (All oil types column). Subgroups classified as Highly vulnerable (scores of 7–9) are coloured pink, Moderately vulnerable subgroups (scores of 4–6) are coloured orange, and Low vulnerability subgroups (scores of 0–3) are coloured green. Subgroups having an exposure category score of 1 or less, indicating a low likelihood of exposure, are identified with a *. Species subgroups are read as rows across the figure from left to right, and are comprised of 4 hierarchical levels (e.g., Intertidal | Vascular plants | High energy, rocky habitat | Seagrasses). Contiguous rows sharing the same hierarchical level are merged.*



Subgroups				Pacific species	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Cetaceans	Baleen	Discrete		OVERALL SUBGROUP SCORE	8	9	9	9
				Gray Whale (*Eschrichtius robustus*)	8	9	9	9
				Humpback Whale (*Megaptera novaeangliae*)	5	6	6	6
				Fin Whale (*Balaenoptera physalus*)				
		Dispersed		OVERALL SUBGROUP SCORE	4 *	5 *	5 *	5 *
				Sei Whale (*Balaenoptera borealis*)	4 *	5 *	5 *	5 *
				Blue Whale (*Balaenoptera musculus*)				
				North Pacific Right Whale (*Eubalaena japonica*)				
				Common Minke Whale North Pacific subspecies (*Balaenoptera acutorostrata scammoni*)				
	Toothed	Discrete		OVERALL SUBGROUP SCORE	6	6	6	6
				Southern Resident Killer Whale (SRKW) (*Orcinus orca*)	6	6	6	6
				Northern Resident Killer Whale (NRKW) (*Orcinus orca*)				
				Offshore Killer Whale (*Orcinus orca*)				
				Harbour Porpoise (*Phocoena phocoena*)	5	5	5	5
				Pacific White Sided Dolphin (*Lagenorhynchus obliquidens*)	4	4	4	4
				False Killer Whale (*Pseudorca crassidens*)				
		Dispersed		OVERALL SUBGROUP SCORE	5 *	5 *	5 *	5 *
				Bigg's (Transient) Killer Whale (*Orcinus orca*)	5 *	5 *	5 *	5 *
				Sperm Whale (*Physeter macrocephalus*)	4 *	4 *	4 *	4 *
				Baird's Beaked Whale (*Berardius bairdii*)	3 *	3 *	3 *	3 *
				Hubb's Beaked Whale (*Mesoplodon carlhubbsi*)				
				Stejneger's Beaked Whale (*Mesoplodon stejnegeri*)				
				Dall's Porpoise (*Phocoenoides dalli*)				

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*Figure 8a. Comparison of total vulnerability scores across the three oil types (diesel and gasoline, Bunker C, diluted bitumen) and with the 2022 update for all oil types (DFO 2023) (All oil types column). Subgroups classified as Highly vulnerable (scores of 7–9) are coloured pink, Moderately vulnerable subgroups (scores of 4–6) are coloured orange, and Low vulnerability subgroups (scores of 0–3) are coloured green. Subgroups having an exposure category score of 1 or less, indicating a low likelihood of exposure, are identified with a *. Species subgroups are read as rows across the figure from left to right, and are comprised of 4 hierarchical levels (e.g., Intertidal | Vascular plants | High energy, rocky habitat | Seagrasses). Contiguous rows sharing the same hierarchical level are merged.*

MARINE MAMMALS *continued from previous page*

Subgroups				Pacific species	Vulnerability Score (0-10)			
Subgroup level 1	Subgroup level 2	Subgroup level 3	Subgroup level 4		Diesel & Gasoline	Bunker C	Diluted Bitumen	All Oil Types
Pinnipeds	Thermoregulate with fur			Northern Fur Seal (*Callorhinus ursinus*)	5 *	5 *	5 *	5 *
	Other pinnipeds	Discrete		**OVERALL SUBGROUP SCORE**	4	5	5	5
				Steller Sea Lion (*Eumetopias jubatus*)	4	5	5	5
				Pacific Harbour Seal (*Phoca vitulina richardsi*)				
				California Sea Lion (*Zalophus californianus*)				
		Dispersed		Northern Elephant Seal (*Mirounga angustirostris*)	4 *	5 *	5 *	5 *
Mustelids				Sea Otter (*Enhydra lutris*)	9	9	9	9

Figure 8b. A continuation of Figure 8a, marine mammals, showing pinnipeds and mustelids.

Scenario oil fate and behaviour

We included results from NOAA's (National Oceanic and Atmospheric Administration) ADIOS (Automated Data Inquiry for Oil Spills) oil weathering model so that we could discuss timelines around when the scoring results from this work are applicable. During scoring, we assumed that the oil a species may encounter would be relatively unweathered (i.e., before it evaporates, disperses, and dissolves). Therefore, the resulting scores are most applicable when the oil is freshest before significant weathering has changed its properties.

It should be noted that while the information used to predict the behaviours associated with each oil type and scenario was compiled from a variety of sources, in depth analysis of the literature and extensive verification of the information were not possible within the timelines for this project. As such, the oil fate and behaviour information, and expected oil impacts associated with the scenarios presented, should be considered as general "rules of thumb." Users of this information should be aware that oils vary greatly, even within a specific oil type, and many factors impact how an oil behaves in the environment. It is, therefore, difficult to be assured that the oil fate and behaviour information and expected oil impacts will apply to all situations within the scenario parameters presented, and on-water observations of oil fate and behaviour should guide decision making as soon as they become available during a spill.

Diesel and gasoline

The modelling under different conditions illustrated that a significant portion of diesel and gasoline evaporates within hours, a process sped up by warmer temperature and higher wave energy. Both products penetrate the sediment, with diesel somewhat also adhering to the sediment surface in a more weathered state. While evaporation reduces the oil exposure of many organisms, evaporation of lighter components can impact air breathing species like marine mammals (Harvey and Dalheim 1994).

Bunker C

The rate of weathering for Bunker C was fastest in rough warm water and slowest in calm cold water. As Bunker C weathers, losses due to evaporation and dissolution were found to increase the density and viscosity over time. Weathering was predicted to be fastest over the first two to five days, depending on environmental conditions. The floating stage would be shortest under rough, warm conditions. Given the high viscosity of Bunker C, particularly after weathering, fouling of insulating fur, feeding and respiratory structures are of particular concern with this oil type.

Diluted bitumen

Initial weathering of diluted bitumen occurs within a few hours as the light diluent evaporates. After that the weathering of the heavier fraction is very limited. In high energy conditions droplets can be pushed under water and potentially form oil-particulate aggregates in the water column in areas of high particulate concentration and become negatively buoyant. After initial weathering, diluted bitumen forms a viscous and sticky layer when stranded on the shoreline. The impacts on species that rely on fur for insulation, and species with intricate filter feeding and respiratory structures are of particular concern.

Considerations for oil spill preparedness planning and response

The National Framework (Thornborough et al. 2017) and its Pacific Application (Hannah et al. 2017) are a transparent, repeatable method for assessing the relative vulnerability of species subgroups based on the biology of the organisms under DFO's mandate. The updates presented here provide more granular information and incorporate additional references.

Scoring for the three oil type applications resulted in fifteen fewer subgroups in the high vulnerability category for diesel and gasoline, and seven fewer for Bunker C and diluted bitumen, as compared to the 2022 update for all oil types es (DFO 2023). The updated vulnerability scores presented here allow for a more nuanced and informed prioritization of sensitive species during an oil spill in BC waters. The scores guide DFO's input into the Environmental Unit where DFO priorities are combined with other ecological knowledge and archaeological, cultural, and socio-economic priorities from other partners to prioritize areas for protection and the most suitable clean up strategies.

As outlined in the previous section, the list of highly vulnerable subgroups presented here are most applicable in the early hours of a response, prior to significant weathering of the product taking place. Once significant weathering of the oil has taken place the updated vulnerability framework for all oil types (DFO 2023) would be the most suitable guidance.

It should be noted that there is a wealth of specific information for diesel and gasoline, Bunker C, and diluted bitumen in the justifications for the sensitivity criteria that may be useful to responders throughout the full cycle of the response and remediation of a spill, regardless of how much time has passed or the degree of weathering. A full description of the scoring justifications and supporting references can be found in the two CSAS Research documents applying a framework to assess vulnerability of biological components to three oil categories (diesel and gasoline[1], Bunker C[2], and diluted bitumen[2]).

This framework has particular benefit for species that have little to no information on vulnerabilities and, as such, are not on any conservation lists. This is the case for a large majority of the marine plants, invertebrates, and fish.

Limitations/Sources of Uncertainty

It is important to note that this tool is not designed as the sole method to prioritize areas for protection during an oil spill as it does not consider the cultural or socio-economic values of species or species groups. During a spill scenario, other branches of DFO, outside organizations, and First Nations provide this information, which are all combined for decision making within the Environmental Unit.

Another consideration is that while conservation status was considered under the Recovery Criteria, it did not override the rest of the scoring. For example, the endangered Southern Resident Killer Whales scored '6' or medium vulnerability. However, regardless of their total vulnerability score, Fisheries and Oceans Canada has a mandate to protect species of conservation concern and so would prioritize them for protection.

One criterion that was particularly challenging to score within the framework was the chemical sensitivity (impairment due to toxicity) criterion. Difficulties arose when scoring this criterion due to the breadth of literature, varying and often under-reported methodologies, and inconsistent, or absent, chemical characterization. Chemical sensitivity is highly nuanced, such that it cannot be easily captured in a binary scoring system. Consequently, all subgroups were scored a precautionary 1 (1*) for this criterion unless sufficient evidence was found to give them a score of 1; however, there was no guidance within the framework on how a subgroup could be scored as a 0. This is confounded by additional uncertainty that, for example, diluted bitumen composition is likely to vary seasonally and yearly, and once it (or any crude oil) enters the environment, its composition will rapidly begin to change through weathering processes.

For the next revision of the framework the inclusion of chemical sensitivity should be re-evaluated. At present the chemical sensitivity scoring does not provide a means to differentiate between subgroups as all species were scored as equally sensitive. There are tools available which rank species based on their acute sensitivity to hydrocarbons (e.g., the critical target lipid body burden, interspecies correlation estimates models, species sensitivity distributions), which could be applied where specific data are missing, and provide a means to differentiate sensitivity between subgroups. A suitable path forward may be to adapt a weight of evidence approach to the scoring. For example, this approach has been applied to hazard identification by the International Agency for Research on Cancer, where the amount and strength of evidence is evaluated and then the hazard is classified as Group 1 (Carcinogenic to humans), Group 2A (Probably carcinogenic to humans), Group 2B (Possibly carcinogenic to humans), or Group 3 (Not classifiable as to its carcinogenicity to humans). By providing a transparent means of evaluating the evidence for chemical sensitivity beyond a 0 or 1, this framework will have greater utility towards helping to inform spill response decisions by providing input into the Net Environmental Benefit Analysis (NEBA) or Spill Impact Mitigation Assessment (SIMA) process.

The framework is heavily biased towards the life history of the organism (8 of the 10 possible points are related to life history traits), and sensitivity to oil, or lack thereof, is underrepresented in the total score. While most of the vulnerability scoring results aligned with the literature, eelgrass is one example of a subgroup for which the total vulnerability score produced by the framework differs from the impacts typically seen after an oil spill. Eelgrass (intertidal>vascular plants>moderate to low energy unconsolidated habitat>seagrasses) scored as highly vulnerable for all three oil types (7/10 for diesel and gasoline and 8/10 for Bunker C and diluted bitumen). While there is some evidence of photosynthetic impairment (e.g., Runcie et al. 2004) there are several studies where there were no significant impacts (e.g., Fonseca at al. 2017), even after four weeks of experimental exposure (Banning 2010). For future updates, it would be beneficial to balance the weighting of sensitivity with life history traits (exposure and recovery criteria) in the framework method to better capture the influence of sensitivity, or lack thereof. It would also be beneficial to include additional fate and behaviour modelling scenarios to provide a better understanding of the variability both regionally and seasonally. For example, including different salinities would capture seasonal changes in freshwater input.

CONCLUSIONS AND ADVICE

The 2017 Pacific Vulnerability Framework (Hannah et al. 2017) was adapted and updated to consider vulnerability to three different types of oil: diesel and gasoline, Bunker C, and diluted bitumen, and restricted to the early phase of an oil release prior to weathering.

Oil fate and behaviour modelling was used to estimate the timing and conditions under which weathering would occur, and thus the extent of the early phase of a spill when the oil's chemical and physical properties have not changed and the oil is primarily floating. The results presented here are most applicable during this early phase of oil spill response. Once the oil has weathered and its properties have changed, the updated vulnerability scores for all oil types (DFO 2023) should be consulted to support decision making.

Overall the scoring of vulnerability for specific oil types provided more nuanced and lower scores for a number of species groups. In particular there were differences between the diesel/gasoline scores compared to Bunker C and diluted bitumen. These were largely due to their different mechanical behaviour. diesel/gasoline does not adhere to surfaces to the same degree causing less smothering, but does penetrate sediment. Bunker C and diluted bitumen is more viscous and sticks to surfaces and smothers species or clogs feeding structures. Also, since here we only considered fresh oil, no impacts from sunken oil were considered, leading to lower scores for subtidal groups.

ADIOS model predictions indicate that the rate of weathering is greatest for all products in rough warm water and is slowest in calm cold water. Losses due to evaporation and dissolution were found to increase the density and viscosity of all products over time. Gasoline weathers to the greatest extent (up to 100%) over the time period considered for this framework, while diesel weathers at a slower rate. Diluted bitumen rapidly weathers within the first 2 hrs of a spill, but then the rate of weathering decreases as the diluent component is lost. Weathering of Bunker C is the slowest of all products considered in this framework, with >90% of the product remaining in calm summer or winter conditions. For all oil types, the floating stage will be shortest under rough, warm conditions.

Based on ADIOS modelling predictions, the list of highly vulnerable subgroups determined for each oil type are most applicable within the first six to eighteen hours after a diesel spill, the first hour after a gasoline spill, the first two to five days after a Bunker C spill, and the first two to twelve hours after a diluted bitumen spill. When environmental conditions are such that significant weathering is likely, or if a sufficient amount of time has passed, the oil will behave differently, and the list of highly vulnerable subgroups resulting from the 2022 update for all oil types (DFO 2023) would be most applicable.

Vulnerability to the different oil types could be further distinguished if differences in chemical sensitivity could be better captured. Currently the chemical sensitivity criteria is not able to capture the breadth of effects (e.g., acute, indirect, and cumulative effects) to appropriately delineate differences in vulnerability between oil types. We recommend that for future updates/applications external experts provide an in-depth review on how to include chemical sensitivity in a practical and more meaningful.

Given the continuously growing body of literature that can inform vulnerability scoring, as well as changes in shipping practices (e.g., shift from Bunker C to low sulphur Bunker C), it is recommended to update the scoring every five years.

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SOURCES OF INFORMATION

This Science Advisory Report is from the December 12–15, 2022 regional peer review on the Application of a Framework to Assess Vulnerability of Biological Components to Diesel and Gasoline; Bunker C; and Diluted Bitumen in the Marine Environment in the Pacific Region. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Banning, J. 2010. The effects of diluted bitumen on marine intertidal vascular plants. Master's thesis: Simon Fraser University, British Columbia, Canada.

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