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Pilot ecosystem risk assessment to assess cumulative risk to species in the Pacific North Coast Integrated Management Area (PNCIMA)

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Foreword

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

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

The challenge of managing areas with diverse human activities and effectively evaluating environmental, social and economic trade-offs requires Ecosystem-based Oceans Management. A pilot ecological risk assessment for the Pacific North Coast Integrated Management Area (PNCIMA) was conducted to test the effectiveness of an ecological risk assessment framework developed by O et al. (2015). During the scoping phase, a subset of 17 significant ecological components (SECs) was chosen to represent major functional groups in PNCIMA based on their data availability. Marine, land-based and global activities currently occurring within the area and their associated stressors were identified using an interaction matrix with accompanying evidence tables because Pathways of Effects models were under development and therefore unavailable. A subset of stressors was evaluated (76 in total) for the identified activities. Risk was evaluated using four variables: Spatial scale, Temporal scale, Load, and Consequence. Scoring was based on literature review and an uncertainty score assigned for each variable taking into consideration data availability, quality and scientific consensus. Risk scores for each stressor-SEC combination were calculated using one of two methods:

1. Binned exposure using the methods as outlined by O et al. (2015); and
2. Uncertainty incorporation using Monte Carlo simulation to directly incorporate the uncertainty scores in the risk calculation.

Cumulative risk for each SEC was calculated by summing the risk scores for each SEC. Using the uncertainty incorporation method, the SECs with the highest cumulative risk were Dungeness Crab, Salmon, Sponges, and Seagrasses. The highest ranking stressors across all SECs were trawling-related and most of the highest ranked stressors for each SEC were trawl-related. The relative ranking of risk was similar between the two risk calculation methods but the Uncertainty Incorporation showed where uncertainty was highest between exposure and consequence, and could be used to prioritize research and focus management efforts. The Qualitative Level One ecological risk assessment was found to be an effective triage tool, providing a relative ranking of SECs and stressors. However, the current pilot project is not a complete risk assessment for PNCIMA because it is based on a subset of SECs and stressors affecting PNCIMA and the resulting scores have not been vetted by experts. Therefore the results should not be used for policy or management decisions at this stage.

Évaluation pilote des risques pour l'écosystème en vue d'évaluer les risques cumulatifs pour les espèces dans la zone de gestion intégrée de la côte nord du Pacifique

RÉSUMÉ

La difficulté de gérer des zones où plusieurs activités humaines se déroulent et d'évaluer efficacement les compensations environnementales, sociales et économiques nécessite une gestion écosystémique des océans. Une évaluation pilote du risque écotoxicologique a été réalisée dans la zone de gestion intégrée de la côte nord du Pacifique (ZGICNP) afin de tester l'efficacité d'un cadre d'évaluation du risque écologique élaboré par O *et al.* (2015). Pendant la phase d'établissement de la portée, un sous-ensemble de 17 aspects écologiques d'importance a été choisi pour représenter les principaux groupes fonctionnels de la ZGICNP, en fonction de la disponibilité des données. Les activités marines, terrestres et générales qui sont actuellement menées dans la zone et les agents de stress connexes ont été cernés à l'aide d'une matrice des interactions et de tableaux des éléments probants, car les modèles de séquences des effets étaient en cours d'élaboration et n'étaient pas disponibles. Un sous-ensemble d'agents de stress a été évalué (76 au total) pour les activités cernées. Le risque a été évalué à l'aide des quatre variables suivantes : échelle spatiale, échelle temporelle, charge et conséquence. Une note fondée sur l'analyse documentaire a été attribuée à chaque variable, de même qu'une note d'incertitude, et on a tenu compte de la disponibilité et de la qualité des données, et de l'obtention d'un consensus scientifique. Les notes de risque pour chaque combinaison d'agent de stress et d'aspect écologique d'importance ont été calculées à l'aide des deux méthodes ci-dessous :

1. Compartimentation de l'exposition à l'aide des méthodes décrites par O *et al.* (2015);
2. Incorporation de l'incertitude à l'aide de la méthode Monte Carlo pour intégrer directement les notes d'incertitude dans le calcul du risque.

On a calculé le risque cumulatif pour chaque aspect écologique d'importance en additionnant les notes de risque de chaque aspect. Selon la méthode d'incorporation de l'incertitude, les aspects écologiques d'importance qui présentent le risque cumulatif le plus élevé étaient le crabe dormeur, le saumon, les éponges et les graminées marines. Les agents de stress les plus importants parmi tous les aspects écologiques d'importance étaient liés à la pêche au chalut et la plupart de ces agents de stress pour chaque aspect étaient liés à la pêche au chalut. Le classement relatif des risques était semblable entre les deux méthodes de calcul du risque, mais la méthode d'incorporation de l'incertitude démontrait à quel endroit l'incertitude était la plus élevée entre l'exposition et la conséquence et pouvait être utilisée pour établir l'ordre de priorité des efforts de recherche et axés sur la gestion. L'évaluation qualitative des risques écologiques de niveau un s'est révélée un outil de triage efficace, car elle a permis d'établir le classement relatif des aspects écologiques d'importance et des agents de stress. Toutefois, le projet pilote n'est pas une évaluation complète du risque pour la ZGICNP, car il s'appuie sur un sous-ensemble d'aspects écologiques d'importance et d'agents de stress touchant la zone, et les notes qui en résultent n'ont pas été validées par des experts. Par conséquent, les résultats ne doivent pas être utilisés pour prendre des décisions stratégiques ou de gestion pour le moment.

1 INTRODUCTION

Ecosystem-based Oceans Management is needed to address the challenge of managing areas with diverse activities and effectively evaluate trade-offs for the simultaneous achievement of ecological, environmental and social objectives (Granek et al. 2010, Lester et al. 2010). As part of Canada's Oceans Strategy, Fisheries & Oceans Canada has committed to establishing ecosystem based management objectives for each of its Large Ocean Management Areas (LOMAs) (DFO 2002). To move toward this level of integrated management for the Pacific region, an ecological risk assessment framework (ERAF) was developed by O et al. (2015), based, in part, on risk assessments developed in other regions (Hobday et al. 2011; Samhouri and Levin 2012; Guerry et al. 2012). The goals of the ERAF were to

i. identify and prioritize anthropogenic risks to ecosystem components and
ii. to inform the development of conservation objectives and management strategies to mitigate identified risks.

A significant advance in this framework is the ability to include multiple activities and stressors in order to better understand the potential cumulative risk to individual ecosystem components and manage high-risk stressors.

The Pacific Region ERAF provides a comprehensive approach for assessing all threats to marine ecosystems by evaluating cumulative risk from multiple activities to multiple ecosystem-components for ecosystem-based management (EBM), improving upon international and national best practices in risk assessment that focus solely on single activities (e.g., ERAFs for assessing fisheries impacts) or single ecosystem-components (e.g., habitat-based risk-assessments). This project aims to apply this ERAF in the Pacific Region to the Pacific North Coast Integrated Management Area (PNCIMA) as a pilot project to assess the feasibility and suitability of the ERAF as a tool for determining risk of harm to ecosystem components, and its usefulness for providing transparent and defensible science-based advice on prioritising ecological risk of different activities for ecosystem-based management and MPA management.

The current pilot project tested the ERAF developed by O et al. (2015) using a small subset of SECs and stressors affecting PNCIMA. The resulting scores have not been vetted by experts and should not be used for policy or management decisions at this stage. We emphasize that the results should not be considered a complete risk assessment for PNCIMA.

1.1 PNCIMA

PNCIMA, located along the Pacific coast of British Columbia, is one of five LOMAs in Canada. PNCIMA was defined in 2004 and is bounded at Bute Inlet on the mainland, Campbell River on the east side of Vancouver Island, Brooks Peninsula on the west side of Vancouver Island and extends north to the Alaskan border. The western border is the base of the continental shelf slope.

PNCIMA is host to a wealth of resources important for ecological, economic and cultural reasons, many of which are unique to the region; for example the Glass Sponge reefs, globally significant seabird populations, Salmon, Eulachon, and Killer Whales. In addition, a number of at risk species listed by COSEWIC reside or spend time within PNCIMA, including Humpback Whale, Steller Sea Lion, and Northern Abalone.

A broad range of human activities occur in this region, as reviewed in MacConnachie et al. (2007). Sea-based activities include fishing, aquaculture, tourism, utility and transportation.

Coastal activities also influence the marine and estuarine resources in this region, including human settlement, ports and marinas, and log storage and handling. Land-based activities occurring in the watersheds are connected to coastal marine systems through freshwater runoff and include forestry, agriculture, mining and pulp and paper mills. PNCIMA is also subject to impacts from long-range and global stressors such as climate change, pollutants, and debris.

Here, we apply the ecological risk assessment framework (ERAF) developed by O et al. (2015; Figure 1) to evaluate risk from cumulative impacts from a subset of activities and stressors to a subset of ecologically important species and habitats. This pilot project aims to test the scoping and Level 1 phases of the risk framework (Figure 1) in order to assist in the planning process of PNCIMA. In addition, a practical application of the ERAF will serve to highlight the framework's potential benefits and challenges in order to improve its future application within PNCIMA, and possibly other LOMAs and Marine Protected Areas (MPAs) across Canada.

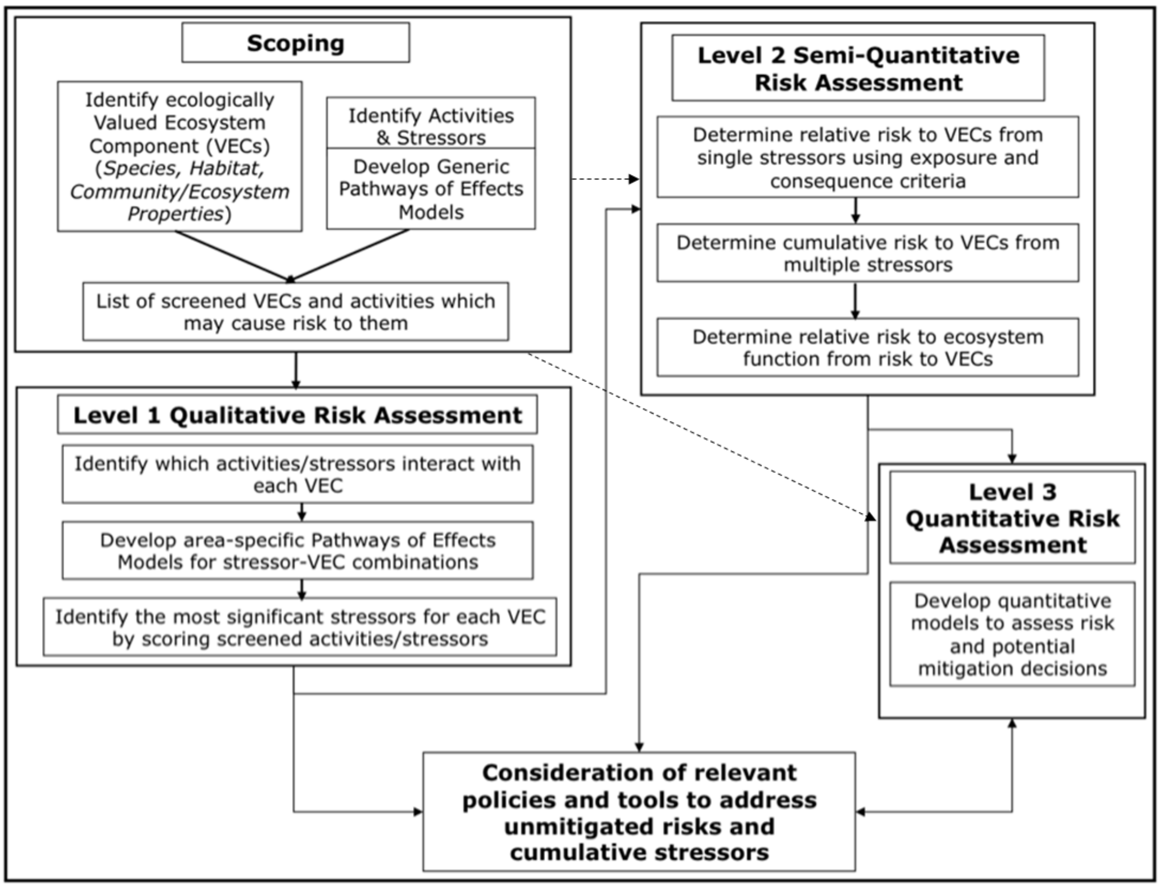

Figure 1. Ecological risk assessment framework (ERAF) modified from O et al. (2015). The solid arrows between the major boxes depict a hierarchical application of the ERAF whereas the dashed lines between Scoping and Levels 2 and 3 show alternative non-hierarchical applications of the ERAF.

2 METHODS

The Ecological Risk Assessment Framework has two phases: Scoping and Risk Assessment. For the current pilot application to PNCIMA, Scoping and Level 1 Qualitative Risk Assessment were completed (Figure 1).

2.1 SCOPING

2.1.1 Identification of Activity/Stressor

Activities occurring within the bounds of PNCIMA were identified and described by MacConnachie et al. (2007). Activities include both sea- and land-based activities. Sea-based activities include fisheries, finfish and shellfish aquaculture, log handling, marine tourism, military operations, oil and gas exploration, wind energy, vessel use, and ports, marinas and harbours. "Land activities" describes stressors that are derived from the runoff of various land activities including Agriculture, Forestry, Human Settlement, Mining, and Pulp and Paper Mills. In order to fully examine cumulative impacts for the region, global stressors such as ocean acidification and temperature increase due to climate change also were examined. The full list of activities and stressors identified for PNCIMA during the scoping phase is presented in Appendix 1.

A subset of activities and stressors were evaluated in this pilot project. Activities were removed if they were not currently occurring within PNCIMA (Oil and Gas, Wind Energy) or if spatial information was unavailable (Military Operations). In order to identify stressors associated with each activity, the ERAF calls for Pathway of Effects (PoE) models to be employed. Relevant PoEs were under development and unavailable at the time of the pilot project and therefore literature review, expert opinion and the description of associated stressors from MacConnachie et al. (2007) were used. The use of established PoEs saves time and effort in risk assessment but the alternate approach used here comprises much of the supporting documentation used to construct a PoE and is acceptable in the absence of an established PoE model. However, users should be aware that without PoEs, multiple low risk stressors could be missed that may not be high risk singly, but can become important when cumulative risk is considered. A subset of these stressors was included in the pilot project and is shown in Appendix 2.

The activity Vessel Use was further divided into Small and Large Vessel Use to reflect the differences in type and scale of associated stressors. For example, small recreational vessels and large container ships are subject to different regulations regarding the use of antifouling paints (IMO 2002). In addition, the scale of oil spills differ in that small vessels have a relatively small volume of oil to potentially spill while large oil tankers have the potential to release huge quantities of oil. Therefore, the nature of their stressors differs. Many of the sea-based activities utilize vessels in their operations; thus the Small or Large Vessel Use stressors and their risk scores were included for activities that use either of these vessel types. The inclusion of Small and Large Vessel Use stressors is illustrated in the list of activities and stressors shown in Appendix 2.

2.1.2 Identification of SECs

The second stage in the Scoping phase of the ERAF is identification of Valued Ecosystem Components (VECs). VECs are defined by the Canadian Environmental Assessment Agency (CEAA) as "environmental elements of an ecosystem that have scientific, social, cultural, economic, historical, archaeological, or aesthetic importance" (Leschine and Petersen 2007). Because the current pilot project only evaluated the scientific components and the "value" portion was not formally evaluated, the term Significant Ecosystem Components (SECs) is used in the remainder of the document.

The PNCIMA ecosystem is composed of an almost infinite number of SECs. For the current ecological risk assessment application, only *ecological* SECs were considered. Using a previously determined candidate list of ecological SECs, 13 SEC subcategories were identified from Lucas et al. (2007) and Clarke and Jamieson (2006). As a pilot project to test the ecological risk assessment framework, 17 example species were chosen from each of the species subcategories based on data availability (Table 1).

Table 1. Final list of pilot Significant Ecosystem Components (SECs)

Category	Sub-Category	Pilot SECs	Scientific name
Plankton	Plankton	Phytoplankton	
		Zooplankton	
Macrophytes	Habitat-forming macrophytes	Kelp	
		Seagrasses	*Zostera* spp.
Invertebrates	Habitat-forming invertebrates	Cold-water Corals	
		Sponges	Hexactinellid, cloud, etc
	Low mobility invertebrates	Geoduck Clam	*Panopea abrupta*
	Mobile benthic invertebrates	Dungeness Crab	*Cancer magister*
	Mobile pelagic invertebrates	Prawn	*Pandalus platyceros*
Fishes	Anadromous fishes	Salmon	*Onchorhynchus* spp.
	Elasmobranchs	Spiny Dogfish	*Squalus acanthias*
	Groundfishes	Lingcod	*Ophiodon elongatus*
	Pelagic fishes	Pacific Herring	*Clupea pallasi*
Marine Mammals	Baleen whales	Humpback Whale	*Eumetopias jubatus*
	Toothed whales	Resident Killer Whale	*Orcinus orca*
	Pinnipeds	Steller Sea Lion	*Eumetopias jubatus*
Birds	Seabirds	Cassin's Auklet	*Ptychoramphus aleuticus*

2.2 LEVEL 1 QUALITATIVE RISK ASSESSMENT

2.2.1 SEC-Stressor Matrix

The first step in the Level 1 Qualitative Risk Assessment is to identify the activities and stressors that interact with each SEC. The potential interaction between the pilot SECs and stressors was evaluated using an expert judgment exercise. The entire set of activities and their stressors were listed against each SEC and a small working group of experts (M. Mach, C. Clarke Murray, M. O and R. Martone) asked to evaluate each intersection as positive for impact (likely) or negative for impact (not likely). The resulting matrix is available in Appendix 2. These relationships were then used to define which stressors of each activity were assessed for their risk to each of the 17 SECs. When a stressor produced by a specific activity is described in the results and discussion sections they are denoted as "Activity/Stressor"; for example, Human Settlement/Debris describes the stressor marine Debris resulting from the Human settlement activity. The methods for assessing risk for these SEC-stressor relationships are described in the sections below.

2.2.2 Qualitative Risk Variables

2.2.2.1 Overview

Risk is a product of the SEC's exposure to a stressor and the consequence of that exposure to the SEC. Risk is calculated according to the following equation:

Equation 1: $Risk_{ij} = Exposure_{ij} * Consequence_{ij}$

Where:

$Risk_{ij}$ to SEC *j* by stressor *i* is the product of the $Exposure_i$ of SEC *j* to stressor *i* and the $Consequence_{ij}$ to SEC *j* when exposed to stressor *i*; where SEC *j* is one of the pilot species selected for this analysis (Table 1) and stressor *i* is a stressor produced by one of the sea or land-based activities in Appendix 2.

In the current pilot project, risk to SECs from stressors produced by sea and land-based activities were assessed using two methods. In Method 1: Binned Exposure, risk is assessed using the method developed by O et al. (2015). The $Exposure_{ij}$ score is binned (dividing by 6) to equate it to the $Consequence_{ij}$ score (maximum score of 6). Uncertainty is not incorporated in calculations of risk in this method, but is tracked in a separate table of uncertainty scores.

In Method 2: Uncertainty Incorporation, risk scores are calculated by random sampling within a normal distribution, with the mean defined by the variable score and the shape of the distribution defined by the uncertainty score, as described further in Section 2.2.5. Method 2 differs from Method 1 in that $Exposure_j$ scores were not binned and instead $Consequence_{ij}$ is squared to make the scale of the score comparable to $Exposure_i$, which is the product of three variables (maximum 36). For Method 2, risk was calculated using the following equation:

Equation 2: $Risk_{ij} = Exposure_{ij} * Consequence_{ij}^{\,2}$

2.2.2.2 Scoring Exposure and Consequence

In both Methods 1 and 2 qualitative scoring of the risk variables used the same scoring methodology defined by O et al. (2015) with one exception. $Exposure_{ij}$ of SEC *j* to stressor *i* was the product of three variables: *Temporal Scale*$_i$ *(TS)*, *Spatial Scale*$_i$ *(SS),* and *Intensity.* After the pilot application of the framework, the variable Intensity was renamed $Load_i$ *(L)* (detailed descriptions below) so that Equation 2 now becomes:

Equation 3: $Risk_{ij} = TS_i * SS_i * L_i * Consequence_{ij}^2$

An uncertainty term was assigned for each variable in Equation 3 (described further in Section 2.2.3). Note that in contrast to the ERAF (O et al. 2015), *Exposure* variables were not scored differently for each SEC-stressor relationship, the scoring was instead specific to the activity and the stressor it produces and thus common across all SECs that interact with the given stressor (scores available in Appendix 4). For example, *Exposure* for sedimentation from trawling was scored and was the same for birds, pinnipeds, *etc.,* because *Exposure*, in practice, was in reference to the characteristics of the stressor itself. This practice is recommended for a Level 1 risk assessment but not for more quantitative assessments (i.e., Level 2 and 3) where Exposure should be scored specifically in reference to each SEC. In contrast, *Consequence* was scored specifically in relation to the stressor's risk to the particular SEC, *i.e*., consequence varies according to the SEC.

Temporal Scale (TS) refers to the frequency of the event, rather than its duration. Consideration was given to how often the stressor occurs, rather than how long the effect is felt by the SEC (which in practice was included in the *Consequence* scoring). Scoring is described in Table 2a.

Spatial Scale (SS) is the scale or spatial extent of the impact from the stressor. For example, under sedimentation from trawl fisheries, consideration was given to how far sediment is carried from the site of the trawl. Scoring for the dive fishery considered the size of the footprint of habitat disturbance from a single dive. Scoring is described in Table 2b.

Load (L) is a measure of the density and persistence of the stressor. It was noted that with the recommendation to change the variable name to Load, persistence was considered part of the load variable. Depending on the stressor or activity in question, Load can refer to effort, density, amount of an activity, or the amount or strength of a stressor (e.g., quantity or concentration of a pollutant or harmful species, rate of change for climate change) across the entire study area (in this case, PNCIMA). For example, load for finfish aquaculture evaluates the number of finfish farms in PNCIMA and how often and how much area is covered by these farms. Scoring described in Table 2c.

Consequence is the impact of the stressor on the individual SEC and is scored for each SEC-stressor combination. Scores range from 1 to 6 from negligible to intolerable consequence, respectively, and indicate the impact of the stressor on the individual SEC, as described in Table 2d. *Consequence* scoring was based on the subcomponent for which information was available (population size, geographic range, behaviour, etc.) but most commonly *Consequence* was scored on the population size or geographic range subcomponent (see Table 3). If information was available for more than a single subcomponent, then the most sensitive subcomponent was used to assign the score. The most sensitive subcomponent is considered to be the subcomponent that is most important for long-term persistence and/or that is the most responsive to the stressor being scored. Uncertainty was also included for the *Consequence* score; see Table 4 for uncertainty categories and scores.

Table 2. Scoring of Exposure variables: a) Spatial Scale, b) Temporal Scale, and c) Load and d) Consequence

Score	Effect	Definition
(a) ***Temporal Frequency Scale***		
1	Rare	Every several years – Decadal
2	Relatively Often	Quarterly – Annually
3	Frequent	Weekly – Monthly
4	Continuous	Daily occurrences or continuous
(b) ***Spatial Scale***		
1	Few restricted locations	1-10 kilometres
2	Localized	10-100 kilometres
3	Widespread	>100 kilometres
(c) ***Load – Density/Persistence***		
1	Low	Low density and low persistence
2	Moderate	High density or persistence
3	High	High density and persistence
(d) ***Consequence***		
1	Negligible	Negligible impact on population/habitat/community
2	Minor	Minimal impact on population/habitat/ community structure or dynamics
3	Moderate	Maximum impact that still meets an objective (e.g. sustainable level of impact such as a full exploitation rate for a target species; maintaining levels of critical habitat)
4	Major	Wider and longer term impacts (e.g. long-term decline in CPUE)
5	Severe	Very serious impacts occurring, with a relatively long time period likely to be needed to restore to an acceptable level (e.g. serious decline in spawning biomass limiting population increase)
6	Intolerable	Widespread and permanent/irreversible damage or loss will occur – unlikely to ever be fixed (e.g. local extinction)

Table 3. Scoring Consequence to species based on subcomponents.

	Score/level					
Subcomponent	**1 Negligible**	**2 Minor**	**3 Moderate**	**4 Major**	**5 Severe**	**6 Intolerable**
Population size	Insignificant change to population size/growth rate (r). Unlikely to be detectable against background variability for this population.	Possible detectable change in population size/growth rate (r) but minimal impact on population size and none on dynamics.	Impacts to the population but long-term recruitment dynamics not adversely damaged.	Significant source of mortality. Affecting recruitment state of populations and/or their capacity to increase.	Likely to cause local extinctions if continued in the longer term.	Local extinctions are imminent/ immediate.
Geographic range	No detectable change in geographic range. Unlikely to be detectable against background variability for this population.	Possible detectable change in geographic range but minimal impact on population range and non on dynamics. Change in geographic range up to 5% of original.	Change in geographic range up to 10% of original.	Change in geographic range up to 25% of original.	Change in geographic range up to 50% of original.	Change in geographic range up to >50% of original.
Genetic structure	No detectable change in genetic structure. Unlikely to be detectable against background variability for the population.	Possible detectable change in genetic structure. Any change in frequence of genotypes, effective population size, or number of spawning units up to 5%.	Detectable change in genetic structure. Any change in frequence of genotypes, effective population size, or number of spawning units up to 10%.	Detectable change in genetic structure. Any change in frequence of genotypes, effective population size, or number of spawning units up to 25%.	Detectable change in genetic structure. Any change in frequence of genotypes, effective population size, or number of spawning units up to 50%.	Detectable change in genetic structure. Any change in frequence of genotypes, effective population size, or number of spawning units up to >50%.
Age/size/sex structure	No detectable change in age/size/sex structure. Unlikely to be detectable against background variability for this population.	Possible detectable change in age/size/sex structure but minimal impact on population dynamics.	Detectable change in age/size/sex structure. Impact on population dynamics at maximum sustainable level, long-term recruitment dynamics not adversely damaged.	Long-term recruitment dynamics adversely affected. Time to recover to original structure up to 5 generations free from impact.	Long-term recruitment dynamics adversely affected. Time to recover to original structure up to 10 generations free from impact.	Long-term recruitment dynamics adversely affected. Time to recover to original structure up to and greater than 100 generations free from impact.
Reproductive capacity	No detectable change in reproductive capacity. Unlikely to be detectable against background variability for the population.	Possible detectable change in reproductive capacity but minimal impact on population dynamics.	Detectable change in reproductive capacity. Impact on populations dynamics at maximum sustainable level, long-term recruitment dynamics not adversely damaged.	Change in reproductive capacity adversely affecting long-term recruitment dynamics. Time to recovery up to 5 generations free from impact.	Change in reproductive capacity adversely affecting long-term recruitment dynamics. Time to recovery up to 10 generations free from impact.	Change in reproductive capacity adversely affecting long-term recruitment dynamics. Time to recovery up to and greater than 100 generations free from impact.
Behaviour/ movement	No detectable change in behaviour/ movement. Unlikely to be detectable against background variability for this population. Time taken to recover to pre-disturbed state on the scale of hours.	Possible detectable change in behaviour/ movement but minimal impact on population dynamics. Time to return to original behaviour/ movement on the scale of days to weeks.	Detectable change in behaviour/ movement with the potential for some impact on population dynamics. Time to return to original behaviour/ movement on the scale of weeks to months.	Change in behaviour. Movement with impacts on population dynamics. Time to return to original behaviour/ movements on the scale of months to years.	Change in behaviour/ movement with impacts on population dynamics. Time to return to original behaviour/ movement on the scale of years to decades.	Change in behaviour/ movement. Population does not return to original behaviour/ movement.

Table 4. Scoring definition of the uncertainty of risk scores.

Uncertainty		
Score	**Literature**	**Definition**
1	Extensive	Extensive scientific information; peer-reviewed information; data specific to the location; supported by long-term datasets (10 years or more)
2	Substantial	Substantial scientific information; non-peer-reviewed information; data specific to the region; supported by recent data (within the last 10 years) or research
3	Moderate	Moderate level of information; data from comparable regions or older data (more than 10 years) from the area of interest
4	Limited	Limited information; expert opinion based on observational information or circumstantial evidence
5	Little to None	Little or no information; expert opinion based on general knowledge

2.2.3 Scoring Uncertainty

Although the original ERAF (O et al. 2015) recommended assigning a single uncertainty value for each overall Risk score, an uncertainty score was given instead for each risk variable analysed during scoring; one uncertainty score for each of *Temporal, Spatial, Intensity* and *Consequence*. A guide for the uncertainty score can be found, in part, in Table 4 and is based on categories outlined in Therriault and Herborg (2008) and Therriault et al. (2011). If no information was available to score one or more of the components a best guess was used and the associated uncertainty was scored as a 5, indicating that the score was highly uncertain.

There are two types of uncertainty inherent in the risk scoring:

1. knowledge of the SEC-stressor interaction as reflected by the scientific literature that is available (described in Table 4) and,
2. consensus about the risk inherent in the SEC-stressor interaction. In some cases, there is a wealth of scientific information but no agreement about its impact.

For example, there is scientific debate about the relative role of river versus open ocean stressors in salmon mortality. The second type of uncertainty is implicitly considered when scoring uncertainty but is not in the Table 4 descriptions. In the current pilot project, the uncertainty score was increased by one when there was no consensus about impact (i.e., no consensus = higher uncertainty).

2.2.4 Calculation of Risk Method 1: Binned Exposure

In accordance with the ERAF developed by O et al. (2015), *Exposure* was calculated as the product of *Temporal Scale, Spatial Scale* and *Load. Exposure* was then binned by finding the integer of 1+(*L*TS*SS*)/6. Total risk for each SEC-stressor relationship was then calculated as the product of $Exposure_{ij}$ and $Consequence_{ij}$ as described in Equation 1. Cumulative risk to each SEC was calculated by adding the total risk scores from each SEC-stressor relationship as shown in Equation 4.

Equation 4: $$Cumulative\ Risk_j = \sum_{i=1}^{i}\left(TS_i\ x\ SS_i\ x\ L_i\ x\ Consequence_{ij}^2\right)$$

2.2.5 Calculation of Risk Method 2: Uncertainty Incorporation

An “uncertainty incorporation” exercise was completed to include the uncertainty of the qualitative risk scoring in the final and cumulative risk scores. Each risk variable (*Temporal Scale, Spatial Scale, Intensity* and *Consequence*) was assigned as the mean of a normal distribution with standard deviation of the distribution set according to the level of uncertainty assigned (see Table 5 for standard deviation levels used; Figure 2 for illustration of the normal distributions). The distribution was bounded by the minimum and maximum scores for each risk variable so that the scores could not be higher or lower than the variable’s scale (*e.g.*, the intensity score cannot be lower than 1 or higher than 3). The score of each risk variable was then randomly sampled from this distribution 100 times. The final risk score for each SEC-stressor relationship was a product of the four risk variable arrays (*SS, TS, I,* and *C*), where the first score generated from each variable array is multiplied across all four risk variables, followed by the second, and so on for all 100 replicates, resulting in a final risk array of 100 scores (Equation 5). The mean and 10% and 90% quantiles from this final array of the overall risk to each SEC-stressor relationship was reported (see Tables 9, 10, 11 and Figure 4 in results). Quantiles were used instead of standard deviation or standard error because the resulting distribution of risk scores was non-normal.

Equation 5: $$Cumulative\ Risk_j = \sum_{i=1}^{i} \widehat{TS_i}\ x\ \widehat{SS_i}\ x\ \widehat{I_i}\ x\ \widehat{Consequence}_i^2$$

Where the hat (^) symbol indicates that the variables are the estimated means of the randomly sampled values.

Table 5. Standard deviation levels assigned for each uncertainty score when calculating the distribution of each subcomponent

Uncertainty Score	Standard Deviation
1	0.2
2	0.4
3	0.6
4	0.8
5	1.0

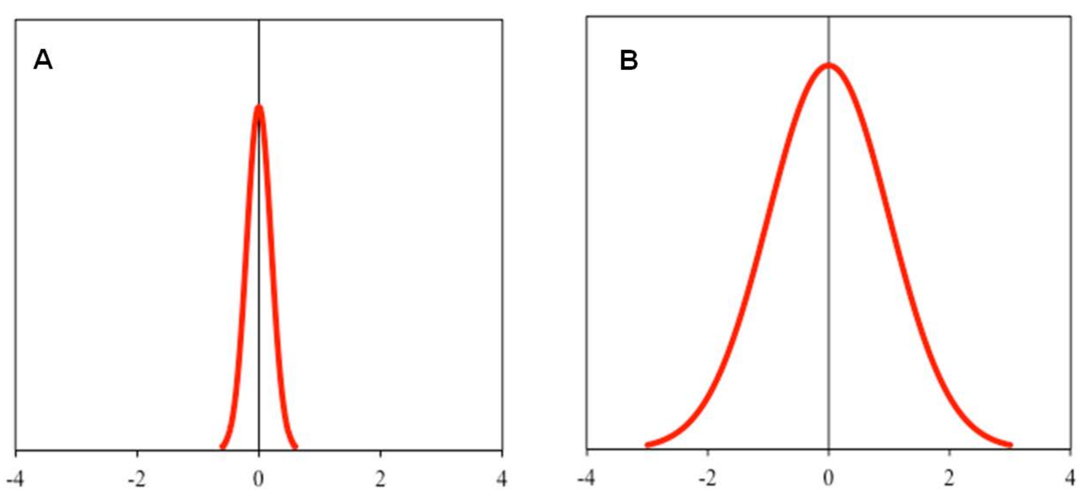

Figure 2. Normal distribution with a standard deviation of (A) 0.2 and (B) 1.0.

Cumulative risk to each SEC was calculated by adding the total risk score produced for each SEC-stressor relationship, where the first score generated from the first SEC-stressor relationship is added to the first score from the second SEC-stressor relationship, and so on for all SEC-stressor relationships, and this is repeated for the second, third and up to 100 scores for that SEC and resulting in a final array of 100 cumulative risk scores. R version 3.2.0 and the car package were used to conduct the uncertainty scoring (R Development Core Team 2008); code available in Appendix 3.

3 RESULTS

3.1 RISK ESTIMATED WITH METHOD 1: BINNED EXPOSURE

We estimated cumulative risk scores for the 17 SECs using the binned exposure method described by O et al. (2015) (Table 7; Figure 3). The highest cumulative risk was estimated for Seagrasses, followed by Salmon and Dungeness Crab. Sponges had the highest number of stressors per SEC. High cumulative risk scores could be attained either via a high number of low-risk stressors affecting the SEC or a smaller number of stressors with high estimated risk values. There are examples of both scenarios within the pilot SECs examined: Sponges had one of the highest numbers of stressors (111) but with a moderate mean risk per stressor (5.2). In contrast, Salmon have a moderate number of stressors (87) but with higher mean risk per stressor (6.8). Resident Killer Whales had the lowest number of stressors (46) and the highest mean risk per stressor (9.1) for a moderate cumulative risk score (420).

Table 6. Cumulative risk scores by SEC, in order from highest to lowest and number of stressors evaluated for each SEC and the mean risk per stressor

SEC	Cumulative Risk	# Stressors	Mean
Seagrasses	608	109	5.6
Salmon	595	87	6.8
Dungeness Crab	586	97	6.0
Sponges	576	111	5.2
Humpback Whale	515	77	6.7
Zooplankton	515	86	6.0
Kelp	480	109	4.4
Steller Sea Lion	448	85	5.3
Cold Water Coral	424	95	4.5
Resident Killer Whale	420	46	9.1
Geoduck Clam	412	90	4.6
Prawn	393	76	5.2
Pacific Herring	384	70	5.5
Cassin's Auklet	372	63	5.9
Phytoplankton	354	84	4.2
Spiny Dogfish	253	58	4.4
Lingcod	221	50	4.4

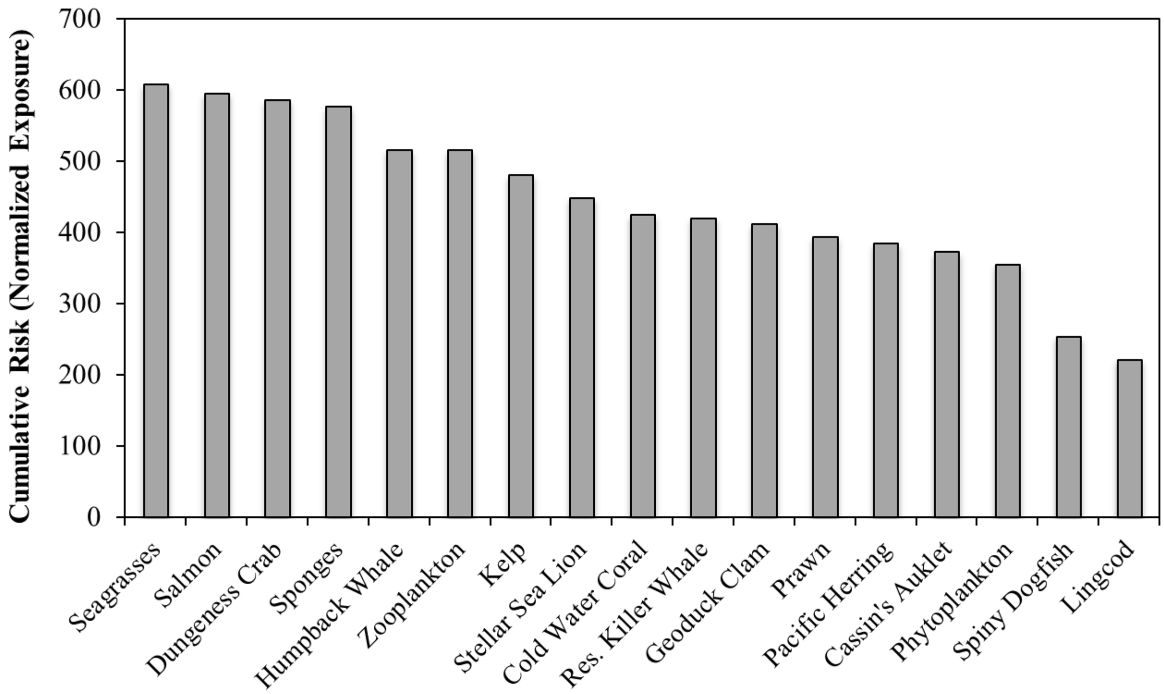

Figure 3. Bar plot of cumulative risk scores from Method 1: Binned Exposure for each pilot SEC

The highest-ranking stressors across all SECs were trawling-related (Bycatch, Habitat Disturbance and Sedimentation) for Cold Water Corals (Table 8). The binned exposure methodology resulted in many risk scores with the same risk for more than one stressor. For example, the seven highest risk SEC-stressor risk scores are all 20. Thus the risk from these relationships cannot be ranked as high to low. Ten of the top thirteen stressors (risk scores of 20 and 16) were trawling-related. Other than trawling stressors, high-rankings stressors include Marine tourism/Disruption of wildlife for Resident Killer Whale and Human settlement/Debris for Cassin's Auklet.

*Table 8. Highest ranking risk scores for total risk (Exposure * Consequence) across all SECs and stressors, for those SEC-stressor relationships with a risk score of 12 and higher.*

Activity	Stressor	SEC	Risk
Trawling	Bycatch	Cold Water Coral	20
Trawling	Bycatch	Sponges	20
Trawling	Habitat Disturbance	Sponges	20
Trawling	Sedimentation	Cold Water Coral	20
Trawling	Sedimentation	Sponges	20
Trawling	Habitat Disturbance	Cold Water Coral	20
Marine Tourism	Disruption of Wildlife	Killer Whale	20
Trawling	Bycatch	Spiny Dogfish	16

Activity	Stressor	SEC	Risk
Gillnet Fisheries	Direct Capture	Salmon	16
Trawling	Habitat Disturbance	Geoduck clam	16
Trawling	Habitat Disturbance	Lingcod	16
Trawling	Sedimentation	Geoduck clam	16
Human Settlement	Debris	Cassin's Auklet	16
Large Vessel Use	Acoustic	Humpback Whale	15
Marine Tourism	Disruption of Wildlife	Humpback Whale	15
Small Vessel Use	Acoustic	Humpback Whale	15
Large Vessel Use	Invasive Species	Cold Water Coral	12
Long Range Contamination	Persistant Organic Pollutants	Cassin's Auklet	12
Human Settlement	Contaminants	Cassin's Auklet	12
Long Range Contamination	Marine Debris	Cassin's Auklet	12
Large Vessel Use	Invasive Species	Dungeness Crab	12
Marine Tourism	Large Vessel_Invasive Species	Cold Water Coral	12
Trawling	Bycatch	Dungeness Crab	12
Trawling	Habitat Disturbance	Dungeness Crab	12
Trawling	Sedimentation	Dungeness Crab	12

The highest ranking stressors and risk scores for each pilot SEC are listed in Table 9. For individual SECs, trawling-associated stressors dominated as the top ranking stressors. Other than Trawling stressors, the top stressor was Human settlement/Debris on Cassin's Auklet, and the top stressors for Humpback Whale and Steller Sea Lion were Vessel Use/Acoustic and Marine Tourism/Disruption of Wildlife. Vessel Use/Invasive Species was a top stressor for Dungeness Crab, Kelp, Seagrasses, Phytoplankton, and Zooplankton.

Table 7. The highest ranking activity/stressor(s) for each pilot SEC; where SECs had more than one stressor tied for the highest-ranking stressor, all the top stressors were reported.

SEC	Activity	Stressor/Impact	Risk
Cassin's Auklet	Human Settlement	Debris	16
Cold Water Coral	Trawling	Bycatch	20
	Trawling	Habitat Disturbance	20
	Trawling	Sedimentation	20
Dungeness Crab	Large Vessel Use	Invasive Species	12
	Trawling	Bycatch	12
	Trawling	Habitat Disturbance	12
	Trawling	Sedimentation	12
Geoduck Clam	Trawling	Habitat Disturbance	16
	Trawling	Sedimentation	16
Pacific Herring	Gillnet Fisheries	Direct Capture	12
	Trawling	Bycatch	12
Humpback Whale	Small Vessel Use	Acoustic	15
	Large Vessel Use	Acoustic	15
	Marine Tourism	Disruption of Wildlife	15
Kelp	Small Vessel Use	Invasive Species	8
	Shellfish Aquaculture	Shading	8
Res. Killer Whale	Marine Tourism	Disruption of Wildlife	20
Lingcod	Trawling	Habitat Disturbance	20
Phytoplankton	Large Vessel Use	Invasive Species	9
Prawn	Trawling	Bycatch	12
	Trawling	Habitat Disturbance	12
Salmon	Gillnet Fisheries	Direct Capture	6
Seagrasses	Human Settlement	Contaminants	9
	Large Vessel Use	Invasive Species	9
Spiny Dogfish	Trawling	Bycatch	16
Sponges	Trawling	Bycatch	20

SEC	Activity	Stressor/Impact	Risk
	Trawling	Habitat Disturbance	20
	Trawling	Sedimentation	20
Steller Sea Lion	Small Vessel Use	Acoustic	10
	Large Vessel Use	Acoustic	10
	Marine Tourism	Disruption of Wildlife	10
Zooplankton	Human Settlement	Contaminants	9
	Land-based Activities	Contaminants	9
	Large Vessel Use	Invasive Species	9
	Long range contamination	Persistent Organic Pollutants	9

An example of one of the species SECs, sponges, is presented in Figure 4 to illustrate a comparison of the mean Exposure and mean Consequence scores. Stressors with the highest Binned Exposure and Consequence risk scores for sponges were Bycatch, Habitat Disturbance, and Sedimentation all produced by Trawling activities. Nutrient Input from Finfish Aquaculture produced the highest Consequence risk score, while Debris from Human Settlement had the highest Exposure score.

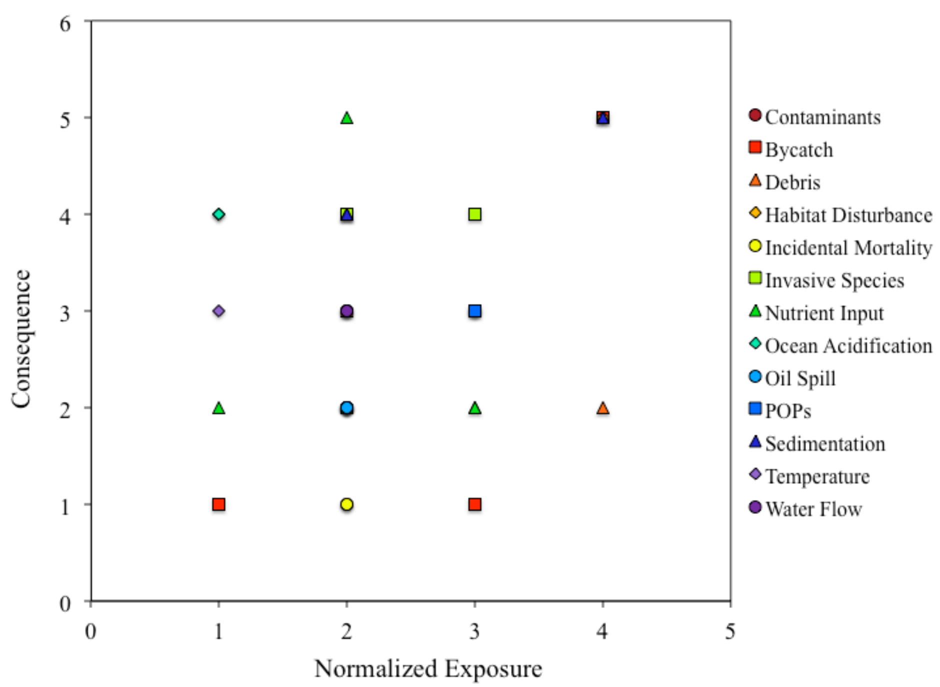

Figure 4. Comparison of the Binned Exposure and Consequence scores for sponges by each stressor (colours and symbols described in the legend) being produced by each of the 20 assessed activities).

3.2 RISK ESTIMATED WITH METHOD 2: UNCERTAINTY INCORPORATION

Using the uncertainty incorporation methodology, the SECS with the highest estimated cumulative risk also had high estimated cumulative risk when Method 1 was used, but the rank order based on cumulative risk varies slightly from the Method 1: Binned Exposure results (Section 3.1). The SECS with the highest risk scores and overlapping quantiles (calculated as 10% and 90% quantiles) are Dungeness Crab, Salmon, Sponges and Seagrasses (Table 9, Figure 5). Because there is substantial overlap in the 10^{th} and 90^{th} quantiles of the Dungeness Crab, Salmon and Sponge SECs, differences in the mean cumulative risk among these SECs are likely not significant. In fact, each time the analysis was run, the order of the most at-risk SECs switches between these four species.

High cumulative risk scores could be attained either via a high number of low-risk stressors affecting the SEC or a smaller number of stressors with high risk values, similar to Method 1. There are examples of both scenarios within the pilot SECs examined: Sponges and Seagrasses had some of the highest numbers of stressors (111 and 109, respectively) but with a moderate mean risk per stressor (289 and 230). In contrast, Dungeness crab and salmon have a moderate number of stressors (97 and 87, respectively) but with higher mean risk per stressor (325 and 361). Resident Orcas had the lowest number of stressors (46) and the highest mean risk per stressor (479) for a moderate cumulative risk score.

Table 8. Mean cumulative risk with uncertainty propagation in order of mean risk from highest to lowest, range of error is demonstrated using 10 and 90% quantiles, number of stressors evaluated for each SEC and the mean risk per stressor.

SEC	Mean Cum Risk	10% Quantile	90% Quantile	# Stressors	Risk/Stressor
Dungeness Crab	8471.6	7924.1	8904.4	97	325
Salmon	8297.1	7674.5	8873.5	87	361
Sponges	8104.5	7699.5	8668.0	111	289
Seagrasses	7562.1	7247.9	8070.6	109	230
Zooplankton	7320.6	6813.4	7919.2	86	322
Humpback Whale	6732.9	6121.1	7333.2	77	259
Kelp	6305.8	5672.0	7043.7	109	197
Res. Killer Whale	5961.5	5574.2	6397.1	46	479
Cold Water Coral	5574.0	5058.9	6138.9	95	208
Steller Sea Lion	5165.9	4795.2	5586.8	85	185
Geoduck Clam	5158.6	4626.3	5641.5	90	188
Cassin's Auklet	4895.2	4402.0	5413.5	63	283
Pacific Herring	4687.9	4184.9	5075.5	70	239
Prawn	4687.0	4266.7	5082.3	76	224
Phytoplankton	3467.1	2979.1	3997.3	84	115
Spiny Dogfish	2762.7	2416.9	3050.8	58	127
Lingcod	2412.7	2206.2	2664.1	50	143

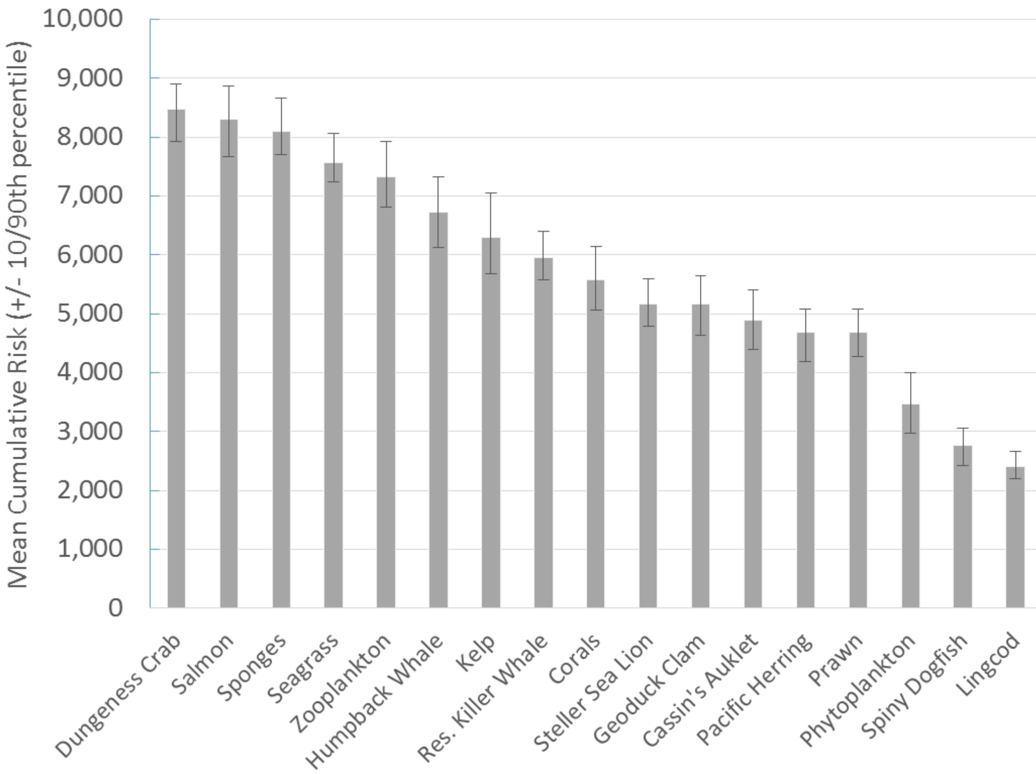

Figure 5. Bar plot of mean cumulative risk scores from Method 2: Uncertainty Propagation (10/90% quantile) for each pilot SEC

Species with the greatest uncertainty error range (widest quantile margin; in order from high to low) include Kelp (1371.7), Humpback Whale (1212.1), and Salmon (1199.0) while species with the smallest uncertainty error range (narrowest quantile margin; in order from low to high) include Lingcod (457.9), Spiny Dogfish (633.9), and Steller Sea Lion (791.6).

The highest ranking stressors across all SECs remain Trawling-related stressors (Sedimentation, Habitat Disturbance and Bycatch,) for Cold Water Corals and Sponges (Table 10) as they were using Method 1. Ten of the top twelve stressors were Trawling-related. Although similar in order to the Method 1 SEC analysis (both resulted in the same top seven stressors), many of the uncertainty margins for top ranking activities and stressors overlap, so SEC- stressor combination risk results are not necessarily different and caution should be exerted when ranking stressors. In addition to Trawling-related stressors, Marine Tourism/Disruption of Wildlife for Resident Killer Whale, Gillnet/Direct Capture of Salmon, and Human settlement/Debris for Cassin's Auklet, had high risk scores.

*Table 9. Highest ranking mean risk scores for total risk (Exposure * Consequence) with uncertainty propagation (Top 25) across all SECs and stressors, showing 10% and 90% quantiles to indicate the spread of the data.*

Activity	Stressor	SEC	Total Mean Risk	10% Quantile	90% Quantile
Sponges	Trawl	Sedimentation	453.2	334.5	569.3
Corals	Trawl	Sedimentation	445.6	329.0	564.0
Sponges	Trawl	Habitat Disturbance	444.5	360.1	542.4

Activity	Stressor	SEC	Total Mean Risk	10% Quantile	90% Quantile
Corals	Trawl	Habitat Disturbance	438.7	350.5	553.7
Sponges	Trawl	Bycatch	436.5	349.4	534.9
Corals	Trawl	Bycatch	433.8	340.3	518.7
Res. Killer Whale	Marine Tourism	Disruption of Wildlife	377.3	223.3	540.0
Spiny Dogfish	Trawl	Bycatch	302.4	151.9	441.9
Salmon	Gillnet	Direct Capture	289.1	188.3	421.7
Clam	Trawl	Sedimentation	283.9	174.5	402.6
Lingcod	Trawl	Habitat Disturbance	282.8	208.4	364.6
Clam	Trawl	Habitat Disturbance	272.0	167.7	368.4
Cassin's Auklet	Human settlement	Debris	263.9	95.7	507.8
Res. Killer Whale	Land activities	Contaminants	262.7	128.4	396.8
Res. Killer Whale	Long range contamination	POPs	236.8	133.2	354.3
Res. Killer Whale	Ports	Large vessel_Oil	234.7	171.6	300.8
Salmon	Long range contamination	POPs	232.8	118.5	383.3
Res. Killer Whale	Large vessel	Oil Spill	232.4	174.9	288.0
Humpback Whale	Ports	Small vessel_Acoustic	231.7	114.0	353.1
Res. Killer Whale	Marine Tourism	Large Vessel_Oil	230.3	171.6	293.2
Sponges	Trap	Small Vessel_Invasive Species	228.0	67.5	423.3
Humpback Whale	Small vessel	Acoustic	225.6	109.9	335.1
Kelp	Shellfish aquaculture	Small Vessel_Invasive Species	220.8	74.4	422.5
Humpback Whale	Large vessel	Acoustic	220.0	108.4	336.3
Cassin's Auklet	Long range contamination	POPs	219.1	131.3	338.3

The highest ranking stressors for each pilot SEC are listed in Table 11. Again, trawling-related stressors dominated as the top ranking stressors (five of the 17 SECs). The only changes from the Method 1 results in the top stressors per SEC were Finfish Aquaculture/Acoustic for Pacific Herring, Land-based activities/Change in freshwater flow for Prawn and Shellfish Aquaculture/Shading for Seagrasses, and Land Activities/Contaminants for Steller Sea Lion and Large Vessel Use/Oil Spill for Zooplankton.

Table 10. Highest ranking activity/stressor for each pilot SEC, showing 10% and 90% quantiles to indicate the range of the data

SEC	Activity	Stressor	Mean Risk	10%	90%
Cassin's Auklet	Human Settlement	Debris	263.9	95.7	507.8
Cold Water Coral	Trawling	Sedimentation	445.6	329.0	564.0
Dungeness Crab	Large vessel	Invasive Species	207.7	93.0	349.0
Geoduck clam	Trawling	Sedimentation	283.9	174.5	402.6
Pacific Herring	Finfish aquaculture	Acoustic	215.7	129.6	297.0
Humpback Whale	Small vessel use	Acoustic	231.7	114.0	353.1
Kelp	Small vessel use	Invasive Species	220.8	74.4	422.5
Res. Killer Whale	Marine tourism	Disruption of Wildlife	377.3	223.3	540.0
Lingcod	Trawling	Habitat Disturbance	282.8	208.4	364.6
Phytoplankton	Large vessel use	Invasive Species	117.8	47.7	212.9
Prawn	Land-based activities	Change in Freshwater Flow	205.0	161.4	257.2
Salmon	Gillnet fisheries	Direct Capture	289.1	188.3	421.7
Seagrasses	Shellfish aquaculture	Shading	137.5	99.4	180.7
Spiny Dogfish	Trawling	Bycatch	302.4	151.9	441.9
Sponges	Trawling	Sedimentation	453.2	334.5	569.3
Steller Sea Lion	Land activities	Contaminants	165.7	30.3	338.7
Zooplankton	Large vessel use	Oil Spill	157.4	64.6	250.8

A comparison of the mean Exposure and mean Consequence scores for the Sponges SEC is shown in Figure 6. Again, the stressors and activities with the highest mean Exposure and mean Consequence risk scores for sponges were Sedimentation-Habitat Disturbance, and Bycatch, all of which were produced by Trawling activities. Large Vessel Oil Spill produced the highest mean Consequence risk score, while Wildlife Disturbance from Marine Tourism and Acoustic Disturbance from Small Vessel Use had the highest mean Exposure scores.

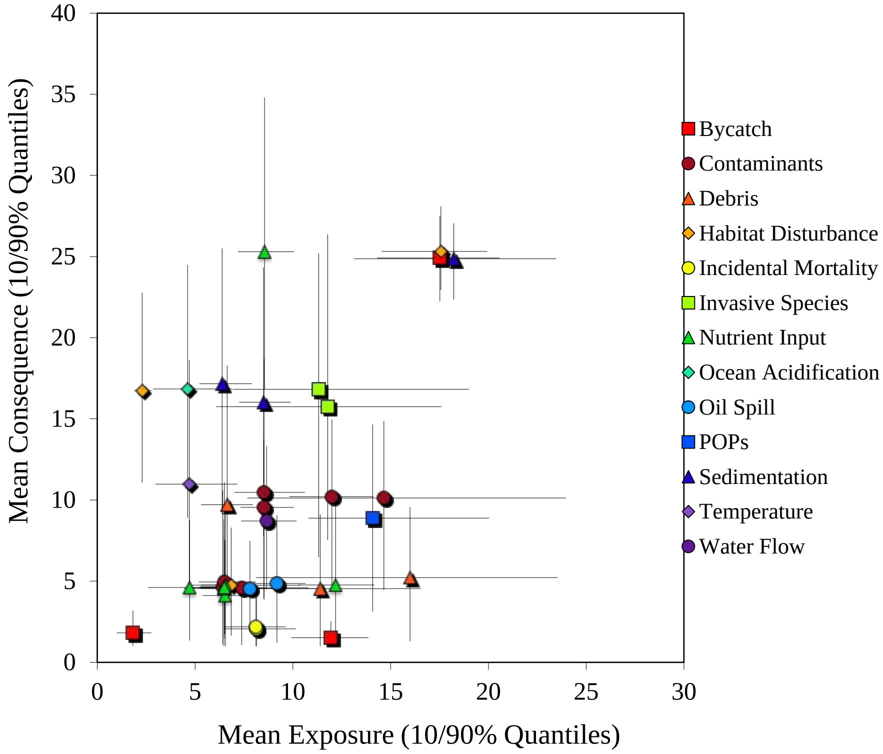

Figure 6. Comparison of the mean Exposure and mean Consequence score for Sponges by each stressor (colours and symbols described in the legend) being produced by each of the 20 assessed activities. Uncertainty is represented by 10/90% quantile error bars.

4 DISCUSSION

4.1 PILOT RISK ASSESSMENT

The current pilot project tested the Level 1 ERAF methodology developed by O et al. (2015) using a subset of SECs and stressors known to occur in the PNCIMA. The resulting scores have not been vetted by experts and should not be used for policy or management decisions at this stage. We emphasize that the results should not be considered a complete risk assessment for PNCIMA.

SECs with the highest estimated cumulative risk were Seagrasses, Salmon, Dungeness Crab, and Sponges when the binned exposure method for scoring (Method 1) was used. When uncertainty was included into the risk score (Method 2), the highest estimated cumulative risk scores were for Sponges, Dungeness Crab, Salmon, and Zooplankton. The order of highest risk SECs cannot be compared between the two methods as the uncertainty method demonstrates that the most at-risk SECs overlap in their uncertainty error scores, however four of the five most at-risk SECs are the same species – Salmon, Sponges, Seagrasses and Dungeness Crab have high estimated cumulative risk when either method of scoring is used. It is not surprising that some of these species have high risk scores. Salmon are exposed to a wider range of stressors than fully marine species because of their connection to both freshwater and marine ecosystems (Beger et al. 2010) while Sponges are long-lived, slow growing structural species with long regeneration times (DFO 2010) and therefore Consequence risk scores are high for these two SECs, even in deep water habitats. In contrast, Seagrasses on average are exposed to lower risk stressors, but their location in intertidal mudflats brings that them into contact with many of those stressors. Thus, their cumulative risk score is one of the highest of all SECs considered. Although the order of the cumulative risk scores for each SEC tells us something about the risk to these species, only 17 SECs were examined as part of the pilot project so it is less useful to compare SECs against one another.

The binned exposure scoring (Method 1) is the original ERAF methodology (O et al. 2015) and is simple to apply and understand. However, uncertainty is not included in the risk scores and can be potentially ignored by users of the results. In contrast, when uncertainty is incorporated into the risk estimate (Method 2), it explicitly uses uncertainty around the variable scores to estimate overall risk. This approach allows a more precautionary estimate of risk and ensures that uncertainty is not ignored in the risk assessment process. It is recommended that future applications of the Level 1 ERAF use the uncertainty incorporation method to estimate risk to SECs.

The Monte Carlo simulation results used to incorporate uncertainty into the risk equation are dependent on the sampling distribution and the number of replicates chosen for the simulation. Here a normal distribution was used, as it was the simplest choice where no information was available to warrant the use of a different distribution. Other sampling distributions can be used for this purpose when merited by the available information. Additionally, the sample mean should more closely approximate the expected value of a score as the number of replicates increases. In the pilot project the simulation was run 100 times for each SEC-stressor combination to reduce processing time, which results in a wider confidence interval around the mean. Future risk assessment applications (rather than a pilot test) in which uncertainty is incorporated into the risk calculation should use at least 10,000 runs in order to ensure that the mean score is a reasonable approximation of the expected value.

Regardless of the method used, understanding the uncertainty of each SEC's cumulative risk value reveals where information on the Exposure and Consequence to each SEC is sufficient, and where it is lacking. For example, there is more scientific research on the risk of Exposure and Consequence of various activities and their stressors on Pacific Herring, Lingcod, Spiny Dogfish, and Phytoplankton, while there is relatively little information on Sponges, Kelp, Cassin's Auklet, and Zooplankton. Uncertainty around mean Exposure and Consequence risk scores, as opposed to total risk, can be used to specifically target whether the uncertainty is associated with Exposure to a stressor or Consequence to the SEC. In most cases, Consequence scores had greater uncertainty than Exposure scores, resulting from a general lack of scientific understanding of how stressors affect population size, distribution, and genetic diversity, of each of the species SECs considered. These uncertainty scores describe a gap in knowledge that the risk assessment helps to highlight.

Exposure was scored specific to the activity and the stressor it produces and thus was common across all SECs that interact with the given stressor. This practice recognizes that Exposure scores are qualitatively dependent on the characteristics of the stressor itself and is recommended for a Level 1 risk assessment only. More quantitative Level 2 and 3 assessments should score Exposure in reference to each SEC assessed.

The Level 1 risk assessment is useful as a triage tool for rapidly assessing the risk to SECs. Interpreting cumulative risk estimates should be limited to relative rather than absolute scales. Absolute scores or differences in scores are not meaningful at in a Level 1 assessment except as a mechanism for ordering SECS. A Level 1 ecological risk assessment may be more useful for comparisons among stressors and activities. Using Method 1, 10 of the top 13 stressors were related to Trawl Fisheries, along with Disruption of Wildlife, Marine Debris and the Gillnet Salmon fishery. When uncertainty was incorporated (Method 2), the highest risk stressors were also trawling-related (eight of the top 12 stressors) along with Disruption of Wildlife, Marine Debris, Gillnet Salmon fishery and Large Vessel/Oil Spill. The incorporation of uncertainty adds a layer of complexity to the risk assessment that better informs the availability of information for each of the activities and their stressors in the PNCIMA. For example, Invasive Species stressors associated with Aquaculture and Large and Small Vessel Use activities were higher ranking using the uncertainty propagation methodology because of a high level of uncertainty associated with the Consequence risk score of Invasive Species introductions, evidenced by the wide quantiles around the mean risk: Small Vessel Use/Invasive Species had an estimated mean risk of 1000 but ranged from 200-2000. This high range of uncertainty for the Consequence score results from the potentially large impact of an Invasive Species but highly dependent on the identity, location and timing of the introduction, thus the high uncertainty values. Understanding which activities and stressors result in the greatest uncertainty may help target future research to improve risk estimates of these activities to species in PNCIMA.

4.2 FUTURE CONSIDERATIONS

4.2.1 Significant Ecosystem Components (SECs)

The pilot risk assessment used a subset of species important to ecological processes in the PNCIMA. There are additional species, habitats, and community processes that contribute to a high-functioning ecosystem and these additional SECs should be incorporated into a full ecological risk assessment for PNCIMA.

The pilot SECs included a mix of species and species groupings including Corals, Sponges, Kelp, Seagrass, Phytoplankton and Zooplankton, which represent multiple species. These species groupings are taxonomically imprecise and therefore were difficult to score. Scoring was especially difficult for Sponges as there are common species in shallow nearshore systems but most of the impact literature in the PNCIMA relates to deep water Hexactinellid sponge reefs. Future applications of this risk assessment methodology should consider single species SECs or species groupings consisting of species that co-occur in the same habitats. SEC lists should be collaboratively defined and reviewed externally and then screened against the selection criteria for incorporation into the ERAF for a full risk assessment process.

4.2.2 Stressors and Activities

The list of activities considered in the current pilot project did not include Oil and Gas activities, Wind Energy or Military Operations. The activities are either not currently occurring within PNCIMA (Oil, Gas and Wind Energy) or the data were inaccessible (Military Operations). In addition, the suite of activities occurring on land were merged into a single set of common stressors under the heading “Land-based Activities” because the source activity of the stressor (Sediment, Nutrient, Contaminants) was often difficult to assign. This category includes Forestry, Agriculture, Pulp and Paper Mills, Aluminum Smelter and Onshore Mining. In addition, DFO does not have jurisdiction over land activities even if they have impacts in the marine realm. However, having a better understanding of the pathways of effects of stressors from Land-based activities to marine ecosystems would provide a starting point for meaningful dialogue and cross-jurisdiction management, a stated goal of EBM (McLeod et al. 2005; Halpern et al. 2008; Lester et al. 2010; Curran et al. 2012).

Vessel Use was divided into Small and Large Vessel Use since the magnitude of impacts and spatial distribution are different. The Vessel Use stressors were then added into the table associated with each of the activities that use some type of vessel. Fishing activities were given the stressors and associated scores for small vessels while Marine Tourism was given both Large and Small Vessel Use stressors to account for small boats used in whale watching and cruise ships used for tourism. Since this approach raised the concern that the final results could be driven by Vessel Use stressors, we ran additional analyses without Vessel Use stressors and found that the top SECs and top stressors did not vary significantly relative to the inclusion of Vessel Use stressors; they were still dominated by Trawling stressors.

Completing the SEC-stressor matrix without assessing risk for each SEC-stressor relationship is faster and less data intensive than the full Level 1 Risk Assessment completed in this report. However, it does not yield enough information to estimate cumulative risk to SECs and therefore limits information on species that have many SEC-stressor relationships of low risk individually, but important cumulative risk. In addition, this approach may ignore species that are affected by a few high risk stressors that would produce a high cumulative risk. High-ranking SECs were a mix of both SECs impacted by high numbers of low risk stressors and SECs impacted by a smaller number of high-risk stressors. For example, Sponges and Seagrasses were exposed to high numbers of low- to moderate- risk stressors, while Resident Killer Whales were exposed to a few high-risk stressors. If cumulative risk is not used to estimate overall risk, then it is likely that those species with low SEC-stressor risk relationships would be missed.

Ideally, the Pathways of Effects (PoE) models should be used to fill in the SEC-stressor matrix to ensure that all impacts are captured for the SECs under consideration. In particular, PoE models should be used in circumstances where SECs are likely to be exposed to a large number of stressors, even if the risk from those stressors is low. PoE models were not available at the time of this pilot project but should be used in the application of a formal risk assessment process or in future uses of this method. In their absence, literature review and evidence tables as used in this pilot application, are an acceptable alternative.

4.2.3 Cumulative Impacts

The methods of estimating cumulative impacts presented here assume that risk is additive, rather than some other relationship (multiplicative, nonlinear, etc). Little is known about interactions among stressors and additional study is required to investigate the nature of these relationships using both ecological experimentation and modeling (Crain et al. 2008). Even with additional research, the results are likely to be specific to the study area, scale and species and may not be easily generalizable. In addition, the risk equation used in the ERAF (O et al. 2015) uses the product of Exposure and Consequence to calculate risk. Other risk assessment frameworks have used Euclidean distance to calculate risk (e.g., Samhouri and Levin 2012). Euclidean distance is the straight line distance between two points in space. Using Euclidean distance would change the magnitude of the results slightly but the relative rankings of SECs based on estimated risk would be similar.

4.3 CHALLENGES AND LIMITATIONS

The spatial, temporal and depth overlap between a SEC and an activity is not considered in the current risk scoring because of the separation of Exposure and Consequence scoring as described earlier (Section 2.2.2.1). This separation means that in the PNCIMA, all stressors were combined to assess cumulative risk, assuming that all risks from multiple stressors overlap spatially and temporally for that species SEC. Whether SECs overlaps with the activity in space, time and at all depths was not assessed, but these relationships could be explicitly scored as part of Level 2 Risk Assessment or with an additional spatially-explicit mapping exercise.

The method used in this pilot risk assessment for scoring Exposure differed from the description in O et al. (2015). Consideration should be given to whether Exposure should be scored strictly for the stressor itself (as was done in this pilot study) or scored individually for the SECs' exposure to each activity and its stressors. The advantage of scoring Exposure in a way that does not consider the SEC is that a library of Exposure scores could be built and SECs scored for Consequence as they are added to the risk assessment. However, it means that Exposure does not explicitly address whether the SEC interacts with a stressor spatially or temporally and therefore potentially inflates risk values. The Level 2 Semi-Quantitative Risk Assessment could be used to address this issue by mapping SECs and activities, and scoring based on percentage overlap for spatial and temporal scales.

The comparison of Exposure and Consequence scoring may provide guidance in applying policy and management actions. While the Consequences of a stressor to a SEC are difficult to manage, Exposure to a stressor could be reduced or eliminated under certain management scenarios. For example, the seasonal fallowing of finfish aquaculture facilities has been implemented in some areas to reduce exposure of migrating wild salmon to parasites and contaminants concentrated in farm conditions, while still allowing farming activities to continue (Naylor et al. 2003). The Exposure score itself, composed of the temporal scale, spatial scale and intensity variables may be further explored by adding a variable that considers management mitigation or feasibility as is done in the INVEST tool (Guerry et al. 2012). If the Exposure of a SEC to a stressor can be limited by managing the stressors produced by various activities, a sensitivity analysis could be used to test the effectiveness of management measures to reduce overall risk. This method could then be used to demonstrate how mitigating various stressors might reduce cumulative risk to a SEC.

Indirect impacts are not considered in scoring SEC-stressor interactions, only direct impacts of the stressor. For example, although trawl sedimentation does not directly impact Spiny Dogfish, it may reduce habitat or prey species; but these risks were not included in the risk scores for SECs. Sedimentation was scored directly for habitat-forming species and prey species to prevent double counting of risk. However, additional analyses that include trophic and habitat interactions would more fully identify risk.

Positive impacts are not captured in the current risk-scoring model described by the ERAF. For example, additional nutrient input might increase productivity for some SECs (e.g., Kelp) (Steneck et al. 2002), and temperature may increase phytoplankton productivity (Harley et al. 2006) or secondary productivity for some species (e.g., mussels) (Menge et al. 2008) and ocean acidification is linked to increased seagrass growth (Harley et al. 2006). However, the current risk assessment has no method for incorporating these positive effects into the final risk score. In the future, it may be important for cumulative risk scores to decrease when positive effects increase population densities or species ranges of SECs.

Relatively little primary data currently exists for activities and stressors at the scale of large ocean management areas (e.g., PNCIMA), and therefore a method such as the Level 1 qualitative risk assessment permits a systematic assessment of relative risks across a broad geographic region. In performing the risk scoring, we found that some SECs have literature on impacts specifically within the PNCIMA while others rely on generalizations in other regions or other species. A qualitative assessment permits a more general assessment that can utilize research from the BC coast and other locales. It is likely that in a data-poor region, such as the PNCIMA, conducting a quantitative assessment would be challenging. The uncertainty scores incorporate some of the issues of data availability and help to pinpoint where access to relevant scientific information would improve risk estimation for species with high uncertainty.

While the uncertainty scoring methodology described in the original ERAF document takes into account the type of literature available on the SEC-stressor relationship, from recent peer-reviewed articles to expert opinion, it does not consider the level of scientific consensus about the risk inherent in the SEC-stressor interaction. Either the scoring tables should be revised to consider consensus explicitly, or the uncertainty scoring should be increased to the next level of uncertainty in Table 4 when no consensus is apparent, as implemented in the current pilot project. An additional concern is related to the scaling of risk estimates. For example, in some cases the primary literature may show that there is likely a large risk from a stressor to a SEC in a specific area, but the degree of that risk at the PNCIMA scale may be relatively unknown.

4.4 NEXT STEPS

The current assessment was a pilot application of the Level 1 ERAF methodology (O et al. 2015) based on a subset of SECs, activities and stressors. Although we focused on a subset of ecological or species SECs, habitat and community property SECs important to this region should be scoped (Scoping phase, ERAF, Figure 1) and assessed using the Level 1 Qualitative Risk Assessment. Future assessments also should consider a broader suite of SECs, potentially including ecological, social and economic SECs, developed through a consultation process with the multiple stakeholders that use the PNCIMA region. However, this is outside the scope of this ERAF, and integration of this kind of data is not currently possible as the scoring rubrics are ecologically based. Activities and stressors considered in this risk assessment were also limited. We provide a list that includes most of these activities in Appendix 1, and future work should complete scoping of this list and integrate these into future Level 1 Risk Assessments. An extensive formal risk assessment will support the Pacific Region's integrated management plan.

A Level I assessment may be the best method for assessing risk at the PNCIMA spatial scale. The next steps in the ERAF, the Semi-Quantitative Level 2 Risk Assessment and Quantitative Level 3 Risk Assessment may be best performed at local or regional scales, or on a few species of interest. The data requirements for Level 2 and 3 are much higher than the Level I Qualitative risk assessment completed here and for many of the SECs, existing data may be insufficient data. The Level 1 risk assessment can help to highlight gaps related to a lack of data (which may be filled with some monitoring effort) and gaps related to a lack of knowledge (which may require a longer reasearch program to address). A Level 2 risk assessment could be completed on specific SECs or activities of research or management interest with sufficient data quality. The Level 2 risk assessment has been developed to assess risk to MPAs along the BC coast (i.e., Bowie Seamount and Endeavour Hydrothermal Vents). These regions are small, have relatively few activities and stressors, and have a smaller set of SECs making them more suitable for use with the higher-level risk assessments. Identifying the best uses for each level of the ERAF will be an important requirement for future use of these risk assessments.

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APPENDIX 1. ACTIVITIES AND ASSOCIATED STRESSORS IDENTIFIED IN THE PNCIMA.

Appendix Table 1. Full list of activities and associated stressors identified in the PNCIMA.Stressors followed by an asterisk (*) were included in the current pilot study.

Sea	Sea	Sea	Sea	Land
Dive Fisheries Acoustic Direct Capture* Habitat Disturbance* Small Vessel Use*	*Finfish Aquaculture* Acoustic* Barrier to Fish Passage Contaminants* Disease & Parasites Erosion Fish Escapement* Habitat Disturbance Incidental Mortality Nutrient Input* Predatory Control* Sedimentation Shading Small Vessel Use*	*Military Operations* Acoustic Contaminants Debris Munitions Disposal Small Vessel Use	*Small Vessel Use* Acoustic* Boat Wake Contaminants* Debris Disruption of Wildlife Habitat Disturbance Incidental Mortality* Invasive Species* Nutrient Input* Oil Spill* Sedimentation Vessel Strikes	*Agriculture* Contamintants Nutrient Input Sedimentation
Gillnet Fisheries Bycatch* Debris Derelict Fishing Gear Direct Capture* Small Vessel Use*	*Large Vessel Use* Acoustic* Boat Wake Contaminants* Debris Disruption of Wildlife Habitat Disturbance Incidental Mortality Invasive Species* Light Nutrient Input* Oil Spill Sedimentation Vessel Strikes*	*Offshore Oil & Gas* Acoustic Contaminants Debris Habitat Disturbance Incidental Mortality Light Oil Spill Sedimentation Seismic Surveys	*Water Diversions* Barrier to fish passage* Change in water flow* Habitat Disturbance Incidental Mortality	*Aluminum Smelter* Contaminants Debris Nutrient Input Sedimentation Temperature Change
Hand Digging Direct Capture*	*Log Handling* Acoustic Change in Water Flow Contaminants* Debris* Habitat Distrubance* Nutrient Input Obstruction Shading Small Vessel Use*	*Ports, Marinas, Harbours* Acoustic Change in Water Flow* Contaminants* Debris Habitat Disturbance* Incidental Mortality Large Vessel Use Light Nutrient Input* Obstruction Oil Spill Sedimentation Shading Small Vessel Use* Temperature Change	*Wind Energy* Acoustic Change in Water Flow Collision Contaminants Decommissioning of Turbines Electrical Transmission Habitat Disturbance Sedimentation Seismic Surveys Small Vessel Use	*Forestry* Contaminants Debris Habitat Disturbance Nutrient Input Sedimentation Temerpature Change Water Temperature
Hook and Line Bycatch* Derelict Fishing Gear Direct Capture* Small Vessel Use*	*Marine Tourism* Acoustic Contaminants Debris Disruption of Wildlife Habitat Disturbance* Nutrient Input Small Vessel Use*	*Shellfish Aquaculture* Acoustic Barrier to Fish Passage Change in Water Flow Contaminants Debris Disease and Parasites Habitat Disturbance Incidental Mortality Invasive Species* Nutrient Introduction Sedimentation Shading* Small Vessel Use*	**Long Term** Climate Change Circulation Change Freshwater Input Log Handling Ocean Acidification* Sea Level Rise* Strom Frequency Temperature Change*	*Forestry* Contaminants Debris Habitat Disturbance Nutrient Input Sedimentation Temerpature Change Water Temperature
Recreational Fishing Bycatch* Derelict Fishing Gear Direct Capture* Incidental Mortality Sedmentation Small Vessel Use*			*Long Range Contamination* Marine Debris* Persistant Organic Pollutants*	*Human Settlement* Acoustic Contaminants* Debris* Habitat Disturbance Nurtient Input* Sedimentation* Waste Water
Seine Fisheries Bycatch* Derelict Fishing Gear Direct Capture* Small Vessel Use*			*Ozone and UV Radiation* Ozone and UV Radiation	*Land-based Activities* Contaminants* Nutrient Input* Sedimentation* Temperature Change*
Trap Fisheries Bycatch* Derelict Fishing Gear Direct Capture* Incidental Mortality Sedimentation Small Vessel Use*				*Mining (Onshore)* Acoustic Contaminants Debris Nutrient Input Sedimentation
Trawling Bycatch* Derelict Fishing Gear Direct Capture* Habitat Disturbance* Large Vessel Use* Sedimentation*				*Pulp and Paper Mills* Acoustic Contaminants Debris Nutrient Input Sedimentation Temperature Change
Trolling Bycatch* Derelict Fishing Gear Direct Capture* Habitat Disturbance Small Vessel Use*				

APPENDIX 2. MATRIX OF SPECIES AND STRESSORS ASSESSED IN PNCIMA PILOT PROJECT.

Appendix Table 2. Pilot Project Stressor-SEC Matrix (as of December 3^{rd}, 2012) with 17 SECs and a subset of activities and stressors. Cells with 1's indicate a potential interactions between SEC and stressor while blank spaces indicate no potential interaction.

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Fisheries																	
Dive Fisheries																	
Direct Capture							1										
Habitat Disturbance							1	1									
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Gillnet Fisheries																	
Bycatch					1	1				1	1		1			1	1
Direct Capture										1			1				

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Hand Digging																	
Direct Capture			1	1			1										
Hook and Line																	
Bycatch					1	1					1	1					
Direct Capture											1	1					
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Recreational Fishing																	
Bycatch								1	1	1	1	1					
Direct Capture								1	1	1	1	1	1				
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Seine Fisheries																	
Bycatch										1	1		1				
Direct Capture										1	1		1				
Small Vessel_Acoustic														1	1	1	1

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Trap Fisheries																	
Bycatch								1	1		1	1					
Direct Capture								1	1								
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Trawling																	

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Bycatch					1	1	1	1	1	1	1	1	1			1	
Direct Capture									1		1	1					
Habitat Disturbance					1	1	1	1	1			1					
Sedimentation					1	1	1	1			1						
Small Vessel _Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Trolling																	
Bycatch										1	1	1				1	1
Direct Capture										1							
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Land																	
Human Settlement																	
Contaminants	1	1	1	1	1	1		1	1	1	1	1	1		1	1	1
Debris		1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
Nutrient Input	1	1	1	1	1	1		1	1	1		1					
Sedimentation			1	1	1	1		1		1							
Land-based Activities																	
Change in freshwater flow	1	1	1	1			1	1	1	1			1				
Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nutrient Input	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	
Sedimentation			1	1	1	1	1	1	1	1	1	1	1	1		1	1

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
LongTerm																	
Climate Change																	
Ocean Acidification	1	1	1	1	1	1			1								
Sea level rise			1	1				1		1						1	1
Temperature Change	1	1	1	1	1	1	1	1	1	1	1	1	1			1	1
Long Range Contamination	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	2
Marine Debris		1	1	1	1	1	1	1	1	1	1	1	1				1
Persistent Organic Pollutants	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sea																	
Finfish Aquaculture																	
Acoustic													1	1	1	1	
Contaminants	1	1		1		1	1	1	1	1	1	1					
Fish Escapement										1							
Nutrient Input	1	1	1	1	1	1	1			1		1					
Predatory Control																1	

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Large Vessel Use																	
Acoustic														1	1	1	1
Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Incidental Mortality			1	1	1	1								1	1	1	
Invasive Species	1	1	1	1	1	1	1	1		1							
Nutrient Input	1	1	1	1	1	1	1	1	1	1		1	1				
Oil Spill	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Log Handling																	
Contaminants	1	1			1	1		1	1	1	1	1					1

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Debris			1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Habitat Disturbance			1	1			1	1		1		1		1	1	1	
Nutrient Input	1	1			1	1				1							
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Marine Tourism																	
Disruption of Wildlife														1	1	1	
Habitat Disturbance			1		1	1											
Large Vessel_Acoustic														1	1	1	1
Large Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Large Vessel_Incidental Mortality			1	1	1	1								1	1	1	

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Large Vessel_Invasive Species	1	1	1	1	1	1	1	1		1							
Large Vessel_Nutrient Input	1	1	1	1	1	1	1	1	1	1		1	1				
Large Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Ports, Marinas, Harbours																	
Change in water flow	1	1	1	1	1	1	1	1	1	1		1	1				
Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1		1		
Habitat Disturbance			1	1		1	1	1	1	1		1				1	
Large Vessel_Acoustic														1	1	1	1
Large Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1

Activities and Stressors	**Phytoplankton**	**Zooplankton**	**Kelp**	**Seagrasses**	**Cold Water Coral**	**Sponges**	**Geoduck clam**	**Dungeness Crab**	**Prawn**	**Salmon**	**Spiny Dogfish**	**Lingcod**	**Pacific Herring**	**Humpback Whale**	**Resident Killer Whale**	**Steller Sea Lion**	**Cassin's Auklet**
Large Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Large Vessel_Invasive Species	1	1	1	1	1	1	1	1		1							
Large Vessel_Nutrient Input	1	1	1	1	1	1	1	1	1	1		1	1				
Large Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Nutrient Input	1	1	1	1	1	1	1	1	1	1		1					
Small Vessel_Acoustic														1	1	1	1
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_IncidentalMortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Shellfish Aquaculture																	
Invasive Species	1	1	1	1			1	1		1							
Shading			1	1													
Small Vessel_Acoustic														1	1	1	1

Activities and Stressors	Phytoplankton	Zooplankton	Kelp	Seagrasses	Cold Water Coral	Sponges	Geoduck clam	Dungeness Crab	Prawn	Salmon	Spiny Dogfish	Lingcod	Pacific Herring	Humpback Whale	Resident Killer Whale	Steller Sea Lion	Cassin's Auklet
Small Vessel_Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Small Vessel_Incidental Mortality			1	1	1	1								1	1	1	
Small Vessel_Invasive Species	1	1	1	1	1	1	1	1									
Small Vessel_Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Small Vessel_Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1
Small Vessel Use																	
Acoustic														1	1	1	1
Contaminants	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
Incidental Mortality			1	1	1	1								1	1	1	
Invasive Species	1	1	1	1	1	1	1	1									
Nutrient Input	1	1	1	1		1	1	1	1	1			1				
Oil Spill	1	1	1	1	1	1	1	1	1	1	1		1	1		1	1

APPENDIX 3. R CODE FOR METHOD 2 UNCERTAINTY INCORPORATION CALCULATIONS OF RISK AND CUMULATIVE RISK.

In order to calculate risk and cumulative risk with Method 2 Uncertainty Propagation, the following R code is available. The data must be in the format specified in Table 1 below.

Table 1. Example of .csv datasheet for use with the uncertainty propagation code. Row 2 and 3 of the table are examples of each risk relationship scored, in the actual data sheet there may be 100s or 1000s of these rows of SEC-stressor risk relationships.

SEC	Sector	Activity	Stressor	Intensity	intunc	Temporal. Scale	tempunc	Spatial. Scale	spaunc	Consequence	concunc
Prawn	Sea	Trawling	Bycatch	3	1	1	1	1	1	3	4
Prawn	Land	Human Settlement	Debris	2	2	1	1	1	1	2	3

```
#Uncertainty Propagation Code

#Developed for use with R by Gerald Singh (PhD Student, Resource Management and Environmental Studies, University of British Columbia)

#December 13, 2012


#Open "car" Package

library(car)

#Open file that contains columns of VEC, Activity, Stressor, Intensity Score, Temporal Scale Score, Spatial Scale Score and Consequence Risk Scores

imp <- read.csv(file.choose(), stringsAsFactors = FALSE, strip.white = TRUE)


#Label the exposure and consequence variables, assign the columns in the datasheet that contain these data to these labels

imp1<-imp

Int<-as.numeric(imp1$Intensity)

Temp<-as.numeric(imp1$Temporal.Scale)

Spa<-as.numeric(imp1$Spatial.Scale)

Con<-as.numeric(imp1$Consequence)


#Define uncertainty bounds, where an uncertainty of 1 is assigned a standard deviation of 0.2 while uncertainty of 5 is assigned a standard deviation of 1

unc1<-0.2

unc2<-0.4

unc3<-0.6

unc4<-0.8

unc5<-1


#Apply uncertainty bounds based on code, these are on a scale between 1 and 5
```

```
imp1$intunc<-
ifelse(imp1$intunc==1,unc1,
ifelse(imp1$ intunc ==2,unc2,
ifelse(imp1$ intunc ==3,unc3,
ifelse(imp1$ intunc ==4,unc4,
ifelse(imp1$ intunc ==5,unc5,0))))) #uncertainty around Intensity

imp1$tempunc<-
ifelse(imp1$ tempunc ==1,unc1,
ifelse(imp1$ tempunc ==2,unc2,
ifelse(imp1$ tempunc ==3,unc3,
ifelse(imp1$ tempunc ==4,unc4,
ifelse(imp1$ tempunc ==5,unc5,0))))) #uncertainty around Temporal

imp1$spaunc<-
ifelse(imp1$ spaunc ==1,unc1,
ifelse(imp1$ spaunc ==2,unc2,
ifelse(imp1$ spaunc ==3,unc3,
ifelse(imp1$ spaunc ==4,unc4,
ifelse(imp1$ spaunc ==5,unc5,0))))) #uncertainty around Spatial

imp1$concunc<-
ifelse(imp1$ concunc ==1,unc1,
ifelse(imp1$ concunc ==2,unc2,
ifelse(imp1$ concunc ==3,unc3,
ifelse(imp1$ concunc ==4,unc4,
ifelse(imp1$ concunc ==5,unc5,0))))) #uncertainty around Consequence

#Random selection of risk score based on normal distribution curve as assigned by the uncertainty score (and assigned standard deviation), replicated 100 times

spac<-paste(imp1[,1],",",imp1[,3],",",imp1[,4]) #assign the columns that will be the label for each row, in our data sheet column 1 is VEC, column 3 is Activity, and column 4 is Stressor. Comma's were added for easy splitting of text to columns in Excel for viewing and sorting results.

randrisk<-array(NA,dim=c(nrow(imp1),4,100))
for(k in 1:100){for(i in 1:nrow(imp1)) {randrisk[i,1,k]<-Int[i]+(rnorm(1,0,imp1$intunc[i]))
```

```
            randrisk[i,2,k]<-Temp[i]+(rnorm(1,0,imp1$tempunc[i]))
            randrisk[i,3,k]<-Spa[i]+(rnorm(1,0,imp1$spaunc[i]))
            randrisk[i,4,k]<-Con[i]+(rnorm(1,0,imp1$concunc[i]))}

      {rownames(randrisk)<-spac
      colnames(randrisk)<-c("Int","Temp","Spa","Con")}

#Sets the upper and lower bounds so risk scores do not go above or below the range of the variables being sampled

randrisk[,1,]<-recode(randrisk[,1,],"lo:1=1");randrisk[,1,]<-recode(randrisk[,1,],"3:hi=3") #Intensity - scored between 1 and 3
randrisk[,2,]<-recode(randrisk[,2,],"lo:1=1");randrisk[,2,]<-recode(randrisk[,2,],"4:hi=4") #Temporal Scale - scored between 1 and 4
randrisk[,3,]<-recode(randrisk[,3,],"lo:1=1");randrisk[,3,]<-recode(randrisk[,3,],"3:hi=3") #Spatial Scale - scored between 1 and 3
randrisk[,4,]<-recode(randrisk[,4,],"lo:1=1");randrisk[,4,]<-recode(randrisk[,4,],"6:hi=6") #Consequence - scored between 1 and 6

#hist(randrisk[1,4,],breaks=50)

#hist(lograndrisk[1,4,],breaks=50)

#### Producing Risk Scores ####

#Produce summary statistics on the various risk scores giving mean and error (the 10 and 90% quantiles) for every VEC and stressor interaction across all 100 runs

stat<-array(NA,dim=c(nrow(imp1),12))
for(i in 1:nrow(imp1)) {
      stat[i,1]<-mean(randrisk[i,1,1:k],na.rm=T)
      stat[i,2]<-quantile(randrisk[i,1,1:k],probs=c(0.1),names=F,na.rm=T)
      stat[i,3]<-quantile(randrisk[i,1,1:k],probs=c(0.9),names=F,na.rm=T)
      stat[i,4]<-mean(randrisk[i,2,1:k],na.rm=T)
      stat[i,5]<-quantile(randrisk[i,2,1:k],probs=c(0.1),names=F,na.rm=T)
      stat[i,6]<-quantile(randrisk[i,2,1:k],probs=c(0.9),names=F,na.rm=T)
      stat[i,7]<-mean(randrisk[i,3,1:k],na.rm=T)
      stat[i,8]<-quantile(randrisk[i,3,1:k],probs=c(0.1),names=F,na.rm=T)
      stat[i,9]<-quantile(randrisk[i,3,1:k],probs=c(0.9),names=F,na.rm=T)
```

```
	stat[i,10]<-mean(randrisk[i,4,1:k],na.rm=T)
	stat[i,11]<-quantile(randrisk[i,4,1:k],probs=c(0.1),names=F,na.rm=T)
	stat[i,12]<-quantile(randrisk[i,4,1:k],probs=c(0.9),names=F,na.rm=T)

	rownames(stat)<-spac
	colnames(stat)<-
c("IntMean","10%Q","90%Q","TempMean","10%Q","90%Q","SpaMean","10%Q","90%Q","ConMean","10
%Q","90%Q")}

####Produce Exposure and Consequence Scores across 100 iterations ###

expcon<-array(NA,dim=c(nrow(imp1),2,100))
for(i in 1:nrow(imp1)) {
	for(k in 1:100){
		expcon[i,1,k]<-randrisk[i,1,k]*randrisk[i,2,k]*randrisk[i,3,k]

		expcon[i,2,k]<-randrisk[i,4,k]^2

	rownames(expcon)<-spac
	colnames(expcon)<-c("Exposure","Consequence")}}

###Produce Total Risk Scores across 100 iterations###

risk<-array(NA,dim=c(nrow(imp1),1,100))
for(i in 1:nrow(imp1)) {
	for(k in 1:100){
		risk[i,1,k]<-randrisk[i,1,k]*randrisk[i,2,k]*randrisk[i,3,k]*randrisk[i,4,k]^2

	rownames(risk)<-spac
	colnames(risk)<-"Risk"}}

#hist(risk[1,1,],breaks=50)

####Summary Stats for exposure and consequence for every VECxActivity/Stressor combination###

statexpcon<-array(NA,dim=c(nrow(imp1),6))
for(i in 1:nrow(imp1)) {
	statexpcon[i,1]<-mean(expcon[i,1,1:k],na.rm=T)
```

```
	statexpcon[i,2]<-quantile(expcon[i,1,1:k],probs=c(0.1),names=F,na.rm=T)
	statexpcon[i,3]<-quantile(expcon[i,1,1:k],probs=c(0.9),names=F,na.rm=T)

	statexpcon[i,4]<-mean(expcon[i,2,1:k],na.rm=T)
	statexpcon[i,5]<-quantile(expcon[i,2,1:k],probs=c(0.1),names=F,na.rm=T)
	statexpcon[i,6]<-quantile(expcon[i,2,1:k],probs=c(0.9),names=F,na.rm=T)

	rownames(statrisk)<-spac
	colnames(statrisk)<-c("ExpMean","10% Quantile","90% Quantile","ConMean","10%
Quantile","90% Quantile")}

###Record Exposure and Consequence summary stats for every VECxActivity/Stressor combination###

write.table(statexpcon,file="RiskScoresExpConCalc.csv",col.names=NA,sep=",") #Summary table for
every Exposure and Consequence Score
write.table(logstatexpcon,file="RiskScoresExpConCalcTrans.csv",col.names=NA,sep=",") #Summary
table for every Exposure and Consequence Score

#Summary Stats for Risk Scores for every VECxActivity/Stressor combination###

statrisk<-array(NA,dim=c(nrow(imp1),3))
for(i in 1:nrow(imp1)) {
	statrisk[i,1]<-mean(risk[i,1,1:k],na.rm=T)
	statrisk[i,2]<-quantile(risk[i,1,1:k],probs=c(0.1),names=F,na.rm=T)
	statrisk[i,3]<-quantile(risk[i,1,1:k],probs=c(0.9),names=F,na.rm=T)

	rownames(statrisk)<-spac
	colnames(statrisk)<-c("RiskMean","10% Quantile","90% Quantile")}

###Record output into .csv files for every VECxActivity/Stressor combination###

write.table(stat,file="RiskScoresExpCon.csv",col.names=NA,sep=",") #Summary table for every Exposure
and Consequence Score
write.table(statrisk,file="RiskScoresRaw.csv",col.names=NA,sep=",") #Summary table for combined raw
risk score for every VEC x activity combination

####Look at Cumulative Risk for each VEC #####

species<-imp1[,1]
```

```
as.list(species)

agrisk<-aggregate(risk,list(species),sum,na.rm=T)

agriska<-as.data.frame(t(agrisk[,-1])) ##Creates a dataframe with all cumulative risk scores across 100 replications


colnames(agriska)<-agrisk[,1]


##Summary Stats for Cumulative Risk Scores for each VEC #####


statagrisk<-array(NA,dim=c(length(agrisk[,1]),3))

for(i in 1:length(agrisk[,1])) {

        statagrisk[i,1]<-mean(agriska[1:length(agrisk[,1]),i])

        statagrisk[i,2]<-quantile(agriska[1:length(agrisk[,1]),i],probs=c(0.1),names=F)

        statagrisk[i,3]<-quantile(agriska[1:length(agrisk[,1]),i],probs=c(0.9),names=F)


        rownames(statagrisk)<-agrisk[,1]

        colnames(statagrisk)<-c("AgRiskMean","10%Q","90%Q")}

write.table(statagrisk,file="CumRiskVEC.csv",col.names=NA,sep=",") #Summary table for aggregate risk to VECs
```

APPENDIX 4. ACTIVITY-STRESSOR EXPOSURE RISK SCORES AND JUSTIFICATION

Table 1: Exposure scores and description for each Activity-Stressor examined in the pilot project. Exposure scores were common across SECs and detailed in the following table, TS = Temporal Scale, SS = Spatial Scale, Int = Intensity, Exp = Exposure score and U = Uncertainty. The Uncertainty value following each Exposure variable is specific to that variable, includes justification from literature.

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Climate change	Ocean acidification	1	3	1	3	3	1	3	Harley et al. 2006: "When compared with physically driven changes such as warming and sea level rise, the impacts of chemical changes in the ocean are poorly understood. Short-term experimental elevation of CO2 results in reductions in subcellular processes such as protein synthesis and ion exchange (for review, see Pörtner & Langenbuch 2005). These physiological effects are more pronounced for invertebrates than for fish (Pörtner & Langenbuch 2005), suggesting that certain taxa may be disproportionately affected by changes in CO2 and pH."
Climate change	Sea level rise	1	3	1	3	3	1	3	Harley et al. 2006: "Sea level rise impacts on marine ecosystems are the least studied consequence of climate change. The most obvious consequence of sea level rise will be an upward shift in species distributions. Most species are expected to be able to keep pace with predicted rates of sea level rise, with the exception of some slow-growing, longlived species such as many corals (see Knowlton 2001 for review). However, dramatic ecological changes could result from decreased habitat availability within a particular depth zone. For example, intertidal habitat area may be reduced by 20–70% over the next 100 years in ecologically important North American bays, where steep topography and anthropogenic structures (e.g. sea walls) prevent the inland migration of mudflats and sandy beaches (Galbraith et al. 2002). Sea level rise may also reduce the spatial extent of biogenic habitat by outpacing the accretion rates of marshes and coral reefs (Knowlton 2001; Scavia et al. 2002)."
Climate change	Temperature change	1	3	1	4	3	1	3	fu et al. 2008: "A range of models and greenhouse gas and aerosol emissions scenarios project global average warming from +1 to +6 C by the year 2100 (IPCC 2007). For the Pacific Northwest (coastal North America from northern California to southern British Columbia, Figure 1), warming is projected to be near the global average."

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Dive Fisheries	Direct Capture	1	1	2	1	1	1	2	Booth et al. 2007[1]: Dive fishery for Pacific Geoduck, sea urchin
Dive Fisheries	Habitat Disturbance	1	1	2	1	1	1	2	Fuller et al. 2008: Hydraulic tools used in diving in the Pacific Geoduck fishery can disturb sediment and infauna. There is also the potential to disturb kelp and invertebrates through handling of the species.
Finfish Aquaculture	Acoustic	2	1	4	1	1	1	8	Booth et al. 2007[1]: "Declines in killer whales and Pacific white-sided dolphins were attributed to noise avoidance (from acoustic deterrence devices). Changes in behavior of harbour porpoises and herring are also believed to be related to sensitivity to high frequency noise and sound pressure."
Finfish Aquaculture	Contaminants	2	1	4	1	1	1	8	Booth et al. 2007[1]: "Contaminants include antifouling paints, wood treatment, antibiotics and disease chemical treatments. Copper based anti-fouling paint is toxic to aquatic organisms, such as phytoplankton, zooplankton, amphipods and mollusks. Sealice agents are toxic to crustaceans. Antibiotics are toxic to phytoplankton, zooplankton and possibly other species. Although generally of low toxicity to most species, antibiotics have the risk of developing resistant strains of microorganisms that have the potential to transfer genetic resistance traits among bacteria of the same or of different species."
Finfish Aquaculture	Fish Escapement	2	1	3	1	2	1	12	Booth et al. 2007[1]: "The escapement of Atlantic Salmon can cause stress to wild salmon populations in terms of additional competition for resources. The escapement of cultured fish has the potential to spread domesticated genes into wildfish populations. Escaped Atlantic salmon have potential to out compete wild salmon in some river systems (Volpe et al. 2001, Naylor et al. 2005)."

[1] Booth, J., Dale, N., and Haggarty, D. 2007. Ecosystem Assessment Pacific North Coast Management Area (PNCIMA). Unpublished technical report.

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Finfish Aquaculture	Nutrient Input	2	1	4	1	1	1	8	Booth et al. 2007[1]: "Accumulation of organic waste food and feces below net pens cause reductions in benthic faunal diversity, increased community metabolism and creation of anoxic conditions. Salmon aquaculture may introduce nutrients from waste food and feces, and possibly increase the risk of algal blooms. Reductions in benthic faunal diversity, increased community metabolism and creation of anoxic conditions have been quantitatively related to organic matter supply (Hall et al. 1990, Holmer and Kristensen. 1992, Lim and Gratto 1992, Hargrave et al. 1993, Hargrave 1994, Pohle et al. 1994, Hargrave et al. 1997, Pohle and Frost 1997, Wong et al. 1999, Brooks et al. 2003)."
Finfish Aquaculture	Predator Control	2	1	4	1	1	1	8	Booth et al. 2007[1]: Includes the shooting or trapping of seals and sea lions as a form of predator control in aquaculture facilities.
Gillnet Fisheries	Bycatch	1	3	1	3	1	3	1	Booth et al. 2007[1]: "Bycatch of species that have the potential to be caught in fisheries by gear type, including salmon, sea otters, porpoises, sea turtles and more. Bycatch can be defined as the unintended or incidental catch of non-target species. There are a variety of types of bycatch. They can be categorized as regulatory discards and economic discards. Regulatory discards are fish harvested in a fishery which fishermen are required by regulation to discard whenever caught, or are required by regulation to retain but not sell. Economic discards are fish which are not retained because there is no or limited market for them."
Gillnet Fisheries	Direct Capture	2	1	3	1	3	1	18	Booth et al. 2007[1]: Surface gillnets have more buoyant cork lines, float at or near the surface, and may be anchored in place with weights or moored to the vessel from which it was deployed. Surface gillnets are used in all regions to target salmonids (e.g. Pacific Salmon, Arctic Char) as well as small pelagic species (e.g. herring, mackerel).
Hand Digging	Direct Capture	2	3	4	2	2	2	16	Booth et al. 2007[1]: Hand digging for shellfish
Hook and Line	Bycatch	2	1	3	1	2	1	12	Booth et al. 2007[1]: Bycatch of species that have the potential to be caught in fisheries by gear type, including salmon, sea otters, porpoises, sea turtles and more.

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Hook and Line	Direct Capture	2	1	3	1	2	1	12	Booth et al. 2007[1]: "In general, there are two types of hook and line gear used in these fisheries, longline and handline. Typically, the former delivers "iced" fish while the latter delivers live fish to market (Bonnet and Hardy, 2003). Hook and line fishermen target halibut, blackcod, dogfish, lingcod, inshore rockfish (primarily yelloweye, quillback, tiger, and china) and slope rockfish (primarily rougheye, shortraker and redbanded), and generally use squid as bait. Prior to 2005, the hook and line fishery was divided into five management zones but later adopted the eight zones used in the other groundfish fisheries (Figure 9). The hook and line fishery is generally distributed over near shore reef habitats which are unable to be exploited by trawl."
Human Settlement	Contaminants	2	1	3	1	2	1	12	Booth et al. 2007[1]: "The principal categories of concern tend to be pollution, especially from sewage and, in some places, land reclamation on wetlands for housing and commercial development. In large urban areas runoff from paved surfaces is a major source of various contaminants. Sewage sludge can be toxic to many different organisms, and have different effects through life cycle stages. Contaminants include organochlorines, heavy metals, and pharmaceuticals."
Human Settlement	Debris	2	4	3	3	3	3	18	Dayton et al. 1995: "Marine debris includes all human-origin debris. Floating plastic debris has become a major concern as it has low degradation rates and leaches contaminants. A range of wildlife species have been shown to consume plastic debris and suffer mortality, lesions, starvation and infections as a result."
Human Settlement	Nutrient input	2	1	3	1	2	1	12	Booth et al. 2007[1]: "The principal categories of concern tend to be pollution, especially from sewage and, in some places, land reclamation on wetlands for housing and commercial development."
Human Settlement	Sedimentation	1	1	3	1	2	1	6	Booth et al. 2007[1]: The construction of roads can impact anadromous fish through the alteration of water flow and consequently siltation.
Land-based Activities	Change in Freshwater Input	2	1	2	1	2	1	8	Now includes freshwater input from multiple activities (Agriculture, Aluminum Smelter, Forestry, Onshore Mining and Pulp Paper Mills).

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Land-based Activities	Contaminants	2	3	4	3	2	3	16	Now includes contaminants from multiple activities (Agriculture, Aluminum Smelter, Forestry, Onshore Mining and Pulp Paper Mills). Heavy metal bioaccumulation can have impacts on marine mammals and species of fish.
Land-based Activities	Nutrient Input	1	3	3	3	1	3	3	Now includes nutrient input from multiple activities (Agriculture, Aluminum Smelter, Forestry, Onshore Mining and Pulp Paper Mills).
Land-based Activities	Sedimentation	2	1	4	1	1	1	8	Now includes sedimentation from multiple activities (Agriculture, Aluminum Smelter, Forestry, Onshore Mining and Pulp Paper Mills). Higher sediment loadings from land-based activities can cause coastal areas to become over-productive and either hypoxic or anoxic (Goolsby 2000)
Large Vessel Use	Acoustic	2	1	4	1	3	1	24	Booth et al. 2007[1]: “Low frequency noise from engines, propellers and other commercial shipping noise can have impacts on marine mammals. Cumulative impacts of ocean noise are becoming a major concern. Also blasting, sonar and fog horns increase noise levels. Depending on the frequency and the incidence of acoustic emissions, problems for marine mammals range from disturbance and avoidance through the masking of important auditory cues, to short-term, long term damage and even mortality (Richardson 1995).”
Large Vessel Use	Contaminants	2	1	3	1	1	1	6	Booth et al. 2007[1]: “The amount of contaminants discharged into the water depends on the type of engine used. 2 Although regulations attempt to minimize potential contamination, vessel coatings can be sources of anti-fouling chemicals, copper, and zinc. These chemicals can be harmful to a wide variety of marine organisms. Especially in semi-enclosed areas, the addition of phosphates, nitrates in sewage as well as coliform contamination can lead to changes in structure and function of marine communities. Scraping down of boats and treatment of hulls with antifoulants (usually copper and arsenic-based paints) is one of the main causes for release of toxic substances into the tidal area. A once commonly used highly toxic antifoulant TBT (tributyltin) was banned in 2003 on boats under 25 metres in length but is still used in slow release compounds for larger vessels.”

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Large Vessel Use	Incidental Mortality	2	1	2	1	2	1	8	Gregr et al. 2006: Vessel strikes can result in the mortality of whales, and is more problematic in species which spend time in the shallower waters closer to shore, which often correspond to shipping lanes. Incidental mortality can also occur during grounding events, propeller scouring and anchor dragging.
Large Vessel Use	Invasive Species	2	3	3	2	2	2	12	Booth et al. 2007[1]: "Many invasive species have been introduced to the Pacific Coastal waters through ballast water and attached to ships. Examination of ballast water upon arrival of vessels has revealed bacteria (McCarthy and Khambaty 1994), protiests (Galil and Hulsmann 1997, Pierce et al. 1997), dinofagellates (Hallegraeff and Bolch 1991), diatoms, zooplankton, benthic invertebrates, and fish (Williams et al. 1988, Carlton and Geller 1993, Wonham et al. 2000). Other exotic "hitch-hikers" arrive as organisms that have encrusted on hulls."
Large Vessel Use	Nutrient Input	2	1	3	1	1	1	6	Warren 2011: Excess macronutrient input into the marine environment can increase biomass of phytoplankton and gelatinous zooplankton, and change the level of production of macrophytes and vascular plants. Forestry, agriculture, vessel use and marine tourism have been identified by Warren (2011) as potential human activities that lead to nutrient introduction in the marine environment. can reduce the health and size of marine coral populations.
Large Vessel Use	Oil spill	3	1	1	1	3	1	9	Burger 1993: The marine ecological consequences of a major oil spill have been studied opportunistically in many parts of the world. While quite rare, these events carry disastrous effects. Global and North American estimates are that recreational vessels exceed tankers as a chronic source (National Research Council of the National Academies (US) 2002).

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Log handling	Contaminants	2	1	3	1	1	1	6	Booth et al. 2007[1]: "The consequences of log-handling sites are intensified by increased biochemical oxygen demand (BOD), production of hydrogen sulfide and ammonia during log decomposition and woody debris, and the release of leachates from logs. Dilution usually prevents accumulation of contaminants, but in poorly flushed areas, this can be a problem. Epibenthic organisms were less abundant in poorly flushed log handling areas where decomposing bark and wood debris had accumulated. Storm runoff from the log handling area may contain significant concentrations of resin acids (Tian et al. 1998); these may be toxic to marine fish. Contaminants from wood storage include phenols, tropolones, resin acids, tannins and lignins and volatile fatty acids."
Log handling	Debris	2	1	3	1	1	1	6	Booth et al. 2007[1]: "Wood waste deposition at an industrial log-handling site was shown to impact bivalves. In such poorly flushed locations the build up of wood debris and soluble wastes can create significant local harm to benthic communities and bottom feeders."
Log handling	Habitat disturbance	2	1	3	1	1	1	6	Booth et al. 2007[1]: "Contact of logs with surface and disturbance from anchoring structures. Clams, crabs, oysters, sedentary polychaetes and macrophytes may be affected when logs come into contact with the bottom substrate during log dumping. Log abrasion can remove intertidal algae, affecting invertebrate abundance, and/or species composition of invertebrate communities. Life history phases most likely to be affected by log handling and storage operations are rearing, migration, spawning and incubation. Impacted species include anadromous salmonid species, marine smelts, herring, rockfishes, and bottom dwelling species."
Log handling	Nutrient input	2	1	3	1	1	1	6	Warren 2011: Excess macronutrient input into the marine environment can increase biomass of phytoplankton and gelatinous zooplankton, and change the level of production of macrophytes and vascular plants. Forestry, agriculture, vessel use and marine tourism have been identified by Warren (2011) as potential human activities that lead to nutrient introduction in the marine environment can reduce the health and size of marine coral populations.
Long range contaminants	Marine debris	1	3	4	3	3	4	12	Marine debris does not include derelict fishing gear within this stressor, but is considered separately under fishing activities

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Long range contaminants	Persistent organic pollutants	1	3	4	1	3	1	12	Johannessen et al. 2007: "Global pollutants of concern today typically comprise those chemicals considered as persistent, bioaccumulative and toxic (PBT chemicals). Such chemicals can readily move into remote regions, such as the PNCIMA, do not degrade quickly, accumulate in aquatic food webs, and cause endocrine disruption in biota. Legacy POPs remain a potential contaminant issue in PNCIMA, despite its remote nature and sparse human population. A number of factors influence the movement of chemicals away from source and their accumulation in food webs, including their volatility, solubility in waters (or lipids), and their persistence (half-life) in the environment. Species that are vulnerable to the accumulation of high levels of PBT compounds and their associated effects include those at the top of aquatic food webs, such as fish-eating seabirds, seals, whales, and terrestrial species relying on marine foods. Organochlorines are readily transported through the atmosphere and thus are found in regions considered to be pristine and removed from direct sources of these contaminants (Phillips, 1995). For example, PCB congeners have been measured in the brown alga Desmarestia sp. from the Antarctic Peninsula, far from any direct sources (Montone et al., 2001). POP sources include pesticides, industrial products and byproducts. There has been little testing of the levels of POPs in PNCIMA and the temporal and spatial scale of their introduction into the region remains uncertain."
Marine Tourism	Disruption of Wildlife	2	3	4	1	3	1	24	Booth et al. 2007[1]: Active pursuit of marine mammals for tourism (whale watching etc)
Marine Tourism	Habitat Disturbance	1	3	2	1	3	2	6	Di Franco et al. 2009: During SCUBA recreational diving humans often make contact with the benthic community, which can cause damage to invertebrates, macrophytes and resident fish.
Ports, Marinas, Harbours	Change in water flow	2	1	4	1	1	1	8	Booth et al. 2007[1]: "Changes in local circulation pattern through construction of piers, breakwaters, docks and pilings which can alter and interrupt currents."

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Ports, Marinas, Harbours	Contaminants	2	1	4	1	1	1	8	Johannesen et al. 2007: "Harbour dredging can cause the release of contaminants that have previously accumulated in muds. Use of treated wood structures can lead to introduction of toxic substances (creosote, CCA, PCP). Creosote-treated wood loses polyaromatic hydrocarbons (PAHs) to the water as long as the wood is in service. PCP in particular has been found in elevated levels in many parts of the BC coastal environment, including Campbell River's harbour, and is thought to originate from wood preservatives (Yunker et al. 2002). Metal oxide-treated wood leaches primarily in the first few weeks after installation, although some metals will continue to be lost at very low levels for months. Low levels of PAHs are biodegradable in aerobic sediments once appropriate microbial flora have become established. In anerobic sediments, PAHs may not be broken down appreciably (Hutton and Samis 2000). The leachates remain localized in sediments and high rates of tidal flushing will dilute and flush any accumulations in the water column (Sanger et al. 2004). Vessel maintenance and use of zinc anodes can lead to introduction of heavy metals and other toxins (can be cumulative) from paint residues from sand blasting, high pressure water cleaning and paint scraping during ship repairs. Even if all the waste is collected at ship repair yards, toxic compounds in antifouling paints will be released continuously from the hull and contaminate harbour sediments. Leaching of zinc from sacrificial anodes is est. at ~ .29 kg/yr for a typical yacht (Bird et al. 1996). Ports and marinas are sources of oil and polycyclie aromatic hydrocarbon (PAH) contamination. BC harbours have up to 260 times the PAH concentration of non-harbour sites."
Ports, Marinas, Harbours	Habitat Disturbance	2	1	1	1	1	1	2	Johannesen et al. 2007: "Harbour dredging, armouring of shorelines and construction of breakwaters can cause direct benthic habitat disturbance. Changes in intertidal and nearshore habitat and along-shore sediment movements. Change in habitat and possible changes in circulation, salinity, and temperature especially in estuaries."
Ports, Marinas, Harbours	Nutrient Input	2	1	3	4	1	1	6	Warren 2011: Excess macronutrient input into the marine environment can increase biomass of phytoplankton and gelatinous zooplankton, and change the level of production of macrophytes and vascular plants. Forestry, agriculture, vessel use and marine tourism have been identified by Warren (2011) as potential human activities that lead to nutrient introduction in the marine environment. Nutrient input can reduce the health and size of marine coral populations.

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Recreational Fishing	Bycatch	1	3	3	2	1	1	3	Booth et al. 2007[1]: Bycatch of species that have the potential to be caught in fisheries by gear type, including sea birds, salmon, sea otters, porpoises, sea turtles and more. Bycatch in recreational fisheries can include non-target species as well as juveniles and gravid females of the target species (e.g. dungeness crab).
Recreational Fishing	Direct Capture	1	3	3	2	1	1	3	Johannesen et al 2007: In this context, recreational fishing includes small boat hook and line, shoreline casting, pot and trap on a recreational license. The removal of biomass from the oceans through fisheries has often not been considered sustainable (Pauly *et al.* 2002). Overfishing is a term that is often used to describe a situation where the level of fishing mortality reduced the long-term capacity of a population to produce a maximum sustainable yield (MSY) on an on-going basis (Dayton *et al.* 2002).
Seine Fisheries	Bycatch	2	1	3	1	1	1	6	Booth et al. 2007[1]: Bycatch of species that have the potential to be caught in fisheries by gear type, including salmon, sea otters, porpoises, sea turtles and more.
Seine Fisheries	Direct Capture	2	1	3	1	1	1	6	
Shellfish Aquaculture	Invasive Species	2	1	1	1	2	1	4	Booth et al 2007[1]: "The introduction of non-native species (cultured shellfish) can increase levels of competition and cause subsequent displacement of native species."
Shellfish Aquaculture	Shading	2	1	4	1	1	1	8	Booth et al 2007[1]: "Shading of water column by aquaculture structures can reduce abundance of benthic invertebrates and reduce growth rates of benthic marine plants."
Small Vessel Use	Acoustic	2	1	4	1	3	1	24	Booth et al. 2007[1]: "Low frequency noise from engines, propellers and other commercial shipping noise can have impacts on marine mammals. Cumulative impacts of ocean noise are becoming a major concern. Also blasting, sonar and fog horns increase noise levels. Depending on the frequency and the incidence of acoustic emissions, problems for marine mammals range from disturbance and avoidance through the masking of important auditory cues, to short-term, long term damage and even mortality (Richardson 1995)."

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Small Vessel Use	Contaminants	1	3	3	2	2	2	6	Booth et al. 2007[1]: The amount of contaminants discharged into the water depends on the type of engine used. Although regulations attempt to minimize potential contamination, vessel coatings can be sources of anti-fouling chemicals, copper, and zinc. These chemicals can be harmful to a wide variety of marine organisms. "Especially in semi-enclosed areas, the addition of phosphates, nitrates in sewage as well as coliform contamination can lead to changes in structure and function of marine communities. Scraping down of boats and treatment of hulls with antifoulants (usually copper and arsenic-based paints) is one of the main causes for release of toxic substances into the tidal area. A once commonly used highly toxic antifoulant TBT (tributyltin) was banned in 2003 on boats under 25 metres in length but is still used in slow release compounds for larger vessels."
Small Vessel Use	Incidental mortality	2	1	2	1	2	1	8	Gregr et al. 2006: Vessel strikes can result in the mortality of whales, and is more problematic in species which spend time in the shallower waters closer to shore, which often correspond to shipping lanes. Incidental mortality of kelp and seagrass can occur during grounding events, propeller scouring and anchor drag
Small Vessel Use	Invasive Species	1	4	3	3	3	2	9	Booth et al. 2007[1]: Many invasive species have been introduced to the Pacific Coastal waters through hull fouling and live wells in small vessels. Other exotic "hitch-hikers" arrive as organisms that have encrusted on hulls.
Small Vessel Use	Nutrient Input	2	1	3	1	1	1	6	Warren 2011: Excess macronutrient input into the marine environment can increase biomass of phytoplankton and gelatinous zooplankton, and change the level of production of macrophytes and vascular plants. Forestry, agriculture, vessel use and marine tourism have been identified by Warren (2011) as potential human activities that lead to nutrient introduction in the marine environment. Can reduce the health and size of marine coral populations.
Small Vessel Use	Oil spill	1	4	3	1	2	1	6	Burger 1993: The marine ecological consequences of a major oil spill have been studied opportunistically in many parts of the world. While quite rare, these events carry disastrous effects. Global and North American estimates are that recreational vessels exceed tankers as a chronic source of smaller volume oil spills (National Research Council of the National Academies (US) 2002).

Activity	Stressor	Int	U	TS	U	SS	U	Exp	Justification
Trap Fisheries	Bycatch	2	1	3	1	1	1	6	Booth et al. 2007[1]: Bycatch can include juveniles and under-size target species or bycatch of other species
Trap Fisheries	Direct Capture	2	1	3	1	1	1	6	Booth et al. 2007[1]: "Crab traps in PNCIMA are set either on single lines or on ground lines with multiple traps. The dungeness crab fishery is almost exclusively in the northern portion of Hecate Strait and can be over 4000 soak days per year."
Trawling	Bycatch	3	1	3	1	2	1	18	Booth et al. 2007[1]: "Bycatch by groundfish trawls mainly consists of juvenile groundfish and small pelagic fish. The groundfish bottom trawl bottom fishery is non-selective and results in numerous species caught as bycatch including lingcod and spiny dogfish."
Trawling	Direct Capture	3	1	3	1	1	1	9	Booth et al. 2007[1]: Includes groundfish and shrimp trawls.
Trawling	Habitat Disturbance	3	1	3	1	2	1	18	Booth et al. 2007[1]: "Trawling can cause benthic disturbance. Large catches of sponges and coral have also been recorded. The primary fishing methods that are known or suspected to contact the benthos include those using trawls, longlines or traps."
Trawling	Sedimentation	3	1	3	1	2	2	18	Booth et al. 2007[1]: Sediment clouds generated by turbulence from trawl doors can contribute to sediment resuspension. When sediment settles, benthos can be smothered.
Trolling	Bycatch	2	2	3	1	3	1	18	Booth et al. 2007[1]: Bycatch of species that have the potential to be caught in fisheries by gear type, including salmon, sea otters, porpoises, sea turtles and more.
Trolling	Direct Capture	2	2	3	1	3	1	18	Booth et al. 2007[1]: Troll fishery for salmon species

APPENDIX 4 REFERENCES

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