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Cumulative Impact Mapping and Vulnerability of Canadian Marine Ecosystems to Anthropogenic Activities and Stressors

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Canada

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.

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ABSTRACT

The consideration of cumulative effects, in efforts ranging from environmental assessment to marine spatial planning, continues to pose challenges for both scientists and managers. The assessment of cumulative effects is a rapidly evolving field with a diversity of approaches and methodologies. Cumulative impact mapping is one established method for representing the spatial impacts of multiple activities and stressors. Since its first publication by Ben Halpern and colleagues in 2008, cumulative impact mapping has been applied at various spatial scales in regions around the world, including Canada. It is an established, semi-quantitative model that spatially represents the additive effects of human activities and stressors on marine ecosystems. The cumulative impact mapping model involves compilation and standardization of high-quality spatially explicit marine data. Three sets of data are required:

1. Spatial representation of human activities and/or stressors,
2. Spatial representation of habitats (or species), and
3. A matrix of scores to represent the relative vulnerability of each habitat to each activity or stressor.

Impact scores are summed across all habitats and activities for each grid cell to produce a map of relative cumulative impact. The results of the model allow visualisation of the relative cumulative impact within the target region, highlighting areas most and least affected by human activities. In this paper, we give an overview of the cumulative impact mapping method and its application in Canadian waters. We present the results of an expert review of the vulnerability matrices for Pacific and Atlantic Canada and the suggested changes for use in cumulative impact mapping efforts going forward. Finally, we discuss the limitations and assumptions of the method and its applicability for various management contexts.

1. INTRODUCTION

1.1. CUMULATIVE IMPACTS IN MARINE ECOSYSTEMS

1.1.1. Context

Marine ecosystems are under pressure from both local and global stressors (Duarte et al. 2020). With growing coastal human populations comes an increasingly diverse use of marine spaces and resources, from transportation and recreation to extraction and industrial activities. Significant change is expected because stressors at multiple scales of space and time can interact to affect a marine ecosystem across ecological scales (Hodgson and Halpern 2019), from localised nutrient enrichment to variations in the global climate system. As a result, the need to sustainably manage marine systems requires not only an understanding of the impacts of single stressors, but urgently, an understanding of their resulting cumulative effects.

The assessment and management of cumulative effects is a rapidly evolving field with diverse approaches and methodologies (Clarke Murray et al. 2020; Hodgson and Halpern 2019). Several spatial analysis methods for cumulative effects have proliferated in recent years (From Stock and Micheli (2016): Coll et al. 2012; Goodsir et al. 2015; Kelly et al. 2014; Knights et al. 2015; Marcotte et al. 2015; Parravicini et al. 2012; Stelzenmüller et al. 2010). Some approaches are spatial only in the scoping step, where the area of interest is first defined and those activities or stressors associated with the area are then assessed. Risk-based approaches have been used within defined geographic areas, such as marine protected areas and enclosed seas (Stelzenmuller et al. 2020; Rubidge et al. 2018). Linkage or pathway-based approaches (Knights et al. 2015; Stelzenmüller et al. 2010) explicitly define the relationships between activities, stressors, and ecological components, which can then be linked to risk variables to identify higher risk sectors/activities/stressors, or ecological components at high risk (O et al. 2014; Rubidge et al. 2018). Pathway-based approaches can also link to population models to compare scenarios of impact (Murray et al. 2020). Effects-based approaches are explicitly spatial by defining the spatial extent of the effect of activities, pressures and effects (Elliot et al. 2020) but does not extend to impacts on specific components. Cumulative impact mapping (Halpern et al. 2008), based on the relative vulnerability of habitats to activities or stressors, remains the most commonly applied spatial analysis method because of its ability to work at larger scales with flexible data requirements.

Cumulative impact mapping is an established method of translating human activities into ecosystem impacts, using defined extents and overlaps of ecosystems and anthropogenic activities. This spatially explicit analysis can be adapted for study areas of any size and conducted with data of varying detail and resolution. The adaptability and customizability of the method make it a useful tool to support marine spatial planning. The method was originally described by Halpern and colleagues (Halpern et al. 2008) and is well established in the literature, having been applied at a global scale (Halpern et al. 2007; Halpern et al. 2015; Halpern et al. 2008; Halpern *et al*. 2019; O'Hara *et al*. 2021) and at a regional scale in California (Halpern et al. 2009), Hawai'i (Selkoe et al. 2009), Massachusetts (Kappel et al. 2012a), the Arctic (Afflerbach et al. 2017; Andersen et al. 2017), the Baltic Sea (Andersen et al. 2015) and the Mediterranean and Black Seas (Micheli et al. 2013). The method has been applied repeatedly in Pacific Canada (Agbayani et al. 2015; Ban et al. 2010; Clarke Murray et al. 2015a; Clarke Murray et al. 2015b; Perry 2019; Singh et al. 2020) and has been completed for the

Maritimes region[1]. Since its publication in 2008, numerous applications have supported incremental improvements to the method. For example, with advances in computing power the potential complexity that can be included in a spatial model continues to increase. High spatial resolution, multiple stressors per activity, and the inclusion of other interaction effects are now possible, although including interaction effects other than additive in this method are rare (but see Brown et al. 2014). In addition, the underlying assumptions and uncertainties of the method have been investigated (Halpern and Fujita 2013), and analyses have been conducted to define the model components of greatest sensitivity to uncertainties and unknowns (Stock and Micheli 2016).

Cumulative impact maps allow visualisation of the relative cumulative impact within the target region, highlighting areas most affected by human activities as well as those that have less impact (i.e., hot spots versus cold spots). The process of preparing for cumulative impact mapping requires compiling and standardizing high-quality spatially explicit marine data, which on its own benefits planners, stakeholders, and other scientists (Hammar et al. 2020; Hodgson et al. 2019). Here, we provide an overview of the cumulative impact mapping method and its use in Canadian waters. We also detail an expert review of the vulnerability matrix scores for the Pacific and Atlantic coasts in order to finalize the vulnerability matrices for use in ongoing cumulative impact mapping efforts. Finally, past and potential future applications of the method are reviewed and discussed.

1.1.2. Client request

The national Marine Spatial Planning program aims to include spatial representations of cumulative effects in its planning efforts. Marine Planning and Conservation (MPC) has requested that DFO Science review the existing cumulative impact mapping method and provide advice on its applicability and appropriateness for marine spatial planning and ecosystem-based management. The objectives of this working paper are to:

1. Review the scores in the Pacific and Atlantic vulnerability matrices and recommend revisions to individual scores, as necessary.
2. Assess the cumulative impact mapping method in terms of the utility of its outputs for marine spatial planning and other management programs in Canada.
3. Identify areas of uncertainty and knowledge gaps.

2. CUMULATIVE IMPACT MAPPING METHODS

2.1. OVERVIEW OF METHOD

The cumulative impact mapping method uses a spatially explicit, additive cumulative impact model to link the footprints of human activities and habitat classes to the potential impact on the ecosystem via a matrix of vulnerability scores (Halpern et al. 2008; Teck et al. 2010). The method was first introduced and applied at a global scale by Halpern and colleagues (2007). The method requires three data sources:

[1] Murphy, Grace; Kelly, Noreen (2023) Cumulative human impact maps for the Bay of Fundy and Scotian Shelf. Published September 2023. Coastal Ecosystems Science Division, Fisheries and Oceans Canada, Dartmouth, N.S.

1. Spatial distribution of marine habitat classes (e.g., beach intertidal, shallow pelagic, seagrass bed, etc.),
2. Spatial distribution and relative intensity of human activities (e.g., fishing, shipping, industrial sites, etc.) and knowledge of their associated stressors (e.g., sedimentation, noise, etc.), and
3. A matrix of vulnerability scores to quantify the relative impact of each stressor on each habitat class.

Fundamentally, cumulative impact mapping uses a relatively simple model that identifies areas where activities and habitats intersect in space, then applies a vulnerability weight to determine an impact score for each activity-habitat intersection. The scores are summed across all activities and all habitats within each grid cell to yield a map of cumulative impact scores for the entire study region (Figure 1). The results are typically presented as heat maps, with colours denoting the level of cumulative impact in each cell (e.g., blue or cooler colours representing relatively lower impacts, red or warmer colours representing relatively higher impacts).

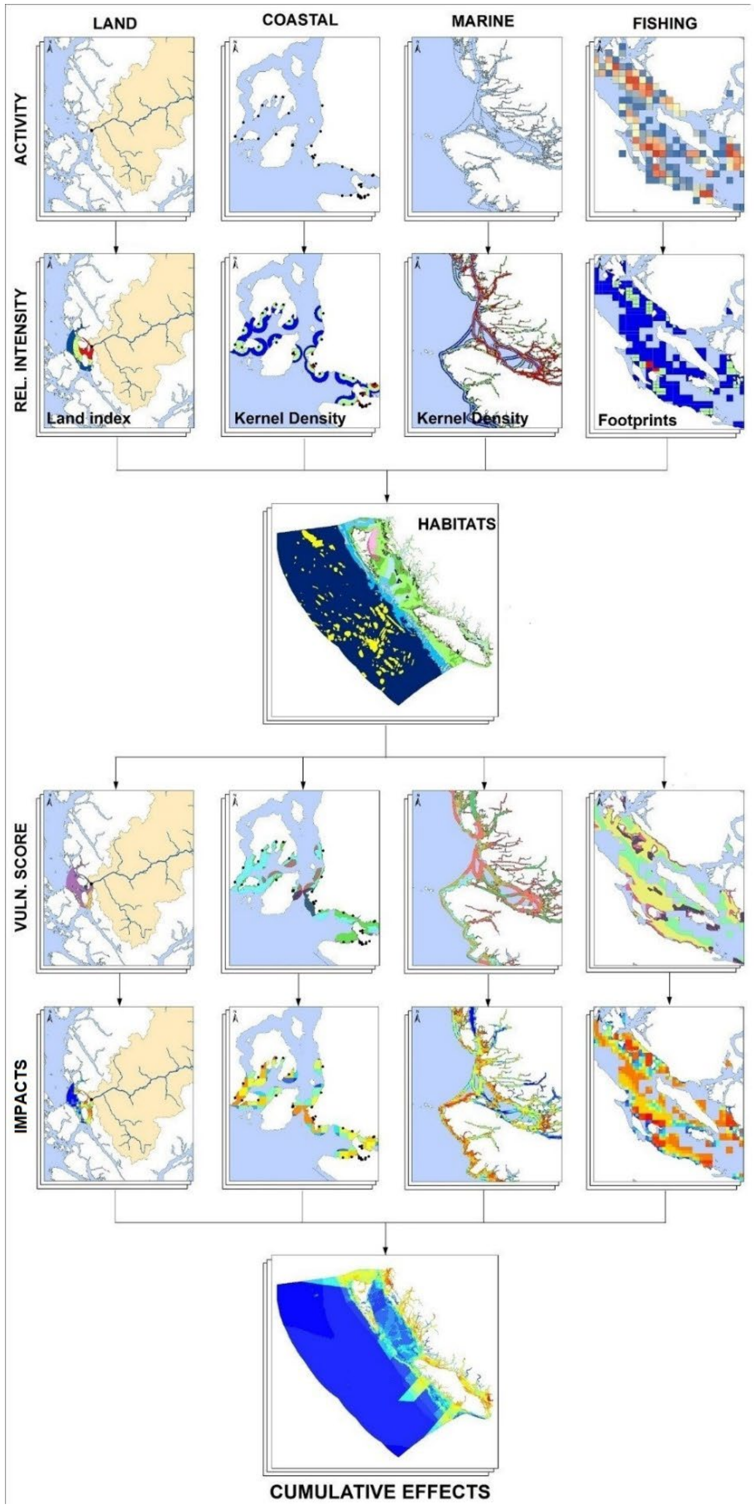

Figure 1: Overview figure of cumulative impact mapping methods. Human activity data can be divided into four types: Land, Coastal, Marine, and Fishing. The relative intensity (Rel. Intensity) of each activity layer was intersected with Habitats (benthic, biogenic, and pelagic), and vulnerability scores (Vuln. Score) were assigned to activity-habitat combinations. All impact scores were summed across all activity layers and all habitats to calculate cumulative impact scores. Adapted from Clarke Murray et al. *2015b, Supplementary Figure 1.*

2.2. HABITATS

Cumulative impact mapping has been largely focused on impacts to habitats, as a proxy for impact on the ecosystem supported by that habitat. Habitats can include both benthic and pelagic habitats as well as biogenic habitats such as sponge reefs or seagrass beds. Other efforts have expanded the method to include impacts to animal and plant species (Hammar et al. 2020; Maxwell et al. 2013; Trew et al. 2019; O'Hara et al. 2021), via food webs (Beauchesne et al. 2021), or on ecosystem services (Singh et al. 2020).

2.2.1. Pacific habitats

The habitats in the most recent Pacific Canada study were based on the habitat classes used in past vulnerability scoring exercises (Teck et al. 2010). These were stratified by depth, substrate, and geomorphic type (Table 1) and cover the entire Canadian exclusive economic zone with non-overlapping polygons (Figure 2). Biogenic habitats such as seagrass, kelp, and sponge reef were placed overtop the relevant benthic habitat type. Pelagic habitats were stratified by depth, where shallow pelagic represented the photic zone and deep pelagic represented the aphotic and abyssal zones. Existing habitat maps and models were useful in informing the creation of the dataset, for example shallow and deep substrate models (Gregr et al. 2021), and bottom patches (Gregr et al. 2013). However, we were unable to use existing Canadian Pacific habitat models because of a mismatch between them and the habitats used in the vulnerability matrix. The cumulative impact mapping model requires an exact match between the input habitat data and the habitats assessed in vulnerability scoring; as such, the Pacific habitats are derived from those in Teck et al. (2010).

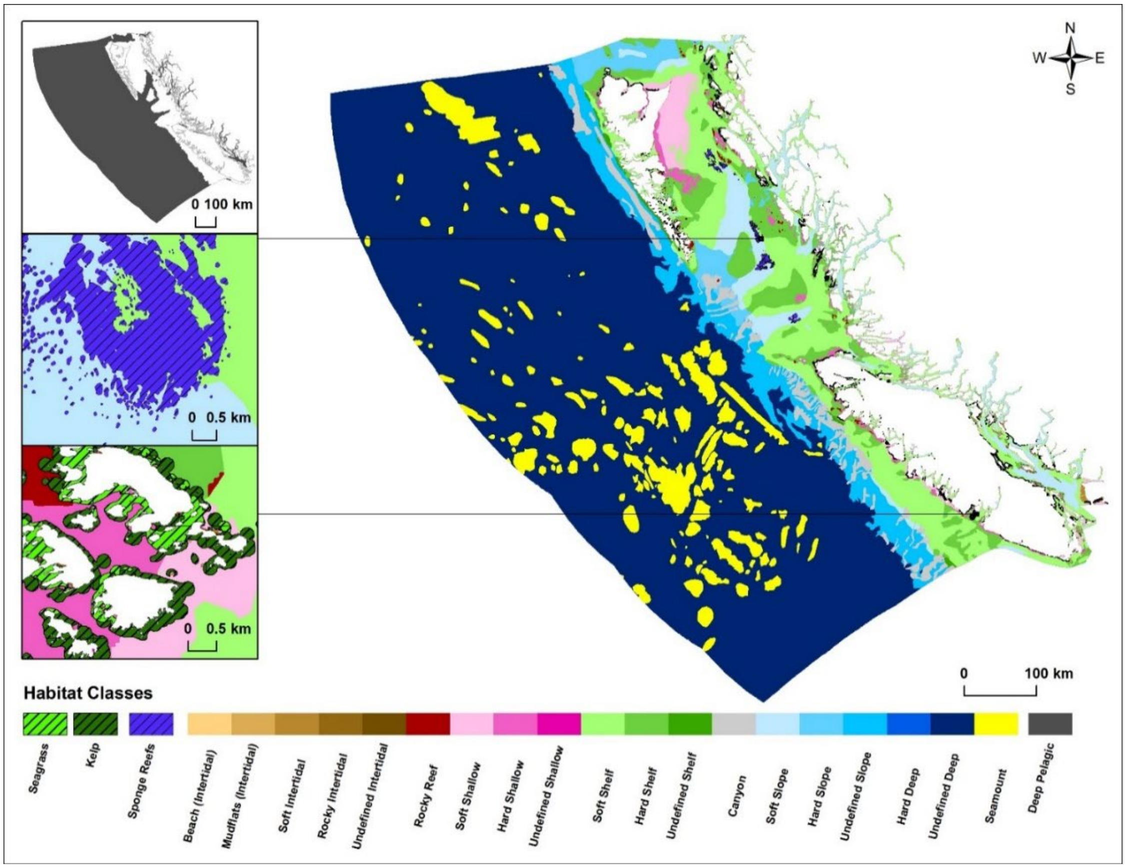

Figure 2: Habitat classes defined in Pacific Canada for cumulative impact mapping (from Clarke Murray et al. *2015b, supplemental materials figure 3). Biogenic habitats (Seagrass, Kelp, and Sponge Reefs) are layered on top of geophysical habitat classes. Soft Bottom Deep habitats are not depicted as there was insufficient data. Shallow Pelagic habitats are not depicted. Habitats of known depth but unknown substrate are mapped but use an average vulnerability score for the habitat type (e.g., the Undefined Intertidal score is an average of hard and soft intertidal habitat classes' scores).*

Table 1: Definition of habitat types used in Pacific Canada for cumulative impact mapping. Habitats of known depth but unknown substrate are mapped but not defined here as they are a mix of the other habitat types (e.g., Undefined Intertidal score is a combination of the soft and hard intertidal habitats).

Habitat Class	Habitat category	Depth interval (m)	Description
Beach intertidal	Intertidal	Areas between high and low tide	Intertidal areas characterized by soft sediment (primarily sand) that are affected by the tides and water activity (shore waves), i.e., sandy beaches
Mudflat intertidal	Intertidal	Areas between high and low tide	Relatively flat intertidal areas characterized by fine sediment (mud) that are submerged or exposed by the changing tides. E.g., mudflats
Soft intertidal	Intertidal	Areas between high and low tide	Soft sediment habitats (sand/silt/mud) of the intertidal zone

Habitat Class	Habitat category	Depth interval (m)	Description
Hard / rocky intertidal	Intertidal	Areas between high and low tide	Bedrock or rocky shoreline habitat within tidal zone
Kelp forest	Shallow (subtidal)	0 – 30	Habitat resulting from the presence of very large canopy forming brown algae (Laminariales and/or Fucales) supported by hard substrate, e.g., Bull Kelp (*Nereocystis luetkeana*) and Giant Kelp (*Macrocystis pyrifera*)
Seagrass	Shallow (subtidal)	0 – 30	Habitat resulting from presence of seagrasses (*Zostera marina*) in soft sediments (sand/silt) covered by water. May be intertidal or subtidal
Soft bottom shallow	Shallow (subtidal)	0 – 30	Soft sediment habitats (sand/silt/mud) up to 30 m deep
Hard bottom shallow	Shallow (subtidal)	0 – 30	Hard bottom habitats (bedrock/boulders) and rocky reefs up to 30 m deep
Soft bottom shelf	Shelf	30 – 200	Soft sediment habitats (sand/silt/mud) on the continental shelf
Hard bottom shelf	Shelf	30 – 200	Hard bottom habitats (bedrock/boulders) and rocky reefs on the continental shelf
Sponge reefs	Shelf	30 – 200	Globally unique ecosystem where sponges form a reef by growing on the skeletons of dead sponges on soft substrate.
Soft bottom slope	Slope	200 – 2000	Soft bottom habitat along the continental slope, past the shelf break, and some deep fjord habitats along the coast. Some fjord habitats along the coast also fall within this depth range.
Hard bottom slope	Slope	200 – 2000	Hard bottom habitat along the continental slope, past the shelf break. Some fjord habitats along the coast also fall within this depth range.
Canyons	Slope	200 – 2000	Submarine canyon, steep-sided valley cut into the seabed of the continental slope (may extend into the continental shelf).
Seamounts	Deep	> 2000	Submerged mountain > 1000 m in height above the sea floor, which will usually support a rich biological community, even when the surrounding areas are unproductive. Seamounts are > 2000 m at the base, but summits may be shallower.

Habitat Class	Habitat category	Depth interval (m)	Description
Soft bottom deep	Deep	> 2000	Soft sediment habitats (sand/silt/mud) > 2000 m depth
Hard bottom deep	Deep	> 2000	Hard bottom habitats (bedrock/boulders) > 2000 m in depth
Shallow pelagic	Pelagic	0 – 200	Open water habitat where organisms are surrounded by water (no surfaces, sides, or floors); within the pelagic zone, from surface waters to 200m depths, representative of the photic zone.
Deep pelagic	Pelagic	> 200	Open water habitat where organisms are surrounded by water (no surfaces, sides, or floors); within the pelagic zone, at greater than 200m depths, representative of aphotic and abyssal zones.

2.2.2. Atlantic habitats

Mapping of Atlantic habitats for use in cumulative impact mapping is currently underway (Figure 3) and definitions have been adapted from Teck et al. (2010) and Kappel et al. (2012a, b) (Table 2). Similar to the Pacific, biogenic habitats (salt marsh, kelp, algal zone, seagrass, horse mussel bioherm, deep-water corals, sponges, and sea pens) were layered on top of the base benthic habitats. Pelagic habitats were stratified by depth with pelagic habitat in waters <30 m deep considered as part of the benthic habitat (i.e., fully coupled) as per Kappel et al. (2012a, b).

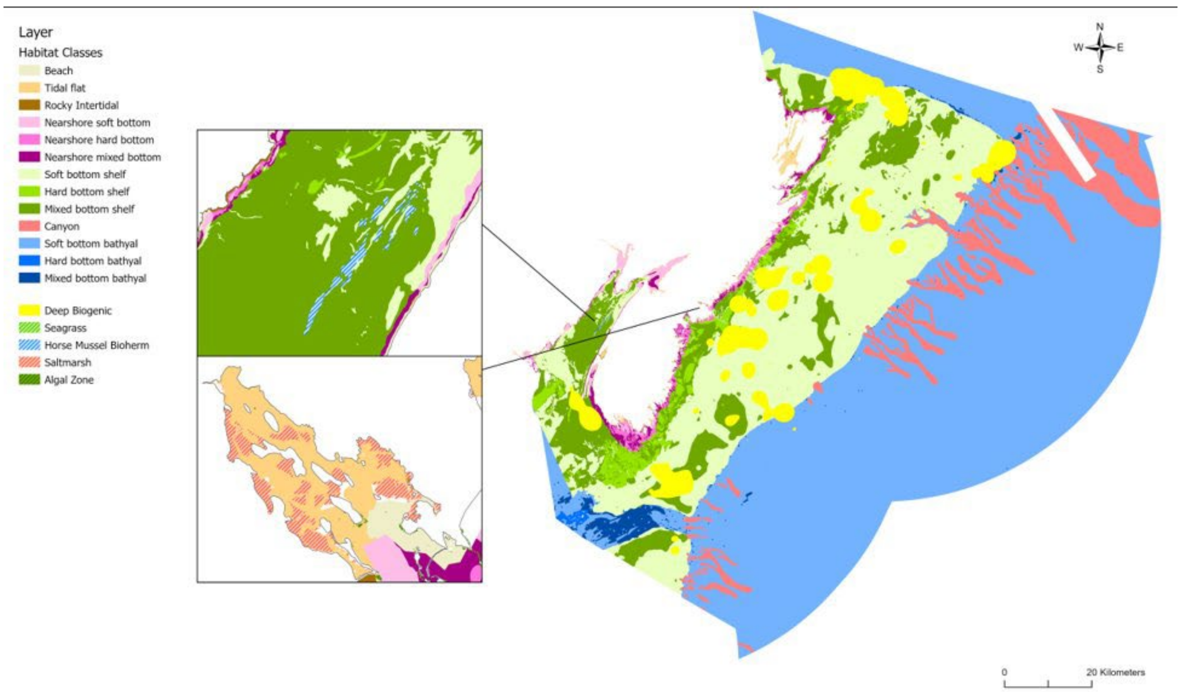

Figure 3: Habitat classes defined in Atlantic Canada (adapted from Kappel et al. *2012a, b). Kelp forest habitat is not currently included in the map due to insufficient data.*

Table 2: Definition of habitat types used in Atlantic Canada (adapted from Kappel et al. *2012a, b).*

Habitat class	**Habitat category**	**Depth interval (m)**	**Description**
Beach	Intertidal	0 – 2	Sand, pebble, cobble, and/or mixed sediment shoreline habitat within tidal zone
Tidal flat	Intertidal	0 – 2	Un-vegetated sand or mud habitat within the tidal zone
Rocky intertidal	Intertidal	0 – 2	Bedrock or rocky shoreline habitat within tidal zone
Salt marsh	Intertidal	0 – 2	Marsh (e.g., dominated by *Spartina* spp.) or vegetated estuarine or shoreline habitat within tidal zone
Kelp	Subtidal	2 – 30	Nearshore subtidal habitat dominated by canopy-forming kelps (e.g., *Laminaria*, *Saccharina* spp.)
Algal zone	Subtidal	2 – 30	Nearshore subtidal habitat dominated by rockweed species
Seagrass	Subtidal	2 – 30	Nearshore subtidal habitat dominated by *Zostera marina*
Nearshore soft bottom	Subtidal	2 – 30	Soft subtidal bottom with mud, sand and mud or sand substrates
Nearshore mixed bottom	Subtidal	2 – 30	Sand and gravel, mixed sediment, or gravel sediment substrates
Nearshore hard bottom	Subtidal	2 – 30	Hard subtidal bottom with boulders, continuous bedrock, or discontinuous bedrock substrate
Horse mussel bioherm	Shelf	30 – 200	Reef-like masses formed by the accumulation of sand and horse mussel shells
Soft bottom shelf	Shelf	30 – 200	Mud, sand and mud, or sand substrates
Mixed bottom shelf	Shelf	30 – 200	Sand and gravel, mixed sediment, or gravel substrates
Hard bottom shelf	Shelf	30 – 200	Boulders, continuous bedrock, or discontinuous bedrock substrate
Shallow pelagic	Shelf	30 – 200	Open water habitat where organisms are surrounded by water; within the pelagic zone above 200m in all areas >30m deep. Note: pelagic zone in <30m depth is considered coupled with the benthic habitat.
Soft bottom bathyal	Deep	> 200	Silt, mud, or sand substrate

Habitat class	Habitat category	Depth interval (m)	Description
Mixed bathyal	Deep	> 200	Sand and gravel, mixed sediment, or gravel substrates
Hard bottom bathyal	Deep	> 200	Cobble, boulder, or bedrock substrate
Deep biogenic	Deep	> 200	Significant areas dominated by cold-water corals (Alcyonacea), sponges (Porifera), and sea pen (Pennatulacea) communities
Canyons	Deep	> 200	Submarine canyon, steep-sided valley cut into the seabed of the continental slope
Deep pelagic	Deep	> 200	Open water habitat where organisms are surrounded by water; within the pelagic zone, at greater than 200m depth

2.3. HUMAN ACTIVITIES AND STRESSORS

Human activities affect ecosystems through one or more stressors (sometimes called pressures). Human activities are the actions that are undertaken for resource use, transportation, or tourism and can include fully marine, coastal, and land-based activities that have some effect on the marine environment. Marine activities occur in the ocean (e.g., shipping, fishing, disposal at sea), while coastal activities occur at the interface between land and sea (e.g., marinas, aquaculture, log booms). In cumulative impact mapping, spatial representation of human activities is often performed at the level of the activity (fishing, shipping, aquaculture, etc.), but may also be done at the stressor level (noise, pollutants, invasive species, etc.). A stressor is “any physical, chemical, or biological means that, at some given level of intensity, has the potential to change an ecosystem or one or more of its components” (O et al. 2015). There may be several stressors associated with any single activity. Activities and stressors included in the current study are presented in Table 3.

The cumulative impact mapping method treats both activities and stressors equally and the user can decide what level to employ. Previous studies have generally assigned a single representative stressor to an activity for practical reasons (Afflerbach et al. 2017; Andersen et al. 2015; Ban et al. 2010; Clarke Murray et al. 2015b; Halpern et al. 2009; Kappel et al. 2012a; Singh et al. 2020; Teck et al. 2010). For example, Clarke Murray et al. (2015b) matched one stressor to each of the activities included in their analysis in order to apply the vulnerability score of that stressor (see Clarke Murray et al. 2015b, Table 1). However, some activities such as aquaculture and fishing are assigned a vulnerability score directly because their impacts are well known through extensive research, making them simpler to score as an activity than as a series of stressors. For other activities, there may be data available on one stressor associated with the activity, but there may not be sufficient information on others. For example, modeled data on shipping noise in the Pacific region is available (Erbe et al. 2012), but data on shipping waste discharges are not as readily available.

As further research on the impacts of human activities on the environment is conducted and additional data is made available, more opportunities will arise to support the consideration of multiple stressors from single activities. This, in combination with advancements in analysis tools and increased computing power, may allow for multiple stressors to be assigned for each activity allowing a more fulsome representation of cumulative impacts.

Each activity or stressor is represented in the cumulative impact mapping model as a relative intensity value. These intensity values may be derived in various ways, depending on the nature of the activity or stressor, the way they may interact with the habitat, and data availability. For example, relative intensities may be derived from the area covered by a physical footprint (e.g., building a permanent structure on the sea floor), the amount of pollutant being released by a point source (e.g., contaminant loads released from sewage outfalls), or the duration of an activity within each grid cell (e.g., effort hours dedicated to fishing in specific areas). For marine activities with polygon or grid data, intensity may be effort hours, number of fishing events per cell, or total catch, and are area-weighted where appropriate. For coastal and marine point data or linear features, a kernel density may be applied with highest intensity at the source, up to a maximum impact distance based on values derived from literature where available, or the distance equivalent to the minimum grid cell size (Ban et al. 2010, Clarke Murray et al. 2015b). For land-based activities (polygon, linear, or point data), a least-cost path diffuse plume model or kernel density effect distance can be used to spread stressor levels out from the mouth of the watershed (Halpern et al. 2008, Kappel et al. 2012a, b, Clarke Murray et al. 2015b). Hydrodynamics (i.e., local oceanography) is not typically considered in the application of the kernel density nor cost-path surface because of insufficient data.

The units and range of intensity values vary with each stressor or activity; therefore, it is necessary to normalize the intensity values relative to each other. Some studies have used log-transformed values that were then rescaled from 0-1 (Ban et al. 2010; Halpern et al. 2009; Halpern et al. 2008), and others have classified intensity values into three classes (0.5 / 1.0 / 1.5) representing high, medium and low intensities using the Natural Breaks/Jenks method (Clarke Murray et al. 2015a,b). When the majority of the datasets in the study are available as continuous variables, rescaling the data from 0 to 1 may be the best method to normalize the data. The Natural Breaks method can be useful when the activity data available are limited in detail, or available as categorical data only. Log transformation is useful in reducing the influence of extreme outliers in certain data layers and may not be necessary for all datasets.

Table 3: Definitions of activities and stressors, adapted from Teck et al. *2010, Ban* et al. *2010, and Clarke Murray* et al. *2015b. "Habitat-modifying" and "low-habitat modifying" refers to the expected likelihood of habitat modification, rather than the actual amount. Single asterisks (*) indicate Atlantic-only activities and stressors, double asterisks (**) indicate Pacific-only.*

Human activities and stressors	Definition
Aquaculture: Finfish	Marine farming of finfish, including salmon. Stressors may include biomass input, infrastructure effects, nutrient input, shading, artificial light, and noise
Aquaculture: Plants and algae	Marine farming of plants and algae. Stressors may include biomass input, infrastructure effects, nutrient input, shading, artificial light, and noise
Aquaculture: Shellfish	Marine farming of shellfish. Stressors may include biomass input, infrastructure effects, nutrient input, shading, artificial light, and noise
Benthic structures	The presence of structures connected to the benthic substratum; For example, pipelines, communications structures, oil & gas platforms, windmills, etc.

Human activities and stressors	**Definition**
Climate Change: Ocean Acidification	Increasingly acidified seawater
Climate Change: Sea level rise	Rising sea level
Climate Change: Sea temperature change	Changing sea temperature
Climate Change: UV change	Increasing ultraviolet exposure
Coastal Engineering: Altered flow dynamics	Altered flow dynamics due to presence of seawalls, piers, jetties, etc.
Coastal Engineering: Habitat alteration	Altering habitat through construction of permanent structures or changing substrate. The addition of seawalls, piers, and jetties add new hard substrate, while beach nourishment, sand mining, land fill, and reclamation may cover or remove existing habitat
Direct Human Impact: Trampling	Damage caused by humans and pets walking on intertidal substrate or wading in shallow waters
Disease or pathogens	Diseases or pathogens introduced to the marine environment; may be from sewage, urban runoff, aquaculture, ballast water, etc. Includes bacteria, fungi, parasites and viruses that cause disease in humans or in marine organisms
Dredging	Excavation of the seabed by removal of sand, mud, weeds, etc. with a dredge apparatus. Stressors may include physical disturbance, sedimentation, and noise
Energy infrastructure: Liquid natural gas*	Structures related to liquid natural gas terminals including liquefaction facilities, storage facilities, regasification facilities, and ports for import and export. Stressors may include physical disturbance, benthic structures, noise, and pollution input
Energy infrastructure: Tidal*	Structures related to tidal energy power plants including turbines, barrage systems, substations, and related infrastructure and electric cables. Stressors may include physical disturbance, benthic structures, and noise
Fishing: Aquarium	Live fish, invertebrates and plants caught for sale in the local and global aquarium trade. May occur via traps, hand-picking and dive collecting
Fishing: Demersal, habitat-modifying	Biomass removal using demersal fishing gear known to cause habitat and/or substrate damage. • Atlantic gear type examples: Bottom gillnet, bottom (otter) trawl, bottom longline, scallop dredge, hydraulic clam dredging, shrimp trawl, clam drag

Human activities and stressors	Definition
	• Pacific gear type examples: Groundfish bottom trawl, scallop dive/trawl, shrimp trawl
Fishing: Demersal, low-habitat-modifying, high bycatch	Biomass removal using demersal fishing gear with high bycatch that may cause incidental habitat modification. • Atlantic gear type examples: Gillnet, seine • Pacific gear type examples: Halibut hook and line, sablefish longline, rockfish hook and line
Fishing: Demersal, low-habitat-modifying, low bycatch	Biomass removal using gear with little or no bycatch that may cause incidental habitat modification. • Atlantic gear type examples: Dive fisheries (sea urchin), trap fisheries (snow crab, inshore lobster) • Pacific gear type examples: Crab trap, geoduck dive, gooseneck barnacle dive, green urchin dive, octopus dive, prawn trap, red urchin dive, sablefish trap, schedule II (other groundfish spp.) hook and line, sea cucumber dive
Fishing: Low-habitat-modifying, artisanal	Small-scale fisheries using relatively small amount of capital and energy, relatively small fishing vessels (if any), making short fishing trips, close to shore, mainly for local consumption. • Pacific gear type examples: Hand collecting, line fishing, seine, and gillnet
Fishing: Pelagic, high bycatch	Biomass removal using pelagic gear with high rates of non-target catch, but with no known benthic habitat destruction concerns. • Atlantic gear type examples: Atlantic herring bait fishery (midwater gillnet), pelagic longline, mid-water trawls, purse seine (herring, mackerel) • Pacific gear type examples: Herring roe gillnet, herring roe seine, herring seine, krill seine, salmon gillnet, salmon seine, sardine seine
Fishing: Pelagic, low bycatch	Biomass removal using pelagic gear with low rates of non-target catch and no known habitat destruction concerns. • Atlantic gear type examples: harpoon (swordfish, tuna), handline, tended line • Pacific gear type examples: Salmon troll
Fishing: Recreational	Biomass removal by recreational fishers; may cause incidental habitat damage. • Atlantic example: sportfish angling • Pacific gear type examples: anadromous hook and line, crab trap, groundfish hook and line, prawn and shrimp trap

Human activities and stressors	Definition
Freshwater: Input decrease	Decreased freshwater input into marine waters from changes in flow rate, dam construction, agricultural diversion, etc.
Freshwater: Input increase	Increased freshwater input into marine waters from changes in flow rate, channelization, etc.
Invasive species	Non-native species distributed by shipping, aquaculture, aquarium trade, coastal development, etc.
Marine component of forestry operations**	Storage and handling of logs in coastal areas. Floating log booms may shade the benthos below and woody debris may smother the seafloor
Military activity	Military activities including training, maintenance, active service, etc. Stressors may include vessel operations, sonar, explosive testing, etc.
Nutrient input into eutrophic waters	Higher than usual nutrient load added to waters that are already rich in nutrients
Nutrient input into mesotrophic waters**	Higher than usual nutrient load added to waters with an intermediate level of nutrients
Nutrient input: into oligotrophic waters*	Higher than usual nutrient load added to waters with low level of nutrients
Nutrient input: Causing Harmful Algal Blooms	Harmful algal blooms caused by nutrient input. E.g., outbreaks of paralytic shellfish poisoning near city outflows
Nutrient input: Causing hypoxic zones	Abnormally low oxygen caused by nutrient input; can cause fish die offs
Ocean dumping: Lost fishing gear	Incidental loss of nets, long-lines, etc. that are not recovered
Ocean dumping: Marine debris	Accidental or intentional release of debris into the ocean, either from land or ocean-based activities. E.g., plastics, bottles, miscellaneous trash
Ocean dumping: Shipwrecks	New and historical sunken or beached wrecks of recreational and commercial vessels. Stressors may include physical disturbance, new benthic structures, noise, and pollution input
Ocean dumping: Toxic materials	Chemical waste disposed of in the ocean, can be a permitted or illegal activity
Ocean mining: Sand, minerals, etc.	Mining the ocean floor for materials of value. Could include mining hydrothermal vents, nodule fields, gas/oil development, diamonds, sand/gravel, or large-scale coral mining. Stressors may include physical disturbance, sedimentation, and noise
Ocean pollution from ships and ports	Ship-based and port-based pollution. May include bilge water, scrubber discharge, antifouling paint debris, oil or fuel residue, trash, etc.

Human activities and stressors	Definition
Pollution input: Atmospheric	Atmospheric deposition of pollutants settling from the air; can include dust, black carbon, jet fuel, heavy metals
Pollution input: Inorganic	Input of inorganic pollutants including, but not limited to, heavy metals, trace elements, mineral acids, metals, metal compounds, inorganic salts, sulfates, cyanides, petroleum products, anti-fouling paints, bilge water, etc.
Pollution input: Light	Light outside of the habitat's natural range. E.g., ship running lights illuminating the surrounding waters and benthic substrata
Pollution input: Noise	Noise outside of the habitat's natural range. E.g., noise from a ship engine or anchor chain
Pollution input: Organic	Input of organic pollutants, including, but not limited to, insecticides, herbicides, PCBs, phthalates, dioxins
Pollution input: Urban runoff	Water and associated materials that drain from urban areas, which may reach the ocean through rivers, storm sewer drainage, or overland flow
Power and desalination plants	Water is drawn in for cooling power plants or for desalination, entraining larvae, small plants, etc. from an area around the intake pipes, and may include discharge of heated water
Scientific research and collecting	Collection of organisms for research, with removal of biomass from the system. Hand picking or collecting by SCUBA or remotely operated vehicle. Stressors may include biomass removal, physical disturbance, and noise
Scientific research experiments/surveys	Incidental or intentional damage caused by scientific experiments or surveys. Biomass not removed. Stressors may include physical disturbance and noise
Sediment input: Decrease	Lower than usual sediment added to the water, e.g., change in upstream substrata to sediment that is less mobile
Sediment input: Increase	Higher than usual sediment added to the water, e.g., reduced vegetation near rivers allowing increased sediment to enter water and flow to ocean
Shipping (large vessels)	Disturbance caused by large vessels, includes commercial shipping, ferry, and cruise traffic. Stressors may include physical disturbance from groundings/scrapings and related anchoring, strikes, noise, wake and turbulence
Tourism: Kayaking	Disturbance caused by kayak tourism and recreation activities. Stressors may include physical disturbance from accidental grounding, dragging kayaks through the intertidal for storage above the high tide line, and noise
Tourism: Recreational boating	Boating for recreation, including tours and personal use. Stressors may include noise, wake and turbulence, and

Human activities and stressors	Definition
	physical disturbance from groundings/scrapings and related anchoring
Tourism: Scuba diving	Physical disturbance caused by repeated visits from SCUBA divers and dive operations. Stressors may include physical disturbance from anchoring and divers, light from the ship and divers, and noise
Tourism: Surfing	Physical disturbance caused by surfers and gear. Stressors may include physical disturbance from walking through intertidal to reach the surf, noise, and human presence
Tourism: Whale watching*	Disturbance caused by whale watching operations. Stressors may include noise, wake, and turbulence

2.4. VULNERABILITY MATRIX

The vulnerability (or sensitivity) of ecosystem components to stressors is a key element of any environmental assessment and thus of cumulative impact mapping. However, not all studies define vulnerability in the same way, and this can lead to variable and incompatible results.

> "The impact of a threat on a species or ecosystem is determined by the ecosystem's vulnerability to that threat" - Halpern et al. (2007)

Vulnerability may be defined as the potential for loss, likelihood of biodiversity loss, as a combination of exposure and intensity of a threat with its consequence or impact (Wilson et al. 2005), or as the severity of the response of a system to adverse effects made up of a system's exposure, sensitivity, or adaptive capacity (Adger 2006). Vulnerability scores give a relative assessment of the impact of a stressor or activity on an ecosystem or its components. Vulnerability can be arranged as a matrix between stressors and end points (ecosystems, habitats or species) to give a relative score for each pair (vulnerability matrix). Given the complexity of standardising impacts across stressors and habitats, most vulnerability scores have been determined based on expert elicitation and/or literature review (Halpern et al. 2007; Maxwell et al. 2013; Teck et al. 2010). The resulting scores are used as weighting factors in the cumulative impact mapping model when there is an intersection between a habitat and a stressor or activity.

2.5. CUMULATIVE EFFECTS FORMULA

Relative cumulative impact scores (I_C) are calculated according to Equation 1:

$$I_c = \sum_{i=1}^{n} \sum_{j=1}^{m} D_i * E_j * \mu_{i,j} \quad (1)$$

where D_i is the log-transformed and normalized value (e.g., scaled between 0 and 1) of an anthropogenic activity *i*, E_j is the presence or absence of a habitat or ecosystem *j* (either 1 or 0, respectively), and $\mu_{i,j}$ is the vulnerability weight for the anthropogenic activity *i* and ecosystem *j* (from Teck et al. 2010), given *n* activities and *m* ecosystems. The values for all activities and all habitat types were summed for each grid cell to arrive at the cumulative impact score per cell in the study area.

3. CUMULATIVE IMPACT MAPPING IN CANADA

Efforts to map cumulative impacts on marine habitats in Canada to date have been primarily focused on the Pacific region. The first study conducted by Ban and colleagues (2010) adapted methods applied in the California Current region to the Pacific region. Clarke Murray and colleagues (2015b) later introduced additional methodological improvements to the analysis and generated updated cumulative impact scores using more recent datasets where available.

3.1. BAN ET AL. 2010

The cumulative impact mapping method was first applied to marine habitats in Pacific Canada by Ban et al. (2010) (Figure 4). They conducted a literature review to explore the links between each activity occurring in Pacific Canada and their predominant stressors and cross-referenced these stressors with the vulnerability table from Teck et al. (2010). The vulnerability scores from Teck et al. (2010) were then adapted to the specific activities and stressors occurring in Pacific Canada. Vulnerability scores for commercial fishing in Pacific Canada were refined based on fishing gear types as reported in Chuenpagdee et al. (2003). A detailed discussion on the vulnerability matrix currently used in Pacific Region can be found in Section 4.1.3.

Methodological advancements implemented by Ban et al. (2010) included explicitly defining an area around each activity that denotes a likely zone of influence, represented by linear decay. This accounted for impacts that may extend beyond an activity's immediate footprint or point source, decreasing in intensity of impact with increasing distance from the activity. This method was applied for both land and marine activities, and only coastal land activities within the distance of likely zone of impact were included in the analysis.

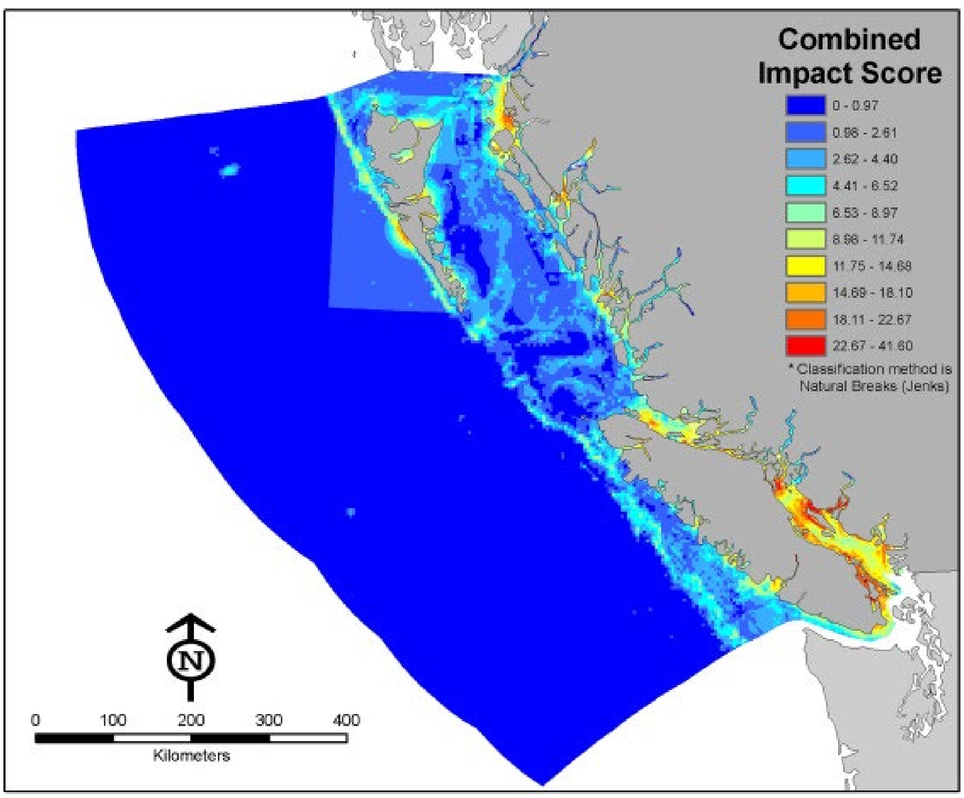

Figure 4: First cumulative impact map for Pacific Canada (from Ban et al. *2010)*

3.2. CLARKE MURRAY ET AL. 2015

The application for Pacific Canada by Clarke Murray et al. (2015b) included several changes from Ban et al. (2010), enabled by greater computing power and automation. In this analysis, new and updated data on activities were included, the land impact analysis was improved to include activities from watersheds with large rivers and streams flowing directly into the Pacific Ocean, and the habitat classes were updated to include data on intertidal habitats and sponge reefs.

Human activities were divided into four data types: land, coastal, marine, and fishing activities.

1. Land activities were mapped as points, lines, or polygons, and standardized by watershed size to create an index that is applied to the mouth of the estuary with a linear kernel density decay to represent an impact distance relative to the volume of river flow.
2. Coastal activities were represented by points or polylines, which were used to create a linear kernel density decay.
3. Fully marine activities were represented by polygon footprints, and
4. Fishing activities were represented either by intensity of fishing effort in grid cells, statistical areas, or polygons, depending on the fishery.

For each mapped activity, a representative stressor was determined by literature review, with the identified stressor used to refer to the Teck et al. (2010) vulnerability matrix, following the method of Ban et al. (2010). To represent the additional impact from the presence of a fishing vessel in addition to the activity's main stressor, the recreational boating stressor was also added to fishing activity layers (e.g., a fishing trawl event has the destructive fishing stressor score as well as the recreational boating score for the vessel).

Benthic habitat classes were updated with intertidal data, and biogenic habitat classes (kelp, seagrass, and sponge reefs) were separated from the benthos. Biogenic habitats were layered on top of substrates so that impacts could occur to both the biogenic (e.g., seagrass) and underlying habitat (e.g., soft shallow). A full list of changes to habitats can be found in Clarke Murray et al. (2015b), Supplementary Table 3. For habitats not evaluated in Teck et al. (2010), such as habitats of known depth but unknown (or undefined) substrate, vulnerability scores were calculated or assigned based on existing habitat scores (Table 4).

Table 4: Vulnerability scores that were calculated or assigned based on existing habitat scores from Teck et al. *(2010), as found in Clarke Murray* et al. *(2015b), Supplementary table 4.*

Habitat	**Vulnerability score**
Soft intertidal	Mean of mudflat intertidal and beach intertidal
Undefined intertidal	Mean of soft intertidal and hard intertidal
Undefined shallow	Mean of soft shallow and hard shallow
Undefined shelf	Mean of soft shelf and hard shelf
Undefined slope	Mean of soft slope and hard slope
Undefined Deep	Mean of soft deep and hard deep

Habitat	Vulnerability score
Sponge reefs	Sponge reefs in BC are largely found in deep waters and have characteristics similar to seamounts, so the seamount vulnerability score was used

In response to a common critique of the method, that the resolution of both habitats and stressors are too coarse for the desired use of the analysis (Halpern and Fujita 2013), the polygon shape and size for habitat layers were preserved in the intersection with human activity layers, rather than rasterizing the data so that only one habitat was represented in each grid cell. This method allowed for the occurrence of multiple habitats in one grid cell, and it allowed for the inclusion of habitat areas that may be smaller than the grid cell. Marine activities that occur as footprints were also retained as polygon data. Activity data that were available in coarse resolutions were limited to areas where they may reasonably occur. For example, geoduck fishing data available in 4 × 4 km grid cells were limited in area to soft shallow habitats, where geoduck fishing is most likely to occur (Figure 5).

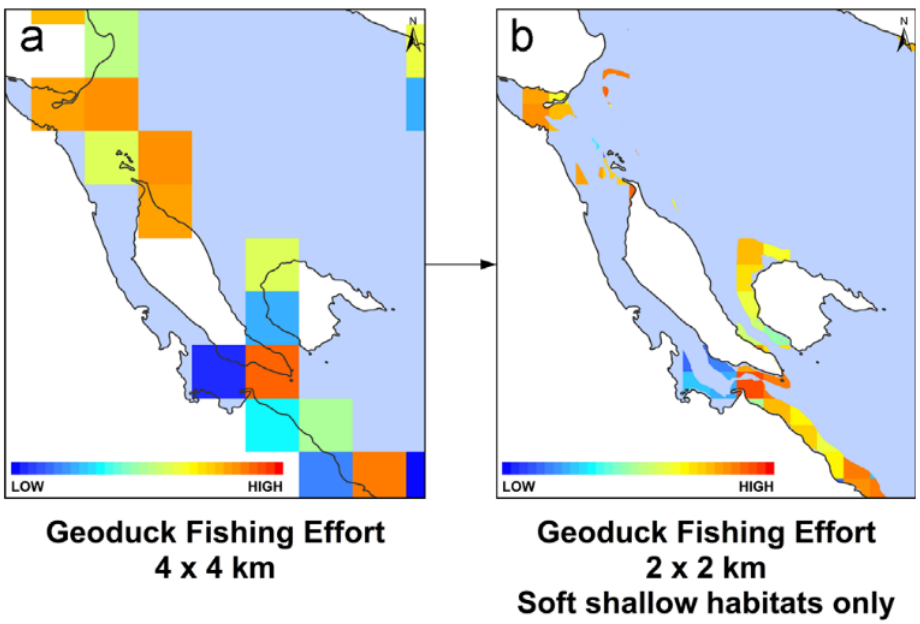

Figure 5: Illustration of improvement in assigning fishing effort for the geoduck fishing dataset (Fig 1. in Clarke Murray et al. *2015b).*

Region-specific fishing gear severity rankings (on a scale from 0 to 10) from Fuller et al. (2008) were used to weight vulnerability scores for fisheries to further refine situations where the stressor category did not adequately reflect the variability in impact between fishery gear types. For example, sablefish trap and dive fisheries were initially associated with the same stressor: demersal non-destructive, low bycatch. However, dive fisheries are known to have a much lower impact on bottom habitats, reflected by a lower gear severity ranking and vulnerability weight, compared to large sablefish traps (Fuller et al. 2008). This method of vulnerability score refinement has been found to better reflect the differences in impact between fisheries that fall within the same stressor category but use gear types that have a significantly different level of impact on habitats (Agbayani et al. 2015). A full list of gear severity score rankings used for the Pacific mapping is presented in Clarke Murray et al. (2015b), supplementary Table 5. The resulting cumulative impact map for Pacific region is shown inFigure 6.

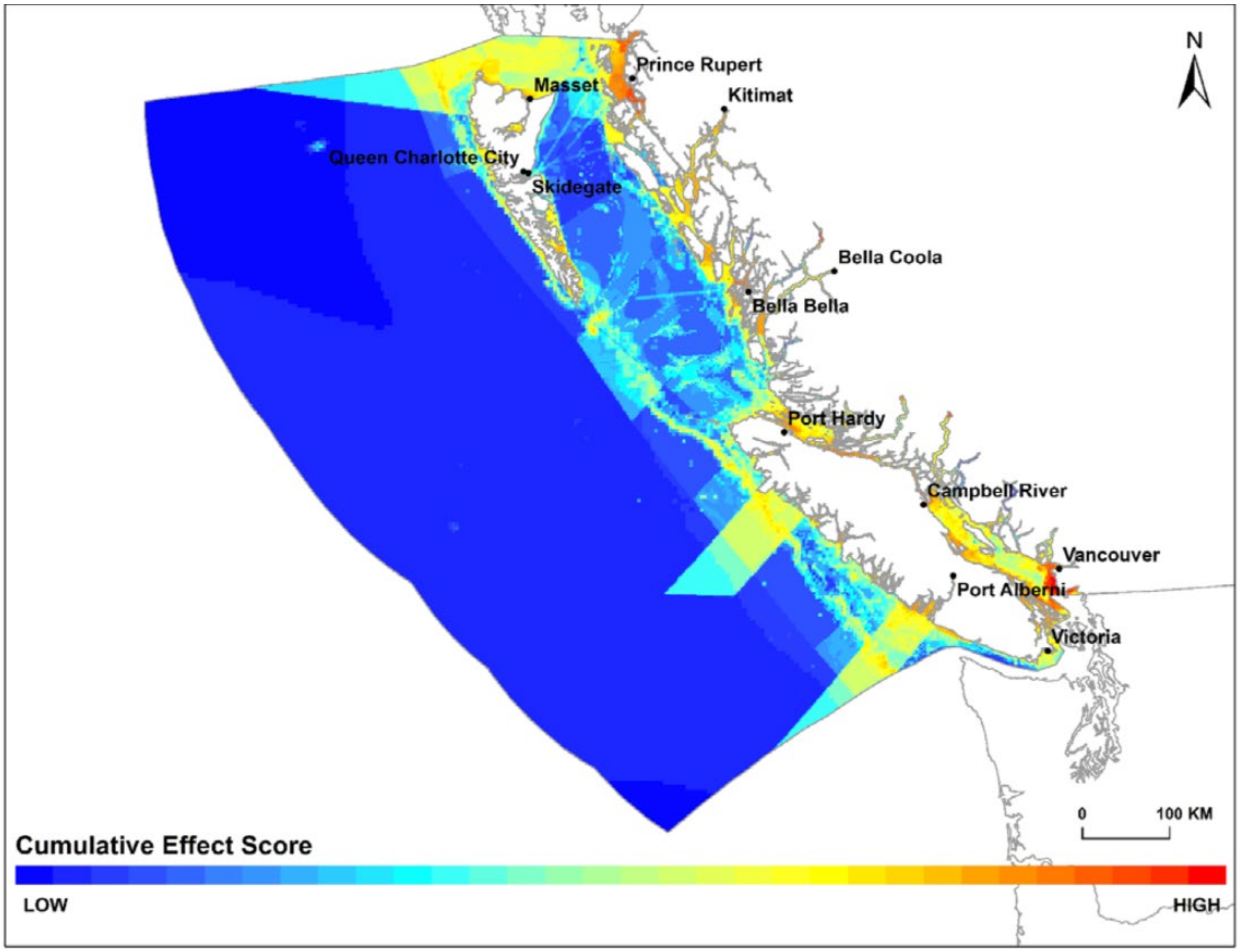

Figure 6: Cumulative impact map from Clarke Murray et al. *(2015b)*

3.3. PACIFIC UPDATE

The marine spatial planning effort to update the cumulative impact maps in Pacific followed the methods used by Clarke Murray et al. (2015b), with updated data layers and methodological advancements. The updated analysis used a higher resolution planning grid (1 × 1 km). The marine habitat layer was updated with higher resolution bathymetry and substrate data, and included updated data on seamount boundaries, seagrass, and sponge reefs[2]. Updates to human activity data were included where available, and the analysis allowed for the integration of multiple stressors where possible. The updated maps were completed in 2024[3].

3.4. MARITIMES

Similar to the Pacific, cumulative impact mapping in the Maritimes region followed the methods of Clarke Murray et al. (2015b), also used a high-resolution planning grid (1 × 1 km), but with regional adaptations that account for differences in habitats and human activities. The marine

[2] Pacific Marine Habitat Classes

[3] Cumulative impacts from anthropogenic activities and stressors on marine ecosystems in Pacific Canada

habitat layer was compiled from multiple sources that previously mapped and classified different portions of the benthos (i.e., coastal or shelf substrata), along different depths (i.e., nearshore to 100 m, or >200 m depth), or targeted particular areas of interest (i.e., coral and sponge significant benthic areas, horse mussel bioherms, rockweed). All human activity layers were included where available, prioritizing data sources measured within the previous decade. The availability of data sources varied widely for the Maritimes region, with some data sources measured at much higher frequencies or spatial resolutions (e.g., commercial shipping vessel traffic, certain fishing activities), some sources estimated from models (e.g., nutrient input from land-based sources, invasive species distribution models), while still others contained point source locations only (e.g., aquaculture, recreational activities) and lacked associated measures of intensity. Atlantic-region specific gear severity rankings, used for weighting the vulnerability scores of different gear types classified within the same fishing stressor category, were adapted from Fuller et al. (2008) for East Coast fishing gear types, which differ in many cases from those used in the Pacific. The cumulative impact maps were completed in 2023[1].

4. EVALUATING THE VULNERABILITY MATRIX FOR CANADIAN OCEANS

Vulnerability of marine habitats to stressors was estimated using expert elicitation based on the various components believed to make species or ecosystems more sensitive to disturbance. The vulnerability matrix used in Pacific Canada (Clarke Murray et al. 2015b) was based on those defined for the California Current (Teck et al. 2010) with some modifications to account for differences in the two regions. The same Teck matrix has been used in other global and regional applications of habitat-based cumulative impact mapping, with one exception. A subsequent vulnerability matrix was developed for coastal Massachusetts by Kappel et al. (2012a) using the same methodology as Teck et al. (2010) but, instead, surveyed experts working in marine ecosystems of New England, U.S.A. The cumulative impact mapping efforts in Maritimes region use the Kappel et al. (2012a) matrix because the geographic setting and ecological context are more similar. The Atlantic vulnerability matrix is intended to be used across the entire area, including Maritimes, Newfoundland and Labrador, and Gulf regions. The current mapping effort to support Marine Spatial Planning is only occurring in the Maritimes region. Here we evaluate the applicability of these two vulnerability matrices to Canadian ecosystems.

4.1. MATRIX SCORES

4.1.1. California Current (Teck et al. 2010)

Teck et al. (2010) calculated vulnerability scores as the weighted sum of five vulnerability criteria: spatial scale, frequency, trophic impact, percentage change in biomass, and recovery time (Table 5; Equation 2):

$$Vulnerability = \sum_{k=1,\ldots,5} W_k S_{i,k}^{j} \tag{2}$$

where $S_{i,k}^{j}$ is the value of criterion *k* for stressor *i* in ecosystem *j*, and W_k is the weight assigned to criterion *k*, such that the sum of W_k is equal to 1. Calculating these scores required knowledge of both the value of each criterion and its associated weight (i.e., the relative importance given by an expert in judging an ecosystem's vulnerability to a particular stressor). Teck et al. (2010) determined their vulnerability scores through the use of expert surveys. To estimate the value for each criterion ($S_{i,k}^{j}$), experts were asked to judge (accept or revise) a given value for each vulnerability criterion for each ecosystem-stressor combination. Experts were separately asked to rank a set of hypothetical scenarios with different anthropogenic stressors and ecosystems in terms of expected negative human impact at the ecosystem level. This ranking exercise was used to determine the criteria weights (W_k) that experts implicitly place on the five vulnerability criteria, so that the five criteria were not limited to equal weighting when combined into the single vulnerability score. Criteria weights were derived using a decision theory approach (i.e., applying a multi-criteria decision model and probabilistic inversion statistical methodology to expert survey results), multiplied by the average criteria values (calculated from the population of experts surveyed in the first exercise), and then summed across the five criteria to give the overall vulnerability score (Equation 2). Experts in both California (Teck et al. 2010) and Massachusetts (Kappel et al. 2012a,b) placed the greatest weights on trophic impact and percent change in biomass vulnerability criteria, although the magnitude differed between locations (California: 89%; Massachusetts: 81.1%). The same criteria weights were applied to all ecosystems and stressors to allow for direct comparison among ecosystem-stressor combinations. The defined model was then used to calculate the vulnerability score of all habitat-stressor combinations.

Table 5: Vulnerability criteria used to calculate vulnerability by Teck et al. *(2010)*

Vulnerability criteria	**Description**
Spatial Scale	The spatial scale (km^2) at which a single act of an activity impacts the ecosystem, both directly and indirectly, e.g., spatial scale of a single trawl rather than the whole trawl fishery.
Frequency	The mean annual frequency (days per year) of the activity at a particular location within a given region.
Trophic impact	The primary extent of marine life affected by an activity within a given ecosystem and region.
Percentage change	The degree to which the species, trophic level(s), or entire ecosystem's ''natural'' state is impacted by the activity.
Recovery time	The mean time (in years) required for the affected species, trophic level(s), or entire community to return to its former, ''natural'' state following disturbance by a particular activity.

The vulnerability matrix for the California Current region (Teck et al. 2010) scored 19 ecosystems and 53 activity/stressors, through a survey completed by 107 experts. The resulting matrix has been used in regional applications around the world (Afflerbach et al. 2017; Andersen et al. 2015; Ban et al. 2010; Clarke Murray et al. 2015b; Micheli et al. 2013; Selkoe et al. 2009). The highest scoring combinations were Climate Change: ocean acidification on soft slope (3.4) and rocky intertidal (3.1), and invasive species on beach (3.0). The stressor with the highest vulnerability score was Climate Change: ocean acidification (2.5). The most vulnerable ecosystems were beach and mudflat (1.1) followed by rocky intertidal, suspension reef, and salt marsh (1.0).

4.1.2. Massachusetts (Kappel et al. 2012a, b)

The vulnerability matrix for the Massachusetts region (Kappel et al. 2012a) used the same methodology as Teck et al. (2010). The authors scored 14 ecosystems and 58 activity/stressors.

Fifty-seven experts from the wider New England area agreed to participate, resulting in a total of 87 completed ecosystem vulnerability surveys (because some experts were knowledgeable about more than one ecosystem), and 35 ranking surveys completed. The highest scoring combinations in the resulting matrix were Climate Change: Sea Temperature Change on tidal flat (6.1) and Diseases and Pathogens on soft bottom shelf (6.1). Other stressors with high vulnerability scores were related to climate change activity: sea temperature change (4.6) followed by UV change (3.4) and ocean acidification (3.4). The most vulnerable ecosystems were hard bottom shelf (2.8) followed by nearshore soft bottom habitats (2.3). When compared to the California Current vulnerability matrix generated in Teck et al. (2010), the scores for the Massachusetts region had a slightly wider range (0 – 6.1 vs. 0 – 3.4 for Teck et al.). This difference may be due to the differences in criteria weightings derived from the different pools of experts surveyed in the California Current and Massachusetts regions when calculating vulnerability scores (Kappel et al. 2012a).

4.1.3. Pacific Canada (Clarke Murray et al. 2015b)

The Teck et al. (2010) vulnerability matrix was modified for use in the Canadian Pacific (Ban et al. 2010; Clarke Murray et al. 2015b). Hexactinellid sponge reefs were not present in the region evaluated by Teck et al. (2010), so they were adapted from the vulnerability score for Seamounts, under advice of one of the Teck et al. (2010) authors. Fishing stressors in the matrix were adapted by modifying the fishing vulnerability scores with the severity scores of fishing gear types, following Chuenpagdee et al. (2003), based on a Canada-specific fishing gear impact assessment by Fuller et al. (2008). Additionally, to consider the three-dimensional nature of the ocean, the habitats were divided into benthic, shallow, and deep depth classes following previous methodology (Ban et al. 2010). The matrix for the Canadian Pacific presented in Clarke Murray et al. (2015b) contains 47 human activities and 26 habitats.

4.1.4. Atlantic Canada (Kappel et al. 2012a,b)

The vulnerability matrix from Atlantic Canadian waters was adapted from Kappel et al. (2012b). Despite conducting an independent survey of New England regional experts, Kappel et al. (2012b) were unable to determine vulnerability scores for several ecosystem-stressor combinations. Scores for missing ecosystem-stressor combinations were gap-filled from Teck et al. (2010), being rescaled to match the range of scores for the Massachusetts region matrix, as the median vulnerability scores across all stressors and habitats were higher in Kappel et al. (2012b). For example, kelp forests, hard bottom bathyal habitats, and canyons were not included in Kappel et al. (2012b) so scores for these habitats were inserted with rescaled scores from Teck et al. (2010). Two biogenic habitats, horse mussel bioherm and deep biogenic (corals, sponges, and sea pens), were not included in either the Teck et al. (2010) nor Kappel et al. (2012b) matrices so they were inserted with rescaled vulnerability scores from Teck et al. (2010) for Suspension-feeding Reefs and Seamounts, respectively (following Clarke Murray et al. 2015b). As four Energy Infrastructure stressors were not included in Teck et al. (2010), we conducted a literature review to gap-fill those scores for the missing habitats. Vulnerability scores for “mixed” substrate habitats (see Table 2), which also did not appear in the Teck nor Kappel matrices, were averaged from the scores of hard and soft bottom habitats within the same depth ranges (e.g., for each stressor, the vulnerability scores for nearshore mixed bottom were averaged from the scores of nearshore hard bottom and nearshore soft bottom habitats; following Clarke Murray et al. 2015b). The resulting matrix for the Canadian Atlantic contains 54 human activities and 21 habitats.

4.2. WHY VULNERABILITY SCORES VARY BY REGION

Biogeographic conditions differ between Canada's Pacific, Arctic, and Atlantic coasts (DFO 2009) because of the wide range of oceanographic and hydrodynamic conditions as well as differences in current and historical exposure to anthropogenic stressors among regions. As a result, vulnerabilities are not expected to be equivalent between coasts (Gunderson et al. 2016; Murphy et al. 2021). For example, eelgrass (*Zostera marina*) life history, phenology, and general species assemblages are similar among the Atlantic, Pacific, and Arctic coasts (Murphy et al. 2021). However, the differing biogeographic conditions have resulted in eelgrass having adapted differently to these conditions among coasts, or having differing morphology or associated species, which may affect how they respond to human impacts (Murphy et al. 2021). Variation in physical energy regimes (measured as a combination of benthic boundary shear stress and depth) among regions may determine the vulnerability (specifically the recovery time) of benthic substrates to the effects of bottom-contact fishing gear (Grabowski et al. 2014). Vulnerability to non-indigenous species invasions may also differ among coasts, due to varying levels of propagule and colonization pressure and the degree of similarity between hull and harbour fouling species in recipient communities (Sylvester et al. 2011). Rather than attempt to find agreement between the Atlantic and Pacific coastal ecosystems and experts, the authors have opted to use separate matrices between coasts to account for their differing biogeographic properties.

4.3. MATRIX PRE-REVIEW

The vulnerability scores in both the Teck et al. (2010) and the Kappel et al. (2012b) matrices were evaluated for use in Canadian habitats. We elicited expert opinion from relevant ecosystem experts in a pre-review of Pacific and Atlantic vulnerability scores and rankings. The Atlantic and Pacific teams collaborated on the creation of the survey instrument but conducted surveys separately to ensure that the results were specific to the appropriate regional ecosystems (Murphy et al. 2021). Individual spreadsheets were created for each habitat listing the vulnerability to each activity/stressor in rows (see example in Appendix 1). The surveyed experts were asked to review and compare the scores for a single habitat, thus evaluating the vulnerability from a habitat perspective, rather than a stressor one. To simplify the review process, the relative vulnerability scores were binned into five classes (Negligible, Low, Medium, High, and Extreme) using Jenks natural breaks (Table 6; R version 4.0.4, package BAMMtools, R Studio, version 1.2.5019).

Table 6: Vulnerability score classes created for the Pacific and Atlantic regional expert surveys

Vulnerability score classes	Pacific value range	Atlantic value range
Negligible	0	0
Low	>0.1 to ≤0.6	>0.1 to ≤1.2
Medium	>0.6 to ≤1.2	>1.2 to ≤2.3
High	>1.2 to ≤2	>2.3 to ≤3.5
Extreme	>2 to ≤3.4	>3.5 to ≤6.1

Experts were identified based on publication history with the respective habitats and contacted experts could suggest additional experts. The full list of expert pre-reviewers is presented in Appendix 2. Each expert was asked to examine the ranked list of vulnerability classes for a particular habitat across all activities/stressors. If they disagreed with the relative placement of a stressor, the expert(s) could suggest changes: an alternative class or movement within a class.

The survey instrument had space to include their rationale for changes, comments, and supporting citations. Prior to sending to the experts, the survey instrument was tested on two colleagues who were not directly involved with the survey and updated based on their feedback. The Pacific and Atlantic surveys were sent to experts on their respective coasts.

In a Delphic exercise, the completed spreadsheets were compiled by habitat and the proposed class changes based on the expert feedback were sent back to the same group of experts for further comment and consideration. The experts could view the other experts' anonymous changes and comments and make further agreement or rebuttal.

Completed spreadsheets from the second round of review were used to make final recommendations for changes to the vulnerability classes. Based on the experts' comments and suggestions, we moved the activities or stressors into their newly proposed classes using a common rule set. Additional rules were applied when experts suggested different classes, even after the combined stage. If both experts suggest a change in same direction, but not the same class, we made the most conservative change. If one expert suggested a change (with rationale included) while another expert suggested a change in the same direction (without a rationale given), we changed to the first expert's suggested class If one expert suggested a change (with rationale) and the second expert didn't comment, we changed to the suggested class. In rare cases of disagreement between experts, the change suggested by the majority was made. If tied, the authors acted as tie breaker.

The proposed class rankings were then converted back to numerical scores. When an expert suggested a relative location (e.g., between two other stressors, or top of a class), the stressor score was assigned that score. When a class was changed and no specific location noted, it was moved to the nearest numerical value of that class for the most conservative change. Conservative changes were made because the original scores were the result of a large and thorough expert elicitation exercise. The suggested revisions and changes to both matrices are presented in Section 4.3.1.

4.3.1. Suggested additions, deletions, or changes

4.3.1.1. Pacific matrix

Pacific surveys were sent to 35 experts, with 29 completed surveys returned from a total of 24 experts. Each of the Pacific habitats had at least one expert review the scores, except Canyon. Many experts asked clarification questions and included citations in their comments, demonstrating thoughtful engagement with the survey instrument. For each habitat, experts reviewed the stressor rankings and suggested at least one change while including comments explaining the selection. The revised matrix includes these proposed changes (Table 7). Of the 988 scores, 14.8% (146) were changed, with 12.1% (120) increased in value (i.e., greater vulnerability), and 2.6% (26) decreased (i.e., lower vulnerability).

4.3.1.2. Atlantic matrix

Atlantic surveys were sent to 52 experts, with 42 completed surveys returned from a total of 33 experts. Each of the Atlantic habitats had multiple experts review the scores with the exception of three habitat surveys only reviewed by one expert each (beach, nearshore soft bottom, and deep pelagic). As with the Pacific surveys, experts reviewed the stressor rankings and suggested changes with many providing justification and citations for their changes. The revised matrix with proposed changes is shown in Table 8. Changes were made to 20% of the scores in the matrix, with 9.2% of the scores increased in value (i.e., greater vulnerability) and 10.8% of the scores decreased in value (i.e., lower vulnerability).

4.3.1.3. Additional suggestions

Several experts, on both coasts, suggested additional stressors for consideration in the matrices, as they felt there was no existing activity/stressor present in the vulnerability matrix which adequately described impacts from these identified stressors. In the Pacific, air temperature was suggested by experts to address air exposure in the intertidal. "Climate change: sea temperature change" is currently part of the matrix and the long-term trend of air temperature will be captured in sea temperature changes.

In the Atlantic, deoxygenation due to climate change was suggested by an expert to address the extreme impacts of low oxygen environments, particularly for deep sea biogenic habitats. Another expert brought to our attention the increasing commercial interest in harvesting wild kelp (on the Atlantic coast and worldwide), which would have an extreme impact on kelp forests under high harvesting levels. We recognize the importance of these emerging stressors; however, we were not able to incorporate them at this time due to a lack of understanding of the direct and indirect impacts of these activities on other habitats (i.e., there are no existing estimates of all habitats' vulnerabilities to these particular emerging stressors), nor the information available to estimate these activities across the wider region (i.e., we do not have accurate spatial maps of their regional extent). These stressors could be added in future applications with expert elicitation and/or literature review.

Table 7: Revised vulnerability matrix for the Pacific Coast. Vulnerability scores that were changed during the matrix pre-review are bolded with an arrow to indicate the change direction. Note: scores for mixed substrate habitats do not appear in this table, as no expert surveys were consulted for these habitats.

Activities and stressors	Beach intertidal	Hard intertidal	Soft intertidal	Mudflat	Seagrass	Kelp forest	Hard shallow	Soft Shallow	Hard shelf	Soft shelf	Hard slope	Soft slope	Hard deep	Soft deep	Seamounts	Sponge reefs	Canyon	Shallow pelagic	Deep pelagic
Aquaculture: Finfish	**0.2** ↑	0.2	**0.1** ↑	0.0	0.3	**0.7** ↑	1.0	**0.1** ↑	0.7	0.9	0.0	0.5	0.0	**0.7** ↑	0.0	**2.3** ↑	0.0	1.2	0.0
Aquaculture: Plants and algae	0.0	0.8	0.2	**0.7** ↑	0.4	**0.7** ↑	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.7** ↑	0.0	0.0	0.0	0.0	0.0
Aquaculture: Shellfish	**0.7** ↑	1.0	**0.7** ↑	**1.3** ↑	1.6	**0.7** ↑	**0.7** ↑	0.5	**1.1** ↑	0.2	0.0	0.0	0.0	**0.7** ↑	0.0	0.0	0.0	0.2	0.0
Benthic structures	1.4	0.9	1.9	2.4	**1.1** ↓	1.6	1.7	1.4	2.4	2.2	2.3	1.4	0.0	**1.3** ↑	0.0	**0.7** ↑	2.3	0.4	0.0
Climate Change: Ocean Acidification	1.8	**1.7** ↓	2.1	2.4	**1.1** ↓	2.0	2.2	**1.3** ↑	2.7	2.6	3.4	3.4	3.4	2.5	2.6	2.6	2.6	**1.8** ↓	2.7
Climate Change: sea level rise	1.7	2.7	1.8	**2.1** ↑	1.9	**0.6** ↓	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
Climate Change: sea temperature change	1.7	2.7	1.8	1.8	1.9	2.9	2.2	0.0	1.9	1.7	**3.4** ↑	**3.4** ↑	**1.3** ↑	0.5	0.0	**1.3** ↑	1.7	2.5	**2.1** ↑
Climate Change: UV change	1.8	**1.2** ↓	1.8	**2.1** ↑	1.5	1.6	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.8
Coastal Engineering: altered flow dynamics	1.3	1.5	1.7	2.0	1.1	1.2	0.7	**1.3** ↑	0.0	0.2	0.0	0.0	0.0	0.0	0.0	**2.3** ↑	0.0	0.0	0.0
Coastal Engineering: habitat alteration	1.3	**2.7** ↑	1.7	2.1	**1.7** ↑	1.4	1.1	**1.3** ↑	0.0	0.2	0.0	0.0	0.0	**1.3** ↑	0.0	**2.3** ↑	0.0	0.2	0.0
Direct Human Impact: trampling	**0.7** ↓	1.6	**0.6** ↓	0.3	**1.3** ↑	0.1	0.2	**0.0** ↓	0.0	**0.0** ↓	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Disease or pathogens	1.1	**1.7** ↑	1.1	1.1	**1.3** ↑	1.0	1.0	0.0	1.1	0.9	1.2	0.0	0.0	0.0	0.0	**2.3** ↑	1.1	**0.7** ↑	0.0
Dredge	1.6	0.2	1.7	1.7	1.7	**1.3** ↑	**0.7** ↑	**1.3** ↑	0.0	0.6	0.0	0.0	0.0	0.0	0.0	**2.3** ↑	0.0	0.1	0.0
Fishing: aquarium	0.0	0.6	0.1	0.1	0.1	0.7	**0.5** ↓	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fishing: demersal, habitat-modifying	0.9	0.7	1.0	1.1	**0.6** ↑	**0.7** ↑	**1.3** ↑	1.2	1.6	2.0	2.3	2.3	2.8	2.2	2.7	2.7	2.5	0.3	0.0

Activities and stressors	Beach intertidal	Hard intertidal	Soft intertidal	Mudflat	Seagrass	Kelp forest	Hard shallow	Soft Shallow	Hard shelf	Soft shelf	Hard slope	Soft slope	Hard deep	Soft deep	Seamounts	Sponge reefs	Canyon	Shallow pelagic	Deep pelagic
Fishing: demersal, low-habitat-modifying, high bycatch	1.3	0.4	1.1	0.9	**0.8** ↑	1.2	1.3	0.6	1.3	1.3	1.8	1.3	**2.5** ↑	1.3	1.3	1.3	1.3	0.4	0.0
Fishing: demersal, low-habitat-modifying, low bycatch	0.8	0.4	0.8	0.7	0.5	1.2	1.2	0.4	1.1	0.8	1.1	**1.3** ↑	0.9	0.8	**1.3** ↑	0.9	0.8	0.3	0.0
Fishing: low-habitat-modifying, artisanal	0.7	0.8	0.7	0.6	0.4	0.2	0.3	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Fishing: pelagic, high bycatch	0.0	0.2	0.0	0.0	0.0	0.3	0.9	0.0	0.0	0.2	0.0	0.0	**0.7** ↑	0.1	0.0	**1.3** ↑	0.0	1.6	1.6
Fishing: pelagic, low bycatch	0.0	0.0	0.0	0.0	0.0	0.2	0.8	0.0	0.0	0.3	0.0	0.3	**0.7** ↑	0.0	0.0	0.0	0.0	1.1	1.5
Fishing: recreational	1.0	1.2	1.1	1.1	0.9	**1.2** ↓	1.4	0.8	1.2	0.4	1.6	0.0	0.7	0.8	0.7	0.7	0.0	1.1	0.0
Freshwater: input decrease	0.6	**1.3** ↑	0.9	1.1	**0.8** ↑	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Freshwater: input increase	0.9	**1.3** ↑	1.1	1.2	0.8	0.8	1.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0
Invasive species	3.2	2.6	3.1	3.0	1.7	**1.2** ↓	1.8	**0.6** ↓	1.5	0.7	0.0	0.0	**0.7** ↑	1.1	**0.35** ↑	**1.3** ↑	0.0	0.3	0.0
Marine component of forestry	**0.7** ↑	0.5	**1.3** ↑	0.7	**1.3** ↑	**1.3** ↑	0.0	**0.8** ↑	**1.3** ↑	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Military activity	1.4	0.4	1.1	0.8	0.8	1.0	0.3	0.6	1.3	1.3	1.3	1.2	1.3	**1.3** ↑	1.2	1.2	1.3	**1.2** ↓	1.4
Nutrient input: causing Harmful Algal Blooms	1.7	1.1	1.7	1.7	**0.8** ↓	1.1	1.3	0.5	1.4	1.1	1.3	0.0	0.0	0.0	0.0	**1.3** ↑	0.0	1.5	1.8
Nutrient input: causing hypoxic zones	1.5	0.8	1.6	**2.1** ↑	0.9	**1.3** ↑	**1.3** ↑	**1.3** ↑	1.8	1.5	**3.4** ↑	**1.3** ↑	0.0	0.0	0.0	**1.3** ↑	0.0	1.8	2.0
Nutrient input: into eutrophic water	1.5	0.9	1.3	**1.3** ↑	0.9	**1.3** ↑	1.0	0.3	1.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.1	0.9
Nutrient input: into mesotrophic water	1.1	1.0	**1.3** ↑	1.2	0.9	**1.3** ↑	0.9	0.3	1.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.4	2.1

Activities and stressors	Beach intertidal	Hard intertidal	Soft intertidal	Mudflat	Seagrass	Kelp forest	Hard shallow	Soft Shallow	Hard shelf	Soft shelf	Hard slope	Soft slope	Hard deep	Soft deep	Seamounts	Sponge reefs	Canyon	Shallow pelagic	Deep pelagic
Ocean dumping: lost fishing gear	1.5	1.0	1.5	1.4	0.9	1.1	1.1	0.4	1.2	1.2	1.2	1.3	**2.5 ↑**	1.2	1.3	1.3	1.2	1.3	1.3
Ocean dumping: marine debris	1.0	0.9	1.0	1.0	**0.8 ↑**	0.8	0.9	0.4	1.0	0.8	1.0	0.9	0.9	0.8	0.7	**1.3 ↑**	0.6	1.0	0.8
Ocean dumping: shipwrecks	1.6	1.5	2.0	2.3	**1.1 ↓**	1.7	2.1	1.0	2.4	1.8	2.5	1.6	2.5	1.3	2.3	2.3	2.3	0.0	0.0
Ocean dumping: toxic materials	1.4	0.9	1.5	1.5	1.1	0.9	1.0	**1.3 ↑**	1.1	1.1	1.4	1.1	1.1	**2.2 ↑**	1.1	**1.3 ↑**	1.3	1.1	1.3
Ocean mining: sand, minerals, etc.	1.1	0.1	0.6	0.0	0.5	**1.3 ↑**	0.0	**1.3 ↑**	0.0	1.3	0.0	**2.3 ↑**	**3.4 ↑**	**2.2 ↑**	**0.7 ↑**	**2.3 ↑**	0.0	0.0	0.0
Ocean pollution from ships and ports	0.8	1.3	1.1	1.3	0.9	0.9	1.0	0.4	1.0	0.8	1.3	0.0	0.0	0.0	0.0	0.0	0.9	1.4	0.0
Pollution input: atmospheric	0.9	1.1	1.1	1.3	1.0	1.0	1.1	0.0	1.2	1.1	0.7	0.0	0.0	0.0	0.0	0.0	1.3	1.6	0.9
Pollution input: inorganic	1.3	1.2	1.3	1.3	0.9	1.3	1.5	0.8	1.1	1.6	0.0	2.0	0.0	1.9	0.0	0.0	1.3	1.6	1.3
Pollution input: light	1.2	0.9	1.2	1.2	**0.8 ↑**	0.1	0.0	0.3	0.0	0.2	0.0	0.0	**0.7 ↑**	**0.1 ↑**	0.0	0.0	0.0	0.4	0.8
Pollution input: noise	1.2	0.9	1.2	1.2	**0.8 ↑**	0.1	**0.5 ↑**	0.3	**0.7 ↑**	0.2	**0.35 ↑**	**0.6 ↑**	**0.7 ↑**	**0.5 ↑**	**0.6 ↑**	**0.7 ↑**	**0.9 ↑**	0.4	0.8
Pollution input: organic	1.9	1.3	1.9	1.9	1.1	1.3	1.5	1.4	1.3	1.5	0.0	2.0	0.0	2.5	0.0	0.0	1.2	1.5	1.3
Pollution input: urban runoff	1.2	1.1	1.2	**1.3 ↑**	0.9	0.7	1.2	1.0	0.4	0.9	0.9	1.2	0.0	1.9	0.0	0.0	0.8	1.1	0.8
Power and desalination plants	1.7	1.5	1.5	1.3	0.5	0.8	1.1	0.5	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.2
Scientific research and collecting	0.7	0.8	**0.6 ↓**	0.7	**1.3 ↑**	0.7	0.7	0.1	0.7	0.9	0.0	**1.2 ↓**	0.7	0.7	0.7	**0.35 ↓**	0.7	0.7	0.4
Scientific research experiments/surveys	0.7	0.9	**0.6 ↓**	0.7	0.8	0.7	0.8	**0.6 ↓**	0.8	1.0	0.0	**1.2 ↓**	0.9	0.8	0.9	0.9	0.9	1.0	0.5
Sediment input: decrease	1.2	0.8	1.8	2.3	0.8	0.1	0.0	0.6	0.0	0.3	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
Sediment input: increase	1.8	1.5	1.6	**2.1 ↑**	**1.6 ↑**	**2.4 ↑**	**1.3 ↑**	0.8	**0.4 ↑**	**0.1 ↑**	1.0	0.0	0.0	1.2	0.0	**1.3 ↑**	1.4	**0.7 ↑**	0.0

Activities and stressors	Beach intertidal	Hard intertidal	Soft intertidal	Mudflat	Seagrass	Kelp forest	Hard shallow	Soft Shallow	Hard shelf	Soft shelf	Hard slope	Soft slope	Hard deep	Soft deep	Seamounts	Sponge reefs	Canyon	Shallow pelagic	Deep pelagic
Shipping (large vessels)	1.4	0.2	0.9	0.4	0.3	0.0	0.3	0.0	**0.4** ↑	0.3	0.0	0.0	0.0	0.0	0.0	**0.7** ↑	0.0	**1.2** ↓	0.0
Tourism: kayaking	0.4	0.4	0.4	0.4	**1.3** ↑	0.6	0.5	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0
Tourism: recreational boating	0.2	0.0	0.5	**1.3** ↑	**1.3** ↑	0.9	1.0	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.5** ↓	0.0
Tourism: scuba diving	**0.4** ↑	0.0	0.0	0.0	0.1	1.0	**0.5** ↓	0.0	0.2	0.1	0.0	0.0	0.0	0.0	**0.35** ↑	0.0	0.0	0.2	0.0
Tourism: surfing	0.4	0.6	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0

Table 8: Revised vulnerability matrix for the Atlantic Coast. Vulnerability scores that were changed during the matrix pre-review are bolded with an arrow to indicate the change direction. Mixed habitats are mapped but use an average vulnerability score for the habitat type (e.g., the Mixed bottom shelf is an average of the Soft and Hard bottom shelf habitat classes' scores). As no expert surveys were conducted for these habitats, they do not appear in this table.

Activities and stressors	Beach intertidal	Tidal flat	Rocky intertidal	Saltmarsh	Kelp forest	Seagrass	Algal zone	Nearshore soft	Nearshore hard	Horse mussel bioherm	Soft shelf	Hard shelf	Shallow pelagic	Soft bathyal	Hard bathyal	Canyon	Deep biogenic	Deep pelagic
Aquaculture: finfish	0.0	0.2	**2.4 ↑**	0.9	**1.3 ↑**	**1.4 ↑**	**2.4 ↑**	1.9	2.1	0.0	0.6	3.0	1.7	0.0	0.0	0.0	0.0	0.0
Aquaculture: marine plants	0.0	0.8	2.0	0.8	0.0	**1.4 ↑**	0.4	1.8	1.0	0.0	0.6	1.5	1.0	0.0	0.0	0.0	0.0	0.0
Aquaculture: shellfish	0.9	2.0	2.5	1.4	**1.3 ↑**	**2.4 ↑**	1.7	**3.5 ↑**	2.1	2.7	0.6	2.4	**1.3 ↑**	0.0	0.0	0.0	0.0	0.6
Benthic structures	0.0	3.3	2.8	1.9	**1.1 ↓**	**1.4 ↑**	3.7	**2.3 ↓**	2.6	3.6	**3.7 ↑**	3.8	**1.2 ↓**	**3.4 ↓**	0.0	**3.1 ↓**	**2.3 ↑**	1.9
Climate change: ocean acidification	1.8	4.3	**3.3 ↓**	**3.5 ↓**	**2.2 ↓**	**2.3 ↓**	3.2	1.5	**4.2 ↑**	**3.2 ↓**	4.4	5.0	4.7	**3.4 ↓**	4.7	4.7	**2.2 ↓**	3.7
Climate change: sea level rise	4.4	**3.4 ↓**	4.8	4.6	**0.0 ↓**	3.5	**3.6 ↑**	2.0	2.4	**1.1 ↓**	1.0	**1.2 ↓**	**2.3 ↓**	0.0	0.0	0.0	0.0	1.1
Climate change: sea temperature change	4.3	6.1	3.9	**2.3 ↓**	5.2	2.8	3.8	4.8	4.6	3.9	3.5	5.9	5.1	4.3	**4.5 ↑**	3.1	**4.1 ↑**	4.6
Climate change: UV change	2.1	**3.4 ↓**	**3.3 ↓**	**3.5 ↓**	**1.1↓**	**3.5 ↓**	**3.5 ↓**	3.8	3.1	**1.1 ↓**	0.0	**1.2 ↓**	**3.5 ↓**	0.0	0.0	0.0	0.0	3.3
Coastal engineering: altered flow dynamics	3.6	3.6	**3.3 ↓**	3.7	**2.3 ↑**	2.8	2.5	3.2	1.2	4.3	**2.3 ↑**	1.4	1.2	0.0	0.0	0.0	0.0	1.5
Coastal engineering: habitat alteration	3.7	3.6	3.7	**3.7 ↑**	2.5	**4.2 ↑**	3.5	4.2	1.6	4.3	**2.3 ↑**	1.6	1.3	0.0	0.0	0.0	0.0	1.3
Direct human impact: trampling	3.0	2.7	2.0	**1.2 ↓**	0.2	1.6	0.0	0.8	0.6	0.0	0.5	0.0	0.4	0.0	0.0	0.0	0.0	0.9
Diseases and pathogens	**2.5 ↑**	3.2	2.9	1.8	**2.3 ↑**	2.3	2.0	1.8	2.5	2.7	6.1	2.5	2.8	2.3	**1.3 ↑**	2.0	**1.3 ↑**	2.8
Dredging	2.8	3.3	**2.4 ↑**	**2.4 ↑**	**1.3 ↑**	**4.2 ↑**	3.4	3.5	3.2	3.9	**3.7 ↑**	4.1	1.3	**2.3 ↑**	**0.7 ↑**	0.0	**2.3 ↑**	1.8
Energy infrastructure: liquid natural gas	1.2	3.1	3.3	**1.2 ↓**	2.5	2.5	2.5	4.6	2.1	2.4	**2.3 ↓**	**2.3 ↓**	2.8	0.0	0.0	0.0	0.0	2.4

Activities and stressors	Beach intertidal	Tidal flat	Rocky intertidal	Saltmarsh	Kelp forest	Seagrass	Algal zone	Nearshore soft	Nearshore hard	Horse mussel bioherm	Soft shelf	Hard shelf	Shallow pelagic	Soft bathyal	Hard bathyal	Canyon	Deep biogenic	Deep pelagic
Energy infrastructure: tidal	1.4	3.0	**1.3** ↑	**1.2** ↓	**2.2** ↓	2.7	2.7	5.9	2.6	1.7	**2.3** ↑	3.0	2.6	0.0	0.0	0.0	0.0	0.7
Fishing: aquarium	0.0	0.0	0.3	0.3	**1.1** ↓	0.0	0.6	0.4	0.9	0.0	0.6	1.9	0.7	0.0	0.0	0.0	0.0	0.7
Fishing: demersal, habitat-modifying	0.0	3.1	**2.4** ↑	0.5	**1.3** ↑	**4.2** ↑	3.1	3.8	3.5	**3.6** ↑	**3.7** ↑	3.5	2.2	**3.6** ↑	**4.5** ↑	4.5	4.8	2.8
Fishing: demersal, low-habitat-modifying, high bycatch	0.0	1.1	**1.4** ↑	0.8	2.2	**1.5** ↑	2.8	2.6	2.5	**1.1** ↓	3.5	3.9	1.8	2.7	2.2	2.3	2.3	1.4
Fishing: demersal, low-habitat-modifying, low bycatch	0.0	1.1	**1.2** ↓	0.7	**1.1** ↓	**1.4** ↑	2.5	2.1	2.2	2.9	2.2	2.3	**1.7** ↓	**1.2** ↑	1.7	1.4	**2.3** ↑	1.7
Fishing: low-habitat-modifying artisanal (subsistence)	0.6	1.0	0.2	0.7	0.4	0.3	0.3	0.0	2.0	1.6	1.0	2.3	0.3	0.0	0.0	0.0	0.0	0.0
Fishing: pelagic, high bycatch	0.0	1.0	0.0	0.2	0.5	0.0	2.6	1.5	1.6	0.0	2.9	**2.3** ↓	3.2	**1.2** ↑	**0.7** ↑	**1.3** ↑	**2.3** ↑	2.9
Fishing: pelagic, low bycatch	0.0	1.0	0.0	0.2	0.4	0.0	1.7	1.5	1.3	0.0	2.6	2.3	2.8	0.0	0.0	**1.3** ↑	**2.3** ↑	1.1
Fishing: recreational	1.1	2.1	1.2	**2.4** ↑	**1.1** ↓	1.1	1.6	1.5	2.5	1.6	2.0	2.8	2.2	0.0	1.3	0.0	**2.3** ↑	0.9
Freshwater input: decrease	0.2	0.2	1.7	**2.3** ↓	0.4	**2.4** ↑	1.1	0.0	3.0	0.0	2.4	3.4	**1.3** ↑	0.0	0.0	0.0	0.0	0.8
Freshwater input: increase	0.5	**2.4** ↑	2.6	**2.3** ↓	1.4	**2.3** ↓	1.9	1.9	3.0	1.4	2.7	3.4	2.4	0.0	0.0	0.0	0.0	0.8
Invasive species (from ballast, etc.)	3.6	1.8	3.8	3.5	4.3	2.6	**3.6** ↑	**2.3** ↓	3.5	3.8	3.3	4.0	3.2	1.2	**2.3** ↓	0.0	**1.3** ↑	**1.2** ↓
Military activity	0.0	3.1	0.5	**1.3** ↑	**1.1** ↓	**0.3** ↑	0.9	1.1	2.2	0.0	2.3	1.8	**2.4** ↑	2.2	2.3	2.3	**0.0** ↓	2.5
Nutrient input: causing harmful algal blooms	0.2	3.6	**2.4** ↑	1.7	2.0	2.6	2.3	1.5	2.7	3.8	2.9	3.5	3.1	0.0	0.0	0.0	0.0	1.2

Activities and stressors	Beach intertidal	Tidal flat	Rocky intertidal	Saltmarsh	Kelp forest	Seagrass	Algal zone	Nearshore soft	Nearshore hard	Horse mussel bioherm	Soft shelf	Hard shelf	Shallow pelagic	Soft bathyal	Hard bathyal	Canyon	Deep biogenic	Deep pelagic
Nutrient input: causing hypoxic waters	0.2	3.6	**2.4** ↑	1.9	1.8	**4.2** ↑	2.1	3.7	3.2	3.9	**3.7** ↑	3.2	**2.4** ↑	**1.2** ↑	0.0	0.0	0.0	1.1
Nutrient input: into eutrophic waters	0.2	4.0	**3.6** ↑	2.9	1.6	**4.2** ↑	2.3	3.7	3.2	3.9	2.7	**3.5** ↓	2.3	0.0	0.0	1.8	0.0	1.1
Nutrient input: into oligotrophic waters	0.2	**3.6** ↑	0.5	2.5	2.2	2.3	2.9	3.7	1.6	3.9	2.9	3.4	**2.4** ↑	0.0	2.1	2.3	0.0	1.1
Ocean dumping: lost fishing gear	2.5	1.4	1.1	0.7	**1.1** ↓	1.0	2.5	**2.3** ↓	2.4	0.9	3.1	2.8	**2.4** ↑	2.9	2.3	**2.5** ↑	2.3	2.6
Ocean dumping: marine debris (trash, etc.)	3.6	2.7	2.2	1.6	1.4	0.8	3.1	3.3	2.4	1.1	3.7	2.8	3.1	1.4	1.6	**1.3** ↑	1.3	2.9
Ocean dumping: shipwrecks	0.5	1.2	1.6	0.3	**1.1** ↓	0.5	1.8	3.4	1.6	**1.8** ↓	2.8	2.0	1.3	2.3	**3.1** ↓	**1.1** ↓	**0.0** ↓	1.5
Ocean dumping: toxic materials	1.9	3.4	2.6	1.5	1.6	0.7	3.7	**2.5** ↑	2.2	3.1	4.3	3.9	2.3	5.2	2.0	**4.1** ↑	2.0	2.6
Ocean mining (sand, minerals, etc.)	2.3	1.4	1.6	0.7	0.2	**1.4** ↑	0.3	3.8	2.3	0.0	**3.7** ↑	3.7	2.0	**2.3** ↑	0.0	0.0	**2.3** ↑	2.9
Ocean pollution (from ships, ports, etc.)	3.4	3.2	3.3	2.9	1.6	**2.4** ↑	1.7	3.5	3.1	0.0	**3.5** ↓	3.8	3.5	**2.3** ↓	1.7	1.6	**2.3** ↑	2.9
Pollutant input: atmospheric	1.0	2.1	1.8	2.8	**1.1** ↓	1.8	2.1	0.0	**2.3** ↓	**1.1** ↓	**3.5** ↓	**2.3** ↓	3.4	0.0	2.0	2.3	0.0	3.8
Pollutant input: inorganic	1.3	2.6	2.0	3.0	2.3	2.0	**2.4** ↑	1.4	3.5	2.5	4.7	3.9	2.8	**1.2** ↑	1.9	2.3	0.0	2.6
Pollutant input: light	2.1	**0.2** ↑	1.0	0.7	0.2	**0.3** ↑	2.1	1.0	1.5	**1.1** ↓	0.0	1.8	1.5	0.0	1.8	0.0	0.0	1.4
Pollutant input: noise	2.2	1.6	0.6	**1.2** ↓	0.2	**0.3** ↑	0.1	0.5	1.7	**1.1** ↓	0.4	2.4	**3.5** ↑	**1.2** ↑	**0.7** ↑	**4.1** ↑	**1.2** ↑	2.9
Pollutant input: organic	2.3	3.0	3.0	3.0	2.3	3.0	**2.4** ↑	3.8	3.4	2.7	3.8	3.6	3.5	0.0	2.3	2.2	0.0	3.2

Activities and stressors	Beach intertidal	Tidal flat	Rocky intertidal	Saltmarsh	Kelp forest	Seagrass	Algal zone	Nearshore soft	Nearshore hard	Horse mussel bioherm	Soft shelf	Hard shelf	Shallow pelagic	Soft bathyal	Hard bathyal	Canyon	Deep biogenic	Deep pelagic
Pollutant input: trash, etc. (urban runoff)	3.1	2.7	2.1	2.7	1.3	1.9	3.6	4.1	3.1	1.8	3.2	2.4	2.8	0.0	0.7	1.4	0.0	2.1
Power plants and desalination plants	0.0	1.5	1.4	2.1	1.4	1.5	3.2	3.1	2.6	0.0	1.3	3.2	1.5	0.0	0.0	0.0	0.0	1.1
Scientific research: collecting	0.6	**1.2** ↓	1.7	**1.2** ↓	**1.1** ↓	**0.0** ↓	0.5	1.3	0.9	**0.9** ↑	1.8	1.5	0.9	**1.2** ↑	1.3	**1.1** ↓	1.3	1.6
Scientific research: experiments/surveys	0.6	**1.2** ↓	1.6	**1.2** ↓	**1.1** ↓	**0.0** ↓	0.5	**1.1** ↓	0.6	0.0	2.1	2.2	0.4	0.0	**0.0** ↓	**1.1** ↓	1.6	0.6
Sediment input: decrease	2.7	2.0	**1.2** ↓	4.1	**0.0** ↓	1.4	0.8	0.7	1.9	2.9	1.5	**2.3** ↓	1.0	0.0	**0.7** ↑	0.0	0.0	0.8
Sediment input: increase	3.1	3.6	2.4	**1.2** ↓	2.5	**2.4** ↑	2.4	2.3	2.2	2.5	2.8	**2.3** ↓	1.8	0.0	**0.7** ↑	2.5	0.0	0.8
Shipping (commercial, cruise, ferry)	0.9	0.9	1.2	**1.3** ↑	**0.2** ↑	1.7	1.8	0.0	2.8	0.0	1.7	3.2	**1.2** ↓	0.0	0.0	**2.5** ↑	0.0	0.8
Tourism: kayaking	0.7	0.8	1.1	1.2	1.1	0.5	**0.0** ↓	0.0	0.6	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Tourism: recreational boating	1.4	2.3	**1.2** ↓	**2.4** ↑	**1.1** ↓	2.8	2.2	1.7	2.0	0.0	0.7	1.2	1.2	0.0	0.0	0.0	0.0	0.8
Tourism: scuba diving	0.5	0.6	1.1	0.1	**1.1** ↓	0.7	**1.1** ↓	1.5	1.2	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.6
Tourism: surfing	1.2	0.0	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
Tourism: whale watching	0.0	0.0	0.0	0.0	**1.1** ↓	0.0	0.0	0.0	0.6	0.0	0.0	1.9	2.3	0.0	0.0	**1.1** ↑	0.0	1.1

5. DISCUSSION AND CONCLUSIONS

5.1. APPLICATIONS

Since its origin, cumulative impact mapping has been applied in many regions around the world (Afflerbach et al. 2017; Andersen et al. 2015; Andersen et al. 2017; Halpern et al. 2007; Halpern et al. 2009; Halpern et al. 2015; Halpern et al. 2008; Kappel et al. 2012; Micheli et al. 2013; Selkoe et al. 2009). Its most powerful attribute is the ability to simplify and visualize complex information. Cumulative impact maps showcase differences in impact across areas, contrasting relatively low impact and high impact areas. The results of the model provide a simple illustration of cumulative impacts that has been cited broadly in the scientific literature as well as being presented in the popular media (e.g., National Geographic).

Beyond illustration, cumulative impact mapping can be used to prioritise activities and stressors with high impact for management or mitigation action. For example, Mach et al. (2017) evaluated the cumulative impacts to marine protected areas in California and identified those activities under local management control that contribute to cumulative impacts in the context of global climate change. Brown et al. (2014) showed that knowledge of the interaction type between local and global stressors assisted effective management decisions for seagrass beds. Wyatt et al. (2017) modified the cumulative impact mapping method to estimate the cumulative risk to habitats from multiple stressors along the Atlantic coast of the U.S, finding different levels of ecosystem risk to nearshore and offshore ecosystems and identifying different management strategies required to mitigate this risk. A recent effort by Murphy et al. (2022) used known quantitative thresholds in seagrass response to stressors to set quantitative limits for cumulative impact scores.

Cumulative impact mapping can be used to identify a baseline level of cumulative impacts and compare the baseline to alternate future scenarios. Clarke Murray et al. (2015a) compared the present-day cumulative effects with an increase due to proposed industrial developments. Lonsdale et al. (2020) developed a tool to account for differences in temporal scale of stressors, identifying when stressors occur within each phase of a project (construction, operation, decommissioning). Hammar et al. (2020) added a scenario component into a cumulative impacts mapping model to project the positive or negative consequences to ecosystem components of different planning alternatives within the marine spatial plan for Swedish waters of the Baltic Sea.

In theory, cumulative impact mapping could be used to identify areas for planning purposes; low impact areas could be candidate protected areas while high impact areas could be targets for restoration efforts. The results could be used to define the thresholds for the three global conditions for the sea: degraded, shared, and wild (Agbayani and Murray 2020; Locke et al. 2019). Further, as an explicit part of marine spatial planning, cumulative impact scores could be used as a cost layer in Marxan analyses to identify or compare planning scenarios or design marine protected area networks. The impact scores can also be used in monitoring or research as a continuous variable to stratify sampling effort, as it has been applied to estuary habitat in the North Coast Marine Planning Partnership (MaPP) research (Wallace and Martone 2021).

5.2. GAPS AND LIMITATIONS

Cumulative impact mapping has important assumptions that must be acknowledged in any application of the method (reviewed by Halpern and Fujita 2013). First, the model assumes that the effects of all stressors are additive, when there is mounting evidence that synergistic and antagonistic interactions are common (Côté et al. 2016; Crain et al. 2008; Darling and Côté

2008). Stressors are assumed to be of equal importance and that each is uniformly distributed within its spatial representation (grid cell or polygon). The ecosystems of concern are assumed to have consistent, linear responses to individual stressors and to cumulative impacts. Dose-response curves are commonly non-linear, but require extensive laboratory testing to produce (e.g., PCB contamination in killer whales: Hall et al. 2018). With advances in the knowledge of the system, it would be possible to apply non-additive interactions where warranted.

The cumulative impact mapping model has high data requirements, with data gathering and processing comprising the bulk of the work in any application. Source data is compiled for dozens of habitat and activity layers, and as with any model, results are dependent on data quality and availability. The source spatial datasets are often at varying scales and resolutions and a single coarse resolution dataset can complicate the results. For example, the salmon troll fishery dataset used in Clarke Murray et al. (2015b) was only available in large statistical areas and therefore the effort hours were spread across a much larger area than occurred for other datasets, making it seem that there were impacts in places where fishing effort was not likely to occur.

As with any model, the results are highly dependent on data quality and availability and should not be interpreted or extrapolated beyond the scale of the application. The scale of the application should be commensurate with the scale of management and decision making, i.e., global applications should not be downscaled to make decisions about local impacts. Most analyses are conducted at the 1-10 km^2 resolution so would not be suitable for some siting decisions at the local scale, e.g., aquaculture site selection or municipal zoning.

The simplification and visualization in cumulative impact mapping come with a loss of information because data layers of various types are standardised to a single scale. Each application has scores reflective of the number of layers included and cannot be quantitatively compared to other modelled regions, without some form of normalization or standardization. The cumulative impact score is not a quantitative measure or predictor of impacts but can identify areas with a higher impact relative to others in the region. To date, the results of cumulative impact mapping efforts have not been used in a policy or management context.

The robustness of cumulative impact mapping results is not often tested. While some analyses have found the general patterns to be robust to uncertainty and data gaps (Allan et al. 2013; Halpern et al. 2008; Korpinen et al. 2012; Selkoe et al. 2009), Stock and Micheli (2016) found that factors of influence vary between studies and study areas. They concluded that all cumulative impact mapping efforts should include both an uncertainty assessment and a sensitivity analysis (Stock and Micheli 2016).

There have been few empirical tests of the applicability of the scores to dimensions of ecosystem structure and function. The global assessment (Halpern et al. 2008) was weakly correlated with species richness; highly impacted areas had lower species richness (Tittensor et al. 2010). Andersen et al. (2015) found significant negative correlations between biodiversity status and cumulative impacts in the Baltic Sea, providing support for cumulative impact assessment as a measure of overall ecosystem condition across broad spatial scales. In contrast, the few attempts to relate quantitative survey data (i.e. benthic infaunal community composition, seagrass bed indices) to cumulative impact scores across smaller spatial scales (i.e. a single harbour or estuary) found weak or no significant relationships between cumulative impact and ecological condition (Clark et al. 2016; Stockbridge et al. 2021), suggesting the broad patterns illustrated in cumulative impact maps are not well suited to predicting fine-scale ecological condition.

Most applications tend to be conducted at the level of the activity, with a single stressor assigned to the activity with a footprint buffer. In reality, human activities produce multiple stressors (e.g., commercial shipping is associated with dozens of stressors Hannah et al. 2020) that may also interact with stressors from other, nearby activities. Recent advances in the method allow multiple stressors to be assigned to each activity, but care must be taken to select and apply stressors evenly and thoroughly across activities. Assigning more stressors to well-known activities can skew results to show higher impact than less well-studied activities. When possible, stressors with multiple source activities should be directly included (e.g., nutrient concentration, change in freshwater input, etc.), rather than assigned to an activity.

The vulnerability matrix is the basis of the model's ability to compare potential impacts among stressors that occur across different ecosystem types. The particular expert elicitation method created by Halpern and colleagues (2007) allowed the assessment of activities and stressors with different characteristics to be standardized and thus directly comparable. The current effort evaluated and updated the vulnerability matrices for the Pacific and Atlantic coasts using an expert elicitation exercise. The regional scores are not comparable to each other because scores are relative to each other within each region. The vulnerability matrix results are influenced by study area and scale of information, and a different pool of experts was consulted for each region. The experts consulted during this effort compared scores for a specific habitat. It may be useful to further examine the vulnerability scores with a stressor focus, as was done for underwater noise in the current effort. With advances in our knowledge of the system over time, scores should be revisited and evaluated periodically. We suggest that evaluations be conducted at least every ten years or when significant change in system knowledge has occurred.

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APPENDICES

Appendix 1. Example of the survey instrument.

Seagrass (<30m): Habitat resulting from presence of aquatic plants in soft sediments (sand/silt) covered by water, i.e. seagrasses. May be intertidal or subtidal

Activities and stressors (Ranked highest to lowest vulnerability)	Vulnerability class	If class should be changed, which class reflects Pacific status?	Justification for change (citations appreciated)	Comments and/or additional details (optional)
Climate Change: Ocean Acidification	Extreme			
Climate Change: sea level rise	High			
Climate Change: sea temperature change	High			
Dredge	High			
Invasive species	High			
Aquaculture: Shellfish	High			
Benthic structures	High			
Coastal Engineering: habitat alteration	High			
Climate Change: UV change	High			
Ocean dumping: shipwrecks	High			
Sediment input: increase	High			
Coastal Engineering: altered flow dynamics	Medium			
Nutrient input: causing Harmful Algal Blooms	Medium			
Ocean dumping: toxic materials	Medium			
Pollution input: organic	Medium			
Pollution input: atmospheric	Medium			
Tourism: recreational boating	Medium			
Disease or pathogens	Medium			
Fishing: recreational	Medium			
Nutrient input: causing hypoxic zones	Medium			
Nutrient input: into eutrophic water	Medium			
Nutrient input: into mesotrophic water	Medium			
Ocean dumping: lost fishing gear	Medium			
Ocean pollution from ships and ports	Medium			
Pollution input: inorganic	Medium			
Pollution input: urban runoff	Medium			

Activities and stressors (Ranked highest to lowest vulnerability)	Vulnerability class	If class should be changed, which class reflects Pacific status?	Justification for change (citations appreciated)	Comments and/or additional details (optional)
Direct Human Impact: trampling	Medium			
Freshwater: input increase	Medium			
Military activity	Medium			
Scientific research experiments/surveys	Medium			
Sediment input: decrease	Medium			
Fishing: demersal, non-habitat-modifying, high bycatch	Low			
Freshwater: input decrease	Low			
Ocean dumping: marine debris	Low			
Pollution input: light	Low			
Pollution input: noise	Low			
Scientific research and collecting	Low			
Fishing: demersal, non-habitat-modifying, low bycatch	Low			
Marine component of forestry	Low			
Ocean mining: sand, minerals, etc.	Low			
Power and desalination plants	Low			
Aquaculture: Plants and algae	Low			
Fishing: non-habitat-modifying, artisanal	Low			
Aquaculture: Finfish	Low			
Shipping (large vessels)	Low			
Fishing: demersal, habitat-modifying	Low			
Fishing: aquarium	Low			
Tourism: kayaking	Low			
Tourism: scuba diving	Low			
Tourism: surfing	Low			
Fishing: pelagic, high bycatch	Negligible			
Fishing: pelagic, low bycatch	Negligible			

Appendix 2. List of experts consulted in the pre-review of the vulnerability matrices for the Atlantic and Pacific ecosystems

Atlantic	Pacific
Allison Schmidt	Alex Dalton
Anna Metaxas	Carrie Robb
Brooke Maslo	Cherisse Du Preez
Caroline Longtin	Christopher D. G. Harley
Catherine Johnson	Chris Rooper
Danika van Proosdij	Christine Hansen
Daphne E Themelis	Cliff Robinson
David Burdick	Dana Haggarty
David Drolet	Dominique Bureau
David Garbary	Erin Herder
David J.W. Piper	Heidi Gartner
Ellen Kenchington	Ian Perry
Gary Saunders	Jennifer Boldt
Heather Hunt	Joanne Lessard
Heike Lotze	Katie Gale
Hilary Moors-Murphy	Lyanne Curtis
Javier Murillo	Rebecca Martone
Jeffery Clements	Robert DeWreede
Jen Frail-Gauthier	Sally Leys
Jessica Sameoto	Sarah Dudas
John O'Brien	Sharon Jeffery
Katleen Robert	Stephanie Kraft Archer
Kira Krumhansl	Tammy Norgard
Luke Anthony Poirier	Travis G. Gerwing
Marjolaine Blais	Verena Tunnicliffe
Melisa Wong	
Patrick Gagnon	
Paul Snelgrove	
Peter Auster	
Peter Galbraith	
Philippe Archambault	
Robert Gregory	
Thomas Guyondet	
Urs Neumeier	