CUMULATIVE IMPACT MAPPING AND VULNERABILITY OF CANADIAN MARINE ECOSYSTEMS TO ANTHROPOGENIC ACTIVITIES AND STRESSORS

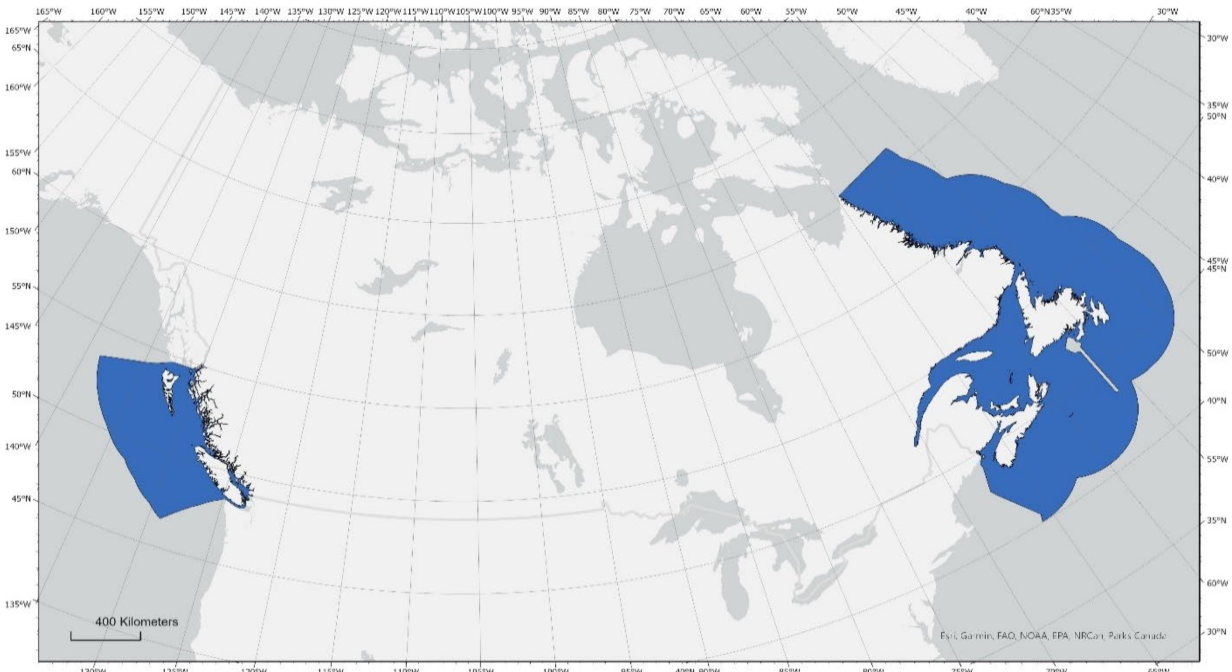

Figure 1. Map of Canada showing the study areas in blue (Pacific and Atlantic regions). The vulnerability matrices reviewed through this process are applicable in these areas; Cumulative impact maps using this approach are being generated for Pacific and Maritimes bioregions.

Context:

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 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 adaptable, 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 ecosystems, and 3) a matrix of scores to represent the relative vulnerability of each ecosystem to each activity/stressor. 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.

The advice arising from this National Peer Review process will be used to inform marine spatial planning processes, providing one approach to evaluate the spatial extent and intensity of cumulative impacts of human activities on marine ecosystems.

This Science Advisory Report is from the November 29-30 and December 2, 2021 National Advisory Meeting on Cumulative Impact Mapping and Vulnerability of Marine Ecosystems to Multiple Anthropogenic Stressors. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Cumulative impact mapping is a spatially-explicit, semi-quantitative method useful for illustrating the relative cumulative effects of human activities on marine habitats over broad spatial scales.
- 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 cumulative impact score is the sum of all habitat-activity intersections within a unit area.
- The method requires three data sources: 1) spatial distribution of marine habitat classes (e.g., beach intertidal, shallow pelagic, and seagrass beds), 2) spatial distribution and relative intensity of human activities (e.g., fishing, shipping, and industrial sites) and their associated stressors (e.g., sedimentation and noise), and 3) a matrix of vulnerability scores to quantify the relative impact of each stressor on each habitat class.
- Habitat classes encompass intertidal, subtidal, shelf, and deep ecosystems, and include inorganic substrates and biogenic features in each. Pelagic ecosystems are also included, separated into shallow and deep classes. Between Pacific and Atlantic coasts, the division of habitat classes is similar, although the depth ranges vary slightly.
- Human activities/stressors are separated into four data types: land-based, coastal, marine, and fishing. Human activities/stressors are represented as a relative intensity value, which depends on the nature of the activity or stressor, the way they may interact with the habitat, and data availability.
- Vulnerability matrices for use in the Canadian Pacific and Atlantic regions were adapted from existing vulnerability matrices developed previously for the California Current (Pacific) and Massachusetts coast (Atlantic). Regional ecosystem experts were surveyed for their expert opinion on vulnerability scores and rankings for all habitat-stressor combinations relevant to each coast.
- Previously generated vulnerability matrix scores were updated in the associated Research Document (Clarke Murray et al 2023) based on expert review, and recommendations were provided for activity/stressor rankings per habitat class. In Pacific region, 120 (12%) habitat-stressor scores were increased and 26 (3%) were reduced based on expert feedback. For the Atlantic matrix, 105 (11%) and 90 (9%) habitat-stressor scores were increased or decreased, respectively. New activities/stressors were also recommended for consideration but not reviewed and could be updated in the future.
- Efforts to update vulnerability scores through elicitation of regional habitat experts was supported as an improvement to previous applications of the Halpern method. Future enhancements could include reviewing vulnerability scores across habitat types with stressor experts (e.g., experts on the impacts of fishing).

- Cumulative impact mapping has a number of potential uses: to inform and assess future environmental change or marine spatial planning scenarios (e.g., to assess planned development and climate change), to inform strategic or regional environmental assessment, to identify areas for field research and investigation, or to prioritize activities or stressors for management or mitigation action. Its specific use within the Canadian marine spatial planning context is still to be determined.
- In addition to the resulting maps, these high-quality spatially-explicit marine data and knowledge products generated as individual components during the cumulative impact mapping process can benefit planners, stakeholders, and other scientists engaged in Marine Spatial Planning and ecosystem-based management, including conservation planning.
- Given this is a data-driven approach, with outputs that represents a snap-shot in time, the quality and age of the data inputs will impact its usefulness for planning. Sensitivity analyses, e.g., further investigating the impact of changing vulnerability scores on overall results, may help to improve confidence in the results.

INTRODUCTION

The assessment and management of cumulative effects is a rapidly evolving field with a diversity of approaches and methodologies (Clarke Murray et al 2020; Hodgson and Halpern 2019). Several spatial analysis methods for cumulative effects have proliferated in recent years (reviewed in Stock and Micheli 2016), but cumulative impact mapping (Halpern et al 2008) remains the most applied method.

ASSESSMENT

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 versatility of the method makes 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 global and regional scales around the world. 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).

The national Marine Spatial Planning program aims to include spatial representations of cumulative effects in its planning efforts. Ongoing efforts include an update in the Pacific region and new cumulative impact mapping for the Maritimes region. 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.

Overview of cumulative impact mapping 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 requires three data sources: 1) spatial distribution of marine habitat classes (e.g., beach intertidal, shallow pelagic, and seagrass bed), 2) spatial distribution and relative intensity of human activities (e.g., fishing, shipping, and industrial sites) and knowledge of their associated stressors (e.g., biomass removal, sedimentation, and noise), and 3) a matrix of vulnerability scores to quantify the relative impact of each stressor on each habitat class. Data gathering and processing comprises the majority of the work in the application of the method. All data used in the model must cover the full extent of the study area, be temporally consistent and the vulnerability scores must be directly applicable to the habitats within the region of interest.

The model 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 to yield a map of cumulative impact scores for the entire study region. The results are typically presented as heat maps, with colours denoting the level of cumulative impact in each cell (i.e., a gradient of blue to red, representing relatively lower to relatively higher impacts).

Habitat classes

Cumulative impact mapping focuses 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. The benthic habitats used for the most recent Pacific Canada study were stratified by depth, substrate, and geomorphic type (Clarke Murray et al 2015b). Biogenic habitats such as eelgrass, kelp, and sponge reef were placed overtop the 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. Mapping of Atlantic habitats for use in cumulative impact mapping is currently underway. Similar to the Pacific, biogenic habitats (salt marsh, kelp, algal zone, seagrass, horse mussel bioherm, and 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 as per Kappel et al. (2012).

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 effects on the marine environment. 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). Each activity or stressor is represented in the cumulative impact mapping model as a relative intensity value which 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). The units and range of intensity values vary with each stressor or activity; therefore, it is necessary to standardize the intensity values relative to each other.

Overview of vulnerability matrix review, expert survey

Vulnerability of marine habitats to stressors has been 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 between the two regions. The same Teck matrix has been used in other global and regional applications of habitat-based cumulative impact mapping, with one notable 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 the New England region. The cumulative impact mapping efforts in Maritimes region use the Kappel et al. (2012a) matrix as the geographic setting and ecological context are more similar.

The vulnerability scores in both the Teck et al. (2010) and the Kappel et al. (2012b) matrices were evaluated for use in Canadian habitats. Expert opinion was elicited from relevant ecosystem experts in a pre-review of Pacific and Atlantic vulnerability scores and rankings. Experts were asked to suggest changes to scores, with accompanying rationale and supporting references. Changes compiled from multiple experts on a single habitat were sent back to the group for further review. The updated scores for both matrices are presented in the associated Research Document for this meeting (Clarke Murray et al. 2023).

Within the framework of the cumulative impact mapping method, the vulnerability scores were designed to translate the exposure of habitats to particular stressors into habitat-specific impacts. Under the framework, exposure is characterized by a spatial representation of the relative intensity of an activity/stressor. It would be inadvisable to apply the vulnerability scores independently of the method, where the exposure to an activity/stressor is not considered. In addition, the experts were asked to review relative scores from a habitat perspective for their specific region. Therefore, the vulnerability scores are not representative of habitats outside the biogeographic region for which they were originally developed.

Sources of Uncertainty

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. The scale of the application should be commensurate with the scale of management and decision making. The results should not be interpreted or extrapolated beyond the scale of the application.

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 additive interactions across all stressors, when there is mounting evidence that synergistic and antagonistic interactions are common. Stressors are assumed to be of equal importance and that each is uniformly distributed within a grid cell. The ecosystems of concern are assumed to have consistent, linear responses to individual stressors and to cumulative impacts.

The simplification and visualization in cumulative impact mapping come with a loss of information and to date, the results have not been used in a policy or management context. Because the results are relative, each application has scores reflective of the number of layers included and cannot be quantitatively compared to other modelled regions. The cumulative impact score should not be interpreted as a quantitative measure or predictor of significant impacts.

The robustness of cumulative impact assessment results is not often field validated because of challenges measuring ecosystem condition across large spatial scales and habitat types. While some analyses have found the general patterns to be robust to uncertainty and data gaps, Stock and Micheli (2016) found that factors of influence vary between studies and study areas. Cumulative impact mapping efforts should include both an uncertainty assessment and a sensitivity analysis whenever possible.

CONCLUSIONS AND ADVICE

Cumulative impact mapping has been used in a number of ways, the main advantage being the ability to simplify and visualize complex information. The maps showcase differences in impact across areas, contrasting relatively low impact and high impact areas. Beyond illustration, cumulative impact mapping has been used to prioritize activities and stressors with high impact for management or mitigation action. Cumulative impact mapping has been used to identify a baseline level of cumulative impacts and compare the baseline to alternate future scenarios.

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. Further, as an explicit part of marine spatial planning, cumulative impact scores could be used as a cost layer in Marxan analyses to identify planning scenarios or conservation networks. The maps could also be used in monitoring or research, as a continuous variable to stratify sampling effort.

Given this is a data-driven approach, with outputs that represent a snap-shot in time, the quality and age of the data inputs will impact its usefulness for planning. Resources and tools that enable us to update and integrate component data layers, and generate composite maps and knowledge products, should be taken into consideration when discussing application within an ongoing Marine Spatial Planning context. For example, a dataset of marine industrial sites published in 1998 may include facilities that are no longer in operation in 2021. The use of this data may or may not be appropriate for inclusion in the cumulative impact model in 2021, depending on the remediation status of the decommissioned sites.

Additional work would be required to apply this method across Canada, or in another region (e.g., Arctic), or to generate standardized products that could be used to compare results across bioregions.

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SOURCES OF INFORMATION

This Science Advisory Report is from the November 29-30 and December 2, 2021, National Advisory Meeting on Cumulative Impact Mapping and Vulnerability of Marine Ecosystems to Multiple Anthropogenic Stressors. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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