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Advancing marine cumulative effects mapping: An update in Canada's Pacific waters

Cathryn Clarke Murray[a,b,*,1], Selina Agbayani[a], Hussein M. Alidina[a], Natalie C. Ban[c]

[a] WWF-Canada, Vancouver, BC, Canada
[b] Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC, Canada
[c] School of Environmental Studies, University of Victoria, Victoria, BC, Canada

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ABSTRACT

The rapidly progressing field of cumulative effects mapping is highly dependent on data quality and quantity. Availability of spatial data on the location of human activities on or affecting the ocean has substantially improved our understanding of potential cumulative effects. However, datasets for some activities remain poor and increased access to current, high resolution data are needed. Here we present an updated analysis of potential cumulative effects in Canada's Pacific marine waters. New, updated datasets and methodological improvements over the previous analysis were completed, including a new index for land-based effects on marine habitats, updated habitat classes and a modified treatment of vulnerability scores. The results show increased potential cumulative effects for the region. Fishing remains the biggest overall impact amongst marine activities, while land-based activities have the highest impact per unit area in affected ocean areas. Intertidal areas were the most affected habitat per unit area, while pelagic habitats had the highest total cumulative effect score. Regular updates of cumulative effects assessments will make them more useful for management, but these require regularly updated, high resolution datasets across all activity types, and automated, well-documented procedures to make them accessible to managers and policy-makers.

1. Introduction

As human populations continue to grow, especially in coastal areas, people's uses of, and impacts on, marine ecosystems are also increasing. Cumulative effects – where multiple stressors originating from various human activities overlap – are a well-recognized issue in marine systems, and although our understanding is still rudimentary, the field is quickly advancing. To date, studies have explored potential cumulative effects on habitat types in marine systems at global [1,2] and regional scales [3–9]. More recently, similar techniques have been applied to species [10] and ecosystem services [11]. Continued advances of the science of cumulative effects make such efforts increasingly relevant for planning and management decisions.

Understanding potential cumulative effects in a specific geography is only as good as the quantity and quality of data available on human activities and habitats, as well as the underlying foundational understanding of the vulnerability of these habitats to human activities [12]. Mapping potential cumulative effects relies on spatial data of human activities to represent where stressors are occurring. This approach is commonly referred to as "cumulative impact" mapping, but the term "potential cumulative effects" is used here (hereafter just "cumulative effects") rather than impacts, because impacts are hypothesized and have not been directly observed. Data on where human activities occur in the ocean are varied and uneven. The ideal dataset is recent, spatially precise with a high resolution, has spatial coverage consistent with the study area, and has an associated measure of relative intensity (fishing effort hours, ship transits, usage, etc.). In reality, such ideal datasets are often lacking and therefore any analyses conducted using the best available data may include dated activity data for differing timescales and ranges. Uneven input data makes it difficult to have current and consistent cumulative effects estimates and hinders progress toward results with consistent timescales approximating real interactions between stressors.

Despite these limitations, cumulative effects assessments have the potential to inform conservation planning and ecosystem-based management, yet to date such mapping efforts are largely limited to static snapshots. Canada's Pacific region is one area where marine cumulative effects mapping has been carried out [5,13]. Data availability and quality has improved since the last study was completed, primarily due to marine planning and analysis efforts [14]. Increased

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[*] Corresponding author at: Institute for Resources, Environment and Sustainability, University of British Columbia, Vancouver, BC, Canada.
Tel.: +1 250 363 6911.
E-mail address: cclarke@eos.ubc.ca (C. Clarke Murray).
[1] Present address: Institute for Ocean Sciences, PO Box 6000, Sidney, BC, Canada V8L 4B2.

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regional data availability provides an opportunity to fill some of the gaps in previous efforts. An updated cumulative effects analysis for Pacific Canada (British Columbia) has been completed, incorporating recent and additional data on human activities, and making methodological improvements to better account for land-based and fishing activities. The current analysis represents the third iteration of cumulative effects mapping in the Canadian Pacific Coast, building the foundation for a time series dataset useful for management and policy.

2. Materials and methods

The spatial location of human activities and habitats weighted by their vulnerability to each activity were combined in a GIS model to map cumulative effects following methods developed by Halpern and colleagues [1] and subsequently applied by Ban et al. [5] (Supplementary section: Cumulative effects analysis; Supplementary Fig. 1). Total cumulative effects scores, as well as the mean effects scores for all of British Columbia's (B.C.) marine waters were calculated. Mean and total cumulative effects scores were compared for land, coastal, marine and fishing activities (Table 1), for each individual human activity and by habitat type. The relative rankings of the updated analysis were qualitatively compared to the original results [5]. All data preparation and analysis was performed in ArcGIS 10.1 (ESRI Environmental Systems Research Institute).

The cumulative effects analysis presented here has four important improvements and modifications over the previous analysis [5]: (1) New and updated human activity data were included; (2) the method to assess the marine impact of land-based activities was improved; (3) habitat classes were updated; and (4) vulnerability scores were modified to better reflect likely impacts on marine ecosystems in the region. The following sections present an overview of the methods of cumulative effects mapping and additional details on the key changes from the previous mapping effort [5].

2.1. New and updated data on human activities

Since the previous analysis, additional activity layers became available, allowing for improved characterization of cumulative effects in the region. Spatial data for 47 human activities were used in the analysis (Table 1; Supplementary Table 1): 16 activity layers of those originally included in the 2010 dataset [5], updated information for 25 layers, and six new layers: commercial halibut fishing, commercial sardine fishing, recreational boating routes, land-based pipelines, paved and forestry roads. Eight activity datasets were split finer or differently than those in the original analysis: sport fishing was split into (1) crab trap, (2) prawn and shrimp trap, (3) anadromous hook and line, and (4) groundfish hook and line; salmon net was split into gillnet and seine; herring roe was split into gillnet and seine; and ports were split into ports and marinas. Two activities in the original analysis were not included here: commercial squid and dogfish fisheries. The commercial squid fishery data were not included because it covered a very small area and contained some ambiguous information. The dogfish fisheries were not included as a separate dataset because they are included in the Schedule II fishery [17].

Fishing, marine (i.e., other than fishing), coastal, and land-based activities were treated in slightly different ways to reflect their respective pathways of potential impact to marine waters (Table 1). Commercial fisheries activities used the footprint of the activity restricted to depths and substrates used by each fishery (e.g. groundfish bottom trawl fleets generally operate in deep waters, while divers generally harvest geoduck from soft substrates in shallow waters less than 30 m deep). Fishing activity was more precisely mapped by weighting fishing effort hours (where available) and distributing them according to the area of each habitat class in a grid cell. For example, if fishing occurred in only one habitat class within the grid cell, all effort was distributed to the relevant habitat only (Fig. 1). As in the 2010 analysis [5], marine activities (aquaculture, disposal at sea, recreational boating routes) were subjected to kernel density decay. Commercial shipping was mapped using a noise propagation model (developed by Erbe and colleagues [16]), as underwater noise was considered the predominant stressor. Coastal activities (human settlements, ports, marinas, industrial sites) were treated as point source impacts and also subjected to kernel density decay.

2.2. Modelling the effects of land-based activities

Impacts from land-based human activities are difficult to include in marine analyses. A watershed activity index was developed that could be calculated for each human activity occurring on land (8 in total) using readily available spatial data for the region. It was conservatively assumed that the largest streams (i.e. those with the largest volumes and the fastest flows) would have the highest probability of carrying sediment and nutrient loads all the way to the estuary. The index therefore included only watersheds with rivers with large stream orders (6 or higher, out of 8 stream orders) with a marine outlet into BC waters [18,19]. For each land-based activity (e.g. agriculture, industry, mining, forestry), the density of the activity in the watershed was calculated (Supplementary Fig. 2). These values were binned into one of three relative intensity categories (high, medium, low) based on that activity's densities across the region. The relative intensity value for each human activity was used to seed the kernel density decay at the mouth of each estuary for the watershed (Supplementary Fig. 2. The radius of the kernel density decay was set by the maximum size of the freshwater plume for that stream order from published literature and satellite images (Stream order 6=10 km; 7, 8=20 km; 9=30 km).

2.3. Updated habitat classes

Building on the methodology described in 2010 [5], the habitat classes were updated to include hexactinellid glass sponge reefs, habitat-forming reefs unique to BC waters [20], and six intertidal habitats (Supplementary Fig. 3). As in the previous analysis, the dataset was divided into three broad habitat classes: the benthos (characterized via depth and substrate), the shallow pelagic waters (top 200 m of the water column) and deep pelagic waters (deeper than 200 m), with 26 habitats in total (Supplementary Fig. 3). In contrast to 2010, biogenic habitats were layered on top of physical habitats so that physical habitat classes and biogenic habitats could occur in the same place. This method considers the impact on both the physical habitat (e.g. soft shelf) as well as any biogenic habitats that occur there (e.g. eelgrass beds) in order to better capture the impact of activities that cause the effective removal of biogenic habitats.

2.4. Use of vulnerability score

The vulnerability of marine habitats to stressors associated with human activities were developed by Teck and colleagues [15], using survey-based expert opinion methods. Habitat classes in the study region were matched with corresponding habitats evaluated in the vulnerability study [15] (Supplementary Table 4). As in Ban et al. 2010, the predominant stressor from each activity was determined from literature review and used to link the activity to a vulnerability score [15] (Table 1). Vulnerability scores from the California Current region [3] were used as this was the closest similar ecological regime with scores available. Hexactinellid sponge reefs were assigned vulnerability scores for Seamounts,