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Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study

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ABSTRACT

Analysis of cumulative human impacts in the marine environment is still in its infancy but developing rapidly. In this study, existing approaches were expanded upon, aiming for a realistic consideration of cumulative impacts at a regional scale. Thirty-eight human activities were considered, with each broken down according to stressor types and a range of spatial influences. To add to the policy relevance, existing stressors within and outside of conservation areas were compared. Results indicate the entire continental shelf of Canada's Pacific marine waters is affected by multiple human activities at some level. Commercial fishing, land-based activities and marine transportation accounted for 57.0%, 19.1%, and 17.7% of total cumulative impacts, respectively. Surprisingly, most areas with conservation designations contained higher impact scores than the mean values of their corresponding ecoregions. Despite recent advances in mapping cumulative impacts, many limitations remain. Nonetheless, preliminary analyses such as these can provide information relevant to precautionary management and conservation efforts.

1. Introduction

Knowing the location and impacts of human activities on the marine ecosystems is critical to effective marine management [1–3]. Identifying, mapping and quantifying the cumulative impact of human activities on ecosystems are essential elements of operationalizing the practice of ecosystem-based management (EBM) [3]. Recent studies have paved the way for analyses of human impacts globally [4], and regionally [5–9]. Mapping potential cumulative effects is relevant to conservation and marine spatial planning in that reducing the stressors resulting from human activities can become an explicit goal. In this paper, regional human use data for Canada's Pacific marine waters were used to map and analyze cumulative impacts and to assess the efficacy of existing spatial conservation designations. The applicability and limitations of this approach is discussed.

The oceans are affected by many marine and terrestrial human activities, yet there is much unknown about the effect of stressors [4,10,11]. Two recent meta-analyses show that stressor interactions are variable and hard to predict [12,13]. The majority of studies on anthropogenic stressors focus on impacts of single stressors [14]. While the understanding of interactive effects may be limited, studies of individual stressors can be used to hypothesize where cumulative effects might occur [4,5], and begin identifying appropriate management measures. Similarly, marine environments differ in their resilience to external stressors, and the cumulative interactions of multiple stressors are poorly understood. While detailed information of the resilience of various habitat types to stressors is lacking, expert opinion can be used as a preliminary basis by which to evaluate and rank the vulnerability of habitats to different anthropogenic stressors [10].

Mapping human impacts in the marine environment is a recent scientific endeavor. Key studies include a simple approach to mapping impacts in British Columbia [5], a global study [4], and subsequent regional approaches [8,9]. These studies use or build upon estimated measures of sensitivity and vulnerability of ecosystems or species to stressors [10,15,16], and rely on spatial data of human activities and resulting stressors. Given the recent emergence of this area of enquiry, opportunities for refinement and application exist, such as this study.

Even though multiple human activities affect most areas and multiple parts of an ecosystem, ocean management has been carried out primarily through a sector-by-sector approach [3,17].

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Potential cumulative effects are thereby not necessarily dealt with. Fisheries, for example, continue to be managed primarily on a species-by-species basis, and their management does not account for other stressors on fish such as pollution or habitat destruction [18] or the impact of fishing on other parts of the marine ecosystem [3,17]. With anthropogenic pressures generally increasing, managing each activity in isolation is insufficient to conserve marine ecosystems [3,17].

This paper advances understanding and application of cumulative impacts by (1) including a zone of likely influence for each of the human activity datasets that attempts to better estimate the actual footprint of stressors; and (2) spatially analyzing stressors within and outside of conservation designations as a coarse-scale evaluation of whether or not existing management mitigates cumulative impacts. Although the nature of these cumulative impacts remains unknown, mapping them is a first necessary step in identifying both "hotspots" and relatively unimpacted areas, both of which could warrant further study and management attention.

2. Method

Using the exclusive economic zone (EEZ) of Canada's Pacific coast as the study area (Fig. 1), four categories of information were combined: (1) spatial data on the location of activities and their intensities if known; (2) types of stressors resulting from these activities; (3) relative impact of activities on habitats; and (4) distance to which the effect of activities is likely distributed (Fig. 2). Unlike other mapping exercises [4,6,7,9], the likely zone of influence of human activities is explicitly included, recognizing that the impacts of these such activities often extend beyond their immediate footprint (see Table 1 and Supplementary Table 1).

The cumulative impact score (I_c) was calculated based on Halpern et al. [8]:

$$I_c = \sum_{i=1}^{n}(m)\sum_{j=1}^{m}(D_i * E_i * \mu_{ij})$$

where D_i is the intensity of the activity at location *i*, derived from a linear decay function from all locations of that activity, binned into one of three intensity categories (low=0.5, medium=1, high=1.5) (as per [19]). This is based on the spatial extent of the impacts beyond the source location (Table 1, Suppl. Tables 1–3). Because the vulnerability scores do not consider the intensity of activities (i.e., an activity has the same score if it is light intensity as heavy intensity), these binned categories were used to seed the density decay. The linear decay of these binned values subsequently gets multiplied by the vulnerability scores (see below). Marine and land-based threats were treated the same, with linear decays starting at the source of the activity. Land-based activities were buffered from the source (i.e., a plume model was not used)—an admittedly simplistic, but easily implementable, approach. E_j is the presence or absence of a habitat. μ_{ij} is the vulnerability score for activity *i* and habitat *j*. *n* is the number of activities, and *m* is the number of habitats. The values for all activities and all habitat types were summed to arrive at the cumulative impact score, using a 200 m grid. Each grid cell contains one benthic habitat type. Supplementary Fig. 1 depicts the steps comprising the mapping approach.

Several types of data were used to map the impact scores. Spatial data for 38 activities were incorporated (Table 1, Suppl. Table 1–2). All available datasets depict activities, not stressors, and likewise management in its current form predominantly addresses regulation of activities, not stressors. The analyses were undertaken at the activity level with the desire to generate information applicable to current management. Stressors resulting from each activity were established through an extensive literature review of published articles and gray literature (Suppl. Table 3). Expert judgement was relied upon to provide vulnerability scores [10]. Other relevant stressors are noted in the Supplementary Materials (Suppl. Table 4). The predominant stressor from each activity was determined from the literature review, and used to link the activity to a vulnerability score (Suppl. Table 5). Scores were taken from expert surveys for the California Current region [15]—the closest area for which such data existed and which has a similar ecological regime to British Columbia (BC). To translate commercial fisheries types in BC to fishing activity categories used in the survey, the fishing gear impact assessment from Chuenpagdee et al.'s [20] review was used. A habitat map was created that corresponded with the habitats used in the survey (Fig. 1; methods described in Suppl. Table 2).

Given that 25 of the 38 activities included in the analysis were fishing-related, sensitivity tests were carried out to ascertain the influence of these data on the results. Three scenarios were used: (1) include each fishery (i.e., each dataset) separately; (2) summarize fisheries by type of impact; and (3) include only one layer for commercial and one for recreational fisheries. Commercial fisheries catch data (in tonnes) were summarized in three categories (high, medium, low intensity) using natural breaks, whereas recreational fishing data were used in their original format of relative importance (i.e., catch data are not available for recreational fisheries). Other studies have carried out sensitivity tests on the expert-informed vulnerability weightings, and have shown the results to be robust to changes to the weightings [4,15].

Potential cumulative impacts were modeled for three broad habitat classes, the benthos, shallow pelagic waters, and deep pelagic waters. The benthos was subdivided into 14 benthic habitats (Fig. 1), whereas both classes of pelagic waters contain no subdivisions. Shallow waters encompass the top 200 m of the water column, and deep pelagic waters are defined as deeper than 200 m. For deep pelagic impacts, it was assumed that connectivity between depth strata exists, and associated effects such as trophic cascades occur. Fishing in shallow waters is therefore assumed to affect deep pelagic habitats, as supported by the latest work on pelagic trawling [21].

To analyze the modeled cumulative impacts, the sum total cumulative impact score for all grid cells was calculated as well as the mean impact scores per grid cell for all of BC's marine waters, for each ecoregion [22], for each activity, and by habitat type. The mean impact scores were also calculated within the boundaries of existing designated MPAs, candidate MPAs, Rockfish Conservation Areas, and important areas designated as critical habitat for two populations of species at risk: northern and southern resident orca whales (*Orcinus orca*), which are listed federally as threatened and endangered, respectively. The mean impact score within each designated area was compared to the mean impact score for the ecoregion in which it occurs.

3. Results

The modeled cumulative impact maps (scores) indicated that the entire continental shelf of Canada's Pacific marine waters is being affected by multiple human activities at some level (Fig. 2). When using individual fisheries as separate layers and other impacts as outlined in Table 1, impacts on shallow pelagic waters accounted for 49.0% of the sum total cumulative impact score, followed by impacts on benthic habitats (42.7%) and deep pelagic waters (8.4%) (Table 2). No part of the continental shelf's benthic habitats and shallow waters appeared impact-free. In deeper and

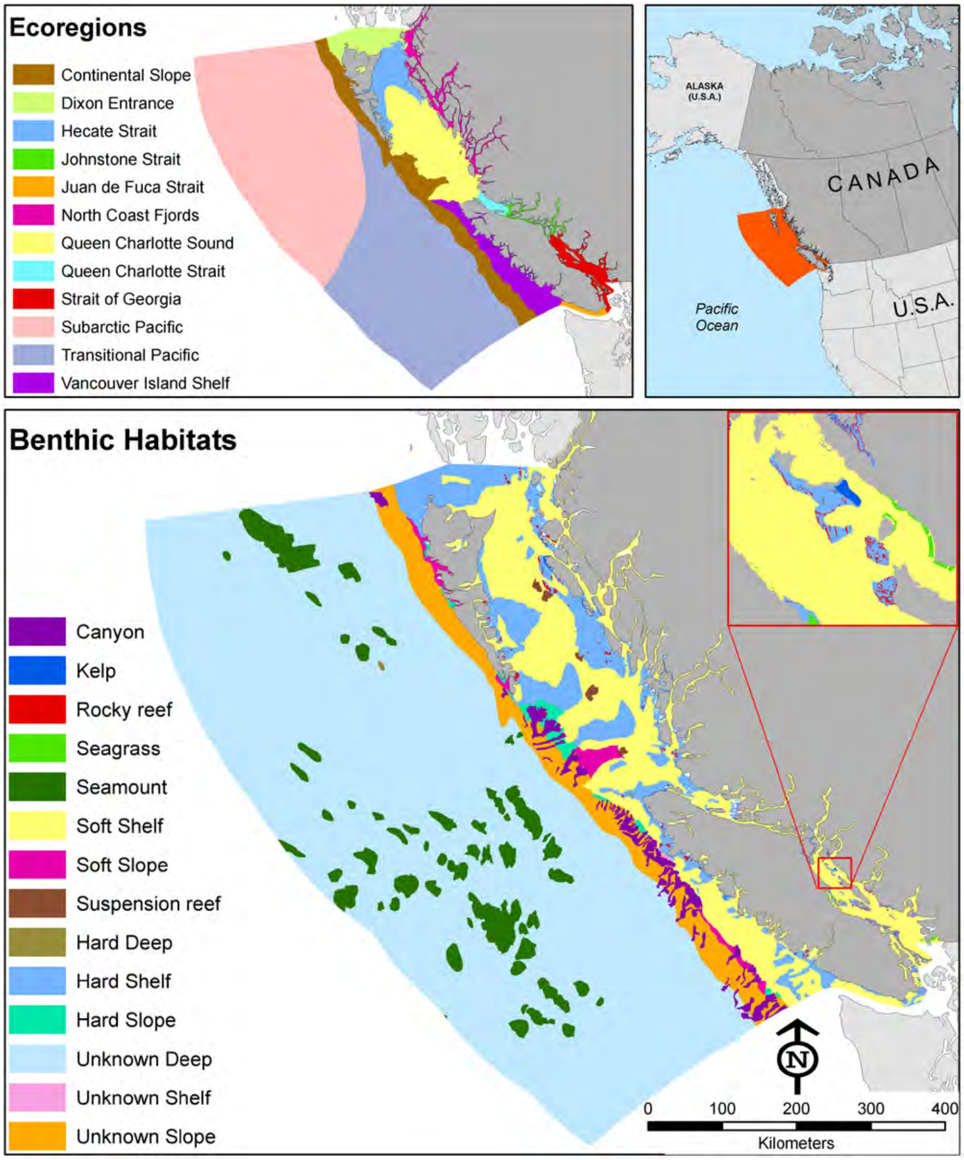

Fig. 1. Overview map and maps depicting the ecoregions and habitats used to summarize impacts. The inset in the benthic habitats map shows the level of detail contained therein.

offshore areas—the subarctic Pacific and transitional Pacific ecoregions—impacts were notably less than on the continental shelf.

The sensitivity tests for inclusion of fisheries data on benthic habitats revealed that the number of layers included did influence the overall results (Table 3). If fisheries are treated as individual layers (i.e., each fishery is considered a separate impact), fisheries appeared as the predominant benthic stressor (Table 3). When fisheries are included by impact type, land-based stressors became comparatively more significant. When fisheries are included as only two layers—one for commercial fisheries, one for recreational fisheries—fisheries contributed less of the overall impact score, but retained the second-most place for impact contribution after land-based impacts. Because the study was intended to examine management measures, the remaining results section reports results for the fisheries scenario that includes each fishery as a separate impact, reflecting the current management approach that focuses on either a single-species or fishing gear type. While this single-fisheries approach could over-estimate cumulative effects, it allows for the differences amongst fisheries to be explicitly incorporated and adjusted in the analysis, as appropriate.

Commercial fishing (i.e., each fishery as a separate layer in the analysis), land-based activities and marine transportation accounted for 57.0%, 19.1% 17.7% of the sum total cumulative impacts score in Canada's Pacific waters, respectively (Table 2). The activities that affected BC's marine waters varied in their impact scores, spatial extent and relative impact per unit area (Fig. 3). Commercial groundfish bottom trawling, and water quality effects from land-based mining operations affect a comparatively large extent of area and have high impacts per unit area on benthic habitats. Fishing methods using nets (squid, herring, salmon net) and mining effects appear to have the highest impact per unit area on pelagic habitats though they occur in varying spatial extents. In the deep pelagic realm, biomass removals from commercial salmon netting and trolling (including bycatch)—assumed to have an impact on the deep pelagic realm [21]—and water quality effects of land-based mining discharging into the deep coastal fjords were the predominant stressors.

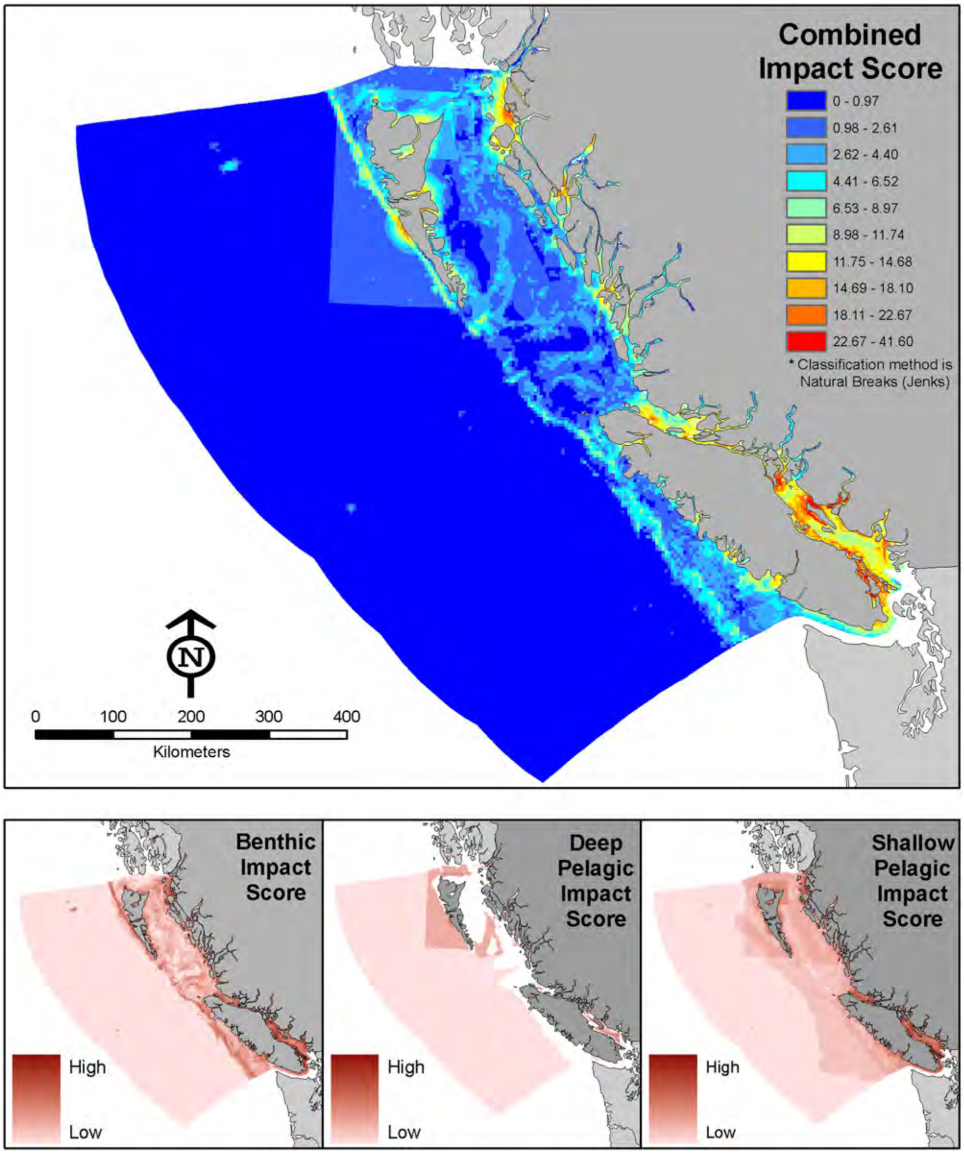

Fig. 2. Modeled impact scores for Canada's Pacific maritime area. Deep pelagic environments are defined as deeper than 200 m. The triangular shape seen off the west coast of the island of Haida Gwaii is the effect of a large fisheries management area where fishing occurs.

The mapped results indicated that potential cumulative impacts were very likely (Figs. 2–4), with the maximum number of overlapping effects from activities within any 200 m grid cell adding up to 19 out of 38 possible activities for which data were available. While all ecoregions were affected by multiple anthropogenic impacts that impacted benthic habitats, shallow and deep pelagic waters (Fig. 4), the Strait of Georgia was the most highly stressed ecoregion, with a per-unit area impact score (mean pixel score) almost 160% (i.e., over $2\frac{1}{2}$ times) greater than the next most stressed ecoregion, the Queen Charlotte Strait. In contrast, the Transitional Pacific and Subarctic Pacific ecoregions had low average impact scores. Ten out of 14 benthic habitat types were affected by multiple activities (Fig. 4). Rocky reefs and seagrasses had the greatest impact per unit area.

Perhaps surprisingly, many of the existing and candidate MPAs had mean impact scores higher than the mean for their corresponding ecoregions (Table 4). Designated MPAs showed higher mean benthic impact scores in 9 out of 12 ecoregions, and higher mean impact scores for shallow pelagic waters in 8 out of 12 ecoregions. Three large proposed candidate MPAs spanned 6 ecoregions, and higher mean impact scores were found in 3 of the 6 ecoregions in at least one habitat component. Rockfish Conservation Areas, designed to protect mainly demersal *Sebastes* species, as designated in 2004, showed lower mean benthic impact scores in 5 of the 8 ecoregions, but higher mean shallow pelagic impact scores in 6 of the 8 ecoregions within which they occur (Table 4).

Critical habitats for northern and southern resident orcas varied in their relative impact scores compared to ecoregion means (Table 4). All important habitat areas of northern resident orcas showed mean impact scores higher than that of the ecoregions in which they were found. The mean impact scores for southern resident critical habitat areas were comparable to scores in northern areas. However, they occurred in an ecoregion with higher mean background scores (Strait of Georgia), and hence had lower scores than that of the ecoregion.

4. Discussion

This study provides a regional quantitative estimate of human impacts and potential cumulative impacts on three broad

Table 1
Summary of stressors associated with activities that affect the marine environment, and the distance to which their effects extend, British Columbia, Canada.

Habitat↓ / Activity→	Coastal marine-based industrial/commercial activities: Aquaculture: Finfish aquaculture	Aquaculture: Shellfish aquaculture	Transportation: Large boat traffic	Transportation: Ports, Marinas and harbors	Other: Ocean dumping (non-toxic)	Other: Log dumping, handling	Land-based activities: Industry	Forestry: sedimentation	Onshore mining	Agriculture	Pulp and paper	Towns: human settlements	Fishing-recreational: Fishing and other lodges	Trap	Dive	Unspecified (likely hook-and-line)
Benthos																
Kelp	0.27	0.44	0.00	1.23	0.94	0.00	1.63	1.72	1.68	1.54	1.08	0.91	1.78	1.78	1.78	1.78
Rocky reef	1.31	0.58	0.32	1.23	1.00	0.00	1.94	1.61	1.92	1.13	1.17	1.39	1.74	1.74	1.74	1.74
Seagrass	0.44	1.84	0.35	1.16	0.71	0.61	1.11	1.56	1.45	1.18	1.39	1.11	1.07	1.07	1.07	1.07
Suspension reef	0.00	1.86	0.00	0.00	0.80	1.48	1.77	1.73	1.93	2.56	1.81	1.29	1.19	1.19	1.19	1.19
Soft shelf	1.24	0.29	0.30	1.01	0.99	0.45	2.03	0.00	1.91	1.09	1.35	1.14	0.47	0.47	0.47	0.47
Soft slope	0.75	0.00	0.00	0.00	1.13	0.00	2.54	0.00	2.54	0.00	1.34	1.59	0.00	0.00	0.00	0.00
Soft deep	0.00	0.00	0.00	0.00	1.02	0.00	2.46	1.44	2.94	0.00	1.34	2.40	1.05	1.05	1.05	1.05
Hard Shelf	0.91	0.00	0.00	1.34	1.20	0.00	1.34	0.00	1.63	1.70	1.34	0.46	1.47	1.47	1.47	1.47
Hard slope	0.00	0.00	0.00	1.64	1.24	0.00	0.00	1.34	0.00	0.00	1.65	1.21	1.83	1.83	1.83	1.83
Hard deep	0.00	0.00	0.00	0.00	1.13	0.00	0.00	0.00	0.00	0.00	1.34	0.00	0.92	0.92	0.92	0.92
Canyon	0.00	0.00	0.00	1.22	0.72	0.00	1.64	1.79	1.55	1.74	1.65	1.10	0.00	0.00	0.00	0.00
Seamount	0.00	0.00	0.00	0.00	0.92	0.00	0.00	0.00	0.00	0.00	1.34	0.00	0.89	0.89	0.89	0.89
Shallow pelagic waters	1.50	0.25	1.98	1.75	1.26	0.00	2.11	0.24	2.04	1.84	1.42	1.26	1.39	1.39	1.39	1.39
Deep pelagic waters	0.00	0.00	0.00	0.00	1.10	0.00	1.77	2.65	1.70	2.65	1.62	1.10	0.00	0.00	0.00	0.00
Stressor distance category	M	M	VL	M	M	SM	M	M	L	M	VL	VL	M	[a]	[a]	[a]

Habitat↓ / Activity→	Commercial fisheries: Bottom trawling	Groundfish ZN	Schedule II	Sablefish trap	Sablefish longline	Prawn trap	Shrimp trawl	Crab	Red urchin	Green urchin	Sea cucumber	Krill	Geoduck	Scallop	Salmon troll	Salmon net	Squid	Octopus	Herring	Herring roe	Gooseneck barnacle
Benthos																					
Kelp	0.37	1.49	1.49	0.37	1.49	0.37	0.37	0.37	1.49	1.49	1.49	0.27	1.49	0.37	0.27	0.41	0.41	1.49	0.41	1.49	1.49
Rocky reef	1.36	1.52	1.52	1.36	1.52	1.36	1.36	1.36	1.52	1.52	1.52	1.03	1.52	1.36	1.03	1.16	1.16	1.52	1.16	1.52	1.52
Seagrass	0.20	0.58	0.58	0.20	0.58	0.20	0.20	0.20	0.58	0.58	0.58	0.00	0.58	0.20	0.00	0.00	0.00	0.58	0.00	0.58	0.58
Suspension reef	0.00	1.84	1.84	0.00	1.84	0.00	0.00	0.00	1.84	1.84	1.84	0.00	1.84	0.00	0.00	0.00	0.00	1.84	0.00	1.84	1.84
Soft shelf	2.35	1.04	1.04	2.35	1.04	2.35	2.35	2.35	1.04	1.04	1.04	0.35	1.04	2.35	0.35	0.22	0.22	1.04	0.22	1.04	1.04
Soft slope	2.74	1.15	1.15	2.74	1.15	2.74	2.74	2.74	1.15	1.15	1.15	0.37	1.15	2.74	0.37	0.00	0.00	1.15	0.00	1.15	1.15
Soft deep	2.61	1.03	1.03	2.61	1.03	2.61	2.61	2.61	1.03	1.03	1.03	0.00	1.03	2.61	0.00	0.12	0.12	1.03	0.12	1.03	1.03
Hard Shelf	1.96	1.25	1.25	1.96	1.25	1.96	1.96	1.96	1.25	1.25	1.25	0.00	1.25	1.96	0.00	0.00	0.00	1.25	0.00	1.25	1.25
Hard slope	2.52	1.24	1.24	2.52	1.24	2.52	2.52	2.52	1.24	1.24	1.24	0.00	1.24	2.52	0.00	0.00	0.00	1.24	0.00	1.24	1.24

Hard deep	2.91	1.18	1.18	2.91	1.18	2.91	2.91	2.91	1.18	1.18	1.18	0.00	1.18	2.91	0.00	0.00	0.00	1.18	0.00	1.18	1.18
Canyon	2.19	1.00	1.00	2.19	1.00	2.19	2.19	2.19	1.00	1.00	1.00	0.00	1.00	2.19	0.00	0.00	0.00	1.00	0.00	1.00	1.00
Seamount	2.83	1.18	1.18	2.83	1.18	2.83	2.83	2.83	1.18	1.18	1.18	0.00	1.18	2.83	0.00	0.00	0.00	1.18	0.00	1.18	1.18
Shallow pelagic waters	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	1.48	0.38	0.38	1.48	1.96	1.96	0.38	1.96	0.38	0.38
Deep pelagic waters	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.01	0.00	0.00	2.01	2.10	2.10	0.00	2.10	0.00	0.00
Stressor distance category	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a

Table cells are vulnerability weights for the habitat-activity combinations.

[a] Stressor distance not used for mapping due to the coarse resolution of the data, Min=minimal, S=short (200 m), SM=short-medium (500 m), M=medium (2 km), ML=medium-long (10 km), L=long (30 km), VL=very long (30 km).

Table 2
Summary of modeled impact scores for each of the activity group on benthic habitats, shallow pelagic waters and deep pelagic waters.

	Benthic impact: % of total	Shallow pelagic impact: % of total	Deep pelagic impact: % of total	% of total
Aquaculture	0.4	2.1	0.0	*2.5*
Marine transportation	1.1	16.6	0.0	*17.7*
Other	0.0	0.0	0.0	*0.1*
Land-based	7.9	9.6	1.7	*19.1*
Recreational fishing	1.2	2.4	0.0	*3.6*
Commercial fishing	32.0	18.3	6.7	*57.0*
Sub-totals	*42.6*	*49.0*	*8.4*	*100.0*

Each fishery is considered as a separate layer in these results.

Table 3
Sensitivity analysis of the influence of fisheries on benthic habitats, depending on how the fisheries data are considered in the analysis.

Scenarios	Total impact score	% of total benthic
Fisheries included as a separate layer for each fishery (original scenario)		
Aquaculture	65,740	1.0
Marine transportation	173,133	2.6
Other	3,791	0.1
Land-based	1,221,166	18.4
Recreational fishing—each fishery included separately	191,883	2.9
Commercial fishing—each fishery included separately	4,965,935	75.0
Total	6,621,648	
Commercial fisheries included by impact category, recreational as one layer		
Aquaculture	65,740	2.9
Marine transportation	173,133	7.6
Other	3,791	0.2
Land-based	1,221,166	53.9
Recreational fishing included as one layer	48,941	2.2
commercial fishing—each impact group included separately	754,472	33.3
Total	2,267,243	
Commercial fisheries included as one layer, recreational fisheries as one layer		
Aquaculture	65,740	3.8
Marine transportation	173,133	10.0
Other	3,791	0.2
Land-based	1,221,166	70.5
Recreational fishing included as one layer	48,941	2.8
Commercial fishing included as one layer	220,242	12.7
Total	1,733,013	

ecosystem components types (benthic, shallow pelagic, and deep pelagic) for the Pacific Waters of Canada. A previous study in British Columbia did not distinguish between these ecosystem components, nor did it consider as many stressors [5]. This study is one of the first such regional studies (see also [5,8,9]). By including the likely zone of influence of human activities, more realistic spatial scenarios were created than previously. The additive estimates of cumulative impacts, though admittedly coarse, provide relative spatial indications of where likely cumulative impacts are occurring, as well as identifying those habitats and regions that are likely the most impacted overall. Cumulative impact maps can inform planning decisions where reductions in human-induced stressors should be an explicit goal, and thus it is important that these techniques continue to be tested and refined to provide meaningful results.

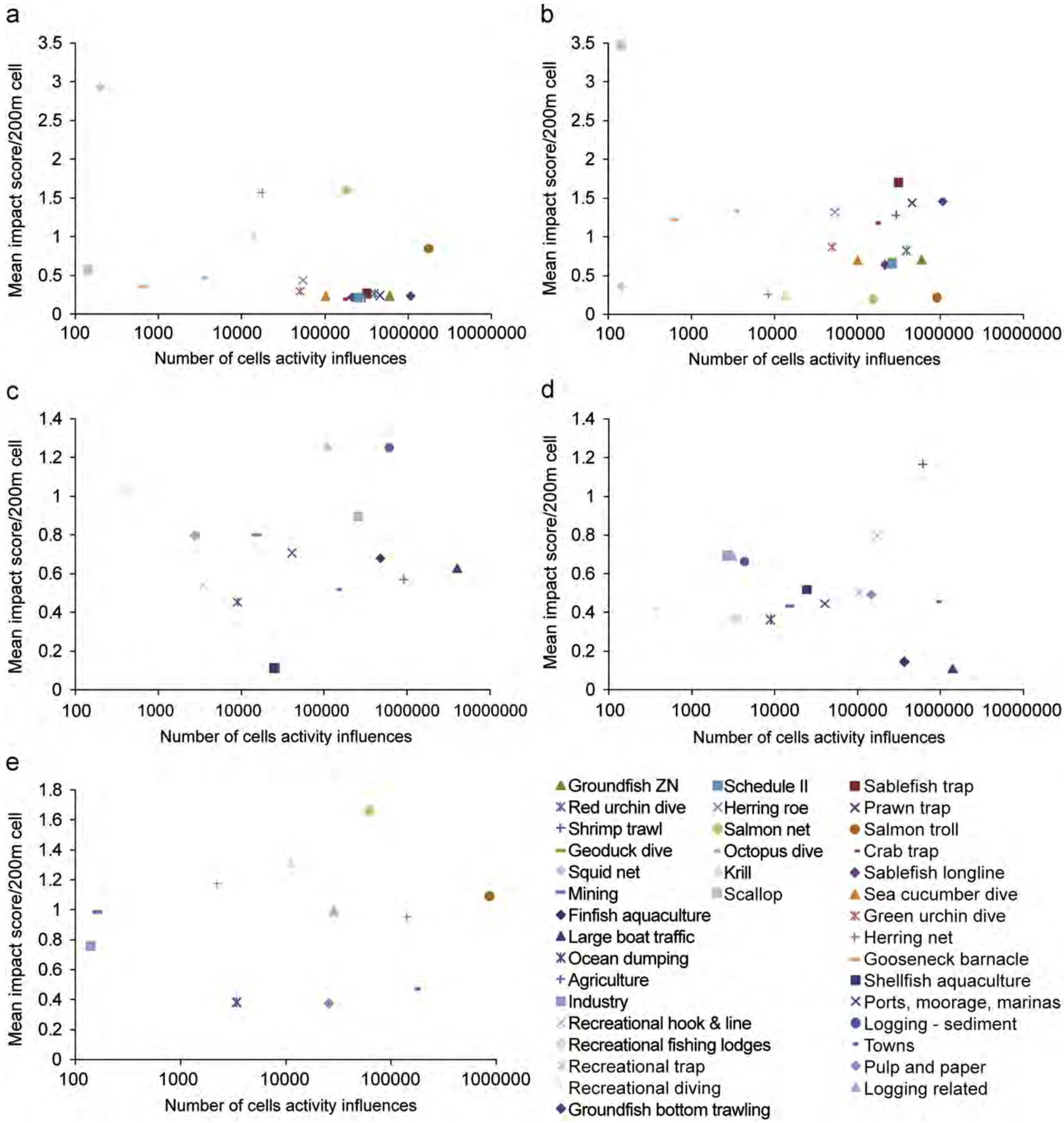

Fig. 3. Relative impact of activities in Canada's Pacific maritime area based on the number of cells the activity influences, and the mean impact score of each activity. a=surface pelagic waters, fisheries; b=benthic habitats, fisheries; c=surface pelagic waters, other activities; d=benthic habitats, other activities; e=deep pelagic habitats, all activities.

Unlike other impact mapping studies [4,5,8,9], the effectiveness of conservation designations at mitigating such impacts was gauged. Existing spatial conservation designations within BC's waters, while they may address a specific activity, do not appear very successful at mitigating spatial human impacts overall, suggesting that existing designations may be failing to meet their overarching conservation objectives and mandates. Several potential explanations exist: first, the conservation designations may not provide sufficient protection, allowing many of the stressors to continue within their boundaries. Second, enforcement may not be sufficient to ensure compliance of regulations. Finally, some of the stressors may originate outside of the boundaries of the designations. Regardless of which explanation may be most correct—likely some combination thereof—the conservation designations and associated regulations should be examined to ensure that they provide adequate protection to achieve their intent. These troubling results emphasize the need for similar impact mapping studies in other geographic regions, as

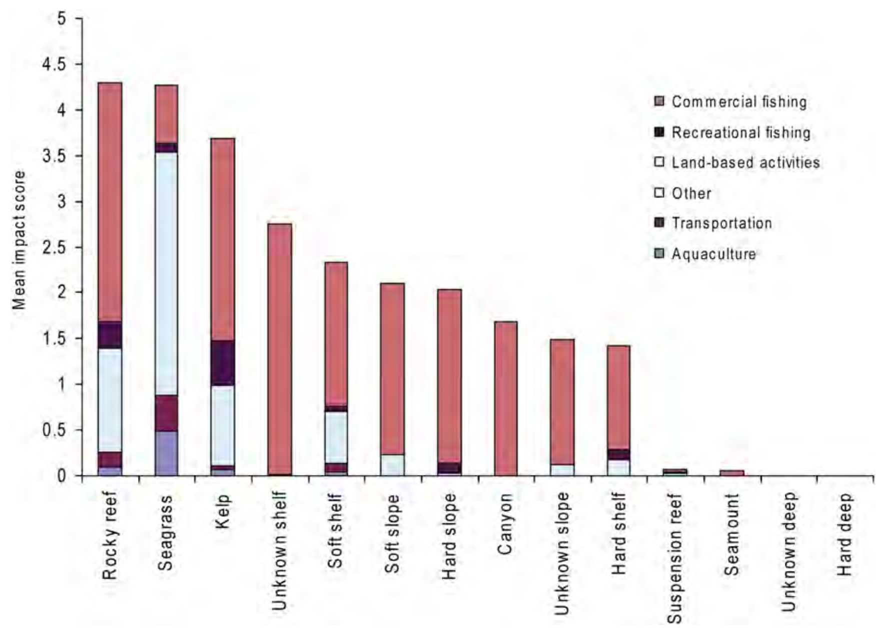

Fig. 4. Mean impact score (per 200 m pixel) on benthic habitats in Canada's Pacific maritime area broken down by activity category.

well as finer scale investigations. This initial study suggests that instead of taking a piecemeal approach, conservation designations would be more effective if a broader range of human impacts were restricted within protected area boundaries and environs.

4.1. Limitations

While there is utility in impact mapping studies for conservation, there are also many gaps in knowledge about cumulative impacts, and limitations in the current analysis. In particular, three core assumptions underlie the analysis: (1) impacts were treated as additive, (2) linear decay from the origin of activities was assumed, and (3) assumed, without dedicated field studies, was that the impact scores approximately reflect relative conditions in the water.

First, stressors are considered additive or incremental when impacts are repeated additions of the same type [23]. This is what mapping studies such as this one assume [4,5,8,9]. However, stressors can be synergistic or interactive when the combined effect is larger than the additive effect of each stressor would predict [23–25]. Both additive and synergistic effects are considered cumulative. Yet stressors can also be antagonistic, when the impact is less than expected [24,25]. Information on stressor interactions was lacking, and hence additivity was assumed. Recent meta-analyses have shown that stressor interactions are additive, synergistic, and antagonistic with little ability to predict which will occur when, and with roughly equal proportions [12,13], and therefore, barring additional information, assuming additivity is appropriate [4,5,8,9]. Similarly, the impact levels at which ecosystem functioning is compromised is an unknown, and will vary from ecosystem to ecosystem [12]. Thus, while this analysis approach can show relative impacts, and areas of particular concern, a better understanding of quantified effects is a critical next step if future analyses are to be explicitly employed to set specific quantitative limits and thresholds for human activities in order to maintain ecosystem resilience. Studies of common marine stressor interactions and their effect on ecosystems would improve both the accuracy of, and confidence in, impact maps.

Secondly, linear decay of impacts from their origin was assumed. In reality, varying distance decays are likely associated with different stressors [3,23]. Overall, not enough is known about the effects of stressors to apply specific functions for each type of stressor. Similarly, the linear decay assumes that stressors diffuse equally in all directions, when in fact currents and river plumes are likely to influence the diffusion of stressors. Further assumptions include that deep pelagic habitats (>200 m) will also be affected by activities that occur or are able to diffuse in surface waters over deep habitats (e.g. chemical pollution, trophic cascade effects, noise, etc.). Future analyses could model such linkages, information permitting, though given the uncertainty of many issues surrounding marine connectivity, there is a risk that after a great deal of effort the results may not be much more accurate, and elaboration of this approach should be taken with care [26].

Thirdly, cumulative impact scores were assumed to reflect relative in-the-water estimates of condition—lower scores indicate a healthier ecosystem, higher scores indicate cumulative impacts are likely occurring. Visually, the results "make sense" to the authors and reflect knowledge of the BC marine environment. Unfortunately data were not available to ground-truth the results of the mapping exercise, an often intrinsic problem also faced by broad regional-scale impact mapping exercises [5,8,9]. The impact scores of the analysis are intended to capture the *relative* impact of human activities; even if ground-truthing data were available, cumulative impact assessment would help to explain ocean conditions for each location. However, such modeling is not intended to provide an absolute indication of the health of any given place in the ocean, but rather a relative indication. In the absence of absolute field measurements, relative modeled measures can still be used to direct future management and field research actions.

As with any study that applies information from the marine environment, there are substantial data gaps, as would apply for any region of the world. Spatial distribution of anthropogenic pressures was available for most, but not all, maritime activities thought to be of possible concern. However, the information

Table 4
Mean impact scores within spatial conservation measures compared to mean impact score for the ecoregion in which they occur (darker (bold italic) values indicated where impact scores in the conservation area are greater than that of the ecoregion, lighter (italic) where they are lower).

			Ecoregion											
			Continental Slope	Dixon Entrance	Hecate Strait	Johnstone Strait	Juan de Fuca Strait	North Coast Fjords	Queen Charlotte Sound	Queen Charlotte Strait	Strait of Georgia	Subarctic Pacific	Transitional Pacific	Vancouver Island Shelf
Mean for Ecoregion		benthic	1.64	1.23	1.81	3.64	3.19	3.05	0.97	3.75	6.23	0.01	0.00	2.04
		shallow pelagic	0.98	1.94	1.94	5.54	4.42	3.36	1.14	5.29	6.82	0.07	0.13	1.92
		deep pelagic	0.30	1.21	1.16	1.70	0.25	1.51	0.88	1.98	3.12	0.06	0.02	1.43
Conservation type														
Protected areas, existing and proposed	MPAs	benthic	***1.81***	***2.26***	***1.95***	***3.67***	***3.49***	*2.86*	***2.29***	***5.09***	*5.87*	***0.18***	*0.00*	***2.34***
		shallow pelagic	***2.62***	***2.97***	***2.46***	***6.40***	***5.09***	*2.31*	***1.69***	***7.09***	*6.07*	*0.03*	*0.00*	***2.20***
		deep pelagic	*0.00*	NA	NA	***1.87***	NA	*1.25*	NA	***2.24***	*0.51*	*0.00*	*0.00*	*0.14*
	Candidate MPAs	benthic	*1.39*	NA	***2.46***	NA	NA	NA	*0.93*	NA	***7.12***	NA	*0.00*	*1.42*
		shallow pelagic	*0.80*	NA	***2.22***	NA	NA	NA	*0.53*	NA	***7.28***	NA	***0.24***	*0.84*
		deep pelagic	*0.11*	NA	***1.18***	NA	NA	NA	*0.19*	NA	3.04	NA	0.00	*0.00*
Fisheries closures	Rockfish conservation areas (2004)	benthic	***2.67***	NA	NA	*3.59*	*3.15*	*1.89*	***2.36***	*3.56*	***7.97***	NA	NA	*1.43*
		shallow pelagic	***2.41***	NA	NA	***6.71***	***5.15***	*1.83*	***2.22***	***4.45***	***7.64***	NA	NA	*1.75*
		deep pelagic	NA	NA	NA	NA	NA	NA	NA	*0.95*	***4.30***	NA	NA	NA
Species at risk critical habitats	Northern resident orcas	benthic	NA	NA	NA	***4.08***	NA	NA	NA	***3.85***	NA	NA	NA	NA
		shallow pelagic	NA	NA	NA	***7.76***	NA	NA	NA	***5.85***	NA	NA	NA	NA
		deep pelagic	NA	NA	NA	***3.63***	NA	NA	NA	***4.05***	NA	NA	NA	NA
	Southern resident orcas	benthic	NA	NA	NA	NA	*3.16*	NA	NA	NA	*5.37*	NA	NA	*1.04*
		shallow pelagic	NA	NA	NA	NA	*4.42*	NA	NA	NA	*6.24*	NA	NA	***3.81***
		deep pelagic	NA	NA	NA	NA	***0.29***	NA	NA	NA	***3.87***	NA	NA	NA

The values are mean impact scores. Each fishery is considered as a separate layer in these results.

necessary to incorporate climate change related stressors was not available, which have been shown to be significant factors in other studies [8,9]. Other activities for which data did not exist—tourism activities such as whale watching, kayaking and diving, and research activities—have low vulnerability scores and would be unlikely to change the results. Historical data or potential future activities were likewise unavailable, and therefore the analysis presents only a snapshot in time. The mapping was limited to the main stressor type for each activity. If better information about the zone of influence of different stressors for each activity becomes available, it would be possible to focus on mapping multiple stressor types for each activity. Another gap is that the analysis, and others like it [4,5,8,9], has not attempted to incorporate spatial-temporal dynamics such as changing habitat types (e.g., kelp, seagrass). These gaps represent opportunities for further refinement of the approach.

Many uncertainties are associated with inputs into cumulative impact maps. The analysis of the effect of summarizing fisheries in different ways showed the sensitivity of the results to the number of layers included in the analysis. At present there is no correct way of deciding how many layers to include, but the context of a study and knowledge about the stressors and activities can help inform the choice of layers. In this case, there was interest in relating the study to management actions, and hence focused on mapping the main stressor for each managed activity. The sensitivity of results to impact weighting schemes has been analyzed and shown to be robust [4,15], but there may be sensitivities to the stressor distance, accuracy of the habitat map, and the number of categories used for the intensity of activities. When better field data become available, future studies could test the effect of these components.

4.2. Conservation and management applicability

While the modeled cumulative impact maps from this project are constrained by data and methodology, as discussed above, they remain the best approximation available in the study region. Therefore such maps should be useful in developing integrated management plans, and in helping to identify strategies for examining, and if required, reducing, anthropogenic impacts in areas of high scores. Such maps can assist in prioritizing both areas for protection (“naturalness” based on low impacts) [6,27], and areas to focus on for recovery/restoration (known ecological values existing in areas of high impacts). In addition, such maps can inform precautionary management measures to reduce and manage impacts from existing human activities and those planned for the future. This work may help initiate discussions among management agencies and interested stakeholders with regard to quantifying and managing cumulative impacts in the Pacific waters of Canada and its other oceans.

Human impacts are pervasive on the continental shelf, particularly near populated areas, and hence associated impacts will need to be taken into account in management of the marine environment. While there is much room to improve knowledge of impacts, there is sufficient information available to begin to model and identify vulnerable areas where cumulative impacts likely occur. Further research should seek to help improve understanding of interactions between various stressors and help inform management thresholds (triggers) and limits for impacts from individual activities and cumulative impacts from multiple activities in a given area. Nonetheless, a precautionary approach would suggest that additional management measures should already be considered for those areas of high relative cumulative impacts, even though absolute limit values cannot yet be assigned.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at 10.1016/j.marpol.2010.01.010.

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