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Short communication

# Cumulative effects of planned industrial development and climate change on marine ecosystems

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ABSTRACT

With increasing human population, large scale climate changes, and the interaction of multiple stressors, understanding cumulative effects on marine ecosystems is increasingly important. Two major drivers of change in coastal and marine ecosystems are industrial developments with acute impacts on local ecosystems, and global climate change stressors with widespread impacts. We conducted a cumulative effects mapping analysis of the marine waters of British Columbia, Canada, under different scenarios: climate change and planned developments. At the coast-wide scale, climate change drove the largest change in cumulative effects with both widespread impacts and high vulnerability scores. Where the impacts of planned developments occur, planned industrial and pipeline activities had high cumulative effects, but the footprint of these effects was comparatively localized. Nearshore habitats were at greatest risk from planned industrial and pipeline activities; in particular, the impacts of planned pipelines on rocky intertidal habitats were predicted to cause the highest change in cumulative effects. This method of incorporating planned industrial development in cumulative effects mapping allows explicit comparison of different scenarios with the potential to be used in environmental impact assessments at various scales. Its use allows resource managers to consider cumulative effect hotspots when making decisions regarding industrial developments and avoid unacceptable cumulative effects. Management needs to consider both global and local stressors in managing marine ecosystems for the protection of biodiversity and the provisioning of ecosystem services.



## 1. Introduction

Understanding the impact of multiple stressors has been highlighted as one of the most important research needs to protect biodiversity and ecosystem services (Sala, 2000). Escalating human activities on land and sea make the consideration of cumulative effects an essential part of ecosystem-based management and spatial planning (Crain et al., 2008; Darling and Côté, 2008). While fishing has traditionally received attention for its impact on marine ecosystems, two other major drivers of change will affect the future of the world's oceans: climate change and industrial development. The effects of climate change, including ocean acidification, are expected to be both profound and complex, and can interact with current and historic impacts to dramatically alter the structure and function of marine ecosystems (Harley et al., 2006). In spite of their significance, climate change stressors have often been treated as externalities in management and planning, because high

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levels of uncertainty in the magnitude and intensity of climate change stressors exist at varying spatial scales. Impacts on marine ecosystems are under study but largely unknown, and how they might interact with local stressors can be used to inform management choices and influence their success (Brown et al., 2013).

In contrast, the impacts of industrial development are relatively well understood, and formal environmental impact assessment has a long history (Wathern, 1988). Coastal and land-based development is a growing concern for marine ecosystems as it is rapidly increasing, is connected to marine ecosystems via freshwater runoff and is often associated with marine shipping as transportation. In many countries, industrial development projects are subjected to formal cumulative effects assessment as part of the environmental impact assessment process (e.g. EU member countries, Canada, United States, Australia, and New Zealand). These assessments require the inclusion of past, present and reasonably foreseeable projects (Hegmann et al., 1999) but largely remain limited to summations of single stressors. The probability of a proposed project proceeding depends not only on approval and permits, but also on social and economic conditions that are subject to change. This uncertainty makes prediction of future development difficult and there have been repeated calls for changes to the environmental assessment process to better account for cumulative effects (Duinker et al., 2012; Palen et al., 2014).

Outside the environmental impact assessment process, spatially-explicit cumulative effects models have been used to illustrate cumulative effects at regional and global scales (Halpern et al., 2008; Selkoe et al., 2009; Ban et al., 2010; Foden et al., 2011; Korpinen et al., 2012; Maxwell et al., 2013; Micheli et al., 2013; Okey et al., 2015; Clarke Murray et al., 2015). These models highlight areas of high and low potential cumulative effects, but have so far only investigated current, not projected, stressors. Here we employ a cumulative effects model to examine and compare the relative contribution of climate change and planned industrial development to cumulative effects in a northern temperate region, British Columbia, Canada. We focus on this region because it is under considerable pressure from planned developments such as oil pipelines and liquefied natural gas facilities, and their associated marine shipping activities—representing many of the pressures that exist in other regions. Also, past marine cumulative effects analyses in this region facilitated our analysis (Ban et al., 2010). We present the cumulative effects of current human activities and investigate the addition of three stressors associated with global climate change: sea surface temperature, acidification and ultraviolet light. We then include potential industrial development in a future development scenario in order to compare the two drivers of change and discuss implications for management of marine ecosystems.

## 2. Methods

### 2.1. Cumulative effects analysis

We completed a cumulative effects mapping analysis, using the methodology developed by Halpern et al. (2008) and modified for regional analyses (Ban et al., 2010; Clarke Murray et al., 2015). For a detailed description of the spatial analysis methodology, see Appendix S1. The spatial analysis combined four types of information: (1) spatial data on the location and intensity of marine, coastal and land-based human activities and climate change stressors (Appendices S2 and S3), (2) location of benthic ($n = 25$), shallow pelagic ($n = 1$) and deep pelagic ($n = 1$) marine habitats (Appendix S4), (3) relative impact of activities on habitats (from Teck et al., 2010), and (4) the effect distance of these activities. The values for anthropogenic and climate stressors were binned into three relative intensity categories. The intersection between habitat and activity used polygons, and the cumulative effects scores were summed across all habitats and activities for each planning unit grid cell. We then compared the resulting cumulative effect scores across four scenarios: (1) Current, (2) Climate change, (3) Planned developments, and (4) Combined Current, Climate and Planned developments using the differences and percentage change in cumulative effects scores between the four scenarios overall, by grid cell, by activity and by habitat.

### 2.2. Current and planned human activities

Spatial data existed for 48 human activities. Of these, nine activities had information about planned developments—agriculture, forestry cutblocks, log booms, forestry roads, finfish and shellfish aquaculture, industry and pipelines, and mining (Appendix S2). Here we focus on planned developments rather than trends in activities because new developments have an associated construction phase and spatial information is available at the required resolution. While multiple stressors may originate from single human activities, spatially explicit data is available at the activity level and thus a single, dominant stressor was assigned for each activity layer (Table 1 in Clarke Murray et al., 2015). To model the effect of land-based activities on the marine ecosystem, we developed a watershed index. This index calculates the density of each terrestrial activity in each watershed. We then mapped the marine influence of the dominant stressor for each land-based activity through a kernel density decay at the mouth of each estuary for the watershed (Appendix S1).

The current scenario included all active and retired sites, with relative intensity reflecting the relative effect of each currently or after retirement. The planned development scenario included all activities in the current scenario plus the planned activities. The difference between the cumulative effects scores from the current and planned scenarios was mapped to highlight the changes between the two scenarios. We obtained the spatial locations of planned activities from the BC Provincial tenure system (updated October 2013) or digitized them from documents on projects currently undergoing