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Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems

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A B S T R A C T

Much knowledge is emerging about the past and potential effects of climate change on the unique and complex marine ecosystems of Canada's Pacific, including variations in the resilience, sensitivities, responsiveness, and non-stationarity of the biota. Such knowledge, however, is rarely synthesized or summarized with any overall integrated analyses that could guide the development of proactive planning for the effects of climate change. Regional and local planning of climate adaptation strategies, for example, requires an examination of ecological sensitivities and vulnerabilities at relevant spatial resolutions. We developed an illustrative example of a habitat-based ecological vulnerability assessment for the whole of Canada's Pacific marine area using existing spatial information from this region and from the California Current ecosystem. Potential climate impacts were calculated as the product of estimated *exposure* (E) of habitats to multiple dimensions of changing climate variables and expert-derived *sensitivity* (S) ratings of those habitats to changes in those climate variables. *Vulnerability* was then derived as the product of the estimated potential climate impacts in a location and the estimated *cumulative impacts* (CI) of non-climate stressors there, which we considered to be an inverse proxy of the *adaptive capacity* (AC) of the biota in those habitats. We found considerable spatial variability of potential climate impacts and vulnerability on the scales of the 12 *Ecosections* of Canada's Pacific, 25 habitat categories, and at finer scales. We produced maps of ecological vulnerability to climate change as an example output for use in spatially-oriented adaptation planning. Our initial assessment indicated that the Strait of Georgia in particular followed by Queen Charlotte Strait, Juan de Fuca Strait, Vancouver Island Shelf, and Johnstone Strait have relatively high vulnerabilities to climate change, in part due to concentrations of local stressors there. On a coast wide basis the habitats that were indicated as most vulnerable are shallow rocky reefs, seagrass habitats, kelp habitats, and deep rocky reefs. This approach for mapping vulnerability to climate change could be improved with finer scale climate data, additional climate variables, and stressor-habitat sensitivity estimates derived specifically for this system. We provide a stepwise manual for policy-makers, managers, or other practitioners to map ecological vulnerability to climate change in other marine settings.

1. Introduction

Global environmental changes associated with the emissions of greenhouse gasses are having a variety of effects on the world's oceans and on marine life, and these effects appear to be accelerating (Doney et al., 2012; Harley et al., 2006; Hoegh-Guldberg et al., 2014; Hollowed et al., 2013; Howard et al., 2013; Poloczanska et al., 2013; Pörtner et al., 2014). Existing knowledge of recent and projected effects of climate change on the marine life and ecosystems of Canada's Pacific region has been reviewed in detail (Okey et al., 2014, 2012), and a recent examination of climate trends and projections in Canada's Pacific Large Aquatic Basin (Christian and Foreman, 2013) was consistent with that synthesis. A wide variety of climate change-related effects have occurred and are expected in this dynamic coastal transition zone wherein the

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biota have varying degrees of resilience, responsiveness, and sensitivities to physical changes in climate (e.g. Hunter et al., 2014).

Summaries of existing knowledge are necessary to provide a general understanding of the vulnerabilities of marine ecosystems to climate change in regions such as Canada's Pacific, but they can lack quantitative analyses that could guide the prioritization of attention and resources for developing focused management strategies that could reduce ecological and social vulnerabilities to novel and accelerating environmental changes associated with greenhouse gas emissions—henceforth referred to generally as *climate change*. The effects of climate change can vary considerably in both time and space, and across broad ranges of scales, making it a challenge to address current and future global environmental changes and their effects. Addressing this challenge is particularly difficult in marine ecosystems because of inherent uncertainties associated with their accessibility, complex dimensionality, and the cumulative effects of stressors that act on them. However, understanding and resolving such heterogeneity of effects or vulnerabilities is a key element for developing more focused and effective adaptation and management strategies. Here we present a spatially-explicit example approach to climate vulnerability assessment as a screening-level step toward more focused climate change adaptation planning in Canada's Pacific marine region.

Vulnerability and its three components—exposure, sensitivity, and adaptive capacity—have been well articulated in climate change literature (e.g. Allen, 2005; McCarthy, 2001; Parry, 2007; Smit et al., 2000; Watson et al., 1996). We follow the convention that (1) potential impact (i.e. risk) on a system, feature, or organism is the product of its exposure to one or more stressors and its sensitivity to those stressors, and (2) vulnerability is the ratio of potential impact to adaptive capacity. Estimating the vulnerability of ecosystems, habitats, areas, or other entities to climate change thus requires quantification of these three elements (Fig. 1) using various indicators that can be easily identified and quantified (e.g. Hobday et al., 2006).

We also used globally modelled estimations of recent changes in climate change stressors (Halpern et al., 2008) and expert-derived ratings of habitat sensitivities to those stressors in California Current marine ecosystems (Halpern et al., 2009; Neslo et al., 2008; Teck et al., 2010), which extend into Canada's Pacific region. Details of the characterization of the three components of vulnerability are discussed in Section 2—Methods.

Screening-level marine ecological risk/vulnerability approaches are being developed based on life history attributes of individual species, species aggregations, and populations, including estimates of productivity and susceptibility to climate change (e.g. Gaichas et al., 2014; Hobday et al., 2011; Hunter et al., 2014; Pecl et al., 2011; Stortini et al., in review). Choosing amongst these different approaches in any given circumstance will likely hinge on the availability of different types of information, in addition to practitioner interests and expertise. Here, we present the first conceptual example of a rapid screening-level vulnerability analysis in primary literature that includes an explicit treatment of adaptive capacity and a spatial overview of ecological risks and vulnerabilities to climate change variables. We summarized findings using 12 ecologically-defined marine *Ecosections* of British Columbia (Fig. 2) delineated as part of the British Columbia Marine Ecological Classification (BCMEC) (BC, 2002), and also using 23 benthic habitats and surface and midwater habitats (Fig. 3).

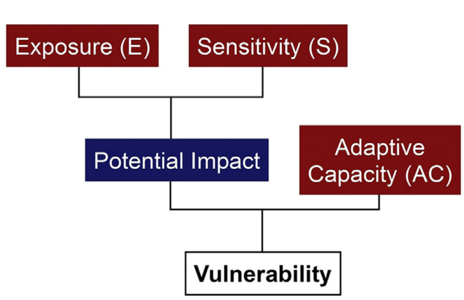

Fig. 1. Components of vulnerability from the Allen report (2005).

Explicitly accounting for *adaptive capacity* is key for the derivation of vulnerability (Marshall et al., 2013). Various approaches are emerging to characterize *social adaptive capacity* related to ocean and coastal resources (e.g. Allison et al., 2009; Cinner et al., 2013, 2012; Melnychuk et al., 2014), but characterizations of ecological adaptive capacity are scarce, with examples using ecological adaptive capacity indicators (e.g. Cinner et al., 2013; Hobday et al., 2006) and in one case using simulation models (Mumby et al., 2014b). These indicator-based analyses were conducted in data rich settings and at geographically small scales (Cinner et al., 2013; Mumby et al., 2014b), or were employed for broad screening (Hobday et al., 2006).

In contrast, Canada's Pacific marine area is both geographically broad and somewhat data-scarce making it infeasible to identify and utilize ecological indicators that would be useful in quantifying the *state* of adaptive capacity across its entire seascape (but see Okey et al., in prep). In the absence of detailed and comprehensive estimates of adaptive capacity in the system, we used the inverse of the cumulative impacts of non-climate human stressors (from Ban et al., 2010) as a proxy of the adaptive capacity of the system to climate change.

Our goal was to provide an example assessment that minimizes subjectivity by using an overarching habitat approach and that can be refined in the future as more information becomes available to support planning and adaptation approaches to cope with future climate-related changes in the region. Such planning could include reductions of local and regional stressors to increase system resilience to climate change, protection of natural "climate refugia," and other climate adaptation approaches that include spatial planning of human use patterns as marine species and populations re-shuffle and shift.

The initial iteration of this vulnerability assessment was presented in Okey et al. (2012), which was the foundation of the present work and of an updated summary of existing knowledge of the effects of climate change (Okey et al., 2014). Our initiative was inspired initially by a broad-scale vulnerability assessment in Australia as part of a synthesis of climate impacts, which also included extensive literature reviews of selected ecosystem components and habitats (Hobday et al., 2006).

2. Methods

To examine *vulnerability* (*V*) to climate change spatially, we represented the three components of vulnerability—exposure (*E*), sensitivity (*S*), and adaptive capacity (*AC*). We used globally modelled estimations of recent changes in climate change stressors (Halpern et al., 2008) to characterize *exposure* (E), and expert-derived ratings of sensitivities of habitats to those stressors in California Current marine ecosystems (Halpern et al., 2009; Neslo et al., 2008; Teck et al., 2010) to characterize *sensitivity* (S). We then used the *cumulative impacts* of non-climate human stressors (*CI*) (Ban et al., 2010) as an inverse proxy of *adaptive capacity* (*AC*).

Although Halpern et al. (2009, 2007) and Teck et al. (2010) used the term *vulnerability* in their often cited example of regional human impacts mapping in marine ecosystems, they were often referring to expert ratings of *sensitivity*. Halpern and colleagues used the term *impacts* in both their global (2008) and California