Global Ecology and Conservation 4 (2015) 110–116

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: www.elsevier.com/locate/gecco

Short communication

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

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

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

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 9 June 2015
Accepted 9 June 2015
Available online 24 June 2015

Keywords:
Cumulative effects
Cumulative impact mapping
Industrial development
Climate change
Marine
Canada

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

* Correspondence to: Institute for Ocean Sciences, P.O. Box 6000, Sidney, British Columbia, Canada, V8L 4B2. Tel.: +1 250 363 6911; fax: +1 250 363 6827.
E-mail address: cclarke@eos.ubc.ca (C. Clarke Murray).

http://dx.doi.org/10.1016/j.gecco.2015.06.003
2351-9894/

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

Table 1
Summary of cumulative effects scores for four scenarios: total cumulative effect score, footprint, and effect per square kilometer.

Scenario	Total cumulative effect score	Footprint (km^2)	Effect/km^2
Current	1,328,062	1,585,313	0.84
Climate	939,697	452,352	2.08
Planned	1,339,972	1,585,313	0.85
Difference between Planned and Current	11,910	7,583	1.57
Combined current + Climate + Planned	2,279,669	1,585,313	1.44

environmental assessment. Within the provincial tenure datasets, we identified planned sites as those tenures in some phase of the application process. Forestry cutblock tenures and forestry roads marked "pending" were considered planned tenures; no information was available on planned paved roads. There were no planned finfish and shellfish aquaculture tenures in the system, so current and planned scenarios were identical for these two activities. Roads associated with pipelines were not included as spatially-explicit information was not available for planned developments. Increases in shipping traffic associated with planned developments were explored but did not increase the relative intensity over current levels and therefore the shipping noise model used current levels of traffic (Erbe et al., 2012). Stressors resulting from the transfer of materials from pipelines to ships were assumed to be associated with nearby ports. Industrial sites marked "disposition in good standing" in the dataset were considered the current operational sites, while industrial sites marked "application" or "approved" were considered planned. Mining sites included in the current scenario were either "producers" or "past producers", while planned mining sites were either a "claim" or an "application". High resolution spatial information about projected increases in towns and cities, or ports and marinas, was not available.

We obtained the spatial locations of all additional planned industrial sites and pipelines from map documents released under the provincial and federal environmental assessment applications, up to October 2013. All planned industrial and pipeline project are expected to begin construction in the next 10 years, if approved. We cross-referenced 51 industrial project documents with provincial tenure datasets. The industrial sites and mines not yet included in the provincial system were digitized by hand and added to the respective activity layer. Planned pipeline impacts were treated the same as the forestry roads: as a linear development, resulting in increased sedimentation.

2.3. Climate change

We used climate change datasets collated by Halpern et al. (2008) on sea surface temperature (SST), acidification and ultraviolet (UV) light. All three climate datasets depict change in actual or modeled conditions from a previous time period to a more recent time period (from 1990–1995 to 2000–2005 for SST, from pre-industrial (1870) to 2000–2009 (projected) for acidification (aragonite saturation state), and from 1996 to 2004 for UV change in the UVB spectrum) (Appendix S3). All three were expressed on a globally standardized scale from 0 to 1 (0 no change, 1 most change). Supplementary documentation associated with Halpern et al. (2008) provides more details on the processing of these datasets for their global analyses.

3. Results

Most human activities that affect the marine environment take place in coastal regions, on the continental shelf or watersheds near the ocean. The biggest change in potential cumulative effects was due to climate change stressors (Fig. 1). Cumulative effects scores from climate are highest in the southern third of British Columbia (Fig. 1(b)), while the highest scores for baseline and planned human activities are restricted to the shelf region and specifically, a small area around Vancouver and Prince Rupert (Fig. 1(c)). Data on planned development was limited to terrestrial activities with possible influences on marine systems, and thus increased cumulative effect scores from planned developments were mainly restricted to coastal and marine areas within the boundaries of estuaries (Fig. 1(c)). The number of planned industrial developments for British Columbia was the highest in Canada; 51 industrial projects are undergoing environmental impact assessment reviews. These included major oil and gas pipelines, liquefied natural gas (LNG) terminals, mineral mines and associated increases in marine shipping. The planned development scenario added a footprint of potential impact (7582 km^2), in addition to the footprint of current developments, but where the planned development occurred there was a relatively high impact per square kilometer affected (Table 1). There were localized impacts associated with planned activities in areas outside the estuaries, but they are quite small. In contrast, climate change stressors have a large footprint (Fig. 1(b)); every part of the study region is affected by climate change stressors.

Current human activities represent 58.3% and climate change represents 41.4% of the total cumulative effects score in British Columbia. The addition of planned developments would contribute a relatively small percentage increase in cumulative effects (0.5%). The human activities causing the largest change in cumulative effects scores between current and planned development scenarios, when summed across all habitats, was for pipelines (74.8%), industrial sites (14.6%) and log booms (13.4%). For those activities with planned data available, industrial activities and pipelines dominated the highest changes for each of the marine habitats examined (Table 2). The biggest change was the impact of pipeline activity on rocky intertidal habitat (161.5%).

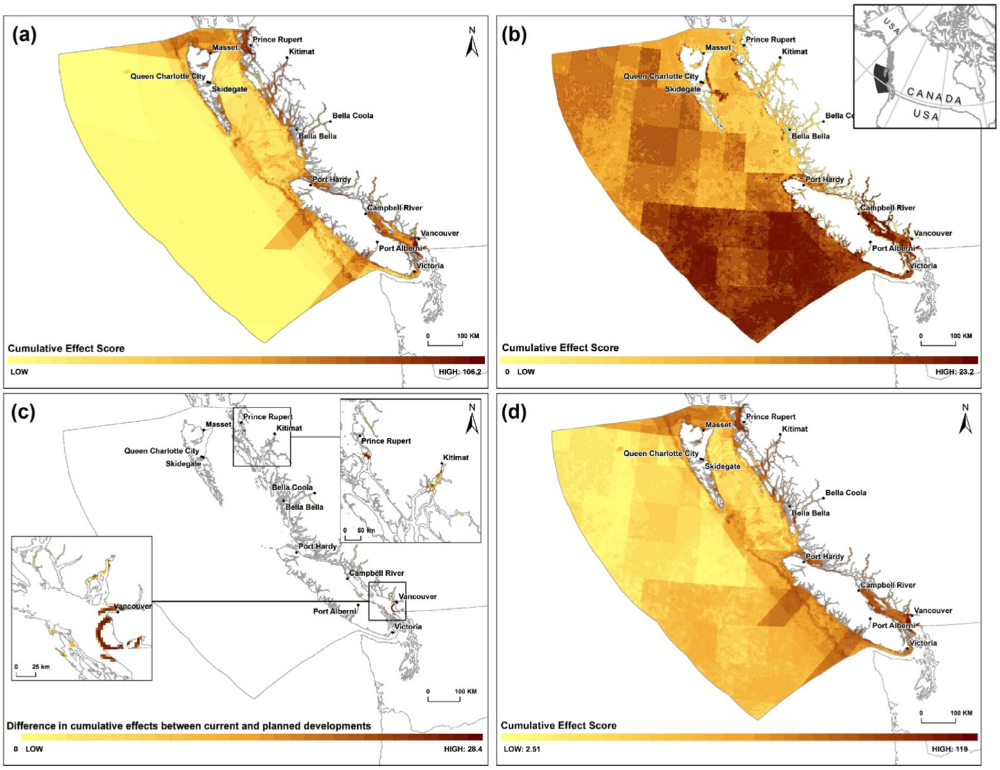

Fig. 1. Cumulative effect scores for (a) current activities, (b) climate change, (c) the difference between planned development and current activities, and (d) combined current activities, climate change, and planned development; inset map shown in upper right panel. Note that the color scheme is the same across the four panels but the high values differ and are noted in the legends. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Activity with highest increase in cumulative effect score for each habitat class between current and planned scenarios, cumulative effect score per square kilometer of habitat, and percent change between current and planned CE scores.

Habitat	Activity	Current		Planned		% Change
		Cumulative effect score	CE/km^2	Cumulative effect score	CE/km^2	
Beach (Intertidal)	Industrial	4.67	0.088	2.9	0.055	+62.4
Canyon	–					0.0
Deep pelagic	Agriculture	272.06	0.001	18.1	<0.001	+6.6
Hard shelf	Industrial	20.11	0.001	14.8	0.001	+73.7
Hard shallow	Industrial	12.19	0.003	9.2	0.002	+75.8
Hard slope	Pipeline	1.27	<0.001	1.3	<0.001	+100.0
Kelp	Pipeline	0.00	0.000	0.4	0.002	+100.0
Mudflat (Intertidal)	Pipeline	9.65	0.194	7.6	0.153	+78.7
Rocky intertidal	Pipeline	5.87	0.012	9.5	0.019	+161.5
Rocky reef non-shallow	Pipeline	1.83	0.003	1.9	0.003	+103.0
Rocky reef shallow	Pipeline	0.95	0.005	1.1	0.006	+120.6
Seagrass	Pipeline	13.25	0.043	16.0	0.052	+120.7
Shallow (Intertidal)	Pipeline	101.10	0.177	44.4	0.078	+44.0
Shallow pelagic	Industrial	1081.90	0.002	148.5	<0.001	+13.7
Sponge reef	–					0.0
Soft shelf	Industrial	413.71	0.009	59.8	0.001	+14.5
Soft shallow	Pipeline	39.13	0.005	39.3	0.005	+100.5
Soft slope	Industry	32.11	0.002	8.6	0.001	+26.7
Undefined deep	–					0.0
Undefined intertidal	Pipeline	12.18	0.103	13.8	0.117	+113.7
Undefined shelf	Industrial	15.63	0.014	3.1	0.003	+19.9
Undefined shallow	Pipeline	3.50	0.014	4.1	0.016	+117.0
Undefined slope	Log boom	0.05	<0.001	<0.1	<0.001	+36.8

Within the estuaries (where the model assigns the footprint of land-based activities on marine habitats), there was a substantial increase in cumulative effects over current levels from land-based planned industrial developments. Estuaries associated with the Skeena River in the north and the Fraser River in the south showed especially high increased cumulative effects with the planned development scenario (Fig. 1(c)). A ring of high impact scores near the mouth of the Fraser River was the result of planned development activities in the Fraser River watershed (Fig. 1(c)), where high impact in the current scenario already existed at the mouth of the estuary (the center of the ring) but adding planned development increased the effects in the next buffer zone distance.

4. Discussion

4.1. Local versus global drivers

The importance of the two drivers of change – climate change and industrial development – on marine ecosystems varied with scale. At the regional scale (British Columbia's EEZ), climate change dominated the cumulative effects scores so that every square kilometer of BC's marine waters are predicted to have been affected by climate change stressors, leading to potential cumulative effects in all three depth classes (benthic, shallow pelagic and deep pelagic) and multiple habitats. Historical climate change was also the top threat in the global analysis (Halpern et al., 2008), in the California Current system (Halpern et al., 2009), and was identified by experts as a top threat for ecozones in the Northwestern Hawaiian Islands (Selkoe et al., 2009), whilst in the Mediterranean Sea, climate change impacts were less widespread (Coll et al., 2012). Climate change impacts have high potential cumulative effects because of their large footprints, and because experts indicated that marine habitats are very vulnerable to climate change stressors (i.e., they have high vulnerability scores, Teck et al., 2010).

Although climate change was the dominant effect at the coast-wide scale, land-based planned activities had higher potential impact at local scales. In particular, planned development had high cumulative effects scores around the estuaries of the Skeena River in the north and the Fraser River in the south, suggesting that these estuaries are in need of increased management to prevent degradation from cumulative effects. Marine spatial planning would be useful in resolving conflicts of use and reducing the cumulative effects in high use areas (Douvere, 2008; Foley et al., 2010). In British Columbia, the majority of potential future marine impacts are from planned developments on land, whereas in other marine regions, such as the Arctic Ocean, planned developments such as offshore drilling occur in the ocean itself, increasing the potential for marine cumulative effects. Further increases in coastal and inland development activity could dramatically increase cumulative effects on marine ecosystems and make the application of this type of analysis even more important (Reeves et al., 2014), especially in combination with future climate change impacts.

Our analysis was the first attempt that we are aware of to incorporate planned development in cumulative effects mapping analyses. Previous cumulative effects mapping efforts focused on evaluating the current state of cumulative effects (Halpern et al., 2008; Ban and Alder, 2008; Halpern et al., 2009; Selkoe et al., 2009; Ban et al., 2010). However, scenario analyses and evaluations of tradeoffs in ecosystem services have been done that incorporate planned activities. For example, the InVEST tool was used to evaluate the impact of planned development of a single sector, mining, on ecosystem services in Colombia, South America (Tallis et al. October 2011). Some countries require formal cumulative effects assessments as part of environmental impact assessments for single proposed industrial projects. These cumulative effects assessments should include past, present and reasonably foreseeable planned developments. However, the scope in application is often limited and researchers have highlighted numerous problems in their application (Duinker and Greig, 2006; Duinker et al., 2012; Clarke Murray et al., 2014). Cumulative effects models within environmental impact assessments are limited to single stressors (e.g. cumulative noise, total habitat loss) and there has been no integration of cumulative effects mapping into the development decision-making process. Repeated calls have been made for the move to regional cumulative effects assessments (Dubé, 2003; Duinker and Greig, 2006; Gunn and Noble, 2009; Duinker et al., 2012) which could utilize tools like the cumulative effect mapping demonstrated here.

4.2. Limitations and future directions

The availability of spatially-explicit, high resolution data is a key component for cumulative effect mapping in any region. While some data sources have regularly updated, high quality datasets, other activity datasets such as commercial fishing can be older and imprecise likely leading to both under and over-estimation of cumulative effects. In order to fill these data gaps, there is a need for regularly updated, spatially precise data. There was limited information on planned future developments for many of the human activities included in our analysis. In particular, there was no available spatially-explicit information on future activity for commercial fishing, sportfishing, recreational boating, paved roads, and human settlements. General industry trend information may be available at a regional scale (e.g. projected increases in leisure boating) but is not applicable at the fine resolution needed for the model. Shipping increases, like those associated with planned industrial development for the North Coast, were explored in preliminary analysis but did not increase relative intensity (RI) because, when compared to coast-wide shipping, it was a relatively small increase. A much larger proposed pipeline expansion terminating in Vancouver harbor was not included in the current analysis as the shipping estimates had not been released at time of analysis. The lack of digitized planned industrial development data is not limited to British Columbia and Canada. Many countries around the world are struggling with sharing planned development information to inform cumulative effects analysis and would be assisted by the creation of a central clearinghouse for monitoring and impact assessment data.

The climate change data used in the current study was relatively coarse and represents recent measured change, not projected future change. As a result of their coarse nature, the impact on offshore ecosystems is better represented than those inshore impacts where local oceanography and conditions modify the impacts of climate change stressors (Halpern et al., 2008 Supplementary Materials). Potential underestimates of inshore climate change impacts may become particularly important in areas under pressure from current or planned industrial developments on land. Future research could incorporate climate change projections, such as those from the Intergovernmental Panel of Climate Change (IPCC, 2013), to identify hotspots of future change, facilitate the protection of potential climate refugia and highlight areas where climate change intersects with already stressed areas, or areas of potential future industrial development. This is an important area of future work as the interaction of local stressors and global change can result in large and unpredictable ecosystem responses that can affect the success of local management interventions (Brown et al., 2013).

While the use of the cumulative effects model in comparing current and future cumulative effects is novel, there remain a number of limitations in analyses of this type. Stressors do not include catastrophic events such as large oil spills, which can have extreme and long-term impacts on marine ecosystems (Peterson et al., 2003). The risk of an oil spill increases as planned oil and gas developments with associated marine shipping components proceed. The current analysis also does not include habitat destruction and alteration of ecosystems associated with planned mitigation measures such as restoration or compensation often conducted as conditions of approval for planned industrial projects. Additionally, the cumulative effects model includes only one stressor per activity, which can underestimate the impact of activities with multiple stressors with potentially high impacts. Future work could expand the model to include multiple stressors from single human activities, as done in risk assessment models (e.g. Kelly et al., 2014) in order to better capture the full cumulative effects.

As identified by previous studies, an important assumption of cumulative effects mapping is that stressors interact additively (Halpern and Fujita, 2013), whereas there is evidence that synergistic and antagonistic interactions are common (Crain et al., 2008; Darling and Côté, 2008). Brown et al. (2014) demonstrated that the nature of interaction is important for management purposes and should be further explored. As in all analyses using this model, the issue remains that cumulative effects scores represent potential, not actual cumulative effects. Increased understanding of the impact of single activities on species, habitats and ecosystems is needed in order to better understand and predict the ecosystem responses to cumulative effects (Halpern and Fujita, 2013). Studies relating cumulative effect scores to measurements and observations of ecosystem health are needed in order to better understand ecosystem response to cumulative effects.

As our results demonstrate, managing cumulative effects of marine ecosystems cannot be done in isolation and the relative impact of different human activities depends on the scale of analysis. Further, the interactions between development and climate change will only become more important in the future (Reeves et al., 2014). Effective planning and management measures must consider regional stressors (land use and coastal industry) as well as global stressors, such as climate change. By directly incorporating tools like the cumulative effects model presented here, the environmental assessment process can move beyond single project decisions to sustainable development outlooks. Integrated marine planning can also use this type of scenario-based cumulative effects analysis to examine the consequences of future opportunities in the context of historical and current human activities. Focusing solely on a single project, scale, or industry increases the risk of ignoring important stressor classes that contribute to cumulative effects, potentially disrupting ecosystem function and the essential services they provide.

Acknowledgments

The authors wish to thank A. Lau for GIS assistance, J. Pfalz and the Skeena Knowledge Trust for spatial data, A. Sierra Martinez for mining impact information, and J. Casey for providing advice on freshwater systems. We would also like to thank H. Alidina and three anonymous reviewers for their advice on improving the manuscript. This research was supported in part by grants from Marine Harvest Canada and the Gordon and Betty Moore Foundation to WWF-Canada (#2229.01). NCB was supported by the Natural Science and Engineering Research Council (NSERC) (#435785-2013).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2015.06.003. Calculating cumulative effects scores (Appendix S1), Human activities datasets (Appendix S2), Climate change stressors (Appendix S3), and Map of habitat classes (Appendix S4) are available. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

References

Ban, N., Alder, J., 2008. How wild is the ocean? Assessing the intensity of anthropogenic marine activities in British Columbia, Canada. Aquat. Conserv.: Mar. Freshw. Ecosyst. 18 (1), 55–85.

Ban, N.C., Alidina, H.M., Ardron, J.A., 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Mar. Policy 34 (5), 876–886.

Brown, C.J., Saunders, M.I., Possingham, H.P., Richardson, A.J., 2013. Managing for interactions between local and global stressors of ecosystems. PLoS One 8 (6), e65765.

Brown, C.J., Saunders, M.I., Possingham, H.P., Richardson, A.J., 2014. Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping. Divers. Distrib. 20 (5), 538–546.

Clarke Murray, C., Agbayani, S., Alidina, H.M., Ban, N.C., 2015. Advancing marine cumulative effects mapping: An update in Canada's Pacific waters. Mar. Policy 58, 71–77.

Clarke Murray, C., Mach, M.E., Martone, R.G., 2014. Cumulative Effects in Marine Ecosystems: Scientific Perspectives on its Challenges and Solutions. WWF-Canada and Center for Ocean Solutions, Vancouver, British Columbia, Monterey, California.

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W.W.L., Christensen, V., Karpouzi, V.S., Guilhaumon, F., Mouillot, D., Paleczny, M., 2012. The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. Glob. Ecol. Biogeogr. 21 (4), 465–480.

Crain, C.M., Kroeker, K., Halpern, B.S., 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecol. Lett. 11 (12), 1304–1315.

Darling, E.S., Côté, I.M., 2008. Quantifying the evidence for ecological synergies. Ecol. Lett. 11 (12), 1278–1286.

Douvere, F., 2008. The importance of marine spatial planning in advancing ecosystem-based sea use management. Mar. Policy 32 (5), 762–771.

Dubé, M.G., 2003. Cumulative effect assessment in Canada: a regional framework for aquatic ecosystems. Environ. Impact Assess. Rev. 23 (6), 723–745.

Duinker, P.N., Burbidge, E.L., Boardley, S.R., Greig, L.A., 2012. Scientific dimensions of cumulative effects assessment: toward improvements in guidance for practice. Environ. Rev. 21 (999), 40–52.

Duinker, P.N., Greig, L.A., 2006. The impotence of cumulative effects assessment in Canada: Ailments and ideas for redeployments. Environ. Manag. 37 (2), 153–161.

Erbe, C., MacGillivray, A., Williams, R., 2012. Mapping cumulative noise from shipping to inform marine spatial planning. J. Acoust. Soc. Am. 132 (5), EL423–EL428.

Foden, J., Rogers, S.I., Jones, A.P., 2011. Human pressures on UK seabed habitats: a cumulative impact assessment. Mar. Ecol. Prog. Ser. 428, 33–47.

Foley, M.M., Halpern, B.S., Micheli, F., Armsby, M.H., Caldwell, M.R., Crain, C.M., Prahlera, E., Rohra, N., Sivasa, D., Beck, M.W., Carr, M.H., Crowder, L.B., Duffy, J.E., Hacker, S.D., McLeod, K.L., Palumbi, S.R., Peterson, C.H., Regan, H.M., Ruckelshaus, M.H., Sandifer, P.A., Steneck, R.S., 2010. Guiding ecological principles for marine spatial planning. Mar. Policy 34 (5), 955–966.

Gunn, J.H., Noble, B.F., 2009. Integrating cumulative effects in regional strategic environmental assessment frameworks: lessons from practice. J. Environ. Assess. Policy Manag. 11 (3), 267–290.

Halpern, B.S., Fujita, R., 2013. Assumptions, challenges, and future directions in cumulative impact analysis. Ecosphere 4 (10), art131.

Halpern, B.S., Kappel, C.V., Selkoe, K.A., Micheli, F., Ebert, C.M., Kontgis, C., Crain, C.M., Martone, R.G., Shearer, C., Teck, S.J., 2009. Mapping cumulative human impacts to California current marine ecosystems. Conserv. Lett. 2 (3), 138–148.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319 (5865), 948–952.

Harley, C.D., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J., Thornber, C.S., Williams, S.L., 2006. The impacts of climate change in coastal marine systems. Ecol. Lett. 9 (2), 228–241.

Hegmann, G., Cocklin, C., Creasey, R., Dupuis, S., Kennedy, A., Kingsley, L., Ross, W., Spaling, H., Stalker, D., 1999. Cumulative Effects Assessment Practitioners Guide. Prepared by AXYS Environmental Consulting Ltd. and the CEA Working Group for the Canadian Environmental Assessment Agency, Hull, Quebec.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kelly, C., Gray, L., Shucksmith, R.J., Tweddle, J.F., 2014. Investigating options on how to address cumulative impacts in marine spatial planning. Ocean Coast. Manage. 102, 139–148.

Korpinen, S., Meski, L., Andersen, J.H., Laamanen, M., 2012. Human pressures and their potential impact on the Baltic Sea ecosystem. Ecol. Indic. 15 (1), 105–114.

Maxwell, S.M., Hazen, E.L., Bograd, S.J., Halpern, B.S., Breed, G.A., Nickel, B., Teutschel, N.M., Costa, D.P., 2013. Cumulative human impacts on marine predators. Nat. Commun. 4.

Micheli, F., Halpern, B.S., Walbridge, S., Ciriaco, S., Ferretti, F., Fraschetti, S., Lewison, R., Nykjaer, L., Rosenberg, A.A., 2013. Cumulative human impacts on mediterranean and black sea marine ecosystems: assessing current pressures and opportunities. PLoS One 8 (12), e79889.

Okey, T.A., Alidina, H.M., Agbayani, S., 2015. Mapping ecological vulnerability to recent climate change in Canada's Pacific marine ecosystems. Ocean Coast. Manage. 106, 35–48.

Palen, W.J., Sisk, T.D., Ryan, M.E., Árvai, J.L., Jaccard, M., Salomon, A.K., Homer-Dixon, T., Lertzman, K.P., 2014. Energy: consider the global impacts of oil pipelines. Nature 510 (7506), 465–467.

Peterson, C.H., Rice, S.D., Short, J.W., Esler, D., Bodkin, J.L., Ballachey, B.E., Irons, D.B., 2003. Long-term ecosystem response to the Exxon Valdez oil spill. Science 302 (5653), 2082–2086.

Reeves, R.R., Ewins, P.J., Agbayani, S., Heide-Jørgensen, M.P., Kovacs, K.M., Lydersen, C., Blijleven, R., 2014. Distribution of endemic cetaceans in relation to hydrocarbon development and commercial shipping in a warming Arctic. Mar. Policy 44, 375–389.

Sala, O.E., 2000. Biodiversity—global biodiversity scenarios for the year 2100. Science 287, 1770–1774.

Selkoe, K.A., Halpern, B.S., Ebert, C.M., Franklin, E.C., Selig, E.R., Casey, K.S., Bruno, J., Toonen, R.J., 2009. A map of human impacts to a pristine coral reef ecosystem, the Papahānaumokuākea Marine National Monument. Coral Reefs 28 (3), 635–650.

Tallis, H., Wolny, S., Lozano, J.S., 2011. Including Ecosystem Services in Mitigation: A Report to the Colombian Ministry of Environment, Mines and Territorial Development, October.

Teck, S.J., Halpern, B.S., Kappel, C.V., Micheli, F., Selkoe, K.A., Crain, C.M., Martone, R., Shearer, C., Arvai, J., Fischhoff, B., Murray, G., Neslo, R., Cooke, R., 2010. Using expert judgment to estimate marine ecosystem vulnerability in the California current. Ecol. Appl. 20 (5), 1402–1416.

Wathern, P., 1988. Environmental Impact Assessment: Theory and Practice. Academic Division of Unwin Hyman Ltd..