Oil sands and the marine environment: current knowledge and future challenges

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The environmental consequences of bitumen extraction from oil sands deposits are at the center of North American natural resource and energy policy debate, yet impacts on ocean environments have received little attention. Using a quantitative framework, we identify knowledge gaps and research needs related to the effects of oil sands development on marine biota. Fifteen sources of stress and disturbance – varying greatly in spatial and temporal scale – are generated via two pathways: (1) the coastal storage and oceanic transport of bitumen products, and (2) the contribution of industry-derived greenhouse gases to climate change in the ocean. Of highest research priority are the fate, behavior, and biological effects of bitumen in the ocean. By contrast, climate-change impacts are scientifically well established but not considered in key regulatory processes. Most stressors co-occur and are generated by other industries, yet cumulative effects are so far unaccounted for in decision making associated with new projects. Our synthesis highlights priority research needed to inform future energy development decisions, and opportunities for policy processes to acknowledge the full scope of potential and realized environmental consequences.

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Bitumen is a dense and highly viscous petroleum found in clay and sand deposits known as bituminous sands, oil sands, or tar sands (Gosselin *et al.* 2010). Escalating extraction of bitumen in North America is furthering global debate about the ecological, economic, and social hazards and opportunities created by developing "unconventional" fossil-fuel sources (Palen *et al.* 2014). However, the scientific study of impacts has largely lagged behind the rapid pace of oil sands development, and where it has progressed, it has focused primarily on effects on regional landscapes, freshwater systems, climate change, and human communities (eg Charpentier *et al.* 2009; Kelly *et al.* 2009; Tenenbaum 2009; Gosselin *et al.* 2010; Rooney *et al.* 2012; Kurek *et al.* 2013). To date, the effects of the industry on marine environments have received relatively little scientific attention.

In a nutshell:

- Hazards and opportunities created by oil sands development are key public-policy issues as decisions are made globally about the future of unconventional fossil fuels
- Oil sands research has focused primarily on environmental effects on terrestrial and freshwater systems, with little attention paid to coastal and oceanic impacts
- Fifteen stressors and disturbances to marine organisms are generated by coastal storage and marine transport of bitumen products, and three by oil-sands-generated greenhouse-gas emissions contributing to climate change in the oceans.
- The extent of public information varies greatly, from little known effects of bitumen products in oceans to well-established consequences of climate change
- Regulations to protect marine environments are hindered by a lack of available science and require holistic, ecosystem-based frameworks to assess cumulative and co-occurring stresses

Although the majority of global oil sands deposits are located >1000 km from coastlines, their development is directly linked to ocean ecosystems by two main pathways: (1) the storage of chemically diluted bitumen (known as "dilbit") in coastal areas and transport by tankers along ocean routes, and (2) climate-change impacts to the oceans associated with greenhouse-gas emissions from the extraction, refining, transport, and combustion of bitumen products (Figure 1). Assessing the cumulative impacts of sources of environmental stress and disturbance (ie "stressors") generated along each pathway – which vary in space, time, severity, frequency, and likelihood of occurrence – requires an interdisciplinary analysis. However, relevant disciplinary research spans many fields and is published in a wide range of sources. Assembling this scattered information and evaluating information needs are key steps in developing informed policy on oil sands development, export, and disaster response. In particular, approaches such as ecological risk assessment modelling depend on robust data that relate development activities to species responses and their interactions (Forbes and Calow 2013). The ability of such models to generate accurate predictions depends on the degree to which they include important ecological processes, and the

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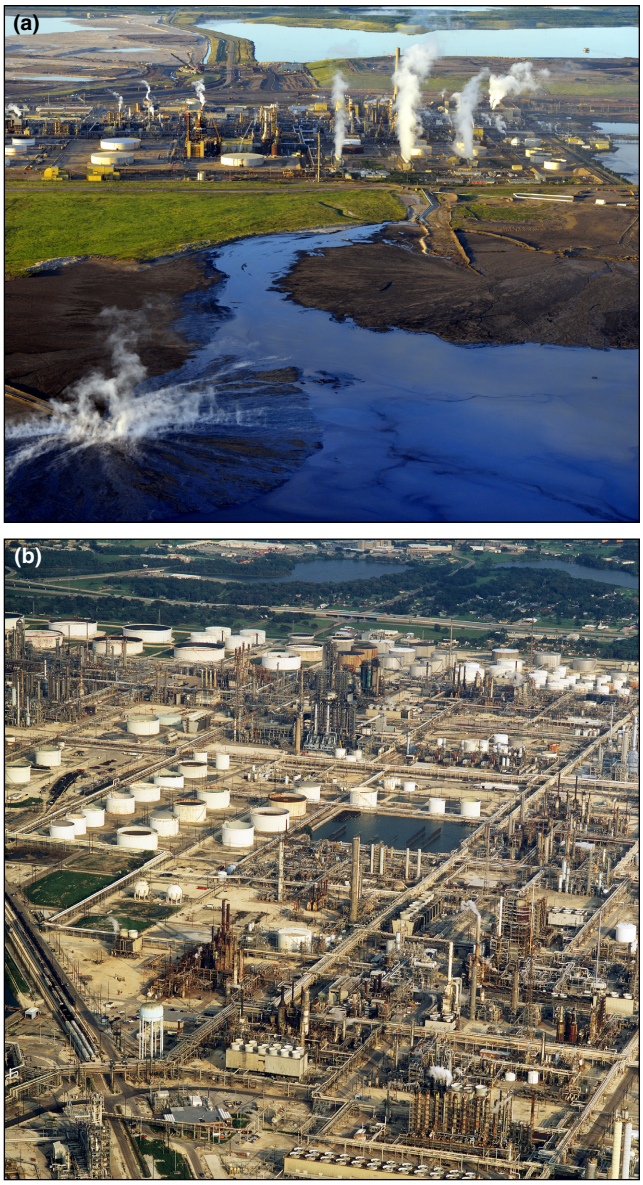

Figure 1. *The development of oil sands deposits like those in Alberta, Canada – the world's largest at 1.7 trillion barrels of accessible bitumen – (a) affects ocean ecosystems via climate change generated from greenhouse-gas emissions during extraction, and via processing and shipping from coastal terminals to world markets, such as the Baytown Refinery on the Gulf of Mexico in Texas, USA (b).*

accuracy and precision of the data used in the forecast (Munns 2006).

Here we provide an overview of the state of knowledge about effects from oil sands development on marine biota globally, with the aim of highlighting research findings and identifying essential research gaps. We also synthesize current knowledge about the biota in two coastal ecosystem types that would be directly affected by current proposals to expand oil sands development and transport in North America – temperate kelp forests and eelgrass systems, which are found along temperate Pacific coastlines – to illustrate the extent of research needs at the scale at which regional ecological risk assessments and resource policy decisions are made.

Analytical framework

We identified 15 sources of environmental stress or disturbance to marine species generated by the production, distribution, and combustion of oil sands products (Figure 2). Several of these stressors are unique consequences of oil sands development, such as spills of diluted bitumen into the environment, whereas others are commonly generated by other types of resource extraction and land use, including coastal development and shipping (Table 1). We classified each stressor according to three metrics: (1) the chance of occurrence, categorized as either certain to occur (eg a planned or unavoidable consequence of oil sands production or distribution) or probabilistic (eg an unplanned or accidental occurrence); (2) the temporal scale of each interaction pathway, estimated as the expected duration of the stress or disturbance (ie seconds to millennia); and (3) the estimated spatial scale based on the average ocean area over which effects were expected to occur (Table 1).

To gauge the current state of knowledge about effects from each stressor on marine species globally, we conducted a systematic review (via keyword search) to quantify the number of peer-reviewed scientific studies indexed within the international database Web of Science and non-refereed literature indexed within the Canadian government library database WAVES, which catalogues all content within Department of Fisheries and Oceans (DFO) libraries and DFO reports. Search terms and protocols are described in WebPanel 1. We categorized resulting studies by the trophic level(s) they addressed, and whether a study considered multiple sources of stress and/or multiple trophic levels simultaneously (WebTable 1). We also identified studies within our search results that focused on species within eelgrass and kelp forest ecosystems (WebPanel 1).

We then prioritized research needs for each stressor, ranked relative to one another, by considering four metrics: three related to the nature of the stressor (spatial and temporal scale of effect, and chance of occurrence [ie certain to occur or probabilistic]), and one related to the current state of knowledge about ecological effects (the number of relevant studies that were available, either peer-reviewed or government literature) (Table 1). For each stressor, chance of occurrence was given a rank of either 1 (certain to occur) or 2 (probabilistic) (Table 1). Spatial and temporal scales of effect were assigned a categorical value of 1–4, with higher values for increasing scale (Table 1). Next, we ranked current knowledge based on the log number of relevant studies for each topic, which ranged from 1–4, multiplied by a factor of 4 to reflect the importance of existing research in developing

relative needs (Table 1; eg Souther *et al.* 2014). Finally, we calculated relative research priorities by summing the four metrics for each stressor. These numeric cumulative metrics correspond to final ranked research priority as: "Low" (<13), "Medium" (13.0–16.0), "High" (16.1–19.0), and "Very high" (>19.0) (Table 1).

There are at least two main assumptions to our approach. First, it assumes that knowledge increases with the number of studies on a topic. While in some cases a few studies may provide key, broadly relevant insights into the nature (ie scale, magnitude, and likelihood of occurrence) of an effect, extensive research may leave key questions unanswered and typically identify multiple new lines of inquiry. Nonetheless, our approach provides a starting place from which to identify knowledge gaps and research priorities (eg Souther *et al.* 2014). Moreover, a complete absence of publicly available research into a stressor generally points to a clear research need. Second, it assumes that the majority of relevant information is publicly available. Yet additional knowledge may exist within proprietary sources that cannot be accessed by public-sector scientists (eg the authors of this paper). Furthermore, access to research that is indexed within databases may be restricted behind pay walls and subscription requirements. In such cases, government personnel tasked with evaluating the ecological consequences of resource development are limited to publically available research journals and technical reports.

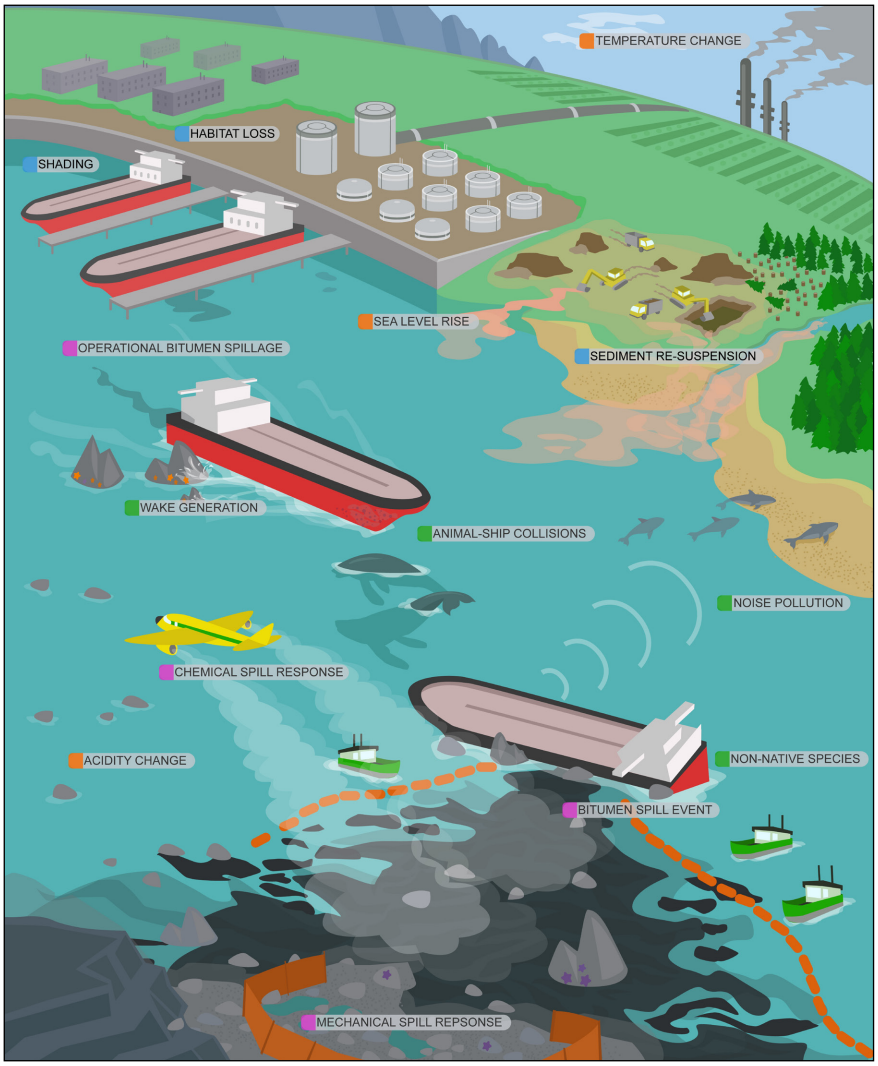

Figure 2. *Sources of environmental stress and disturbance caused by oil sands production and transport in marine systems. Colors associated with each stressor indicate their source: orange = climate change, blue = coastal development, pink = bitumen in the environment, green = shipping.*

Sources of ecological impact

Coastal development

Transporting bitumen via the ocean requires infrastructure to support moving products from rail or pipelines to ships in coastal zones. Converting portions of coastline into docks, buildings, and roads results in at least three deterministic sources of stress to the local marine environment: loss of structural habitat, shading of marine benthos, and resuspension of sediments into the water column (Table 1 and Figure 2). Port development activities vary in scale from relatively minor re-appropriation of existing infrastructure to the construction of new facilities (Figure 3). In some cases, widespread dredging accompanies construction to increase capacity for shipping (Tsinker 2004). These activities re-suspend sediment in the water column, which can shade benthic primary producers (Moore *et al.* 1997), scour (physically displace) species (Kendrick 1991), and reintroduce to the marine food web toxic chemicals and heavy metals that had previously settled to the seabed (Eggleton and Thomas 2004; Torres *et al.* 2009). While sediment suspension generally tapers off following construction, habitat loss, alteration, and shading are permanent within the footprint of the site (Figure 3). Although the effects of coastal development occur over relatively small spatial scales, the certainty and longevity of ecological change qualify as medium and high research priorities (Table 1 and Figure 4). We also found substantial gaps in knowledge on the

Table 1. Relative research priorities for 15 sources of stress generated by oil sands production and transportation in the marine environment, based on literature searches and scales of effect

Source	*Stressor/disturbance*	*Chance of occurrence*	*Temporal scale*	*Spatial scale*	*# of studies*	*Relative research priority*
Coastal development	Habitat loss	Certain *(1)*	Decades *(3)*	Site *(1)*	50 *(2.3)*	Medium *(14.2)*
	Sediment re-suspension	Certain *(1)*	Days–Weeks *(2)*	Local *(2)*	132 *(1.9)*	Low *(12.5)*
	Shading	Certain *(1)*	Decades *(3)*	Site *(1)*	14 *(2.9)*	High *(16.4)*
Shipping	Wake generation	Certain *(1)*	Minutes *(1)*	Local *(2)*	5 *(3.3)*	High *(17.2)*
	Sediment re-suspension	Certain *(1)*	Days–Weeks *(2)*	Local *(2)*	38 *(2.4)*	Medium *(14.7)*
	Noise pollution	Certain *(1)*	Hours *(1)*	Regional *(3)*	68 *(2.2)*	Medium *(13.7)*
	Animal–ship collisions (ship strikes)	Probable *(2)*	Seconds *(1)*	Regional *(3)*	89 *(2.0)*	Medium *(14.2)*
	Non-indigenous species introductions	Probable *(2)*	Years–Decades *(3)*	Regional *(3)*	275 *(1.6)*	Medium *(14.2)*
Bitumen in the environment	Bitumen exposure from operational spillage	Certain *(1)*	Days–Weeks *(2)*	Site *(1)*	0 [2] *(4)*	Very high *(20.0)*
	Bitumen exposure from spill event	Probable *(2)*	Days–Decades *(2)*	Regional *(3)*	3 [1917] *(3.5)*	Very high *(21.1)*
	Chemical spill response	Probable *(2)*	Days–Years *(2.5)*	Regional *(3)*	20 *(2.7)*	High *(18.3)*
	Mechanical spill response	Probable *(2)*	Minutes–Weeks *(1.5)*	Local *(2)*	4 *(3.4)*	High *(18.1)*
Climate change	Temperature Δ	Certain *(1)*	Millennia *(4)*	Global *(4)*	4883 *(0.3)*	Low *(10.2)*
	Acidity Δ	Certain *(1)*	Millennia *(4)*	Global *(4)*	1293 *(0.9)*	Low *(12.5)*
	Sea-level rise	Certain *(1)*	Millennia *(4)*	Global *(4)*	467 *(1.3)*	Medium *(14.3)*

Notes: Numbers in parentheses represent values for each metric describing the (L-R): chance of occurrence, spatial scale, temporal scale, current understanding (# of studies), and sum (ie cumulative value) of these metrics for each stressor. Values in square brackets represent the number of relevant studies for conventional oil in the environment. Spatial scale is given as: site (0.01–1 km^2), local (1–10 km^2), regional (10–1000 km^2), and global (>1000 km^2 to worldwide).

effects of stress generated by coastal development for the majority of trophic groups in temperate eelgrass and kelp forest ecosystems (Figure 5).

Shipping

Increasing transport of oil sands products via ocean tankers is certain to amplify at least three sources of stress to marine ecosystems: wake generation, sediment re-suspension, and acoustic pollution. It will also increase the likelihood of two probabilistic effects: animal–ship collisions, and the introduction of exotic species between ports (Table 1 and Figure 2). Wake generation by large commercial vessels has been associated with decreased species richness and abundance (Rönnberg 1975) given that wave forces can dislodge species, increase sediment re-suspension (Gabel *et al.* 2008), and impair foraging (Gabel *et al.* 2011), although it can increase seaweed abundance in areas without sand scour (Demes *et al.* 2012).

Increased tanker traffic threatens marine fish, invertebrate, and mammal populations by disrupting acoustic signaling used for a variety of processes, including foraging and habitat selection (eg Vasconcelos *et al.* 2007; Rolland *et al.* 2012), and by physical collision with ships – a large source of mortality for marine animals near the surface along shipping routes (Weir and Pierce 2013). Given the regional scale but moderate level of information about noise pollution and increased risk of collision for wildlife, we identified these as medium research priorities (Table 1 and Figure 4). We found little information on the response of most trophic groups in eelgrass and kelp forest systems to these shipping-mediated stressors (Figure 5).

Tankers also serve as a vector for the introduction of non-indigenous species (NIS) via inadvertent transfer of propagules from one port to another (Drake and Lodge 2004), with the probability of introduction depending on the magnitude and origin of shipping traffic along tanker routes (Table 1 and Figure 3; Lawrence and Cordell 2010). We classified NIS introductions as a medium research priority due to the extensive knowledge available on the topic and evidence of active research into potential technical solutions (Table 1 and Figure 4).

Bitumen in the environment

Spills of "conventional" oil (hydrocarbons extracted through wells that are liquid at ambient temperature and pressure; eg crude oil) have profound ecological, economic, and social impacts and consequently have received considerable attention over the past half-century, with thousands of published research papers and dozens of extensive reviews (eg Moore and Dwyer 1974; Teal and Howarth 1984; Chang *et al.* 2014; see also dashed bars in Figure 4). Yet bitumen – which can also directly affect the marine environment when it enters the ocean – is chemically distinct from conventional oil, so ample information on the effects of conventional oil entering marine ecosystems may not apply to bitumen spills.

Diluted bitumen refers to many chemically distinct substances that vary in toxicity and chemical behavior from conventional oil (Crosby *et al.* 2013; Environment Canada 2013). Similar to other forms of oil, diluted bitumen can spill into the environment via normal operational discharge (eg small spills during tanker loading) or accidental spill events, which can vary greatly in duration, volume, and area (Figure 3). Due to the paucity of publicly available research on the effects of diluted bitumen on marine biota, we assigned the highest research priority to this source (Table 1 and Figure 3). In fact, whether bitumen products will float or sink, their response to evaporation, solar exposure, and mixing with water and sediment are determined by their chemical composition (eg King *et al.* 2015), which is largely unknown (Crosby *et al.* 2013) but is the most fundamental requirement for understanding the consequences of bitumen spills (Chang *et al.* 2014). For example, one laboratory study on the behavior of diluted bitumen products in saltwater found that dilbit floated in a similar fashion to conventional oil in water free of sediment, but sank and dispersed as "tarballs" when mixed by wave action with fine seawater sediments (Environment Canada 2013).

The environmental impacts associated with oil spill clean-up efforts (eg mechanical or chemical) may increase the magnitude of ecological damage and delay recovery (Figure 3; Foster *et al.* 1990). Given the relative paucity

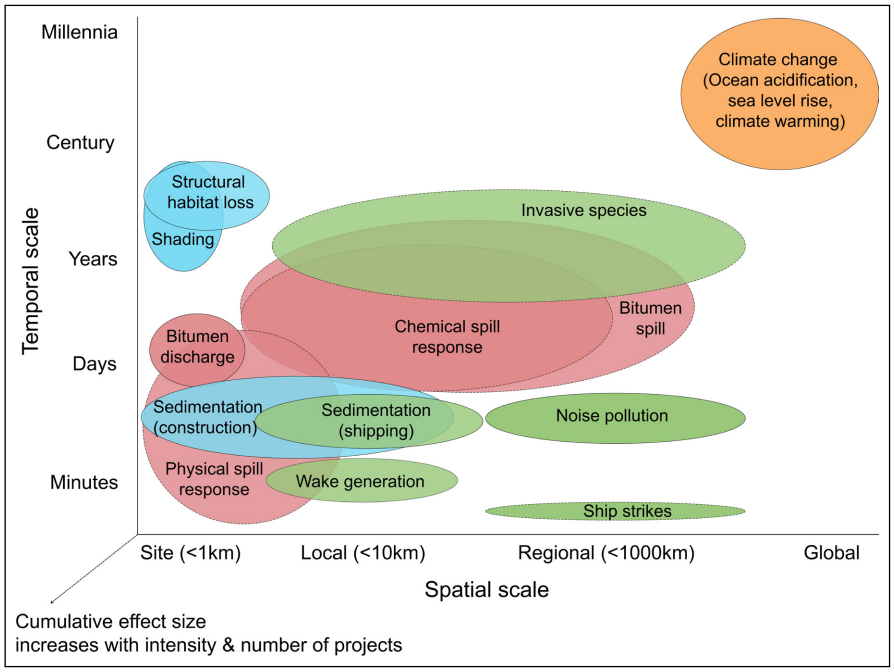

Figure 3. *The spatial and temporal scale of environmental stressors and disturbances associated with oil sands production and transport in the marine environment. The magnitude of effects from each stressor (ie cumulative effect size) will also increase with the intensity and number of projects generating each source of disturbance/stress.*

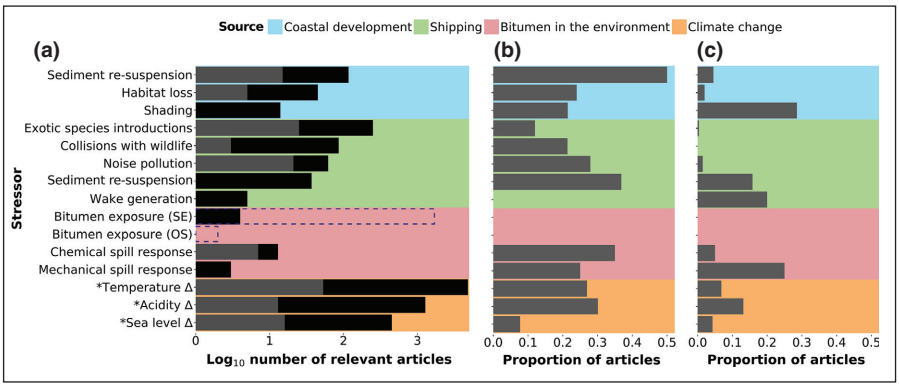

Figure 4. *Publicly available studies on the ecological effects of 15 sources of stress and disturbance generated by oil sands development in the marine environment, sorted by stressor. (a) The number (log_{10}) of peer-reviewed studies archived in the database Web of Science (black bars) and non-refereed government technical reports housed in the Government of Canada WAVES database (gray bars). In (a), the dashed bars for bitumen exposure (SE = spills in the environment) and bitumen exposure (OS = operational spillage) represent the larger number of relevant articles using the search term "oil exposure" rather than "bitumen exposure". For each stressor, we show the proportion of studies that considered (b) the effects on more than one trophic level simultaneously (ie trophic interactions) and (c) at least one additional stressor in the analysis (ie multiple stressors).*

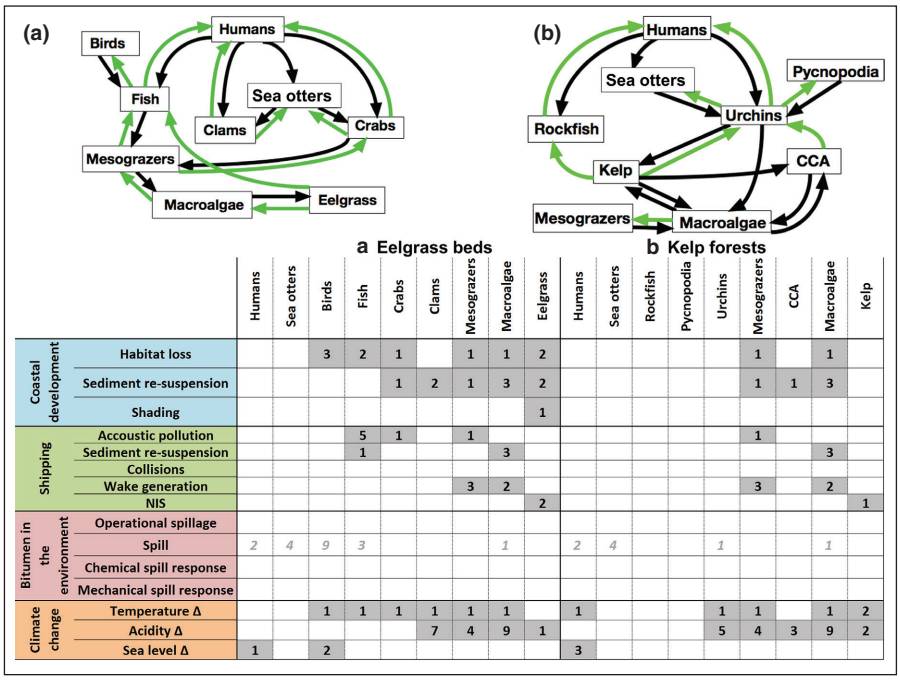

Figure 5. *Number of publicly available studies on the ecological effects of 15 sources of stress and disturbance generated by oil sands development on species groups within temperate Pacific (a) eelgrass and (b) kelp forest ecosystems. Italic values refer to studies on spills of conventional oil. Green arrows denote a positive effect of one species group on the other, whereas black arrows denote a negative relationship.* CCA = *crustose coralline algae.*

of information on the ecological consequences of spill response methods, we ranked these areas of research as a high priority (Table 1 and Figure 4). We did not find studies on either the response of most trophic groups within eelgrass and kelp forest ecosystems to bitumen in the environment, or the impacts of different spill-response methods (Figure 5).

Climate change

The extraction, transportation, and use of oil sands products affect marine ecosystems globally through increased greenhouse-gas emissions, which exacerbate anthropogenic climate change. Per unit of energy delivered, transport fuel derived from oil sands deposits generates more greenhouse gases throughout its lifecycle than other petroleum products (Gordon *et al.* 2015). Here, we focus on three of the most pervasive stressors associated with climate change in the ocean: acidification, warming, and sea-level rise (Table 1 and Figure 3). Elevated CO_2 concentrations in the atmosphere lead to higher dissolved CO_2 concentrations in seawater, which in turn lower its pH. Acidification can alter growth, survival, and reproduction of species (Doney *et al.* 2009; Kroeker *et al.* 2013). At particular risk are organisms with calcareous shells or skeletons that cannot form properly in acidified seawater. These species tend to be at the base of marine food webs, amplifying the impacts throughout marine ecosystems (Harley *et al.* 2006; Kroeker *et al.* 2013). Warming sea-surface temperatures have been associated with decreased productivity, diversity, and resilience of nearshore marine ecosystems over the past few decades (Hoegh-Guldberg and Bruno 2010; Wernberg *et al.* 2011a) and with increased risk of species extinction (Wernberg *et al.* 2011b). Sea-level rise will shift habitat for nearshore marine communities in regionally specific ways, depending on local geomorphology, and is expected to have substantial economic consequences for coastal human populations (eg Hinkel *et al.* 2014). While oil sands development is certain to exacerbate the effects of ongoing climate change, these effects are relatively well-understood, both globally and more specifically for eelgrass and kelp forest systems, and thus have been assigned a relatively low research priority (Table 1 and Figure 4).

Multiple stressors and cumulative effects

Oil sands development affects marine ecosystems via numerous pathways, including at least 15 different sources of stress or disturbance. The scale and magnitude of ecological effects arising from these stressors depends on species-specific responses to individual stressors, the timing and severity of stressors co-occurring with one another, and how tolerant species are to multiple stressors. As many as ten of the 15 stressors are certain to co-occur within the footprint of coastal transport routes at multiple spatial and temporal scales (Table 1 and Figure 3). Yet few studies have examined the effect of two or more sources of stress or disturbance on marine biota simultaneously (0.5% of the 9260 studies we reviewed; Figure 4c). The extent of gaps in information on multiple stressors was particularly evident at a regional scale for eelgrass and kelp forest systems (Figure 5).

Each type of stress and disturbance generated by oil sands development also has the potential to affect species within multiple trophic levels, potentially altering species interactions (eg predation, competition) in marine food webs. Predicting the responses of one species to a particular disturbance therefore requires information on not only the effect of that stressor on the species of interest, but also effects on other species with which it interacts strongly with in the ecosystem. Yet only 25% of all studies we reviewed considered effects across multiple (ie two or more) trophic levels simultaneously (Figure 4 and WebTable 3).

The magnitude of impact also depends on the history of other existing and planned stressors within the ecosystem. Many of the stressors and disturbances associated with oil sands development are also associated with other types of resource extraction activities and marine transport. In some locations already subject to industrialized resource development, the additional effects of oil sands development may be relatively small. Elsewhere, there may be thresholds associated with multiple stressors that – once surpassed and in combination – could lead to increasingly adverse environmental outcomes.

Implications for ecological risk assessment and policy

Regulatory processes that aim to minimize the negative environmental impacts of resource development need a holistic, ecosystem-based framework in which to assess the consequences of multiple stressors and their cumulative effects. Modern approaches such as Ecological Risk Assessment models (Banks *et al.* 2010; Martin *et al.* 2013) require: (1) basic research into the mechanisms driving change, (2) an understanding of the scale over which effects are likely to occur, (3) quantification of the uncertainty associated with each effect and their possible interactions, and (4) links between ecological state and assessment of socioeconomic impacts (Tarazona 2013). In the case of North American oil sands development, our review indicates that basic information is lacking or unavailable for several key sources of stress and disturbance, making it impossible to carry out a complete risk assessment.

In particular, publicly available information on the behavior, fate, and toxicity of bitumen products to marine biota is almost entirely absent. The assumption that risk assessment can be based on best practices for addressing conventional oil spills is not supported by scientific evidence. Chemical composition is one of the first inputs required to evaluate the ways in which contact between a petroleum product and the environment will affect marine life, as well as its downstream impacts on human livelihoods and health (Chang *et al.* 2014). Sampling information for some blended bitumen products reveals high variability in chemical composition and physical properties (Environment Canada 2013; www.crudemonitor.ca). However, the chemical composition of diluted bitumen produced and transported at a given time and place is a trade secret, prohibiting the generation of publicly available science to fill these critical gaps (Crosby *et al.* 2013).

In contrast to the limited information on bitumen effects (three studies), we identified over 6600 studies describing climate-change-driven ocean acidification, temperature increase, and sea-level-rise impacts on marine organisms (Figure 4; WebTable 3). These studies represent a substantial basis of knowledge that can support decisions regarding national and international resource development policy. However, barriers remain to a full accounting of the contribution oil sands development projects to climate change in several key regulatory processes in North America (Palen *et al.* 2014). For instance, Canada's National Energy Board (NEB) is currently precluded from considering the cumulative effects of proposed oil sands developments, as well as downstream environmental and climate impacts in its assessment of individual infrastructure proposals (OAG 2014). In the US, the National Environmental Policy Act (NEPA) obliges federal agencies to consider upstream and downstream effects of oil transport infrastructure on greenhouse-gas emissions. However, considerable discretion is afforded the US State Department for trans-border projects, a regulatory arrangement that resulted in a substantial underestimate of climate-change effects from the proposed Keystone XL pipeline moving bitumen from Canada to the US Gulf Coast (Brown 2012). Thus, limitations on both scientific information and the scope of regulatory policies often prohibit full consideration of the risks from oil sands development.

Our analyses also highlight gaps in knowledge about stressors that are within the scope of North American resource planning and regulatory processes. For example, we were unable to identify any publicly available research on the effects of bitumen exposure, coastal development, or shipping traffic on several major groups of species within the eelgrass and kelp forest ecosystems. These systems dominate coastal marine habitats in western Canada where multiple plans for bitumen pipelines, port facilities, and shipping routes have been federally approved (Joint Review Panel 2013) or are under consideration (National Energy Board 2015). Scientific reviews conducted by the Government of Canada also highlight key information gaps regarding the effects of several of the stressors examined in this study on marine biota in the region (acoustic pollution, bitumen exposure, species invasions, and habitat modification; DFO [2013] and additional references in WebPanel 2). Filling these widely recognized gaps ahead of regulatory decisions would decrease the uncertainty associated with environmental assessments and increase the likelihood that policies will effectively protect marine systems and the human livelihoods and cultures that depend on them.

In general, rigorous consideration of the cumulative effects of multiple, often simultaneous, resource development projects within the same jurisdiction remains elusive in research and policy (Duinker *et al.* 2012; Murray *et al.* 2014). Likewise, North American regulatory processes often treat stress and disturbance generated by multiple spatially and temporally overlapping resource development proposals as independent when they are not (Palen *et al.* 2014; Noble 2015). The effects of coastal development and shipping, and the contribution of greenhouse gases to ocean climate change are also consequences of several other types of resource development. A likely consequence of considering each proposal separately is the underestimation of associated environmental

changes (Gunn and Noble 2011; Duinker *et al.* 2012). Thus, informing sound energy and environmental policy decisions requires simultaneously addressing the research priorities identified here and developing a more sophisticated framework for assessing multiple stressors and cumulative effects across projects.

Filling scientific knowledge gaps requires asking related societal questions about who is responsible for ensuring that information is generated, paying for the costs of research, and coordinating the interpretation and use of research results in policy development and implementation. At least four elements are essential to a regulatory framework that addresses these issues. First, policy for oil sands development must be grounded in comprehensive ecological risk analysis for all relevant stressors, including the cumulative effects of related projects. Second, areas of great scientific uncertainty identified by risk analyses – such as the gaps in knowledge we identified about bitumen composition and studies that span multiple trophic levels – must motivate focused research designed to provide practical guidance to energy developers and regulators. Because research results may be applied to future projects, as well as proposals that identify research needs, funding this component of the assessment framework may be shared by public- and private-sector actors, guided by independent scientific advisors. In North America, the responsibility for regulating marine environmental impacts from the development of Alberta oil sands is shared among federal agencies including Canada's NEB, Ministry of Environment and Climate Change, and DFO, through the Canadian Environmental Assessment Act (CEAA). In the US, NEPA governs the analysis of potential impacts of bitumen transportation, while the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) oversees pipeline safety and the US Coast Guard regulates tanker transport. Various federal and state agencies exercise additional regulatory duties, depending on land ownership and marine jurisdictions. Several aspects of NEPA and CEAA and their implementation limit the scope for full risk assessment and subsequent regulation. Under CEAA, environmental assessments are not required for all proposed projects, and the criteria by which proposals are deemed suitable for risk assessment are not clear (OAG 2014). Under NEPA, the rigor of assessment required varies depending on predetermined estimates of the project's impact to the environment, with criteria varying among federal agencies (GAO 2014). For projects requiring risk assessment, a limited time frame for evaluating environmental information – gathered primarily by the project proponent – mandates that agencies make decisions, even in the absence of a complete understanding of environmental risk (OAG 2014). Third, risk analysis and the research that informs it should conform to standards independently developed in consultation with public-sector scientists and experts and be enforced by regulatory bodies. Research results pertaining to proprietary information should be available in the public domain for peer review and public examination. Currently, independently established and nationally recognized guidelines for ecological study design and risk assessment are lacking for Canada and the US (Deverman *et al.* 2014; OAG 2014), let alone specifically for oil sands. Developing such guidelines would require bringing together public- and private-sector scientists working in environmental risk analysis, supported by regulatory agencies. Finally, establishing per-barrel or per-BTU (British Thermal Unit) taxes on approved projects could fund strong, environmentally targeted oil spill and energy impact liability trusts in Canada, similar to the one created by the US to address environmental concerns in the wake of the *Exxon Valdez* spill of 1989 (Oil Pollution Act of 1990; Kim 2003). In addition to underwriting rapid responses to spills and other environmental repercussions resulting from oil sands production, proceeds from this fund could be used to develop appropriate long-term monitoring and management efforts to safeguard environmental and cultural values in areas of oil sands extraction, processing, and transportation, as well as affected downstream resources.

A large and growing body of work highlights the benefits of precautionary approaches to the development of public resources (eg Raffensperger and Tickner 1999; Cooney 2004; Peel 2005). A precautionary policy approach necessitates weighing the relative risks of alternative development decisions, and ensuring that the burden of proof – in terms of demonstrating that acceptable levels of harm are unlikely to be exceeded – lies with entities regulating development activities before they occur (M'Gonigle *et al.* 1994). For North American oil sands, this requires dialogue between all government bodies that have jurisdiction over the scales at which the 15 environmental stressors we identified operate (ie Indigenous, local, territorial, federal, and international). It also requires the coordination and engagement of diverse stakeholders, including regulators, industry representatives, public-sector scientists, and members of affected communities (eg Lubchenco *et al.* 2012). These are high aspirations, given the relatively circumscribed scale as which current regulatory policy is implemented. Thus, while the precautionary principle provides inspiration and aspirational goals, a practical framework for assessing the multiple stressors and associated risks of oil sands development on marine resources requires a pragmatic approach grounded in the four elements we outline above, and an efficient multi-jurisdictional policy mechanism for implementation.

Conclusions

The development of unconventional fossil fuels continues amidst intense public-policy debate about energy futures in North America and globally. In the case of oil sands development, our study highlights substantial gaps in the scientific knowledge needed to

support sound policy decisions. It also reveals gaps in regulatory mechanisms needed to incorporate existing information into risk assessments in North America, and provides key lessons for jurisdictions internationally that will face these same issues in future. Top priorities for public research identified by our analysis relate to the behavior, fate, and effect of diluted bitumen in the marine environment in the event of a spill. A crucial first step in filling this gap is a requirement that the chemical composition of oil sands products be made available for scientific study and impact assessment. Regulatory decisions made prior to filling these knowledge gaps are at increased risk of conflating "absence of evidence" for ecological effects with "evidence of absence" of impacts that have the potential to degrade valuable natural resources.

Our synthesis also highlights at least two opportunities to improve the use of existing scientific information in risk assessment and regulatory processes. First, incorporating the large body of science documenting climate-change effects into assessments will improve efforts to account for environmental costs of proposals for oil sands extraction, transport, and combustion. Second, accounting for the effects of multiple projects, concurrently, in scientific assessments and planning processes will lead to more accurate assessments of oil sands contributions to cumulative effects on resources that are in the footprint of multiple industries.

Taken together, our approach provides a quantitative way to clearly identify what we know and do not know scientifically about the effects of oil sands development on marine life, to prioritize future research so that it delivers the greatest value to policy makers and regulators, and to illuminate opportunities for scientists, decision makers, and industries to collaborate to improve our understanding of how current and future energy development decisions will affect the oceans.

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