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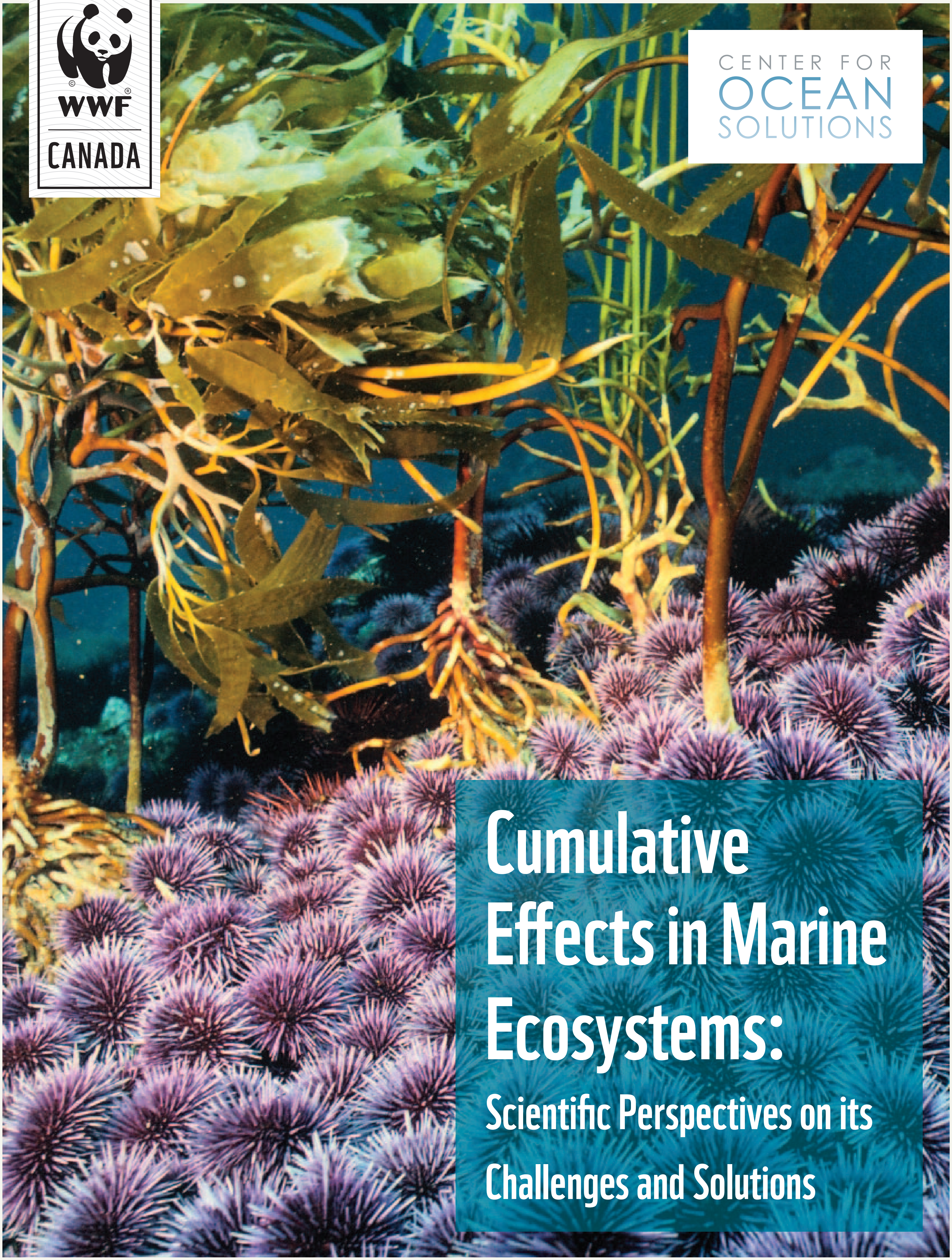

Cumulative Effects in Marine Ecosystems:

Scientific Perspectives on its Challenges and Solutions

Front cover: Giant kelp and purple sea urchins off the coast of California, USA.
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EXECUTIVE SUMMARY

Multiple impacts from human activities are escalating pressure on marine species and ecosystems.

Accurately accounting for the cumulative effects of impacts, however, can be difficult. Human activities produce a range of stressors that may interact and have greater impacts than expected, compounding direct and indirect effects on individuals, populations, communities and ecosystems. In addition, natural variability in ecosystem processes may affect the manifestation of resulting impacts. Assessment of cumulative effects on marine ecosystems requires extensive scientific research that directly tests the effects of multiple stressors; however, our knowledge of cumulative effects is largely based upon studies of single stressors on single ecological components that are combined to estimate the effect of multiple stressors. Therefore, advancing cumulative effects knowledge and assessments requires embracing the complexity, uncertainty, and natural variation in ecosystems and applying the best available science to evaluate and predict cumulative effects. In this review we discuss four components of cumulative effects science and application: (1) how cumulative effects manifest in ecosystems as a result of multiple human activities; (2) challenges in applying scientific knowledge in cumulative effects assessment, including defining spatial and temporal scales, baselines, reference points, indicators, and identifying significant changes in the face of uncertainty and natural environmental variability; (3) models and tools that have been developed to assess cumulative effects; and (4) priorities for science and management of cumulative effects. Conservation of marine ecosystems and support for sustainable development requires using primary research, models, and tools in an integrated, adaptive ecosystem-based framework to address cumulative effects.

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INTRODUCTION

Coastal and marine ecosystems provide a variety of benefits, including seafood, recreation, and energy, and support for human livelihoods and well-being.

The production of these benefits can be degraded (Figure 1), especially as demand for resources from marine ecosystems and activities that impact marine ecosystems increase in number, frequency and magnitude (Agardy et al., 2005; Pauly et al., 2005; Sala, 2000; Worm et al., 2006; Halpern et al., 2008). A broad range of human activities occurs in coastal and marine regions, producing stressors from both land and sea that impact the marine environment. Sea-based activities may include fishing, aquaculture, tourism, power generation and transportation. Land-based activities are connected to marine systems through freshwater runoff and may include human settlement, forestry, agriculture, power plants, mining and pulp and paper mills. Coastal activities also influence marine and estuarine resources, including ports and marinas as well as log storage and handling.

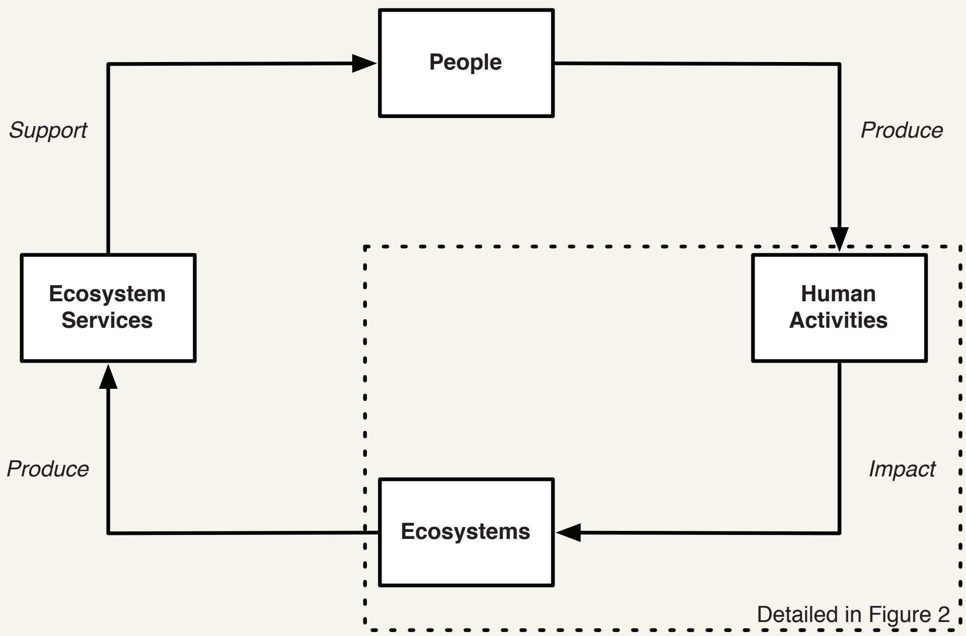
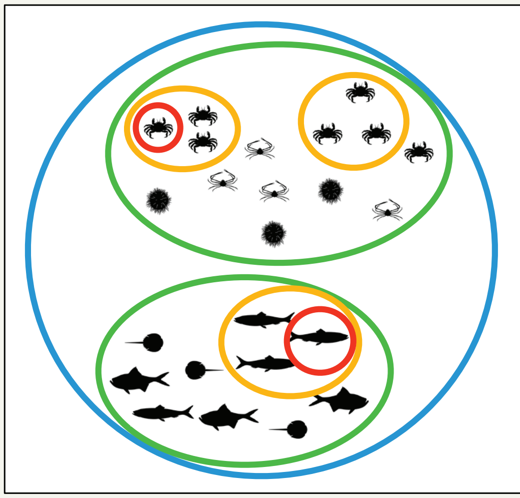


Figure 1: Pathway of service and production between people and ecosystems. People engage in activities that have impacts on ecosystems, which produce ecosystem services used by people.

LIVING IN A STRESSFUL WORLD

Human activities are associated with a number of environmental stressors (also sometimes referred to as "pressures" in the scientific literature; Smeets & Weterings, 1999). Stressors are the physical, chemical, and biological components of the activity that impact the surrounding environment, such as sedimentation, nutrient input, contaminants, shading and noise. For example, trawl fishing has a number of associated stressors: direct capture of target species, mortality and injury of non-target species, habitat disturbance, sedimentation, and noise from the fishing vessel (Hiddink et al., 2006). Ecosystem changes can also occur from natural system drivers, such as natural climate cycles (i.e., El Niño/ Southern Oscillation, Pacific Decadal Oscillation) (Mantua & Hare, 2002; Stenseth et al., 2003). Stressors can have impacts of varying degrees on a suite of species and habitats in ecosystems ranging from mortality to behavioural and physiological changes. Stressors can also act cumulatively with locally-based, extra-regional and global stressors (e.g., climate change, pollutants, marine debris). By definition, cumulative effects (the terms impacts and effects are used interchangeably) result from the incremental, accumulating, and/or interacting impacts of an activity and its stressors on habitats and species, when added to other past, present or potential future impacts (Hegmann et al., 1999). In order to fully account for the cumulative effects on coastal and marine ecosystems from multiple human activities, scientists and managers must be able to understand: (1) which activities cause which stressors; (2) the magnitude, frequency, and spatial scale at which the activities occur; (3) what the resulting direct and indirect cumulative effects will be on the ecosystem; and (4) how multiple ecological components at different levels of organization (e.g., individuals, populations, species, communities, and ecosystems) will respond (Figure 2).



Ecological Components	
Individual	Single organism. One individual of a single species.
Population	Grouping of individuals of a single species or taxa. Populations are considered separate when they form genetically distinct groupings either through behavioural or geographic isolation.
Community	Grouping of species within a single habitat. For example, urchin and crab populations living in the same habitat would be members of the benthic community.
Ecosystem	Grouping of communities into an ecosystem. For example, a kelp forest ecosystem includes all the resident populations of kelp, fish, invertebrate and other species. Communities interact through biophysical processes like nutrient flows.

Figure 2: Increasing complexity and nested structure of ecological components. Red indicates individual, orange represents population, green depicts community and blue represents ecosystem.

Research on the cumulative effects of human activities on marine ecosystems is more limited than research focused on the impact of single stressors on ecological components, and usually does not explicitly elucidate the source activities that produce specific stressors (Mach et al., submitted). Single-stressor studies have examined the ecological effects of pollutant loads and nutrient input levels (e.g., Nantel, 1996; Hinkey et al., 2005;), contaminant concentrations (e.g., Hagen et al., 1997), amount of wood debris (e.g., Williamson et al., 2000), pharmaceuticals (e.g., Halling-Sørensen et al., 1998) and noise (e.g., Erbe et al., 2012), as well as sedimentation rates, oil spills, and many others. To overcome the limited body of research on cumulative effects, studies have frequently combined research on single-stressors to estimate a total additive effect on the receiving environment (Clark et al., 2002; Lawler et al., 2002; Halpern et al., 2009; Cohen 2012). There is great uncertainty in determining cumulative effects, especially considering the unknown interactive effects of stressors on ecological components. Cumulative effect studies are also frequently limited by spatial and temporal scope, making it difficult to assess, for example, how stressors from an activity occurring today might interact with previous activities in the same region and to what extent those historic stressors may have already altered ecological components in the system. In addition, it is difficult to predict how global stressors like sea-level rise and ocean acidification may interact with local stressors.

Understanding relationships between a single human activity that produces a single stressor and its impacts on ecosystems can prove difficult. First, tracing the source of a stressor that caused an impact back to the activity can be a challenge, as many of these stressors are diffuse in the environment and may come from several different activities (McCarty & Munkittrick, 1996). For example, eutrophication, or excess nutrients, can produce toxic algal blooms, shellfish harvest closures and oxygen depletion zones. Pinpointing the source of nutrient stressors, however, is tricky, because nutrients may be discharged from a number of non-point and point sources, including sewage outfalls, agriculture and forestry activities, and coastal development. Second, research on human activities generally focuses on direct rather than indirect effects. For example, studies may examine the impact of dredging on eelgrass beds or the impact of anchoring on coral colonies. Other aspects of habitat disturbance, which are harder to document, may indirectly impact these ecosystems such as how the loss of eelgrass habitat from dredging affects juvenile salmon (Waldichuk, 1993).

GERICK BERGSMA 2009/MARINE PHOTOBANK

Southern sea otters and other species that live in coastal waters are subject to stressors from land and sea activities. For example, coastal power plants, such as this one at the mouth of Elkhorn Slough in Moss Landing, California, cause warming and entrainment of coastal waters.

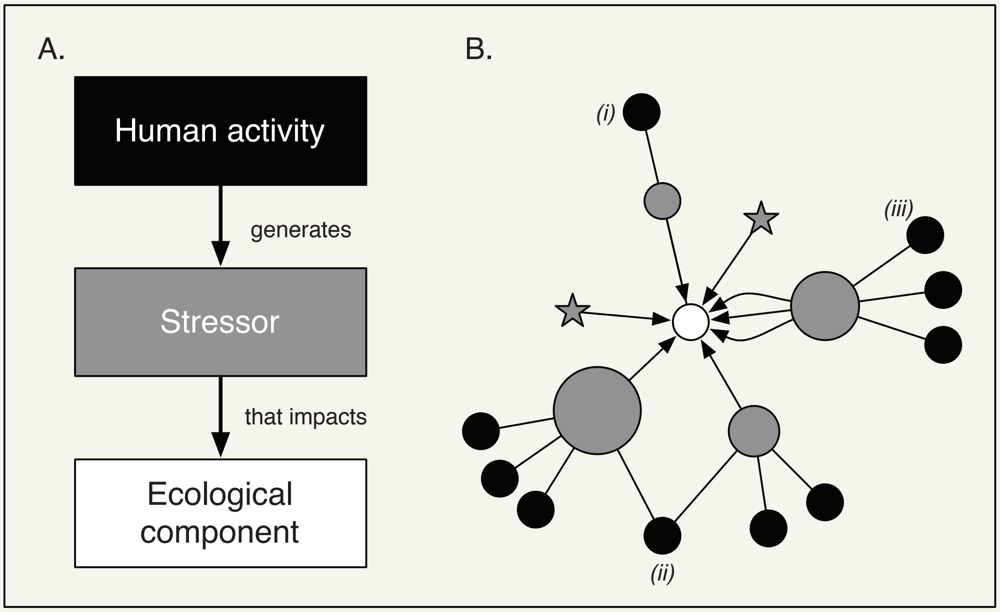


Figure 3: A conceptual network of multiple cumulative effects pathways affecting ecological components (white circle). Different human activities (black circles) can generate multiple stressors (gray circles). The size of the stressor circles suggests that the more activities producing a stressor, the more a stressor impacts the system. Pathways described in Figure 5 are examples of how the (i) Independent (Single Activity - Single Stressor), (ii) Multiple Stressors and (iii) Multiple Activities are all different pathways within the whole network (Whole Ecosystem pathway). Naturally derived stressors (grey stars) also contribute to the cumulative effects pathways. Modified from Knights et al., (2013).

The response of ecological components to *multiple* stressors is even more difficult to document and predict (Figure 3). First, a species' response to a stressor can change in the presence of additional stressors; second, species- or community-level responses may be context-dependent, changing under different environmental background conditions or across seasons; and third, species interactions within a community, such as predation or competition, can alter impacts from stressors and mask or enhance impacts to species. As a result of the complexities associated with stressors and responses by ecological components, stressors may interact to produce effects that differ from the effects of individual stressors alone (Folt et al., 1999; Crain et al., 2008). A study of the effects of nutrients and trace elements on estuarine food webs found that the interactions among stressors and background environmental conditions resulted in either increases or reductions in the temporal and spatial variability of species (Breitburg et al., 1999).

Stressors interact with each other and can be additive or non-additive, and can multiply (synergistic) or reduce effects (antagonistic) predicted from single stressors (Figure 4; Crain et al., 2008). Stressors are considered synergistic when their combined effect is greater than predicted from the responses to each stressor alone and antagonistic when the cumulative impact is less than expected (Folt et al., 1999, Crain et al., 2008; Figure 4). In the face of these uncertainties, research on multiple human impacts to ecological systems has been cited as one of the most important questions in ecology today (Sala, 2000; Zeidberg & Robison, 2007; Parsons et al., in press). Yet, it is also one of the most challenging questions to answer because of the difficulty in designing statistically appropriate tests to assess effect size beyond two or three interacting stressors. Further, these studies often involve complicated experimental designs done in small experimental blocks over short time scales limiting inferences that can be made for real ecosystems. The challenge in advancing cumulative effects research is not that questions have been overlooked, as much as these studies are difficult and costly to pursue, and that long-term data sets over large scales are scarce.

Despite these scientific challenges, many countries, including the United States, Canada, Australia and New Zealand require or recommend formal cumulative effects assessments (Council on Environmental Quality, 1997; Canadian Environmental Assessment Act (CEAA), 2012, 2013a; Resources Management Act, 1991; Ministry of Environment, New Zealand, 1991).

Although formal definitions vary slightly, cumulative effects assessment is "the process of evaluating the potential consequences of activities or development relative to existing environmental quality to predict changes to the environment due to the project combined with the effects of other past, present and reasonably foreseeable future activities" (Dubé, 2003; CEAA, 2012). Environmental impact assessments (EIAs) are often legally required for proposed industrial or resource extraction activities and may require examination of alternative outcomes under various development scenarios (Cooper & Sheate, 2004; Harriman & Noble, 2008).

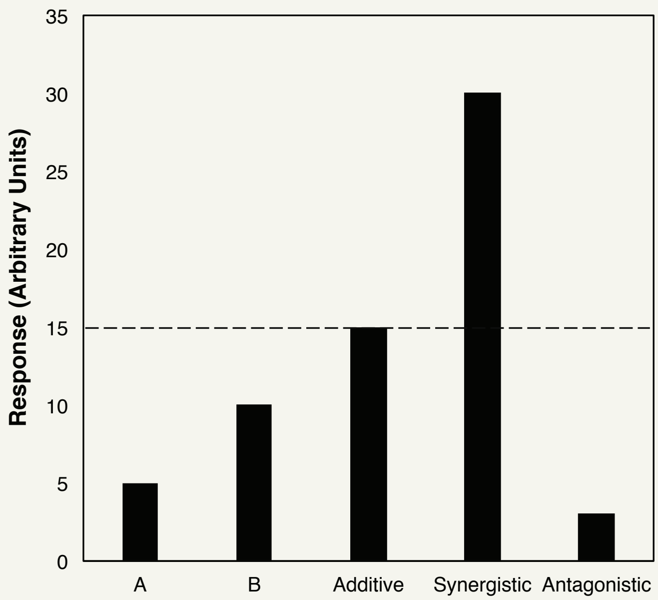
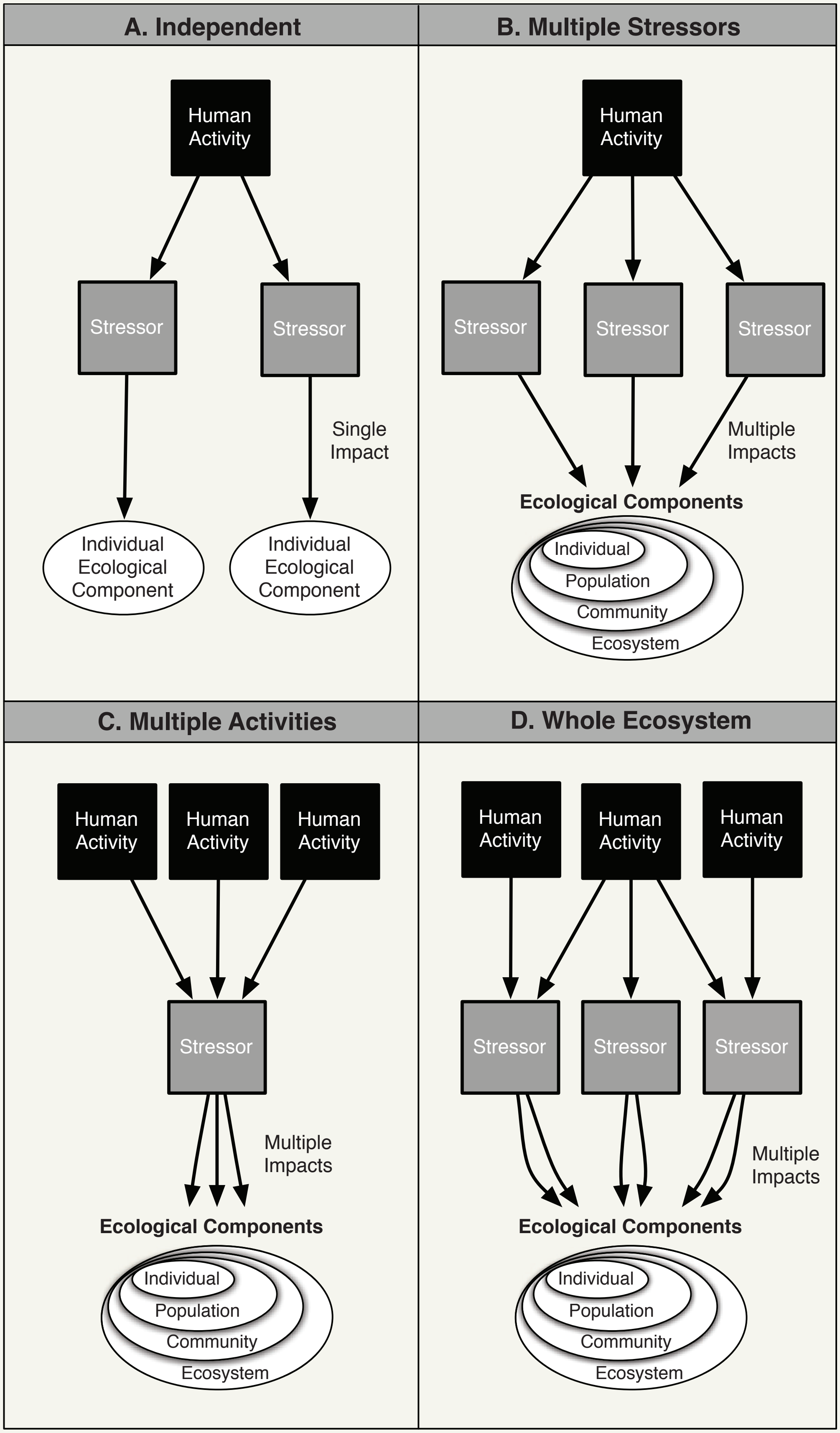


Figure 4: Cumulative effect relationships between individual stressors A and B. The default assumption is that stressors are additive (the dashed line). Additive: stressors add together to create an impact (e.g., A+B). Synergistic: stressors together produce a greater impact than each individually (e.g., A*B). Antagonistic: stressors counteract each other in some way so that together the impact is less than the individual stressors together (e.g., A-B or A/B). Adapted from Crain et al., 2008.

The continued focus on individual project assessments, despite requirements for cumulative effects assessments, has hindered advancement of strategic research studies that comprehensively address cumulative effects (Dubé, 2003; Duinker & Greig, 2006; Duinker et al., 2013). Environmental regulations, are beginning to incorporate cumulative effects because there is consensus among scientists and managers regarding the importance of these effects to ecosystems and the need for an integrated approach to science and management that incorporates the entire ecosystem, including cumulative effects of all human activities (Leslie & McLeod 2007; Levin & Luchenco 2008; Granek et al., 2010; Ruttenberg & Granek, 2011). Currently, management measures and regulations to limit the harmful effects of human activities are often implemented on an industry-by-industry or sector-by-sector basis or are focused on a single species, habitat or feature of interest (Travis et al., 2014). This single-species or single-activity management is not sufficient to address the number and magnitude of marine impacts. An assessment of cumulative effects must consider both the exposure to multiple stressors and the consequence of these stressors for multiple components within and across ecosystems.

Here we present a theoretical cumulative effects framework that describe (1) the pathways scientists and managers use to assess how stressors produced by human activities may interact to impact natural ecosystems, (2) how ecosystems respond to individual and combined stressors and (3) the resultant challenges associated with understanding cumulative effects on ecosystems from multiple activities. We then discuss the challenges of incorporating this science into the practice of cumulative effects assessment, highlighting models and tools that have been developed to extend primary research to assess cumulative effects. Finally, we recommend strategies for advancing science and management to improve cumulative effects assessment, suggesting new directions for research and application.

Figure 5: Theoretical framework of pathways by which independent (A) and cumulative effects (B-D) to ecological components are accounted for (as represented in Figure 4: A) human activities produce multiple stressors that impact ecological components independently – this is the traditional and most common pathway of effects assessment but does not account for cumulative effects, B) a single human activity produces multiple stressors that impact a suite of ecological components, C) multiple activities each produce a common stressor that has multiple impacts on a suite of ecological components or multiple impacts on a single ecological component over space or time and D) accounting for the whole ecosystem, where multiple activities produce multiple stressors that have multiple impacts on a suite of ecological components. Stressors from activities can accumulate across space (local, regional and global stressors) and time (past, present and predicted future activities).



ACCOUNTING FOR CUMULATIVE EFFECTS FROM HUMAN ACTIVITIES

The accumulation of impacts from stressors produced by human activities is accounted for in different ways in scientific research and environmental assessments.

Environmental assessments commonly focus on the activities and stressors produced only by the project being assessed (Multiple Stressors pathway; Figure 5B). This single activity-multiple stressor pathway is an initial step towards accounting for cumulative effects on the suite of ecological components in ongoing environmental assessments. In contrast, observational and experimental research studies may focus on a single stressor that is produced by many activities (Multiple Activities pathway; Figure 5C). Because it is difficult to quantify the extent to which any particular stressor comes from a given activity, most studies do not link the impact they are studying to the original activity. More often researchers discuss the range of existing activities that are likely to have produced the stressors (Mach et al., submitted), and then assess the cumulative effects of the stressors on a suite of ecological components. This lack of connection between stressors and their sources contributes to the challenge of managing the production of stressors from those activities. Ultimately, cumulative effects assessments that attempt to account for impacts of multiple stressors from multiple activities on multiple components are needed (Whole Ecosystem pathway; Figure 5D), but capturing cumulative effects through any of these pathways is a critical first step. Research on these three cumulative effects pathways is outlined further in the following sections.

SINGLE ACTIVITY PRODUCES MULTIPLE STRESSORS

Multiple stressors are produced by many types of activities, including development and construction activities as well as ongoing activities such as fishing, shipping, recreational boating and aquaculture (e.g., Grant et al., 1995; Goldburg et al., 2001; Hiddink et al., 2006; Skjoldal et al., 2009; Burgin & Hardiman, 2011). Fisheries research has documented multiple stressors from single fishing types. For example, benthic trawling stressors include direct mortality to the target species, bycatch mortality and injury to associated species, sedimentation, habitat destruction and stressors associated with the trawl vessel itself (Hiddink et al., 2006). The spatial scale (footprint) of multiple stressors from a single activity can vary across local and regional scales, as well as in persistence and frequency as they accumulate over time. For example, while direct mortality from fisheries may occur only within the fished area, sedimentation may occur over greater areas and habitat destruction may persist over longer time scales (Watling & Norse, 1998; Boutillier, 2012).

Marine transportation is another example of a marine activity that is a source of multiple stressors (Figure 6). Particular stressors depend on the type of vessel; slow-moving barges, powerful tugboats, oil tankers, and cruise ships operate in slightly different ways that can produce a different suite of stressors or vary in the magnitude of impact associated with each stressor (Skjoldal et al., 2009). Acoustic noise, vessel strikes, pollution, oil spills, sedimentation and habitat destruction are some of the stressors that have been associated with shipping activities (Skjoldal et al., 2009; Clarke Murray et al., in revision). A marine transportation vessel may introduce two different stressors—ship strikes and noise. Ship strikes can injure or mortally wound cetaceans (Laist et al., 2001; Panigada et al., 2006) and noise can cause behavioural changes, hearing damage and communication disruption (Ketten, 1995; Castellote et al., 2012). Together, these two stressors could potentially affect the long-term survival of cetacean populations (Kraus et al., 2005).

Cumulative effects can also be produced from a single activity that repeatedly occurs over time in the same region. For example, an intertidal marine reserve that is open to the public may be affected by human trampling. While the number of daily visitors may have a relatively small impact on the system, repeated daily visits may result in a significant cumulative effect to the sessile invertebrates and algae in the intertidal over time (Schiel & Taylor, 1999).

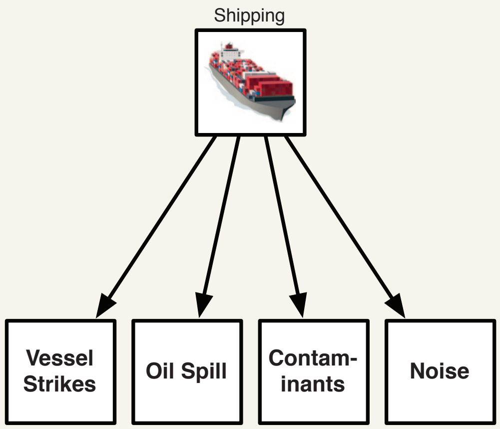


Figure 6: A single activity (marine transportation) can produce multiple stressors (vessel strikes, oil spills, contaminants and noise), all of which have effects on many ecological components (an example of the Multiple Stressors pathway, Figure 5B).

Stressors can also linger in the environment. These "legacy" stressors can continue to impact ecological components long after they have entered the environment, unpredictably interacting with new stressors. For example, while the pesticide DDT has not been used in agriculture since 1973 (Rice et al., 1993), it remains present in coastal sediments because of its extended half-life (Caffrey et al., 2002; Elkhorn Slough Foundation, 2002) and continues to impact coastal bird populations. In 1995, when Caspian Terns in California's Elkhorn Slough estuary failed to nest and reproduce. Researchers discovered high levels of DDT in the eggshells, dead chicks and embryos, as well as abnormalities known to result from DDT exposure (Elkhorn Slough Foundation, 2002).

MULTIPLE ACTIVITIES PRODUCE A SINGLE STRESSOR

Multiple activities may contribute to the production of a common stressor, increasing its magnitude (Figure 7). Examples include pollutants from land activities entering the marine environment through storm drains or wastewater and runoff combining to produce higher contaminant loads in marina environments (Figure 7; Hinkey et al., 2005) dredging, diking and draining for agriculture leading to hydrological changes and subsequent erosion of salt marshes (Van Dyke & Wasson, 2005); and multiple fishery types resuspending sediment that can negatively impact sponge reefs (Boutillier, 2012).

The most common analysis of cumulative effects within environmental assessments is the impact of multiple activities producing similar or "like" stressors. For example, a proposal that increased shipping and a recent harbor upgrade were both included in an assessment of cumulative effects from ship activity (Stantec, 2012). If effects are large from each "like" stressor, the cumulative effect may appear antagonistic because the ecosystem effect will be similar to each large single effect. This is particularly true when effects are great and result in widespread mortality. Additional activities will appear to have no additional stress on the system because it has already been degraded, making it difficult to disentangle and quantify the cumulative effects from the combined activities.

Stressors can also be assessed as the accumulation of similar or "like" activities. For example, desalination plants all produce similar stressors, such as thermal influx of warm water and saline brine outflow, which can accumulate and have effects on coastal wetlands and seagrass beds as was the case for cumulative effects of seven projects in the city of Carlsbad, California (City of Carlsbad, 2006). Multiple stressors from future planned desalination plants were considered, however, because the first desalination plant was found to have no significant impacts, all plants were considered to have no significant impacts and thus, there was a finding of no significant cumulative effects. In addition, the assessment omitted consideration of additional stressors caused by other past, present and future activities in the same area, how these stressors overlap in space or time, and the potential interactions between them. Impacts on ecological components may be underestimated when only similar projects are considered, especially when only significant impacts are included in cumulative effects assessments, as many non-significant impacts may interact to have significant cumulative effects.

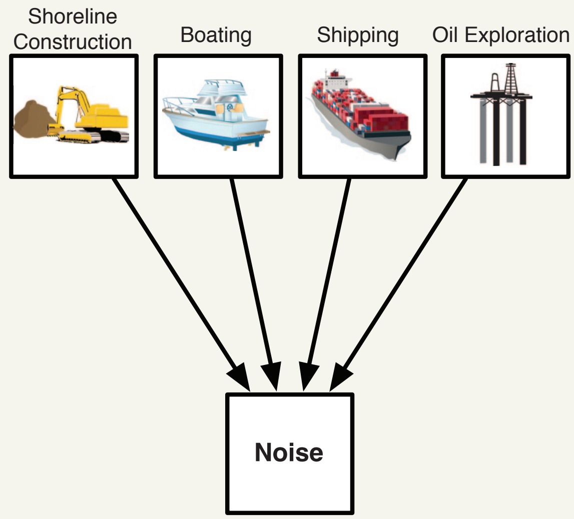


Figure 7: Multiple activities (such as shoreline construction, boating, shipping and oil exploration) can each produce a single stressor (noise) that accumulates in the marine environment, producing a much louder and more regular series of sounds (an example of the Multiple Activities pathway, Figure 5C).

Fisheries management has been traditionally focused on a single stressor, biomass removal, but the activity of fishing can also cause mortality or injury to bycatch species, habitat disturbance, sedimentation, chemical and noise pollution.

MULTIPLE ACTIVITIES PRODUCE MULTIPLE STRESSORS

Multiple activities can overlap in space and time to produce multiple stressors, and only by addressing the interactions between multiple activities and their stressors do we approach the complexity inherent in today's marine environment (Figure 3). Stressors can interact in complex ways; for example, increased ocean acidification due to climate change increases the vulnerability of marine organisms to underwater noise by amplifying sound from shipping or coastal construction (Hester et al., 2008).

Addressing this complexity is difficult and there are few studies that have attempted a full analysis. Even understanding what stressors are produced by human activities and have cumulative effects on marine systems is challenging. In a study by Knights et al. (2013) researchers describe many of these relationships (example of some in Figure 8), capturing a diverse suite of stressors from a wide variety of activities in order to describe their combined impact on ecological components. Experimental scientific research shows the complicated nature of capturing the impacts from even a small number of stressors (Crain et al., 2008; Darling & Cote, 2008; Thrush et al., 2008), emphasizing the daunting challenge of considering the full suite of stressors in cumulative effects assessments.

While there is little primary scientific research that directly incorporates the immense complexity that arises from multiple activities producing multiple stressors, modeling methods designed to address the overlap of multiple stressors can reveal the circumstances under which interactions are likely to occur (discussed further in section "Using models and tools to assess cumulative effects"). For example, spatially-explicit hot spot analyses highlight areas of higher human impact at regional (Ban & Alder, 2008; Ban et al., 2010; Coll et al., 2012; Maxwell et al., 2013) and global scales (Halpern et al., 2008)

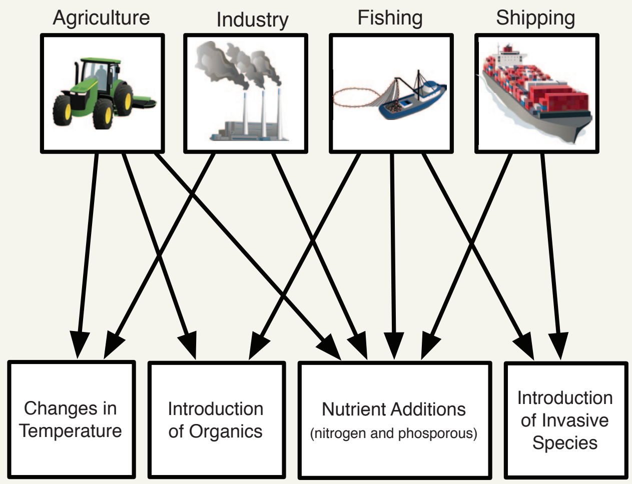


Figure 8: Multiple human activities produce multiple stressors. Stressors shown here are only a subset of those produced by each activity type and only a subset of those found in the original study. For example, agriculture results in changes to coastal water temperature and the introduction of organics and nutrients. Industrial activities change coastal water temperature and increase nutrient levels. Fishing can cause introduction of organics, nutrients and invasive species. Finally, shipping can add nutrients and introduce invasive species-point source toxic contaminants (an example of the Whole Ecosystem pathway, Figure 5D; Examples from Knights et al., 2013)

The intent of documenting and assessing activities that result in cumulative effects is to inform the legal and regulatory mechanisms governing how these activities and stressors are accounted for and managed. While understanding exposure to multiple stressors is necessary for cumulative effects assessment, it is also critical to understand the responses of ecological components of interest to human activities and their associated stressors. If these relationships are understood, managers can more meaningfully predict and evaluate the potential tradeoffs among management actions.

Human activities, such as shipping, can produce a diversity of stressors that impact marine ecosystems.

MULTIPLE STRESSORS IMPACT ECOLOGICAL SYSTEMS

Researchers and managers frequently approach the study of human activities on natural systems by examining ecological changes.

There is an abundance of research on the effect of single stressors on ecological components, including thermal stress, salinity, oxygen, contaminants and nutrient enrichment, among others. For example, low oxygen levels can reduce survival rates of benthic invertebrates in estuaries (Eby et al., 2005). As described above, cumulative effects occur when multiple stressors impact a single ecological component, but these components are part of a larger web of species, habitat and ecosystem interactions. Multiple stressors can affect various components of the ecosystem, which can ultimately lead to cumulative impacts on both a single ecological component of interest as well as on the greater ecosystem (Figure 9). For example, benthic invertebrate survival is reduced under low oxygen conditions. Consequently, fish that eat benthic invertebrates also have reduced growth rates due to reduced food availability, as well as direct exposure to low oxygen conditions (Eby et al., 2005).

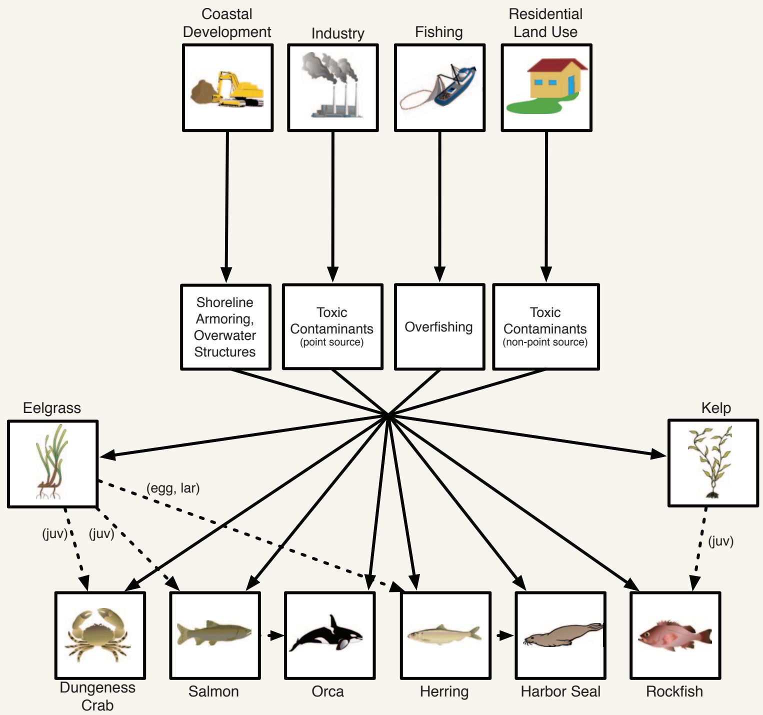


Figure 9: Multiple human activities produce multiple stressors, which can have multiple impacts to ecological components. In Puget Sound, four stressors (shoreline armoring and overwater structures, point source toxic contaminants, overfishing and non-point source toxic contaminants) directly impact ecological components (Dungeness crab, salmon, orca, herring, harbor seal and rockfish) (Samhouri and Levin (2012). Direct impacts from stressors (solid line) on kelp and eelgrass habitats also have indirect effects (dashed line) on juvenile (juv), egg, and larvae (lar) of species. Direct and indirect impacts to salmon and herring indirectly impact orca and harbor seals, respectively. Exposure to stressors and consequences to species vary. Although these stressors may impact all habitats and species, these interactions were visually simplified by streaming all impacts through the central node.

DENNIS HAMILTON 2009/ FLICKR

Multiple human activities converge at the Port of Seattle in Puget Sound, Washington.

Understanding the cumulative response of an ecosystem requires scientific knowledge of how single or multiple ecological components are affected by stressors, both singly and when combined. For example, in a study of Puget Sound, Samhouri & Levin (2012) illustrate how multiple activities can produce multiple stressors that can impact multiple ecological components (Figure 9). Impacts can occur both directly, such as the impacts of toxic contaminants on resident orcas, or indirectly, through the impacts of toxic contaminants, overfishing and shoreline armoring on salmon and eelgrass (juvenile salmon habitat), which may subsequently reduce food availability for resident orcas that eat salmon. The combined effect of toxic contaminants on orcas and reduced food availability are cumulative effects whose magnitude and interactions are difficult to predict (Schiedek et al., 2007).

RESPONSES OF ECOLOGICAL COMPONENTS TO STRESSORS

Cumulative stressors affect multiple scales of ecological components, from an individual organism to the entire ecosystem (Figure 10; Breitburg et al., 1999). At the finest scale, impacts are exerted on individual organisms (Individual) altering behaviour, morphology, and physiology or causing mortality. These impacts feed up into population level affects (Population), changing competition and connectivity of individuals within a single population. Population effects can change the way populations of multiple species of organisms interact (Community), by changing species diversity, functional groups, predator–prey dynamics and competition. Ultimately, changes to individual, population and community dynamics results in ecosystem level changes (Ecosystem) to productivity, nutrient cycling and even ecosystem state. Each ecological component level (Individual, Population, etc.) can have unique responses to stressors in the marine environment and are additionally affected by the biophysical conditions, both physical (e.g., soft sediment, pelagic ocean) and biogenic (e.g., seagrass, kelp), in which they reside (Figure 10).

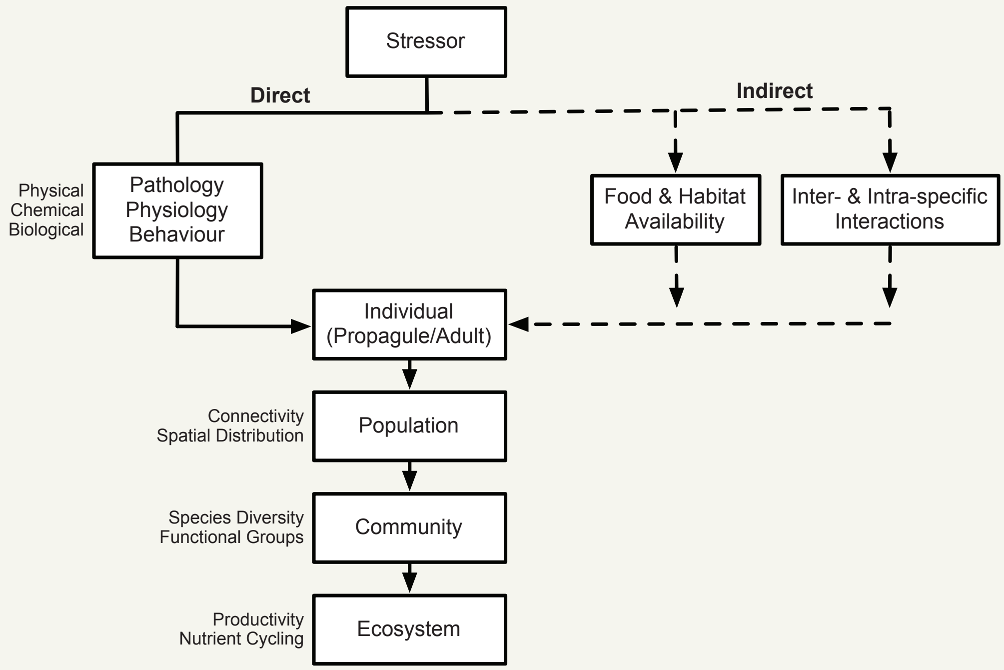


Figure 10: Potential responses of ecological components (individuals, population, community and ecosystem) to stressors produced by human activities and natural drivers. Abiotic and biotic stressors can have direct (solid arrow) and indirect (dashed arrows) effects on individual organisms throughout their life histories. The effects on individuals further affect population level interactions, community level interactions and ultimately result in changes at the ecosystem level. Adapted from Adams, 2005.

Context-dependent effects of multiple stressors

The effect of multiple stressors on an ecological component is highly dependent on the context in which interactions occur and may vary by place, time, and species (e.g., Menge & Sutherland, 1987; Menge et al., 2003; Shears et al., 2008). Stressors may also have greater negative effects on ecological components in impacted systems than in relatively unimpacted systems (Figure 11; Waldichuk, 1986).

Additionally, how an ecological component responds to stressors can change as interactions between species under different assemblages of species and/or stressors change. Whole ecosystems can shift to an alternate state that is composed of different species and species interactions when biophysical conditions are significantly altered in a system. The new ecosystem state may respond differently to stressors than the previous ecosystem state or may follow a different trajectory of recovery.

Direct effects

Stressors can directly affect individuals at different stages of their life cycle (eggs, larvae, juveniles, adults) as a result of stressors produced by human activities or natural drivers, such as long-term oceanographic events (e.g., El Niño-Southern Oscillation) or seasonal changes in temperature and weather patterns. These stressors can alter physical (e.g., upwelling, currents and water exchange) and chemical (e.g., contamination and nutrient levels) conditions that can result in direct biochemical, physiological, morphological, pathological, and behavioural effects (Figure 10) and lead to changes in general condition, reproductive fitness or survival of individuals.

Cumulative effects can occur when single or multiple stressors simultaneously affect these conditions within the same or different life stages of an individual. For example, sediment run-off from logging roads causes reduced survivorship of salmon eggs, while adults exposed to changing ocean temperature may have reduced body condition, fecundity or survival. Although these stressors do not affect the same life stage of salmon, the cumulative effects reduce overall salmon population size (Cederholm et al., 1980). Impacts can also occur via changes to physical processes, such as changes in upwelling patterns or entrainment, which may affect larval settlement and recruitment to adult populations. For example, outward migrating Chinook salmon populations suffer mortality from entrainment in successive dams along a river reach (Walters et al., 2012).

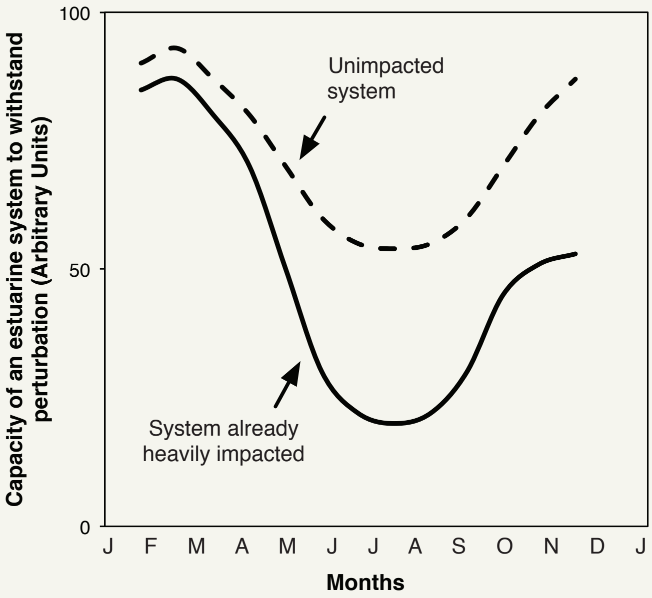


Figure 11: The capacity of an estuarine system to withstand perturbation, showing the expected difference between a system already heavily impacted and an unimpacted system. Adapted from Waldichuk, 1986.

Human stressors can also directly affect marine habitats. These environments include both physical habitats, such as sand and mud flats, rocky reefs, and shallow and open waters and biogenic habitats (species that create three dimensional structure that are utilized by other communities of species), such as eelgrass, kelp and mangroves (França et al., 2009). Physical habitats can be altered by impacts that change the shape and utility of these environments for the species that use them. For example, water diversions, forestry and urban development may reduce sand deposition to sand flats or affect sediment input to eelgrass beds (Kondolf, 1997; Thrush et al., 2004). Loss of eelgrass bed area or reduced density of mangroves can decrease the available habitat area important for survivorship of other species (Figure 10).

Indirect effects

Indirect effects on individual organisms occur through changes in food and habitat availability, and altered inter- and intra- specific species interactions, such as altered predator-prey dynamics and competition for resources (Figure 10). For example, the impact of sedimentation in estuaries from activities like dam construction and logging can directly impact eelgrass by reducing eelgrass area or biomass (Mills & Fonseca, 2003), which has indirect impacts on species using the eelgrass as habitat, reducing juvenile fish densities and community diversity (Baisre & Arboleya, 2006). Changes to the physical environment can similarly cause indirect cumulative effects to biogenic habitats or cause indirect effects to higher-level ecological components. Alternatively, indirect effects may occur through impacts on interacting species (e.g., increased abundance of predators or decreased abundance of prey species) (Figure 10). For example, changes in the productivity of herring population in the coastal or open ocean can further exacerbate adult condition of Pacific salmon (Marmorek et al., 2011).

Higher-level effects

Both direct and indirect changes to individuals and habitats can lead to higher-level effects that ultimately alter population dynamics, community structure and ecosystem function. Higher-level effects are sometimes referred to as “emergent impacts” because they result from impacts to individuals (Harley et al., 2006).

Populations

Impacts on populations are frequently measured by the change in demographic characteristics, such as abundance and biomass or changes in vital rates (e.g., birth rates or reproductive rates) that drive population growth rates (Grant et al., 2008). Individual mortality rate changes population abundance and smaller populations may have different growth rates than larger populations (Hutchings & Reynolds, 2004; Harley et al., 2006). Potential changes in mean age at reproduction, fecundity or the sex ratio of the population can be important population changes to measure and monitor, particularly as shown in fisheries impact studies (Munkittrick & Dixon, 1989; Gibbons & Munkittrick, 1994). Stressors like climate change and habitat destruction can also reduce or shift the range of a population.

Communities

Effects on individuals and populations can lead to higher-level impacts on communities, such as changes in species distributions, biodiversity, productivity and other community and ecosystem functions (Figure 10). Communities manifest changes under the influence of various stressors in numerous ways, including changes in relative abundance of species in the community composition and distribution of biomass across taxa, as well as species richness and evenness of community composition, number or types of functional groups present and trophic diversity (Grant et al., 1995; Hobday et al., 2007; Sandin et al., 2008). For example, historical extirpation of sea otters along California’s central coast led to increased survival and subsequent predation by crabs on key grazers, which led to increasing epiphytes on eelgrass. This, in combination with increasing nutrient pollution, had community-level impacts by reducing the biomass of eelgrass, ultimately reducing diversity of species within an eelgrass habitat in Elkhorn Slough (Hughes et al., 2013). Thus, stressors that impact species biomass or behaviour may alter interactions with other species, affecting interspecific competition and predator-prey dynamics (Silva-Santos et al., 2006; Eby et al., 2005).

Ecosystems

At the highest level, single and multiple stressors can also affect ecosystem structure and functional processes such as nutrient cycling, and primary production of organic and inorganic matter and its flow through the ecosystem which may lead to ecosystem shifts. For example, local extinction of sea otters in the northeast Pacific caused ecosystem shifts from kelp forests to sea urchin barrens (Estes et al., 2004; Estes et al., 2011) that had fundamentally different ecosystem functions and services, including primary production and total standing stock biomass of rocky reef food webs (Singh et al., 2013). Another example of an ecosystem shift occurred in the North Atlantic in the early 1990s. Despite a moratorium on fishing, Atlantic cod populations remain low because the indirect effects of human activities changed key interspecific interactions and the state of the ecosystem. When released from cod predation, sea urchin populations increased to such a high level that kelp forests disappeared in many places. This ecosystem change resulted in poor habitat for cod juveniles, slowing their recovery. Following the boom in green sea urchin, urchin fishing reduced urchin populations and crabs began to emerge as the dominant predator, decreasing urchin recruitment and changing ecosystem state once again (Steneck et al., 2004; Steneck et al., 2011). Cumulative effects at the ecosystem level are difficult to predict and can be very complicated to attribute to the human activities and stressors that caused them. Because of their indirect nature, higher-level effects are not commonly included in cumulative effects analyses.

Multiple stressors can interact in complex ways to change ecosystems and the services that depend on them. For example, urchin harvest increased off the coast of British Columbia when extirpation of sea otters shifted species- rich kelp forest ecosystems to one dominated by urchins.

MANAGING CUMULATIVE EFFECTS FROM MULTIPLE ACTIVITIES ON ECOLOGICAL COMPONENTS

Two venues for formal cumulative effects assessment that consider cumulative effects from multiple activities on multiple ecological components are environmental impact assessment (EIA) and ecosystem-based management.

CUMULATIVE EFFECTS IN IMPACT ASSESSMENT

Two types of cumulative effects or cumulative impacts assessments are highlighted in the environmental impact assessment literature (Duinker et al., 2013): project-based and regional or strategic-based. The most common form of cumulative effects assessment is a project-based assessment. These assessments are typically part of an EIA that is required for project approval. In the U.S., assessment of cumulative effects is required by the Council on Environmental Quality (CEQ) through regulations in the National Environmental Protection Act (NEPA) and in Canada under the Canadian Environmental Assessment Act (CEAA). Both require the project proponent to consider the effects of their project in combination with past, present and reasonably foreseeable future projects (CEQ, 1987; CEAA, 2012). Project-based assessments can minimize associated assessment and monitoring costs by matching the project assessment scale to the geographic footprint of the project. However, this type of cumulative effects assessment does not consider the cumulative effect of all activities on all ecological components (Whole Ecosystem pathway, Figure 5D, Figure 9). Instead cumulative effects tend to be considered in one of two ways: (1) multiple stressors from a single activity (Multiple Stressors pathway, 5B) or (2) single stressor from multiple activities (Multiple Activities pathway, Figure 5C). In some cases, a cumulative effects assessment will consider multiple stressors from multiple activities. However, this type of assessment tends to only include activities occurring within a single project or those considered to be within the scope of the project. For example, an assessment may consider activities associated with the construction, operation and decommissioning phases of a project but often do not consider similar activities that may occur simultaneously from other projects in the same area.

In contrast, regional assessments focus on a region or area of interest and assess cumulative effects from all projects in the area. These assessments are usually conducted as part of a programmatic environmental review for a larger area, but can also be part of a project-level approval that is applied at a broader spatial scale. A strategic assessment is another type of regional assessment that focuses on strategic decision-making to support sustainable development or planning (Harriman & Noble, 2008; Seitz et al., 2011). Even though current scientific consensus calls for regional or strategic cumulative effects assessment (Dube, 2003; Duinker & Greig, 2006; Therivel & Ross, 2007; IOPTF, 2010; Greig & Duinker, 2011; and others), regional assessments are not common. Canadian examples include a review of salmon aquaculture in British Columbia (BC EAO, 1997) and the Bay of Fundy tidal energy strategic environmental assessment (Phase 1: OEER Association 2008).

CUMULATIVE EFFECTS FOR ECOSYSTEM-BASED MANAGEMENT

Environmental management is increasingly focused on protecting ecosystems as a whole, rather than managing individual activities or addressing only one species or habitat at a time. One of the goals of ecosystem-based management (EBM) is to incorporate the cumulative effects of human activities on the whole ecosystem, encompassing all intrinsic ecological components. With increasing human pressure on the oceans, EBM has been championed as the future for marine management because it provides a holistic framework for managing multiple activities and preserving ecosystem health (McLeod & Leslie 2009). For example, the Great Barrier Reef Marine Park Authority planning process used an EBM framework to assess and manage all activities and ecological components associated with the Great Barrier Reef (McCook et al., 2010). Examples of marine EBM efforts in North America include the Puget Sound Partnership (Tallis et al., 2010), Elkhorn Slough National Estuarine Research Reserve (Tidal Wetland Project, 2013) and marine spatial planning efforts such as PNCIMA and Marine Planning Partnership (MaPP) in British Columbia (PNCIMA: J.G. Bones Consulting, 2009; Marine Planning Partnership: MaPP, 2014).

When determining how the cumulative effects of human activities affect entire marine ecosystems, managers and decision-makers must understand what stressors are created by human activities and how these stressors impact ecological components individually and in combination. If these relationships are understood, managers can assess the cumulative effects of proposed or potential changes in activities such as increasing fishing pressure or development proposals. Further, meaningfully incorporating cumulative effects analyses into management decisions can help predict how new development or human activities will combine with current activities to affect ecosystem structure, function and services. Understanding the relationships between activities and their impacts to the environment is necessary when analyzing tradeoffs. For example, the value of a project that provides infrastructure and revenue, such as the installation of a pier, should be compared to the loss of ecosystem services that would be produced if that pier was not built, such as erosion control and presence of nursery grounds for fisheries species (Rodriguez et al., 2006; Halpern et al., 2008).

CHALLENGES OF CUMULATIVE EFFECTS ASSESSMENTS

Despite scientific and management consensus on its importance, cumulative effects assessments remain limited in their effectiveness. There is a disconnect between how scientists conduct cumulative effects research and the information resource managers and environmental impact assessment practitioners need to make decisions. Scientists tend to focus cumulative effects research on understanding how ecological components respond to stressors. For example, scientists study the impact of sedimentation (stressor) on sponges (ecological component) or the impact of temperature change (stressor) on salmon life history stages (ecological component). This approach to research is often taken because connecting a stressor, such as sedimentation, to the activities that produce sediment can be extremely difficult (Mach et al., submitted). In contrast, managers are generally charged with regulating the impacts of human activities, relying on scientific data that connect stressors from each activity to the ecosystem.

Understanding the number of activities and the number of resulting stressors, the interactions between stressors and the effects on ecosystem structure and functioning across different contexts presents multiple challenges to scientists and managers alike. These are the underlying issues that make cumulative effects assessments and EBM challenging in practice (Leslie & McLeod, 2007). However, there are lessons from scientific research and theory that can be used to help understand the impact pathway (activity-stressor-impact), as well as tools that can help visualize and analyze complex cumulative effect scenarios. In this section we focus on four challenges to effective assessment and management of cumulative effects (Duinker & Greig, 2006; Ma et al., 2012): 1) incorporating uncertainty, 2) choosing the appropriate spatial scale, 3) selecting the appropriate temporal scale, and 4) defining significance.

Challenge: Incorporating uncertainty

Because our knowledge of the connections between human activities, stressors and ecological components is incomplete, uncertainty is an inherent component of any cumulative effects analysis. There is uncertainty in quantifying the amount of an individual stressor produced by an activity (e.g., how much sediment is resuspended during a dredging operation) and the extent to which that stressor impacts the ecosystem (e.g., how many species are affected by sediment resuspension). In addition, there is uncertainty in how single stressors interact with one another and how these interactions vary across space and time (Figure 12). For example, if the results of an experiment suggest that the combination of increased sediment and temperature has a synergistic negative effect on a specific coral species, these results may not be applicable to other coral species in a different part of the world because interactions between stressors are context dependent and relationships can be difficult to predict (Crain et al., 2008). Finally, there is uncertainty in how the ecological component is affected. This compounding uncertainty results in high uncertainty in the link between the original human activities and the resulting cumulative effect on an ecological component.

The inclusion of multiple activities and stressors in a cumulative effects analysis is more comprehensive but increases complexity and, by necessity, requires making assumptions and simplifying ecological relationships. Cumulative effects researchers have attempted to reduce uncertainty using highly controlled manipulative laboratory and field experiments, observational field studies, modeled studies, and retrospective analyses of impacts. There is a growing body of research on multiple stressors that experimentally test small numbers of

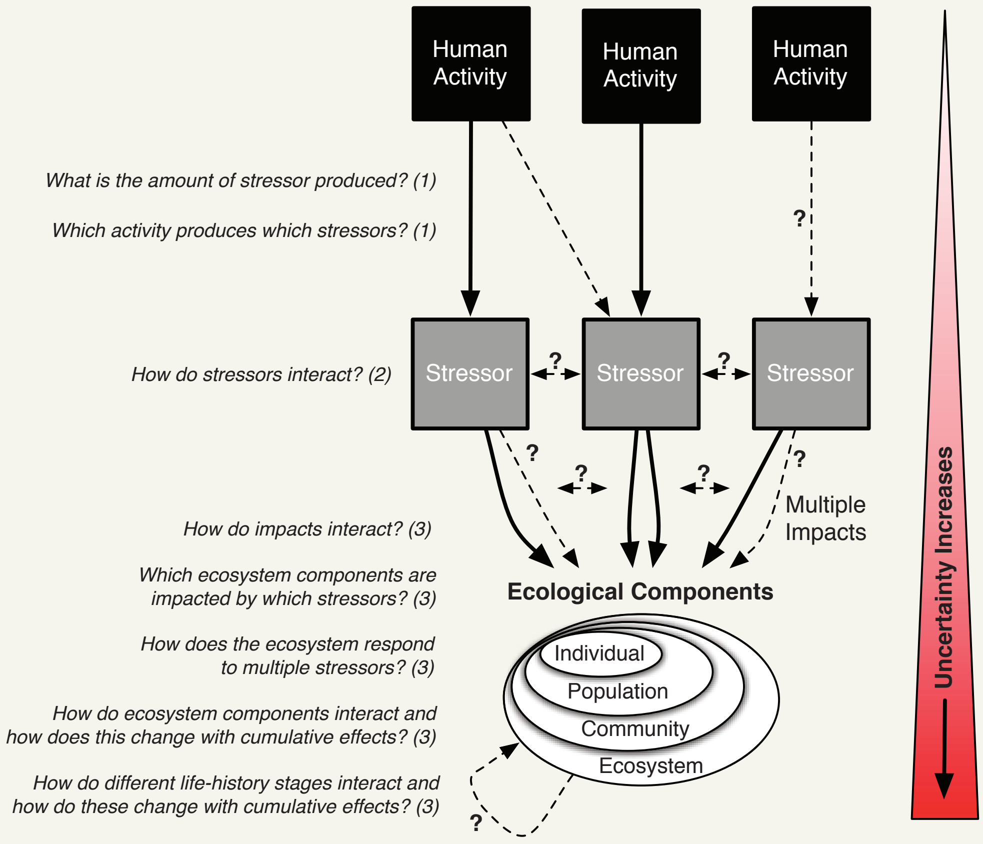


Figure 12: There is scientific uncertainty in (1) the activity producing stressors, (2) how stressors interact with one another, and (3) the impact of cumulative effects within and among ecological components All of which increase the level of uncertainty (red triangle).

Ecosystems are a complex mix of species and interactions among them and this complexity makes it difficult to understand and manage the impacts of multiple human activities.

stressors (2-5 stressors) in either laboratory or field settings (e.g., Martone & Wasson, 2008 (Box 1); reviewed in Crain et al., 2008) or use field observational studies that measure a small number of stressors to infer the impacts on ecological components (e.g., Sandin et al., 2008). Field studies include Before/After-Control/Impact (BACI) methods as well as reactive research and monitoring after major disturbances, such as oil spills or hurricanes (for a review of recent literature see Duinker et al., 2013). In some cases, meta-analyses are used to examine a body of primary research literature in order to draw generalizations about the impact of stressors or the interaction of stressors across study sites or time frames (e.g., Crain et al., 2008).

Modeled studies have been used to bridge the gap between laboratory and field research (Yang et al., 2010) and have been used to extrapolate results to other regions (Strimbu & Innes, 2011) or predict impacts into the future (Great Sand Hills Scientific Advisory Committee, 2007; Strimbu & Innes, 2011). However, the resulting models can be difficult to groundtruth and do not necessarily reduce the uncertainty around cumulative effects or management outcomes. Conceptual models can be developed from ecological theory that may give managers insight into how cumulative effects may manifest. For example, Martone and Wasson (2008) illustrated how theory from community ecology combined with invasion theory improved the power to predict invasions in salt marsh ecosystems (Box 1).

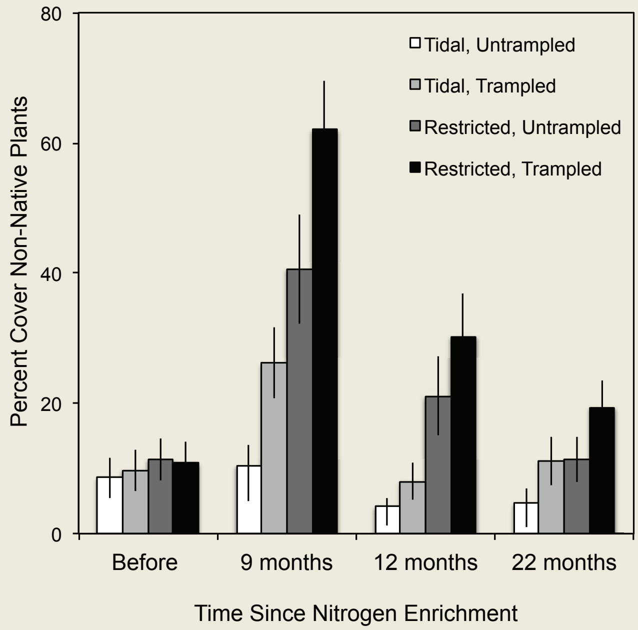
Uncertainty Recommendations:

- Conduct additional observations and experiments in field settings to identify cumulative effects of multiple disturbances and to distinguish between single and cumulative effects (Crain et al., 2008).
- Complete additional research using controlled laboratory experiments to explicitly test a small number of important stressors and their interactions. Lab experiments by definition are greatly simplified versions of natural systems and therefore may not always accurately predict real world events but knowledge of underlying mechanisms is crucially required.

Box 1:

Multiple disturbances to ecosystems can influence community structure by modifying resistance to and recovery from invasion by non-native species. Martone and Wasson (2008) examined the relative impact of perturbations that primarily change abiotic or biotic factors to promote invasion in coastal salt marsh plant communities. They used manipulative field experiments to test the hypotheses that nitrogen enrichment and human trampling facilitate invasion of upland weeds into salt marsh, and that the ability of salt marsh communities to resist and/or recover from invasion is modified by hydrological conditions. Synergistic interactions between human trampling and restricting tidal flow resulted in significantly higher cover of non-native upland plants in trampled areas at tidally restricted sites (Box 1 Figure), and recovery was slower at tidally restricted sites. Thus perturbations that reduce biotic resistance to invasion by removing competitive dominants interact with perturbations that alter abiotic conditions to promote invasion, leading to a greater-than-additive responses.

Box 1 Figure. Percent cover of invasive upland plants (mean +- standard error) in trampled and untrampled plots in tidally restricted and unrestricted marshes before and after trampling and nutrient enrichment ended. Modified from Martone & Wasson, 2008



- Execute further research on how multiple stressors interact to evaluate the relative impact of different stressors and the cumulative effects of their interactions, whether additive, synergistic, multiplicative, compensatory or antagonistic (Figure 4) so that management actions can be appropriately developed and prioritized. Because most research has been conducted on a single or small number of impacts and a single cosystem component, cumulative effects are frequently inferred by combining research on single impacts from multiple studies, and assuming that the impacts are additive. In addition, these additive models often assume community impacts are roughly equivalent to the sum of impacts on single species. However, interactive effects of stressors are common and can be difficult to predict, especially at the community level (Crain et al., 2008).
- Develop and refine methods that allow for the explicit incorporation of uncertainty into models and management decision-making frameworks (DFO, 2012; Samhouri & Levin, 2012; Clarke Murray et al., in revision).

Challenge: Choosing an appropriate spatial scale

Cumulative effects result from the accumulation of stressors—direct and indirect—that overlap and interact across multiple geographic scales (Therivel & Ross, 2007). Delineating the spatial extent of cumulative effects is commonly acknowledged as a challenge for cumulative effects assessments and the management of multiple activities (Dubé, 2003; Duinker & Greig, 2006). Current legal regimes require the effects of the proposed project and other relevant projects to be included in a cumulative effects assessment (Dubé, 2003). The most commonly used spatial scales for cumulative effects assessment include the footprint of a proposed project, the political unit (often a county, state or province) or a watershed in which a proposed project is located. In rare cases, assessments are done for an eco-region, an area containing distinct natural communities, and this spatial scale is often considered more useful for understanding cumulative effects (Ma et al., 2009).

The spatial scale of cumulative effects assessments is typically limited because the spatial extents of effects—particularly indirect effects—are not well documented. As a result, potentially important spatial effects from multiple stressor interactions are omitted because individual projects may contribute only a small amount of stress to the physical environment or specific ecological components in a limited area when compared to the interacting processes that occur among multiple stressors across multiple spatial scales (Spaling & Smit, 1993; Duinker & Greig, 2006). For example, the direct and indirect effects of proposed Project A may be limited to a single population. A nearby Project B, however, may have direct and indirect effects on the community of organisms, including the population affected by proposed Project A (Figure 2). If the spatial scale of the cumulative effects analysis is limited to the distribution range of a single population, the effects of the proposed project may not be considered significant. However, if the spatial scale of the analysis included the effects that are also occurring at the community-level, the additional cumulative effect from the proposed project could be significant.

Assessment and management of cumulative effects should be consistent with the spatial extent of the ecological components in question (e.g., how wide-ranging is the species?) and the human activities and their stressors (e.g., where does the activity occur and how widespread are the associated stressors?). In many cases, defining and choosing among the spatial scale of these parameters is difficult. The scale of analysis for affected ecological components, in particular, can be difficult to define because many marine species have complex life history cycles that include multiple habitats and geographic locations. For example, effects to Marbled Murrelet, a small seabird, can occur via stressors that affect their nesting habitat on land, while stressors that affect their primary prey (e.g., rockfish, sardines) occur in the ocean (Peery et al., 2004; Becker & Beissinger, 2006). The spatial scale of most cumulative effects assessments would not include both habitats essential to Marbled Murrelet populations, possibly resulting in unexpected significant cumulative effects to the population.

In addition, cumulative effects assessments of multiple activities and stressors often apply a single buffer or footprint to the main activity, which may not accurately represent the footprints of all the stressors produced by that activity (Ban & Alder, 2008; Halpern et al., 2008; Ban et al., 2010). For example, Ban and colleagues (2010) used only the dominant stressor from each activity to model the cumulative effects of multiple activities to coastal ecosystems in British Columbia.

The spatial scale of activities and their stressors can also be difficult to define. There are local (e.g., sewage outfall) and global (e.g., climate change) stressors to the environment, each of which can have impacts on ecological components at a local scale. An increasing body of literature includes climate change impacts in studies of multiple stressors (e.g., Ling et al., 2009). However, most agencies only have jurisdiction over managing or regulating local stressors, and global stressors are rarely included in cumulative effects assessments. The scale of an environmental assessment should include these overlapping global stressors as they may alter and interact with other more local impacts. National Environmental Policy

Act (the U.S. federal environmental review statute) guidance directs most federal agencies to consider and minimize the effect of climate change (Council on Environmental Quality, 2010). Canadian EIA guidelines, on the other hand, are less clear on the inclusion of climate change considerations in environmental assessment. Greenhouse gas emissions were addressed in previous practitioners' guides (CEAA, 2003), but they have not been updated to reflect changes in legislation (CEAA, 2012). In practice, recent EIAs do not explicitly include global stressors in their assessment of cumulative effects.

The spatial extent of cumulative effects assessments in practice is likely to be a tradeoff between the scales of the ecosystem and management. Multiple suggestions based on ecological theory have emerged from the scientific literature to better define the spatial scale of cumulative effects analyses. MacDonald (2000) suggests that resources of concern should be used to define the geographic boundaries for assessments. For example, if the resource of interest is a coastal wetland, the spatial scale of an assessment would differ from an assessment in which shorebirds were the resource of interest. This is similar to U.S. and Canadian federal cumulative effects assessment guidance that encourages agencies to define spatial scales according to the resource or system impacted by the project—for example, the relevant watershed, airshed or landscape, rather than the project area (CEQ, 1997; CEAA, 2012). Alternatively a multi-scale approach that identifies local impacts, broader interactions and regional effects in general may be more suitable (Therivel & Ross, 2007). Through an EBM lens, it may be more meaningful to delineate spatial extent based on the geographic extent of ecosystem-level processes (Ma et al., 2009).

Spatial Scale Recommendations:

- Assess and manage cumulative effects at multiple scales. Impacts occur on a much finer scale than management, but can scale up to higher-level impacts on populations, communities and ecosystems that function at different spatial scales. Management of these impacts should therefore span multiple spatial scales.
- Determine the spatial scale of a cumulative effects assessment based on the largest footprint of direct and indirect stressors and the geographic distribution of ecological components affected.
- Carefully assess cumulative effects when the scale of stressors is equal to or greater than the scale of an ecological component (e.g., population) because the stressor could potentially affect the entire ecological component and have much greater impacts.
- Additional research is needed to better understand the spatial scales of direct and indirect effects of human activities on ecological components. Most scientific studies tend to focus on how a specific stressor affects ecological components. However, managers are concerned with linking human activity to the impact on ecological components. A better understanding of the links between activities, stressors, and impacts can help to better define the appropriate spatial scale for cumulative effects analyses.

Challenge: Selecting the appropriate temporal scale

The ecosystem's current state is the result of past (e.g., a pulp mill that is no longer operational) and current activities and their associated stressors (e.g., runoff from deforestation). Ensuring that accumulating past, present and foreseeable future impacts are accounted for requires an appropriate temporal scale against which to compare ecosystem change. The effects from a proposed project are generally evaluated based on temporal scales defined by the construction or initial phase of a project and the operating lifetime of the project and any decommissioning, in combination with the effects of other nearby projects (CEAA, 2012; BC EAO, 2011). A second but related component of temporal scale is defining the baseline to which potential effects are compared. A baseline can be defined based on historical, present day or future conditions, all of which have implications for how the significance of effects is evaluated.

Historic activities

Stressors that persist in the environment are well documented for some single stressors, but are not easily incorporated into cumulative effects assessments. For example, ongoing research on persistent organic pollutants in the marine environment shows these compounds can remain over long time scales, occur at very high levels and accumulate in the food chain, affecting ecological components at multiple trophic levels (e.g., Jones and De Voogt, 1999). However, these types of historic activities are often not included in a cumulative effects analysis, but instead are included in the ecosystem baseline from which the significance of a project's impacts is assessed. For example, if a proposed project adds enough pollutants to result in a significant change to the baseline, the assessment must at least disclose and discuss those impacts, and in some cases avoid, minimize or mitigate those impacts (BC EAO, 2011).[1]

Incorporating historic activities as part of the baseline (in other words, ignoring past effects in current baseline) is likely to mask the ecological effects of additional stressors from proposed projects because, in many cases, the accumulation of historical effects has affected the system far greater than the incremental effects from an additional project (see Shifting baselines below). When historical activities are excluded from cumulative effects analyses, stressors from a proposed project may not result in a significant change to the baseline, eliminating the need to avoid, minimize or mitigate impacts (Figure 13).

Ongoing activities

Ongoing activities include projects that have been permitted and are in operation with continued ecosystem effects (e.g., nuclear power facility) or are being constructed at the of assessment. The frequency and impact of activities and stressors from ongoing activities can vary greatly over time. Expected effects from ongoing activities tend to be included in cumulative effects analyses—either within the current day baseline or as a source of cumulative effects. However, time lags between action and effect can result in cumulative effects going unnoticed until well after the stressor has altered the environment (Reid, 1998). In some cases change may be accumulating so slowly that it may not be observable for decades (Rogers & DeFee, 2005).

Unexpected impacts of ongoing activities are not captured well in current cumulative effects assessments. For instance, catastrophic oil spills and invasive species—which are high impact, low probability events—are rarely included in cumulative effects assessments because the chance they will occur is low, despite the fact that if they do occur the impact would be very high. These unexpected events are difficult to incorporate into current cumulative effects assessment practices because either the risk to the ecosystem would be overestimated because impacts would be large or underestimated because of the low probability of occurrence.

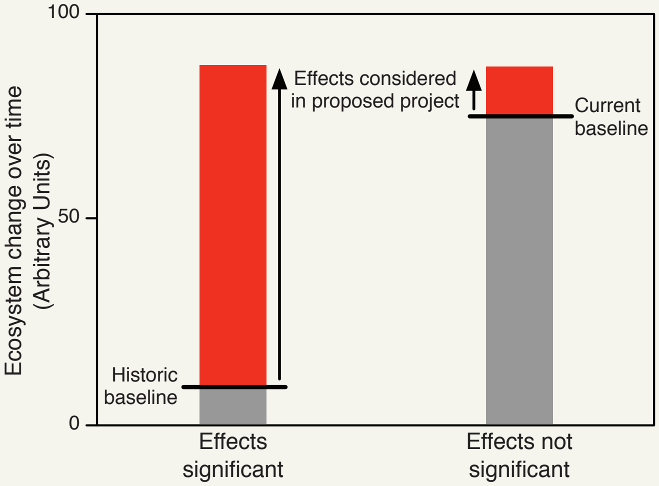


Figure 13. Incorporating historic activities into the current baseline changes how the significance of effects is evaluated. If a historic baseline is used (left) effects since that baseline are included and the proposed project is more likely to have significant effects; if a current baseline is used that incorporates historic activities (right), the effects of the proposed project would not likely be significant.

[1] California Code of Regulations, title 14, § 15021(a)(2) (West 2013).

PAVEL MACH 1979, PACIFIC SUN (SEATTLE), COLD BAY, AK

Commercial crabbing in the Bering Sea has continued for many generations. The impacts of this activity, and others, over time result in cumulative impacts to crab populations and other interacting species.

Proposed activities

Potential future impacts from proposed projects are also an essential element of cumulative effects assessment, including the consideration of predicted conditions and scenarios (Greig & Duinker, 2007; Therivel & Ross, 2007). Assessing future change in an ecosystem from proposed projects requires decision-makers to determine when a project, at some "level of certainty", should be considered a "foreseeable future project". When a project has reached a sufficient "level of certainty", the project must be incorporated into cumulative effects assessments and agencies involved in overlapping projects are required to coordinate assessments. Differences in when a project is defined as a foreseeable future project—and the added uncertainty in the likelihood of approval and implementation of projects (Duinker & Greig, 2006)—makes incorporating future impacts into cumulative effects assessments challenging. In addition, there is little guidance on how to incorporate expected future local and global environmental change.

Shifting Baselines

Ecological baselines in cumulative effects assessments are key ecological components and regional characteristics that can be: (1) monitored over space and time to assess change, (2) projected forward to predict future impacts/change, and (3) used as the baseline conditions against which other future projects can be compared (Harriman & Noble, 2008). Current regulations generally require the use of existing conditions as the legal standard against which human activities and new developments are compared to determine the significance of ecosystem effects (CEQ, 2010; CEAA, 2012)[2]. Setting the standard at current conditions for each new project leads to "shifting baselines", where change is measured against an already degraded system, rather than a comparison to a more pristine systems (Pauly, 1995). Continually shifting the baseline can make detecting anthropogenic impacts difficult because incremental effects are continually absorbed into the baseline.

To determine if an impact to an ecological component is significant, managers need to know if the change is within the normal range of environmental variation. This requires comparing the status and trends of an ecological component to a reference condition at a predefined time. For example, evaluating a project against a reference point from one year ago may produce a different result than comparing it to reference point from fifty years ago (Figure 13). Selecting a reference condition that serves as an appropriate baseline is difficult but necessary in order to: (1) assess the magnitude of change, (2) determine if the amount of change is significant, and (3) evaluate the effectiveness of mitigation and restoration efforts. Baselines can be used to establish the key assessment components and regional characteristics that can be monitored over space and time for assessing change and to predict future impacts and change. While it may be difficult to track historical change due to lack of scientific data, there are some sources of information, such as traditional and local ecological knowledge, that can contribute to our understanding of ecological trends on a longer timescale than most scientific studies (CEAA, 2013b). Most assessments assume past activities are part of current baseline, rather than contributing to cumulative change.

There are two types of baselines that are useful to consider: 1) stressor baselines, such as the level of a pollutant in a bay, and 2) baselines of ecological condition. While environmental impact assessments use present-day baselines, a more appropriate ecological baseline of comparison would be a time in the past when an ecological component was most abundant and/or less affected by human action (McCold & Saulsbury, 1996). Selecting a historical baseline for ecological components, however, is challenging for many reasons. Natural variation can make changes resulting from human activities difficult to identify or interpret (Boettinger & Hastings, 2013). Species abundance and community structure can fluctuate by season and across multi-year time scales, and productivity can vary in response to natural changes that alter temperature, precipitation or nutrient levels (e.g., El Niño or La Niña events). Regime shifts may have occurred such that historical baselines are not relevant to current ecological state. Finally, little information is available that quantitatively documents historic ecological conditions (but see McKechnie et al., 2014).

Temporal Scale Recommendations:

- Include ongoing and persistent historical effects in the cumulative effects assessment in order to fully account for cumulative effects.
- Establish a consistent definition of "foreseeable future projects" to reduce the ambiguity around which projects should be required in a cumulative effects analysis.
- Assess cumulative effects to ecological components against a historic baseline constructed from past ecological conditions, rather than using a current baseline.

Challenge: Determining significance

When the effects of a proposed project are being considered—along with the effects of past, present and reasonably foreseeable future projects—decisions rest on whether cumulative effects are considered "significant." While U.S. and California regulations provide guidance on determining significance under the law, agencies have broad discretion to implement their guidance. (Prahler et al., In press). For scientists, significance can either be determined using rigorous statistical analysis when the data are available or expert judgment when data are lacking. There are two metrics for evaluating significance—indicators and reference points—that standardize how significance of change is defined and determined.

Indicators

In addition to understanding how multiple human activities interact to impact marine ecosystems, marine and coastal managers need to determine the level of impact that is acceptable and does not pose a risk of serious, permanent environmental degradation. The physical and ecological components and processes that provide effective warning signals for changed conditions are commonly called indicators. Indicator species or processes ideally reflect the patterns that are occurring in the broader ecosystem, thus eliminating the need to measure every variable or species of interest in the ecosystem. Biological indicator organisms have frequently been used to evaluate water quality and pollutant levels and to monitor changes in species richness or abundance (Philips, 1977) or physical components in an ecosystem. Examples of indicators used in coastal and marine systems include bivalve density, eelgrass abundance, herbivorous fish abundance, nutrient concentration, mean trophic level of community, proportion of predatory fish in ecosystems and land-use change. Identifying appropriate indicators for ecosystem health and environmental change requires an understanding of how ecological components are connected and how changes manifest in species or habitats (Canter & Atkinson, 2011).

Selecting indicators that provide an accurate view of broader ecosystem structure and function, are easy to monitor and provide early warning for managers can be difficult (Vandermeulen, 1998; O'Boyle et al., 2005; Boettiger & Hastings, 2012). However, an increasing number of EBM regimes are developing suites of indicators to monitor ecosystem change (e.g., Puget Sound Partnership, Great Barrier Reef, Chesapeake Bay, IndiSeas). For example, the Puget Sound Partnership developed indicators to assist managers monitoring ecosystem health in Puget Sound, Washington (Orians et al., 2012). These indicators were co-developed by managers and scientists, creating a set of species and conditions that can be reliably monitored and represent key attributes identified as important to this region. In Canada, Fisheries & Oceans (DFO) is working to identify indicators at a regional and federal level (Irvine and Crawford, 2012; Nelson, 2013). On a more local scale, West Coast Aquatic Management Board researchers on Vancouver Island, British Columbia, are using expert surveys to identify marine indicators useful for a specific site (Okey & Loucks, 2011).

Academic research continues to test methods for identifying indicator species (Dufrêne & Legendre, 1997; Vandermeulen, 1998; Dean, 2008) and research projects like the Ocean Tipping Points Project are performing meta-analyses to identify indicator species and early warning indicators in intertidal, mudflat, coral reef and pelagic ecosystems (www.oceantippingpoints.org). Early warning indicators can alert managers to the risk of crossing ecosystem thresholds—where large, rapid and sometimes abrupt ecological changes occur in response to small shifts in human pressures or environmental conditions (Scheffer et al., 2009; Dakos et al., 2012; Scheffer et al., 2012). For example, increased spatial and temporal variance, and a phenomenon known as "critical slowing down" (Drake & Griffen, 2010; Dakos et al., 2012) in which the time it takes a system to recover from a disturbance increases, are thought to be robust early warning indicators of ecosystem shifts (Scheffer et al., 2009; Scheffer et al., 2012).

Reference points

Indicators of ecosystem health can be used to establish reference points for management. Ideally, a reference point is set for an indicator that alerts managers when a system is approaching a threshold or change point (e.g., high water column nutrient concentration). Understanding ecological thresholds can help managers of marine ecosystems predict how and which new activities are likely to alter ecosystem health and improve the regulation of future development and use of ocean resources. However, ecological thresholds and reference points are difficult to determine and assess because of ecosystem complexity and the presence of multiple drivers and stressors (Hughes et al., 2013). A reference point must also be set such that it provides enough warning to allow managers to address the activities and stressors that

Key species, such as predatory sea stars or kelp, can be used to monitor changes in the ecosystem. However there are few examples of established reference points that delineate an acceptable level of cumulative effects.

are causing changes in indicator values before the impact occurs. Balancing scientific certainty with sufficient time for an appropriate management response makes setting meaningful ecological reference points for indicators of ecosystem health difficult.

Reference points are commonly used in management, from fisheries (e.g., biomass and fishing mortality maximum sustainable yield; Caddy & Mahon, 1995) to water quality (e.g., *E. coli* concentration). Some reference points are set by legislation, such as water and air quality standards, but these usually relate to human health standards rather than ecosystem health. There are very few examples of established reference points that delineate an acceptable level of cumulative stressors or changes to ecological structure, composition or functions from those stressors (Ziemer, 1994; Kilgour et al., 2007). Acoustic noise is one of the few examples of reference points based on marine cumulative effects. The European Union's Marine Strategy Framework Directive (2008/56/EC) specifies that the annual average ambient noise level must not exceed 2012 baseline values (Erbe et al., 2012). Using reference points based on levels of socially acceptable or ecologically tolerable change may serve as placeholders until a better understanding of ecosystem thresholds can be developed.

Determining Significance Recommendations:

- Standardize how significance is determined during the cumulative effects analysis process using a preferential hierarchy (i.e., statistical, body of evidence, and expert knowledge).
- Develop ecological indicators that can be used to assess the significance of cumulative effects on ecological components.
- Once ecological indicators have been developed, set reference points for the indicators to assess when cumulative effects are having a significant negative effect on ecological components.

USING MODELS AND TOOLS TO ASSESS CUMULATIVE EFFECTS

Assessing cumulative effects requires detailed knowledge of how multiple activities produce multiple stressors, which combine to affect multiple ecological components. Estimating these effects is complex but can be greatly advanced by using models and tools.

Assessing cumulative effects at local or regional scales and over long temporal scales requires detailed knowledge of how multiple activities produce multiple stressors, which combine to affect multiple ecological components (e.g., Figure 9). Estimating these effects across larger regions and over longer time scales is complex but can be greatly advanced by using models and tools. Incorporating models and tools in cumulative effects analyses can help test assumptions, evaluate tradeoffs in management assessment and account for increasing uncertainty in estimating the cumulative effects of stressors on ecosystems. Models and tools aim to fill the gaps in primary research by addressing issues and complexity that are difficult to mimic or test in a laboratory or field setting.

Here we distinguish between *models*, which are science-focused and specialized, and *tools*, which are designed for more general users, can be management-focused and generalized. Both models and tools utilize known relationships between stressors and ecological components to estimate change to the ecosystem. Models are conceptual or empirical; probabilistic, deterministic or dynamic; specific to the system or interaction being tested; and are often created for certain ecological components in a specific place and time (see Table 1). This specificity can make models more accurate in depicting the system they were developed to represent, but may not be immediately applicable to other systems or ecological components. Tools are developed using scientific models as the backbone. Tools have models running in the background but often have a user interface that allows a broader range of people to use them. Therefore, the applicability and robustness of a tool depends on the underlying models used to build it. This dichotomy between models and tools is a simplification and it is important to note that models themselves can be directly used for management decisions.

Cumulative effects models and tools can be focused on: (1) visualization, (2) assessment and (3) management of cumulative effects (Table 1). Below we briefly review models and tools and their application in cumulative effects analyses. Additional information can be found in a paper by Duinker and colleagues (Table 4 in Duinker et al., 2013) where models for cumulative effects assessment are reviewed, and in the Decision Support Tool guide produced by the Center for Ocean Solutions that reviews tools and models used in marine spatial planning (Center for Ocean Solutions, 2011).

MODELS

At a basic level, models can be used to assess human activities and their stressors. Conceptual models, such as pathways-of-effects models, are one type of model used to assess cumulative effects. Pathways-of-effects models document how activities produce stressors and the pathway by which these stressors can impact ecological components (Grieg & Alexander, 2009; Knights et al., 2013). Other models addressing overlapping human activities and stressors have been reviewed previously (Dubé, 2003; Duinker et al.,

2013) and include spatial analysis (Ban & Alder, 2008; Halpern et al., 2008; Halpern et al., 2009; Selkoe et al., 2009), network analysis (Cocklin et al., 1992), biogeographic analysis (Johnston et al., 1990), development scenario modeling (Greig & Duinker, 2007) and ecological modeling (Spaling & Smit, 1993).

Models can also be used to assess how stressors affect ecological components, such as the impact of large oil spills (Irons et al., 2000; Peterson et al., 2003). Ecological models include habitat suitability models, population viability analysis, landscape modeling and strength of evidence, among others (Duinker et al., 2013). There are also a number of simulation models that are packaged in a way that facilitates their use as management tools. EcoPath, EcoSim and Atlantis are complex ecosystem simulation models that produce scenarios based on how ecological components (e.g., food web interactions) respond to differing amounts of human activity (e.g., fishing) or management actions (e.g., fisheries management plans). The scenarios can then be used in decision-making processes to determine what types and combinations of human activities produce desired ecosystem outcomes.

Statistical models, such as spatial analysis and multiple regression analyses, look for patterns in data to map or compare and explain the effects of multiple and past impacts (Halpern et al., 2008; Halpern et al., 2009; Ban et al., 2010; Coll et al., 2012). Retrospective (or "smoking gun") models can be used to inform efforts to mitigate future impacts, but are not meant for future predictions. In contrast, predictive models, such as those designed for marine spatial planning, evaluate the probability of events given a set of data (Stelzenmüller et al., 2010; Parravicini et al., 2012). Risk-based assessments can give estimates of risk under various management scenarios to support the development of marine management plans (Stelzenmüller et al., 2010).

TOOLS

Visualization tools can be useful for displaying overlapping human activities and potential cumulative effects. The Multipurpose Marine Cadastre (MMC), developed by Bureau of Ocean Energy Management and NOAA Coastal Services Center (www.marinecadastre.gov), is a regional-scale mapping tool that allows users to visualize potential marine uses and conflicts mainly associated with energy development and fishing. SeaSketch, a product of the Center for Marine Assessment and Planning at the University of Santa Barbara (UCSB), allows stakeholders to display ecological and socioeconomic data and compare alternative management plans for marine areas, such as habitats that might be protected, and gives feedback on metrics of success, such as social and economic costs and benefits that may be used to develop marine spatial plans. Marxan and Marxan with Zones, developed by the University of Queensland, were designed to explore the placement and arrangement of protected area networks that meet biodiversity targets (www.uq.edu.au/marxan). Marxan with Zones has also been used in combination with activity data, such as fishing and recreation, to design multiple-use reserve networks and evaluate the tradeoffs associated with different designs.

Tools for cumulative effects assessments have also been developed that aim to demonstrate how stressors accumulate in ecosystems, how risk to ecological components changes with increasing human activity, and where tradeoffs exist in managing cumulative effects. The Cumulative Impacts tool, developed by the National Center for Ecological Analysis and Synthesis (NCEAS), UCSB and Stanford University, is a spatial analysis tool that maps human activities and their ecological impacts (www.nceas.ucsb.edu/globalmarine). The Cumulative Impacts tool has mainly been used by the scientific community to understand broad-scale patterns in stressor interactions and ecosystem health.

TABLE 1

Examples of commonly used tools and models for visualization, assessment, and management of cumulative effects and their specific research and management goals.

TYPE	GOAL	MODELS & TOOLS
Visualization	To visualize the cumulative effects of human activities	Pathways of effects models (Grieg & Alexander, 2009)
	To identify areas of intense human use from multiple stressors and activities	Spatial analysis (Halpern et al., 2009; Ban et al., 2010; Maxwell et al., 2013); Multipurpose Marine Cadastre (Bureau of Ocean Energy Management and NOAA Coastal Services Center)
	To explain the cumulative effects of past activities	Strength of evidence tables (Clarke Murray et al., *in revision*), Multiple regression (Clarke Murray et al., *in press*)
	GOAL	**MODELS & TOOLS**
Assessment	To estimate cumulative effects on a region from multiple human activities	Statistical models, e.g., Linear and non-linear regression, (Dauer et al., 2000); Risk assessment (Hobday et al., 2011; DFO, 2012; Clarke Murray et al., *in revision*); Redundancy analysis (Perry & Masson, 2013)
	To assess cumulative effects from multiple stressors and activities on a single species or population of concern	Simulation models; Population models (Poot et al., 2011); Ecological models (Spaling & Smit, 1993)
	To assess the impact of a specific event (e.g. oil spill, hurricane) on the ecosystem	Regression (Irons et al., 2000; Peterson et al., 2003)
	GOAL	**MODELS & TOOLS**
Management	To estimate the cumulative effects from a single proposed project with consideration of other nearby projects	Environmental Impact Assessment (CEAA, 2012)
	To assess the trade-offs among ecological and socio-economic components from global change or management scenarios	Ecosystem models (Atlantis; EcoPath with Ecosim); Development scenario models (Greig & Duinker, 2007); Multi-scale Integrated Models of Ecosystem Services (MIMES); Assessment and Research Infrastructure for Ecosystem Services (ARIES); Integrated Valuation of Environmental Services and Tradeoffs (InVEST); Ocean Health Index
	To plan activities for a region of interest that allows sustainable development	InVEST; Spatial analysis (Halpern et al., 2009); MARXAN; Atlantis

Risk assessment frameworks are assessment tools that integrate multiple activities and/or multiple ecological components. Risk assessments evaluate the exposure of an ecological component to a stressor (i.e., does the species range overlap with the stressor?) and the consequence of exposure to the ecological component (i.e., how would the species be affected by the stressor?) based on qualitative and/or quantitative data. Some risk assessment frameworks have been modified for application to specific ecological components, such as seagrass or marine mammals (Grech et al., 2008; Lawson & Lesage, 2013) or activities and stressors (DFO, 2012a), while others are generalized to include multiple ecological components (Suter, 1999; Hayes & Landis, 2004; Hobday et al., 2011; O et al., 2013).

Tools are available that can used to evaluate proposed activities, various scenarios or management actions. EIA, although not traditionally thought of as a tool, is the most commonly used assessment tool by government and project proponents to evaluate the cumulative effect of human activities on the environment (CEQ, 1997; CEAA, 2012). Practitioners use EIA to evaluate the potential environmental impacts of a proposed project or development, considering both beneficial and adverse interrelated effects on economy, culture and human-health.

A number of tools are designed to evaluate tradeoffs associated with management scenarios, predict cumulative effects to the ecological system and estimate the potential change in human benefits supplied by the ecosystem (i.e., ecosystem services). The Multi-scale Integrated Models of Ecosystem Services tool (MIMES), developed by AFORDable Futures combines a suite of models to evaluate how land and sea-use changes affect ecosystem services from global to local scales. MIMES uses GIS and time-series data to simulate ecological components under various management scenarios. MIMES maps the location of ecosystem service provisioning and the flow of services to communities who benefit. The tool can then be used to value ecosystem services and evaluate the tradeoffs to ecosystem services under different management scenarios (www.uvm.edu/giee/mimes). The InVEST tool, developed by the Natural Capital Project, maps the location and production of ecosystem service provisioning and evaluates tradeoffs in development scenarios for changes to ecosystem services of interest (www.naturalcapitalproject.org/InVEST). Artificial Intelligence for Ecosystem Services (ARIES) also evaluates the impact of policy and human use scenarios on the provision of ecosystem services.

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There is an increasing body of knowledge about the impacts of single human activities, such as finfish aquaculture. However, it can be difficult to predict the impacts from multiple overlapping activities, such as dredging, fishing, boat use and finfish aquaculture, on these coastal habitats.

HOW DO WE PROCEED?

Given that science will never have all the answers we must move toward adaptive management that explicitly uses the scientific method within management to provide scientific answers and improve management practices.

OVERCOMING SCIENTIFIC CHALLENGES

Although the scientific community has yet to achieve a solid understanding of the way in which cumulative effects alter ecological components and overall ecosystem functioning, approaches exist to overcome the associated challenges. While there is an abundance of evidence for the effect of single stressors on single species, far less is known about the cumulative effect of multiple stressors from multiple activities on ecosystems and the concomitant provisioning of ecosystem services. In order to move beyond the challenges inherent in cumulative effects research and management, it is necessary to focus on key research needs and questions. The larger goal of cumulative effects research is to understand each link in the activity-stressor-impact pathway and how they accumulate and interact to produce cumulative effects. To achieve this, research must address (1) the connections between human activities and their stressors, (2) interactions between stressors that have cumulative effects on ecological components, (3) interactions between ecological components, and (4) the ecosystem response to multiple stressors. Research contributing to this body of knowledge will improve our understanding of cumulative effects resulting from human activities, and how human activities alter ecological components. In particular, an increased understanding of when and where different threats and sets of threats have significant impacts on ecosystem functioning is crucially needed.

Ultimately, systematic analyses at multiple scales that examine how multiple threats act jointly to alter the functioning of marine ecosystems could begin to address the research gaps noted above. These analyses must identify the suite of activities and stressors that occur from a single project, the potential impacts on ecological components and the overlap and interactions of a single projects' outputs with other local and regional activities. These analyses would be useful for providing guidance on what issues need further research, as well as priorities and tradeoffs between different activities in specific locations and strategies for action.

OVERCOMING MANAGEMENT CHALLENGES

The challenge for ecosystem management is improving integration of science into management practice and advancing our management of cumulative effects. When scientists examine cumulative effects, they often focus on how ecological components respond to stressors—the effects of sedimentation on sponges or the effects of temperature change on salmon life history stages. Connecting an observed change in an ecosystem component resulting from multiple stressors, such as an increase in nutrients and contaminants, to the original activities that produced them can be extremely difficult. Managers can only regulate human activities, not ecological components, and therefore must approach the challenge from the opposite end of the spectrum as scientists, considering how a given activity produces stressors that may affect ecological components. Managers rely on scientific guidance to connect human activity to the ecosystem impact. However, managers struggle to translate scientific research that addresses questions such as, “What is the effect of noise on whales?” to management questions like, “What potential impacts will occur with an increase in shipping?” Better alignment between scientific research questions and management needs could be achieved by incorporating science directly into the management process using adaptive management (see next section). By combining adaptive management with the precautionary approach (detailed below), management can proceed in the face of scientific uncertainty within the impact pathways.

Move to Adaptive Management

In order to better connect science and management we need advances in the science of cumulative effects to occur outside the management framework as well as relevant science explicitly incorporated inside the management process (Figure 14; Greig & Duinker, 2011). Science inside the management process is needed to make specific cumulative effects predictions that inform decision-makers of the potential ecological consequences of human activities (e.g., proposed developments), as well as to measure environmental responses to cumulative effects (e.g., following development start-up) for the purpose of model evaluation and refinement (Greig & Duinker, 2011).

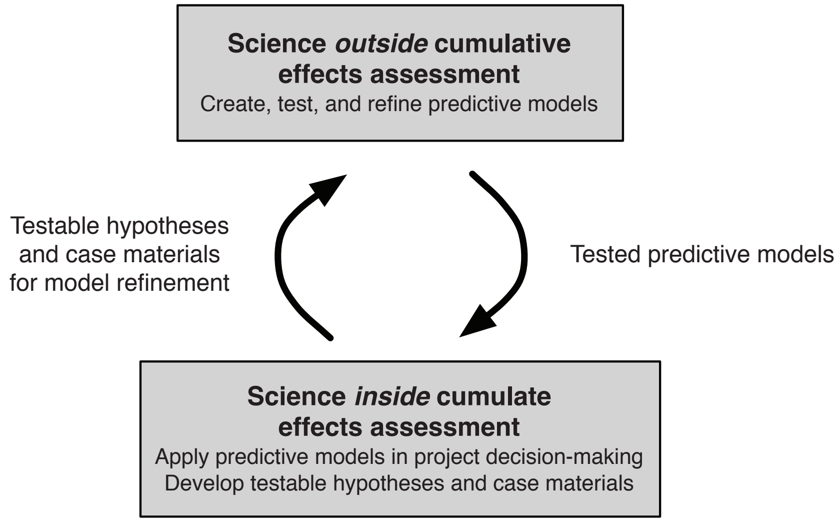


Figure 14. Relationships between science and cumulative effects assessment, with recognition of appropriate forms of scholarship from Boyer (1990). Modified from Greig and Duinker (2011).

Given that science will never have all the answers we must move toward adaptive management that explicitly uses the scientific method within management to provide scientific answers and improve management practices (see Box 2). Management that occurs in a systematic, rigorous framework designed to deliberately learn from management actions with the intent to improve subsequent management policy or practice is Adaptive Management (Duinker & Trevisan, 2003). This type of management explicitly incorporates scientific method so that management itself can be evaluated for its effectiveness and changed as needed (Figure 15). Assessment of the system is followed by the design of a management plan, implementation of the plan, monitoring of appropriate indicators of system response, evaluation of the plan's outcomes, and adjustment of the plan based on the evaluation. The loop is used in order to continually improve understanding of how the system works and how it responds to management actions. Current EIA standards call for adaptive management but in practice there is little or no feedback of post-construction monitoring. As part of adaptive management, it can be useful to prevent additional impacts in areas where impacts are already considered high and preserve some low impact areas (e.g., no-take marine protected areas) in order to monitor and understand changes and differences through time.

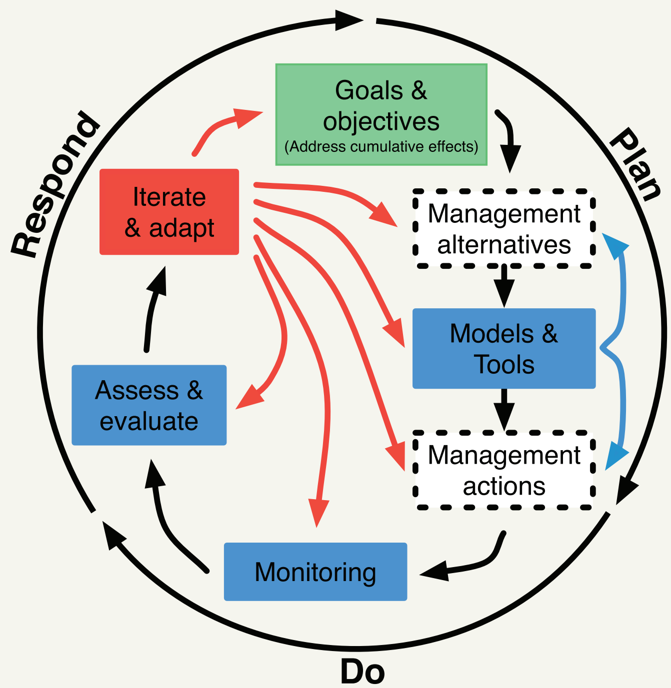


Figure 15. Adaptive management initiates a "planning" step using goals and objectives that address cumulative effects to set up management alternatives, but integrates models and tools in redefining management alternatives and deciding on management actions. In the "doing" phase, management actions are monitored and outcomes assessed and evaluated. Based on those changes the "responding" phase takes the evaluations and informs all other stages such that goals are reassessed, and so on. Stages that can directly apply scientific methods are in blue.

Box 2: It can be done! Successful adaptive management

The leading example of the six phases of adaptive management (Figure 15) in practice is The Great Barrier Reef Marine Park Authority (GBRMPA), which uses marine spatial planning to zone activities (Plan) in combination with scientific research and monitoring (Do) to provide information and analyze ongoing impacts (Assess & evaluate) and feed the information back into the planning processes (Great Barrier Reef Marine Park Authority, 1994; McCook et al., 2010). In this way, marine spatial plans can be used as the start for what are in essence, large-scale experiments.

The GBRMPA marine spatial zoning plan was recently updated (Iterate & adapt) based on the results of research assessing the effect of the management zones on the ecosystem (Day, 2002; McCook et al., 2010). Some areas that were previously designated as no-take reserves were opened to fishing to study the effects of fishing on populations while other areas previously open were closed in order to examine the recovery of these areas from fishing pressure (McCook et al., 2010).

Address uncertainty and use caution

As we have discussed previously, uncertainty occurs at each link between activity and impact and in the interactions between its components. Scientific methods are emerging that allow managers to explicitly account for uncertainty in predictions of impact and estimates of change, and therefore their significance (Samhouri & Levin, 2012; Clarke Murray et al., *in revision*). Moving beyond empirical uncertainty, many advocate the use of the precautionary principle in management. The precautionary principle first appeared in the Rio Declaration of the Earth Summit (1992) and states that “where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation”. The application of the precautionary principle to management action is called the precautionary approach. Since the Rio Declaration, the precautionary approach has been incorporated in fisheries, pollution, resource development, and many other management fields with varying degrees of success (Raffensperger & Tickner, 1999; Gonzalez-Laxe, 2005). For example, the precautionary approach is used in fisheries management in order to set reference points for fisheries management (Gabriel & Mace, 1999; DFO, 2013b). The precautionary approach suggests four central tenets that can be applied to the management of cumulative effects: (1) take preventative action in the face of uncertainty, (2) shift the burden of proof to the proponents of proposed development, (3) explore a wide range of alternatives to harmful actions, and (4) increase public participation in decision-making (Kriebel et al., 2001).

Shift to regional cumulative effects assessment

Cumulative effects assessment is increasingly required as part of EIAs around the world. However, in order to achieve sustainable development we need to move away from project-based impact assessments to regional, comprehensive cumulative effects assessments. Ideally, comprehensive cumulative effects assessments should examine the impact of *all* human activities on all ecological components. Human activities must include all *current* marine activities and all *foreseeable future* projects with the potential for ecological impacts, within the context of historical pressures and global changes such as climate change stressors. Ecological components should include all the ecologically important components of populations, communities, ecosystems and habitats or at least indicators of these critical functions. This is a daunting assignment but crucial when attempting to manage human activities within complex ecosystems.

There is widespread support among scientists, and even some managers and practitioners, for a shift to a management process where individual project EIAs feed into a regional or strategic cumulative effects assessment overseen by government regulatory agencies (Dubé, 2003; Duinker & Greig, 2006; Greig & Duinker, 2007; Duinker et al., 2013). Two of the major barriers to regional cumulative effects assessment are data requirements and cost. A regionally centralized cumulative effects assessment system and governing agency could help to solve both of these issues.

Cumulative effects assessment is data hungry; requiring advanced scientific information about activities, stressors and ecological components. In the current management regime each project proponent completes a cumulative effects assessment and data sharing is limited between neighboring (and sometimes competing) project proponents, rendering the results of the individual assessments incomplete. As an alternative, data collected by proponents as part of their initial baseline studies and monitoring efforts could become part of an independent cumulative effects central database. This central database then becomes the source and archive for cumulative effects assessments. The cost of the regional cumulative effects assessment could be borne by the proponents, which may be feasible and cost effective to implement as project proponents already pay fees to government agencies as part of their environmental assessment process and additionally pay consultants to conduct their individual cumulative effects assessment. The cost of a central data management and analysis system may be less expensive to the individual proponents than current methods, and could facilitate data sharing and regional-level analysis.

Scientists agree that cumulative environmental impacts would be better addressed by regional cumulative effects assessments. In addition, this advancement may promote greater transparency in environmental tradeoffs and decision-making, allowing economic progress without the added cost of unexpected environmental degradation.

Follow the cumulative effects pathways

Overall, the concept of cumulative effects remains poorly understood. Here we presented a theoretical framework of cumulative effects, identifying three pathways that result in cumulative effects to ecological components. The Multiple Stressors pathway is commonly used by project-based environmental assessments and leaves out impacts from other co-occurring projects or activities. The Multiple Activities pathway is emerging as a pathway of interest for environmental impact assessment, but is often limited in spatial and temporal scale. Finally, the Whole Ecosystem pathway is rarely addressed in North American environmental impact assessment, but is essential to capture the complexity of cumulative effects and predict and prevent large-scale ecosystem impacts. The theoretical pathways framework in this report can be used to systematically address each pathway for cumulative effects in order to ensure that impacts are fully assessed. The pathways could be used in environmental impact assessment to identify the scope of the cumulative effects assessment for proposed projects. It could also prove useful in managing for species or ecological components of interest, in recovery plans for species at risk and in EBM. Emerging operational frameworks, such as that developed by Great Barrier Reef Marine Park Authority and Australian Department of the Environment (Anthony et al., 2013), could be used as a standard in cumulative effects assessment going forward.

Management recommendations

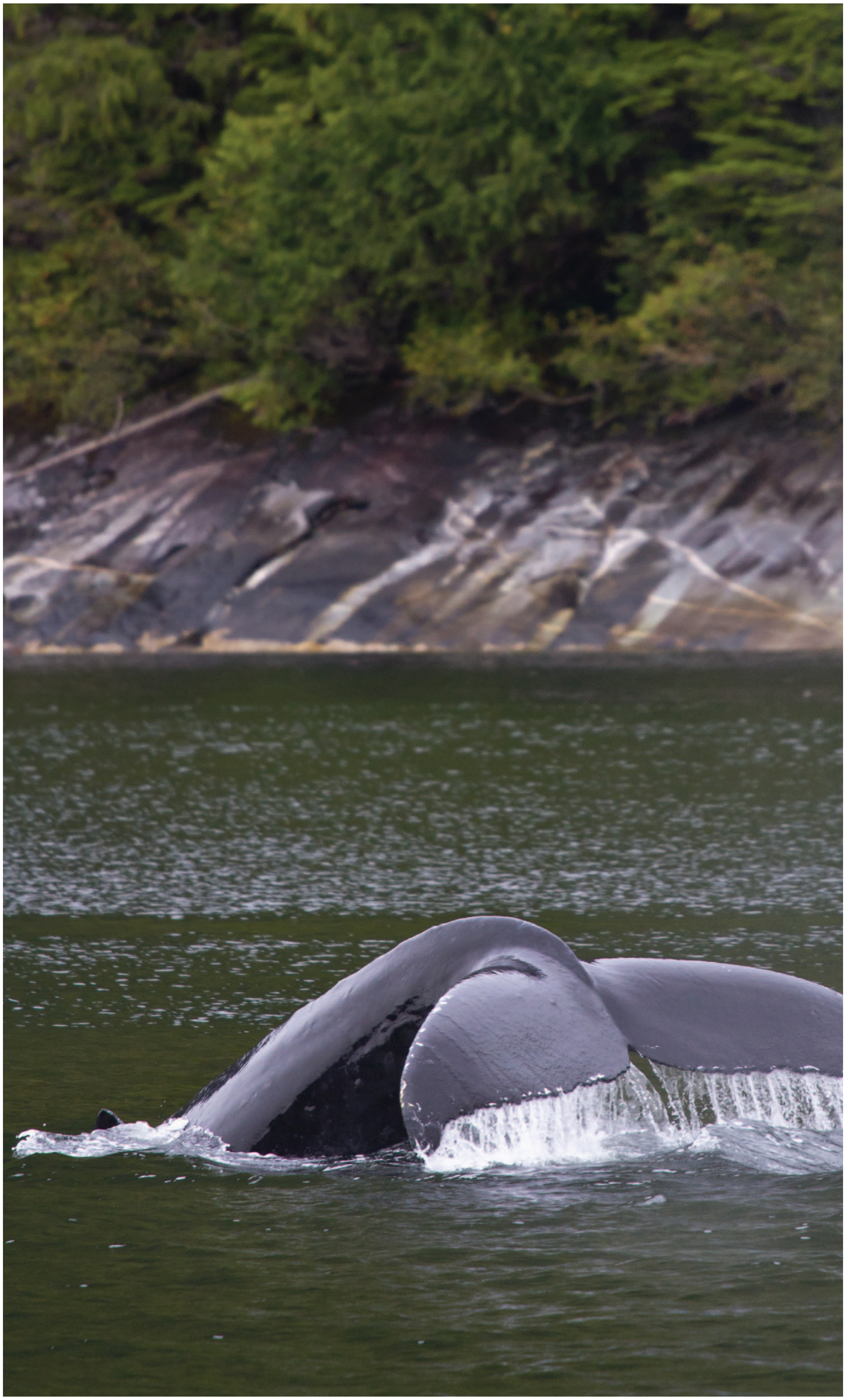
- We recommend moving toward adaptive management to directly include science in the management of cumulative effects.
- We recommend the four tenets of the precautionary approach be applied when managing cumulative effects.
- We recommend a shift to a regionally centralized cumulative effects assessment with central data management.
- We recommend a common and shared framework for cumulative effects assessment that will enable all three cumulative effects pathways be used to achieve uniform and consistent management.

The geoduck (*Panopea abrupta*) is a highly prized mollusc species native to the Pacific Coast of the U.S. and Canada. Farming this species involves seeding geoduck in PVC predator exclusion tubes and later liquefying the sediment to extract the clams. Disturbing the sediments to this degree affects other species that would normally live in these habitats as well as the rest of the ecosystem that would normally feed or grow on these beaches.

CONCLUSIONS

Marine ecosystems are subject to diverse and intensifying human activities making cumulative effects critically important to understand.

In order to protect our environmental resources and the services they provide we need to move away from a single-minded management focus (single-species fisheries management, project-based impact assessment) and towards EBM that includes consideration of cumulative effects. A comprehensive understanding of cumulative effects requires integrated research and management. Scientific research that matches management questions will facilitate great strides in this area. Both science and management should examine all pathways of cumulative effects—accumulating activities, stressors and the impacts on the entire ecosystem. Additional research is urgently needed on the responses of ecological components, processes and functions to cumulative stressors both independent of management and within the management process itself as part of adaptive management. Cumulative effects assessments are increasingly included in environmental assessment, but there is a need to assess at larger spatial scales, moving to regional assessments conducted by a regionally centralized body with shared scientific databases. While science cannot perfectly predict cumulative effects, explicitly addressing uncertainty and applying the precautionary approach can support decisions-making actions aimed at maintaining the natural goods and services relied on by humans. Sound cumulative effects management based on the best available science will allow sustainable development that protects natural resources now and into the future.



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Additional research is urgently needed on the response of ecological components, such as marine mammals, to cumulative effects, both independent of management and within an adaptive management process.

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