

An ecosystem-based approach to marine risk assessment

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Abstract. Risk assessments quantify the probability of undesirable events along with their consequences. They are used to prioritize management interventions and assess tradeoffs, serving as an essential component of ecosystem-based management (EBM). A central objective of most risk assessments for conservation and management is to characterize uncertainty and impacts associated with one or more pressures of interest. Risk assessments have been used in marine resource management to help evaluate the risk of environmental, ecological, and anthropogenic pressures on species or habitats including for data-poor fisheries management (e.g., toxicity, probability of extinction, habitat alteration impacts). Traditionally, marine risk assessments focused on singular pressure-response relationships, but recent advancements have included use of risk assessments in an EBM context, providing a method for evaluating the cumulative impacts of multiple pressures on multiple ecosystem components. Here, we describe a conceptual framework for ecosystem risk assessment (ERA), highlighting its role in operationalizing EBM, with specific attention to ocean management considerations. This framework builds on the ecotoxicological and conservation literature on risk assessment and includes recent advances that focus on risks posed by fishing to marine ecosystems. We review how examples of ERAs from the United States fit into this framework, explore the variety of analytical approaches that have been used to conduct ERAs, and assess the challenges and data gaps that remain. This review discusses future prospects for ERAs as EBM decision-support tools, their expanded role in integrated ecosystem assessments, and the development of next-generation risk assessments for coupled natural–human systems.

Key words: *coupled natural–human systems; ecosystem risk assessment; ecosystem-based management; risk assessment; socio-ecological system.*

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Introduction

Management of marine ecosystems is complex, especially in the face of growing resource extraction, expanding human coastal populations, and a variable and changing climate. Ecosystem-based management (EBM) has been described as a place-based management approach that has the potential to address cumulative impacts and balance multiple, often conflicting, objectives across ocean management sectors (Dolan et al. 2016, Fogarty 2014, Link and Browman 2014). Given the

multitude of interactions within coupled natural–human (CNH) systems, one of the primary challenges under an EBM paradigm is characterizing impacts and the associated risks of these impacts to key components of both biological and human communities, an essential step toward operationalizing EBM. In the United States, federal marine resource managers tasked with implementing EBM within complex marine ecosystems have adopted the integrated ecosystem assessment (IEA) framework to disentangle pressures from natural variability (including ecological compensatory and feedback dynamics), quantify management tradeoffs, and understand the diverse causes and potential consequences of risk (Levin et al. 2009, 2014, Link 2010). While there are several stages of the IEA cycle, ecosystem risk

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assessments (ERA) are a critical link between identifying indicators, quantifying reference levels, and evaluating potential management strategies (Levin et al. 2014).

Risk assessments generally quantify the probability of undesirable events, along with the consequences of those events should they occur (Harwood 2000, Burgman 2005). They have wide application across various fields (ISO 2009a, b, c) and have been used in marine resource management to help evaluate chemical toxicity for individual species (US EPA 1998), the probability of extinction for species of concern (e.g., Mace and Lande 1991, Musick 1999), the risk associated with climate change (e.g., Hare et al. 2016), and the management of data-poor fisheries (e.g., Patrick et al. 2010). The concept of environmental risk has continued to evolve from its early applications for understanding how individual carcinogens affect human health (NRC 1983) to more recent efforts to understand the impact of multiple pressures at regional to global scales (Landis 2005, Adger 2006, Landis and Wiegers 2007, Hobday et al. 2011, Halpern et al. 2012, Maxwell et al. 2013, Cinner et al. 2016).

Divergent interpretations of risk have historically inhibited merging distinct realms of knowledge under a single cohesive analytical framework (Janssen et al. 2006, Carpenter and Brock 2008, De Lange et al. 2010, Benson and Craig 2014, Gao et al. 2014, Bennett et al. 2015, Gibbs and Brownman 2015). Yet, while historical environmental risk assessments often focused on singular pressure effects on species or habitats, recent applications have included risk assessment in an EBM context, providing a framework to unify different conceptualizations of risk through evaluating the compound impact of a pressure—or multiple interacting pressures—on multiple components of ecological and social systems (e.g., individual species, habitats, food webs, human communities, and structuring processes). Examples of ecosystem risk assessments include the potential impact of human or natural perturbations on coastal habitats and communities (Halpern et al. 2008, Samhouri and Levin 2012, Cook et al. 2014) and the vulnerability of human communities to climate change (Cinner et al. 2012, 2016, Morzaria-Luna et al. 2014, Himes-Cornell and Kasperski 2015, McClanahan et al. 2015). Here, we adopt the approach of ecosystem risk assessment from Levin et al. (2014) in the context of integrated ecosystem assessments (IEAs), whereby risk assessments “qualitatively or quantitatively” determine the risk to a focal ecosystem component given a management action and/or change in ecosystem pressure. Additionally, “because the cumulative effect of multiple stressors may not simply equal the sum of the individual stressors’ effects, risk analysis should consider cumulative impacts” (Levin et al. 2014).

In this paper, we describe a conceptual framework for ERAs, with specific attention to ocean management considerations and approaches being used within the U.S. marine resource management community. This framework builds on the ecotoxicological and conservation

literatures on risk assessment (Burgman 2005, Suter 2007), but focuses on more recent advances that assess risks posed by fishing to marine ecosystems (Hobday et al. 2011). We review how selected examples of ERAs from the United States (and abroad) fit into this framework, highlight the variety of analytical approaches used to conduct ERAs, and identify data gaps and challenges that remain in developing the next generation of CNH system risk assessments. This review is non-exhaustive, but rather offers a framework to guide EBM decision-making processes, examples and insights into future prospects for ERAs as decision-support tools, their place in the context of integrated ecosystem assessments, and their critical role in operationalizing EBM.

A Hierarchical Conceptual Framework for Ecosystem Risk Assessment

The foundation of a risk assessment is an analytical approach for relating a subject of interest (species, habitat, community, etc.) to a likelihood and consequence of natural or anthropogenic pressures (Gibbs and Brownman 2015). Hobday et al. (2011) characterized ERAs for the effects of fishing on ecosystems as sequential steps on an increasingly quantitative scale of analyses. Here, we adapt their framework by categorizing ERAs in terms of analytical approach (Levels 1–3), and extend it to include assessments of risk due to any natural or anthropogenic pressure(s) by classifying studies based on the complexity of the CNH system under consideration (Classes 1–3; Fig. 1; Liu et al. 2007). Under this framework, risk can be caused by, and posed to, human and natural systems.

Analytical approaches can range from a conceptual model constructed through expert opinion to a quantitative model with explicit error and probability profiles. There is a natural progression from conceptual to quantitative analytical approaches, as fully quantitative models are built upon conceptual models of ecosystem dynamics. Qualitative ERAs are a rapid and comprehensive assessment to identify a broad range of components at risk from a given pressure (Level 1; sensu Hobday et al. 2011). Components identified as “at risk” (i.e., medium to high risk) during the Level 1 assessment are further considered in the Level 2 semi-quantitative assessments, which may involve rank-based exposure-sensitivity analyses. Finally, components identified as medium to high risk in Level 2 analyses are further evaluated using quantitative model-based approaches with explicit description of the probability of error and uncertainty around a management outcome (Level 3; Hobday et al. 2011).

In addition to distinguishing between three levels of analytical techniques, our ecosystem-based framework builds on the Hobday et al. (2011) framework through extending their approach to three nested classes of system complexity (Fig. 1). System complexity ranges from

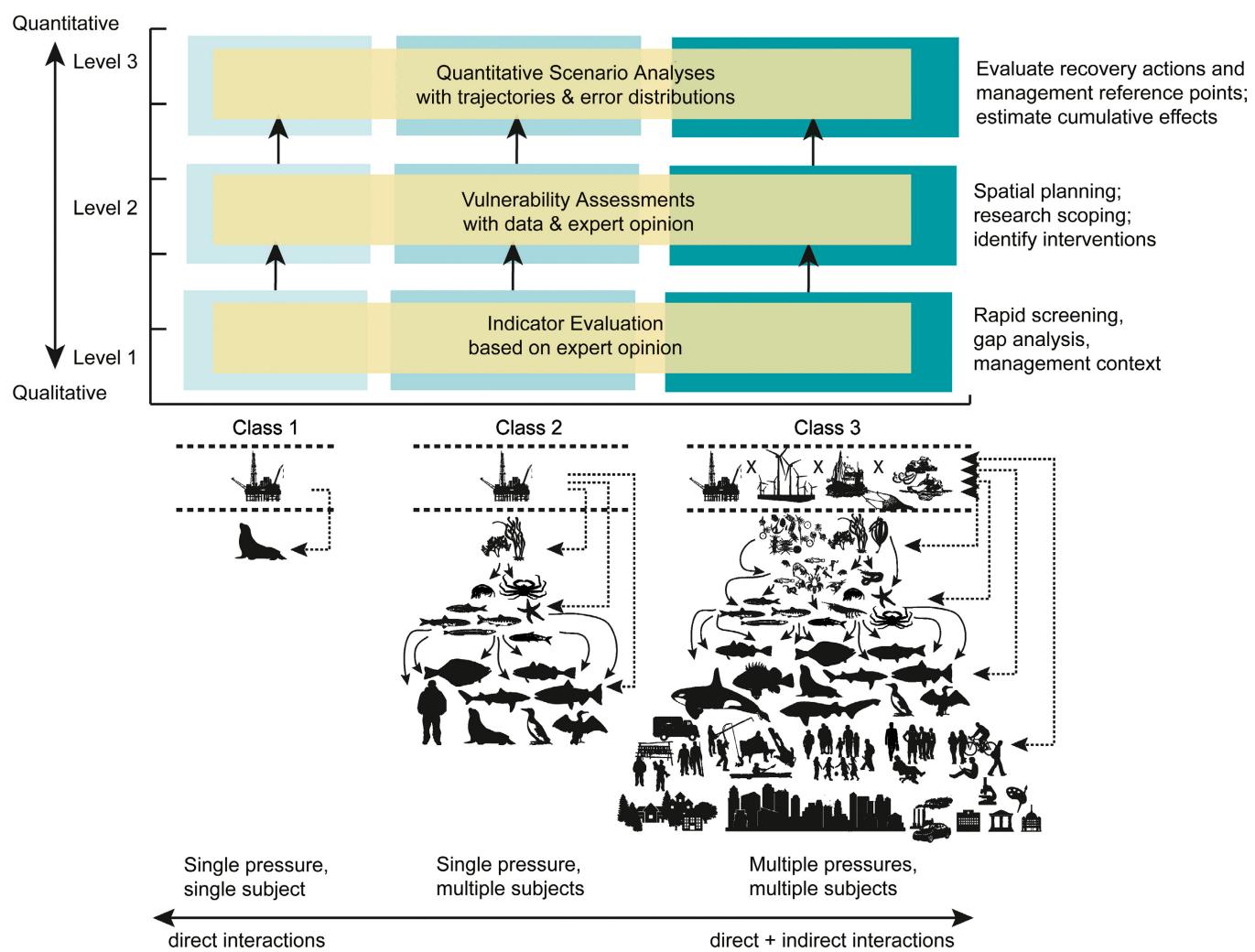


Fig. 1. Hierarchical conceptual framework for ecosystem risk assessment. Modification of Hobday et al.'s (2011) approach (i.e., Class 2). Scoping and stakeholder engagement increases left to right, and data requirements and computational costs increase diagonally from lower left to upper right. Far right column highlights example applications of each level of ecosystem risk assessment. Class 1 represents evaluations of a single pressure on a single focal subject, Class 2 analyses consider impacts of a single pressure on multiple ecosystem subjects or multiple pressures on a single subject, and Class 3 analyses consider the reciprocal and cumulative interactions among multiple (interacting) pressures and multiple interacting subjects.

the direct impact of a single pressure on a given social or ecological subject (e.g., single species or social component; Class 1), to the direct and indirect effects of a pressure on multiple interacting subjects (e.g., the Hobday et al. (2011) example of fishing impacts on ecosystems) or multiple pressures on a single subject (i.e., Class 2), to the direct and indirect effects of multiple interacting pressures on multiple interacting subjects (i.e., Class 3). In this framework, ecosystem models are of particular utility for EBM issues focused on tradeoff analyses between multiple, often conflicting, management objectives across multiple sectors (Class 3). Models of intermediate complexity (MICE; Plagányi et al. 2014) are more appropriate for short term, within-sector risk assessment objectives (Class 2), and simple linear chain models are of utility for specific investigations of the direct impacts of a pressure on a social or ecological component (Class 1). We recommend that selection of the class of system

complexity should be based on the urgency, research capacity, and most importantly, management need to evaluate cumulative (minimally Class 2) and indirect (Class 3) impacts and/or multi-sector tradeoffs (Class 3).

While the concept of a risk assessment is broadly familiar, visualizing how to apply it to EBM questions and challenges (especially in context of IEAs) has been less clear. Below we provide more detailed guidance about our general framework and its context within a growing wealth of information on EBM. To illustrate how existing marine ERAs are categorized under our hierarchical conceptual framework, we summarized U.S. and global representative examples (Table 1). This synthesis is not intended to be an exhaustive review; rather, it demonstrates the range of analytical levels of risk analyses, classes of system complexity, methodological approaches, system focus (natural vs. human), and management applications available to support EBM.

Level 1: Qualitative indicator evaluation

In general, Level 1 approaches rely upon a rapid evaluation of qualitative data—via expert opinion and/or stakeholder input—of the risk posed to an ecosystem. For all classes of system complexity, Level 1 analyses act as a screening or scoping step to flag potential high-risk interactions for more quantitative analyses (i.e., Levels 2 and 3). Rapid and computationally inexpensive, Level 1 risk analyses have particular utility in considering management responses to emergent issues or to quickly identify key pressures that may be affecting a wide range of species, habitats, activities, or other social components. This is of particular importance for prioritizing species or target systems for rapid response measures or more in-depth monitoring. Expert opinion can be harnessed toward a variety of goals, including rapidly evaluating indicators of species productivity (e.g., biomass over time) or potential overlap with a pressure (e.g., species home-range overlaps human activity), or as screening tools to identify vulnerable species for more in-depth (Level 2) analyses of impacts of climate change (e.g., Hare et al. 2016, Table 1). For Class 1 assessments at this initial level—where a single pressure creates risk for a single component (e.g., risk of disease transmission in fish from alternative harvest methods, Munro et al. 2003)—only direct impacts would be considered. In contrast, for Level 1-Classes 2 and 3, both direct and indirect impacts (via changes to food-web structure, for example) would be considered by expert opinion. Examples of Level 1-Class 2 assessments include considerations of risk posed by direct and indirect impacts of multiple fisheries on marine habitats (Williams et al. 2011), and an evaluation of how a variety of climate-driven changes may alter risk to the aquaculture industry (Doubleday et al. 2013). Level 1-Class 3 assessments differ subtly from Level 1-Class 2 assessments in that cumulative pressures (and the interactions between pressures) are considered simultaneously (e.g., Altman et al. 2011 for the Gulf of Maine ecosystem; Cook et al. 2014 for the Florida Coastal Everglades ecosystem; Knights et al. 2015 for the European regional seas; Table 1).

Level 2: Semi-quantitative vulnerability assessments

In general, Level 2 risk assessments employ a combination of quantitative and qualitative data using semi-quantitative analyses to assess the risk posed to an ecosystem component (Table 1; also see Stelzenmüller et al. (2015) for a review of semi-quantitative and risk assessments). As risk assessments move “up” the quantitative scale to Levels 2 and 3, the models and methods used within each class will vary based on the system complexity, data availability, and management needs. Level 2 vulnerability assessments might be similar for Classes 1 and 2, using an exposure–sensitivity–adaptive

capacity framework (e.g., Hobday et al. 2011, Mathis et al. 2015). In both cases, the exposure is usually determined using quantitative methods that predict the likely future exposure to the pressure(s) of interest. The sensitivity and impact is then often determined using a mixture of quantitative and qualitative methods. Level 2-Class 2 risk assessments can reveal relative risk to focal ecosystem or human system components, providing a basis for prioritizing management actions and further analysis. A recent example of a Level 2-Class 2 assessment includes the rapid climate change vulnerability assessment for the NW Atlantic, which combined quantitative climate projections with expert opinion (i.e., qualitative) to rank species most at risk to climate change (Box 1; Hare et al. 2016). For Level 2-Class 3 analyses, the interactions between pressures, as well as direct and indirect impacts, are of interest and can reveal important outcomes of cumulative pressures. For example, Morzaria-Luna et al. (2014) used semi-quantitative methods to determine the relative vulnerability (based on rankings of sensitivity, exposure, and adaptive capacity) of 12 coastal fishing communities in the Northern Gulf of California to cumulative anthropogenic stressors, including climate change. They found that vulnerability varied among communities and was highest for communities that were both dependent on fishing and had lower socio-economic diversification. When indirect impacts are also of interest (Level 2-Class 3 ERAs), qualitative network models (QNM; Puccia and Levins 1985, Melbourne-Thomas et al. 2012), a type of dynamic conceptual model, are useful as they can identify compensatory ecosystem dynamics and non-intuitive outcomes of management actions. For example, Reum et al. (2015) used QNM (i.e., loop analysis) to illustrate that proposed removal of crustacean predators of cultured bivalves might both (1) initially increase bivalve biomass (through release from predation) and also (2) inadvertently increase competitive predator abundance, causing a decline in target bivalve biomass (through increased predation by other predators); the non-intuitive result is therefore a neutral net effect on clam survival. We suggest that Level 2 assessments such as this one are ideal for vetting potential interventions to be evaluated more specifically and quantitatively with scenario analyses (i.e., Level 3 ERAs).

Level 3: Quantitative scenario analysis

Level 1 and Level 2 ERAs are governed by the need to rapidly provide information on potential risk to an ecological component of the ecosystem, computational or other resource limitations, as well as differences in data quality and availability for a broad range of focal ecosystem components. Yet, frequently ecosystem management requires maximizing socio-economic extractive or utilization needs while minimizing risk to ecological components in order to enhance sustainability. In these cases, specific thresholds, based on acceptable probabilities of risk, are required

Table 1. Ecosystem risk assessment examples.

Level and Class	Pressures and targets	Description	
Level 1	Qualitative assessments (expert opinion)		
Class 1	Single pressure (fishing); single target (salmon) Single pressure (eco-parasite); single target (Atlantic salmon)	Qualitative assessment of the impacts of harvest on salmon disease rates in Scotland and Norway Qualitative assessment of the risk of introduction of an invasive eco-parasite to United Kingdom Atlantic salmon	Munro et al. (2003) Peeler and Thrush (2004)
Class 2	Single pressure (climate change), multiple targets (aquaculture species)	Assessing the risk of climate change to multiple aquaculture species in southeast Australia	Doubleday et al. (2013)
Class 3	Multiple interacting pressures and multiple interacting targets	Expert-derived conceptual model of drivers, pressures, ecosystem services, and the responses of the ecosystem and different ecological functions, stressing the interconnectedness of the coupled natural-human system	Fletcher et al. (2014)
	Multiple interacting pressures and multiple interacting targets	Qualitative expert-scored analysis of multiple human and natural pressures and responses of the Gulf of Maine marine ecosystem with a focus on ecosystem services most threatened by cumulative and indirect effects of human activities	Altman et al. (2011)
	Multiple interacting pressures and multiple interacting targets; indirect effects considered	Workshop-facilitated expert opinion scoring of multiple pressures on multiple ecosystem components with explicit scoring of interactions among states or interactions among pressures	Cook et al. (2014)
	Multiple pressures, multiple targets (guilds and habitats); direct effects only	Multiple human and natural pressures impacts on multiple ecological targets (guilds and habitats) with consideration of recovery time if pressures were alleviated	Knights et al. (2015)
	Multiple pressures, multiple interacting targets; indirect effects considered	Food web and expert knowledge parameterized conceptual model of vulnerability of Mediterranean seagrass (<i>Posidonia oceanica</i>) to multiple cumulative human activities, including potential indirect impacts and interactions	Giakoumi et al. (2015)
Level 2	Semi-quantitative assessments using expert opinion and data		
Class 2	Multiple pressures (different fisheries); multiple ecological targets. direct effects only	Systematic prioritization of ecological risks associated with fishing policy goals in SW England through expert opinion ranking of risk using existing data for various species and stakeholder and scientific working groups	Cotter et al. (2015)
	Multiple pressures, multiple targets (coastal ecosystems); direct effects only	Scored assessment of cumulative threats (multiple additive pressures) to different coastal beach ecosystems in South Africa	Harris et al. (2015)
	Single pressure (climate change), multiple targets (human communities); direct effects only	Data-based scored assessment of vulnerability of human communities in Alaska to climate change based on data and projected change	Himes-Cornell and Kasperski (2015)
	Single pressure (climate change), multiple target species; direct effects only	Climate vulnerability analysis (CVA) based on expert-scored assessments of exposure and sensitivity of fish species to climate-driven changes	Hare et al. (2016)
	Multiple pressures (fisheries), multiple targets (fishery species); direct effects only	Productivity and susceptibility indices were used to rank the vulnerability of six U.S. fisheries targeting 162 stocks that exhibited varying degrees of productivity and susceptibility, and for which data quality varied	Patrick et al. (2010)
	Multiple pressures, multiple targets (coastal communities); direct effects only	An assessment the vulnerability of 12 coastal fishing communities in the Northern Gulf of California to cumulative multiple anthropogenic stressors, including climate change. Sensitivity, exposure, and adaptive capacity were qualitatively ranked based on quantitative indices	Morzarria-Luna et al. (2014)
	Multiple pressures, multiple targets (species); direct effects only	Species risk was determined as a function of sensitivity and exposure to various human-mediated pressures (habitat modification, pollution, climate). Scores of low to high (1–4) were assigned based on % change in pressures and exposure (i.e., overlap). Data quality scores were also included. Expert opinion and data-based scoring were compared	Samhouri et al. (2012)
	Single pressures (climate change), multiple targets (15 pelagic coastal species); direct effects only	Rank-based evaluation of climate change vulnerability of 15 fishery species from the California. Relative risk scores were based on quantitative estimates of expected changes in the mean and variability of sea surface temperature and chlorophyll concentrations, and species-specific sensitivity to these changes	Samhouri et al. (2014)

Table 1. Continued.

Level and Class	Pressures and targets	Description	
Level 1	Multiple pressures, multiple targets (human communities); direct effects only	Relative risk to coastal communities determined via ranking of well-being indicator scores (including social, economic, health, and ecosystem conditions); temporal change in change in risk was also determined	Dillard et al. (2013)
	Multiple pressures (natural disasters), multiple targets (human communities); direct effects only	Relative risk to communities in relation to environmental condition (disasters specifically) depicted via semi-quantitative indicator scores	Cutter et al. (2008)
	Single pressures (climate change), multiple targets (species groups)	Vulnerability analysis where scores were based on (low, medium, high) relative rankings of exposure and sensitivity of multiple species groups to multiple direct and indirect climate change pressures	Chin et al. (2010)
	Single pressure (trawling), multiple targets (species); direct effects only	Analysis to determine the relative capacity of species to withstand trawling and to prioritize species for research and management; relative risk was determined for 411 fish species caught as by-catch in the prawn trawl fisheries and were ranked with respect to biological and ecological criteria and indices	Stobutzki et al. (2001)
	Multiple pressures, multiple human and natural system targets	Assessment of coupled natural–human system environmental vulnerability (e.g., sea-level rise, pollution, rainstorms) in Jakarta, Indonesia, using a quantitative index comprising exposure, sensitivity, and adaptive capacity variables	Yoo et al. (2014)
	Multiple pressures (hazards); multiple targets (human communities); direct effects only	Assessment of coastal human communities to coastal hazards based on a scored index with a weighted combination of variables; utilizes regression analysis with storm damage data to determine vulnerability (exposure, sensitivity, and adaptive capacity) to hurricane hazards	Lam et al. (2014)
	Single pressure (climate change), multiple human system targets; direct effects only	Assessment using social and ecological indicators combined to create composites of base vulnerability and climate impact risk for coastal communities; utilizes statistical and geospatial analyses for the indicator development	Messick and Dillard (2016)
	Single pressure (climate change), multiple human system targets; direct effects only	Assessment of infrastructure vulnerability to various climate change scenarios, focusing on the economic, social, health and safety, and environmental impacts of infrastructure loss using a multi-criteria analysis matrix	Johnston et al. (2014)
	Multiple pressures (climate change, fisheries), multiple target components of human and natural systems; direct and indirect effects considered	Calculated the vulnerability of 132 national economies to potential climate change impacts on capture fisheries using exposure, sensitivity, and adaptive capacity; scoring based on a variety of socio-economic indices and two IPCC climate projections of temperature change	Allison et al. (2009)
	Multiple interacting pressures (climate change and management actions), multiple coupled natural–human system targets; direct effects only	The vulnerability of coastal social–ecological systems to temperature-induced coral mortality was evaluated for 12 coastal communities and associated coral reefs in Kenya; five key ecological and social components were rank-scored to determine vulnerability: 1) environmental exposure; 2) ecological sensitivity; 3) ecological recovery potential; 4) social sensitivity; and 5) social adaptive capacity. Vulnerability was also assessed separately for government-operated no-take marine reserves, community-based reserves, and openly fished areas	Cinner et al. (2012)
Level 2	Multiple interacting pressures, multiple targets (coral reef fish species); indirect effects considered	Extinction risk vulnerability analysis of coral reefs in the Indian Ocean where risk was scored 0–4 based on survey-based occupancy data, multiple quantitative climate and extinction risk indices, and expert-based weighting. Interactions between multiple pressures (climate change and fishing) were included	Graham et al. (2011)
	Multiple pressures (multiple management actions), multiple interacting target species; indirect and direct effects are considered	Qualitative network model simulation of the direct and indirect effect of predator control measures on multiple cultured bivalve shellfish species and ecosystem components	Reum et al. (2015)

Table 1. Continued.

Level and Class	Pressures and targets	Description	
Level 3	Quantitative assessment		
Class 1	Single pressure (reduced carrying capacity), single target (sea lion populations)	Extinction risk of declining sea lions populations in western Alaska determined from population viability analysis of simulations with various assumptions about carrying capacities and the presence or absence of density-dependent population regulation	Winship and Trites (2006)
	Single pressure (shipping), single target risk (oil spill)	Oil transportation risk management analysis conducted from 2006 to 2008 in the Puget Sound (United States) and surrounding waters using maritime transportation system simulation	van Dorp and Merrick (2009)
Class 2	Multiple pressures (temperature and ocean acidification), multiple target habitats; direct effects only	Geospatial vulnerability assessment of coastal habitats to the cumulative (additive) impact of climate-driven changes in temperature and ocean acidification. Analysis was conducted using spatially explicit values for projected impacts (exposure) and habitat distribution, historical exposure (adaptation), and habitat-specific expert-derived habitat sensitivities	Okey et al. (2015)
	Multiple pressures (alternative marine survival scenarios), single target (Atlantic salmon); direct effects only	Population viability analysis was used to determine extinction risk for eight sub-populations of Atlantic salmon from Maine (United States) under a range of future conditions and management strategies; results produced management-relevant demographic and extinction probabilities	Legault (2005)
	Multiple pressures (harvest, habitat loss, hatchery production), single target (Chinook salmon); direct effects only	Population viability analysis (PVA) of the effects of hatcheries, habitat loss, and fisheries harvest on Chinook salmon populations; uncertainty around projections is specifically delineated	Ellner and Fieberg (2003)
	Single pressure (shipping), multiple targets (whale species); direct impacts only	Statistical analysis of the risk of ship strikes to multiple whale species	Redfern et al. (2013)
	Single pressure (ozone-mediated bark beetle infestation), multiple targets (forest components and water quality); direct effects only	A stochastic spatial model of land-cover change was used to determine the probability of loss due to ozone-triggered beetle attacks	Graham et al. (1991)
	Multiple pressures (multispecies fisheries and management scenarios), multiple target fish species; no indirect effects	Quantitative assessment of extinction risk under different harvest methods for multispecies fisheries; case study is for eight tuna and billfish populations of the Western and Central Pacific	Burgess et al. (2013)
	Multiple pressures, multiple target species; direct effects only	Cumulative impact of 24 anthropogenic stressors on eight protected predator species in the Pacific California Current Ecosystem; risk was determined using a geospatial model of occurrence (based on telemetry data from 685 individuals) and maps of cumulative anthropogenic stress from a variety of quantitative spatial data sources	Maxwell et al. (2013)
Class 3	Multiple perturbations (simulated extraction at increasing levels), multiple target species groups; indirect effects quantified in food-web model	Quantitative evaluation (using trophic models) of the relative vulnerability of five marine ecosystems in the Gulf of Mexico to varying levels of biomass extraction; natural system only	Arreguín-Sánchez and Ruiz-Barreiro (2014)
	Multiple interacting pressures; multiple targets	Simulated geospatial vulnerability of different benthic habitats to various additive or interacting pressures	Stelzenmüller et al. (2010)
	Multiple pressures (fishing scenarios); multiple natural and human system targets; direct and indirect impacts evaluated through species interactions in food-web model	Management strategy evaluation to determine multiple fishery performance and risk (according to a variety of socio-economic and biological criteria) under various scenarios; simulations conducted using end-to-end coupled ecological socio-economic model	Fulton et al. (2014)
Multi-level			
<i>Levels 1–3</i>			
Class 2	Single pressure (fishing), multiple targets	Multi-level qualitative (screening, Level 1) to quantitative (Level 3) assessment of Australian fishing impacts on benthic habitats	Williams et al. (2011)
	Single pressure (fishing); multiple targets (habitat, fish species)	Multi-level qualitative (rapid screening via expert opinion Level 1), semi-quantitative prioritization (Level 2), to quantitative assessment of Australian fishing impacts on benthic communities	Hobday et al. (2011)

Table 1. Continued.

Level and Class	Pressures and targets	Description	
<i>Levels 1–2</i>			
Class 2	Single pressure (aquaculture of salmon and trout species), multiple ecological targets (wild fish populations and regional habitats); direct effects only	Risk assessment of the effects of aquaculture of Atlantic salmon and rainbow trout on Norwegian marine ecosystems and wild salmon populations based on a variety of ranked and quantitative data regarding exposure and impacts. Cumulative risk is assessed qualitatively (discussion)	Taranger et al. (2015)
Class 3	Single pressure (climate change); multiple ecological targets (aggregated fishing guilds)	Semi-quantitative rank-based analysis of climate change risk for six fish and invertebrate groups in two different ecosystems. Stepwise prioritization approach was used where rapid quantitative assessments (Level 1) were made to screen species and data for inclusion in the semi-quantitative assessment (Level 2). Climate vulnerability was determined through combining scores based on quantitative and qualitative data on ecosystem-specific climate change impacts (exposure) with qualitative expert-scored sensitivities (1–4) of each aggregated fish group	Gaichas et al. (2014)

and risk analyses are designed to characterize risk profiles under alternative management strategies. Level 3 risk assessments produce this level of quantitative information based on a mechanistic understanding and assessment of the system and focal component (Table 1; see Stelzenmüller et al. (2015) for additional examples). The most widespread examples of this are evaluations of the risk of population collapse under various fisheries harvest rates (i.e., harvest impact on a single species; an example of a Level 3-Class 1 risk analysis). Toxicology and endangered species policies are similarly structured around quantitative estimates of acceptable risk (Table 1).

Projections of species populations are often sensitive to trophodynamic processes; thus, ERAs increasingly quantify the direct and indirect cumulative impacts of a pressure on multiple ecosystem components (i.e., Level 3-Class 2) using food-web models (e.g., Watters et al. 2013, Anh et al. 2014), multispecies size-spectrum models (Blanchard et al. 2012, Woodworth-Jefcoats et al. 2015), and multispecies assessment models (e.g., MICE; Plagányi et al. 2014, Holsman et al. 2016). While quantitative MICE have particular utility in short-term tactical applications (Plagányi et al. 2014), both short- and long-term projections can be sensitive to non-stationarity in other drivers and pressures. More complex models, where first principles govern socio-economic, species, and biophysical interactions, have the potential to alleviate issues of non-stationarity in projections. Recently, multiple authors have attempted to employ fully coupled end-to-end models (Rose et al. 2010, e.g., physical-biological-socio-economic models like Atlantis, Fulton 2010) to assess cross-system consequences of management actions (Fulton et al. 2011, 2014); such modeling approaches are increasingly used to evaluate regional management actions under differing large-scale climate change scenarios (Fulton 2010, Plagányi et al. 2014, Woodworth-Jefcoats et al. 2015). These studies generally reveal indirect, non-intuitive outcomes resulting

from interacting pressures (e.g., climate and fishing on multiple target species; an example of Level 3-Class 3) and reinforcing feedbacks that attenuate or amplify impacts, especially over longer projection periods.

Considerations in the Application of the ERA Framework for IEAs

While we present a generalized framework for conducting ERAs and offer guidance in implementing risk assessments in the context of IEAs, the approach need not be prescriptive. A central challenge in conducting ERAs is balancing the need for characterization of error/risk around a management action and the speed at which information is needed. Increasing social-ecological complexity and realism in the models at the core of risk analyses (i.e., moving from left to right in Fig. 1) comes at the price of longer scoping and broader stakeholder engagement, modeling poorly understood relationships, elevated computational demand, greater data requirements, and prolonged project duration (Plagányi et al. 2014). Similarly, advancing from qualitative to quantitative assessments (i.e., advancing vertically in Fig. 1) mandates additional computational and data resources that can extend the time required for risk analyses to be completed. The intensified demand in time and resources associated with more quantitative and complex analyses underscores the importance of a priori alignment of management needs and timelines with social-ecological risk assessment approaches; development of ecosystem risk assessments for use in IEAs (and similar EBM applications) will necessarily reflect these constraints. Our proposed framework can help guide future analyses for EBM (in particular which level and class are optimal for addressing a particular management challenge) so that managers can better evaluate analytical options, focus limited resources, tailor analyses to meet a variety of management objectives and time-frames, and

Box 1. A Level 2-Class 2 Case Study: Fisheries Climate Vulnerability Assessments in the United States

Due to differences in life histories, habitat complexity, and non-uniform climate effects, some ecosystems and species will face greater pressure from changing ocean conditions than others (Pecl et al. 2014). While there have been in-depth modeling efforts (Hazen et al. 2012, Plaganyi et al. 2013, Wayte 2013) and analyses (Hollowed et al. 2009, Nye et al. 2009, Hare et al. 2010, Pinsky et al. 2013), data and resource limitations preclude highly quantitative analyses of the effect of climate change on all fished species. The United States recently embarked on an ambitious nationwide effort to perform rapid climate vulnerability assessments (CVAs) for all of its large marine ecosystems. It used species life history profiles, climate projections, and expert opinion to score the relative vulnerability of federally managed species to climate change. CVAs were initiated for the NW Atlantic (United States; Hare et al. 2016) and are underway in the Alaskan Eastern Bering Sea and NE Pacific California Current. The climate vulnerability in the NW Atlantic provided a high-level perspective that can be used to determine future climate research priorities that ultimately may influence climate change management decisions. Upon completion of the Northeast Fisheries Climate Vulnerability Assessment (NEVA), scientists have expanded CVA efforts to examine protected species (marine mammals, seabirds, and turtles) and human communities with the recognition that a single-sector approach may neglect tradeoffs in management solutions (Colburn et al. 2016).

Similar to rapid climate assessments underway in Australia (Pecl et al. 2014), the CVA approach is a Level 2 risk analysis that integrates expert opinion with data layers on species distribution and climate variability and change. CVAs are wide-reaching in scope but not highly quantitative, nor do they explicitly include subject interactions or interacting pressures beyond climate change (i.e., they are a Level 2, Class 2 analysis); rather, they are scored based on the direct effect of exposure factors (e.g., changes in temperature, productivity, salinity, precipitation) combined with species sensitivity to changes. Such rapid assessments attempt to span data gaps to provide a common currency for comparing among stocks and ecosystems,

yet also can serve as a screening tool to identify species most at need from additional data or analysis. For example, Pecl et al. (2014) identified numerous knowledge gaps on ecological relationships and environmental thresholds in response to climate change that would benefit from additional research. Hare et al. (2016) suggested that the vulnerability narratives were a starting point for identifying additional research and management needs. The NEVA efforts concluded that the process should be completed iteratively and on a similar timescale as the Intergovernmental Panel on Climate Change assessment cycle (i.e., ~7 yr) to ensure that adaptive capacity and new experts were included in the process. While the opportunity has been identified, this nascent approach has not yet resulted in a tiered analysis moving toward Level 3 analyses for species identified most at risk (Fig. B-1). The tiered structure could be a stepwise effort (*sensu* Williams et al. 2011 and Gaichas et al. 2014), where species identified most at risk from rapid assessments may be further analyzed using a Level 3 quantitative approach (i.e., pathway "a" in Fig. B-2).

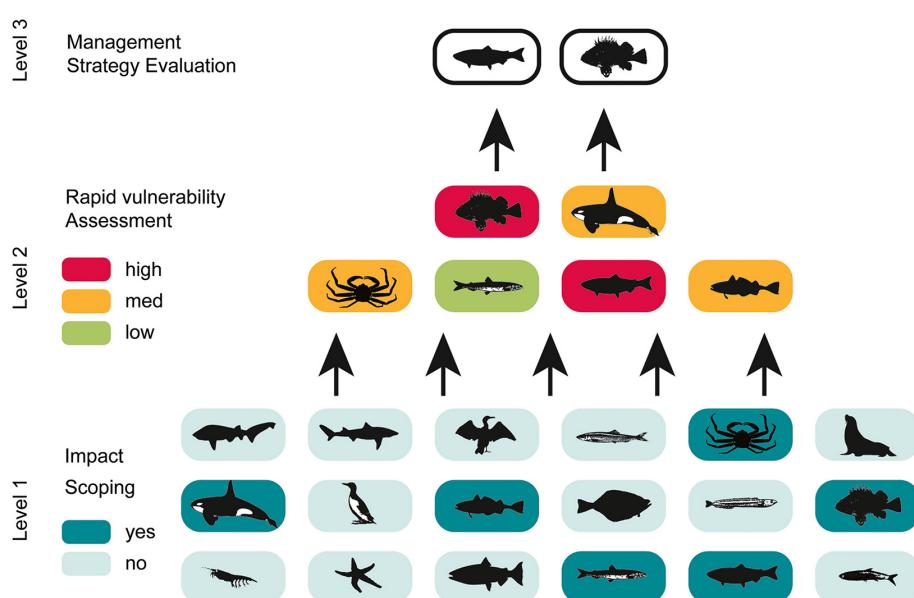


Fig. B-1. Tiered approach to vulnerability assessment where Level 1 rapid scoping identifies species for inclusion in Level 2 CVAs. High-risk species from Level 2 (red) are further examined using a more quantitative Level 3 approach (e.g., projection analyses). Examples here are hypothetical.

Box 1. Continued

To date, most rapid climate assessments focus on a particular sector or discipline such as fisheries (Pech et al. 2014, Hare et al. 2016), habitats (NMFS 2010), or human dimensions (Himes-Cornell and Kasperski 2015, NOAA OCM 2015). However, there are emerging and exciting efforts underway to connect CVAs of fish stocks to human well-being, vulnerability, and resilience in fishing and human communities. For example, in the NEVA, economists and social scientists are combining the fisheries results with social indicators (Jepson and Colburn 2013, Breslow et al. 2014, Himes-Cornell and Kasperski 2016) to inform an assessment of community vulnerability as a function of fleet diversification and fish stock level (Colburn et al. 2016). On a parallel effort, the vulnerability of coastal pelagic species to climate change in the California Current was used to inform estimates of the exposure of associated fisheries, with fleet revenue diversity in each fishery

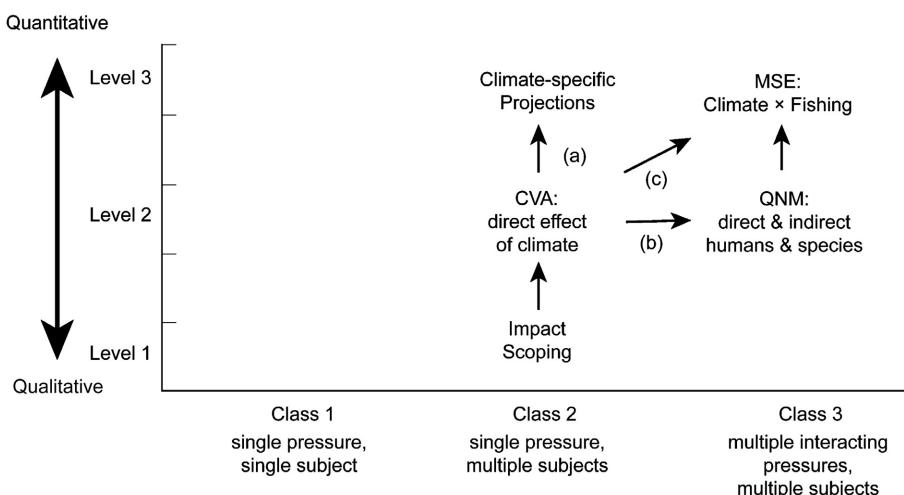


Fig. B-2. Potential future directions for CVAs. (a) Use of CVA results for prioritizing quantitative projections, (b) further development of CVAs to include indirect effects and human communities, and (c) use of CVA results to prioritize management strategy evaluations (MSE) of climate and multiple interacting pressures (e.g., fishing and climate change).

determining the sensitivity axis (Metcalf et al. 2015). This approach identified which fisheries had low revenue diversification (high sensitivity) and targeted stocks most vulnerable to climate change (high exposure). All of these approaches examined each species independently rather than looking at ecological interactions as part of the process (i.e., Level 2, Class 2 approach). A coupled approach that assesses social vulnerability in parallel with the vulnerability of multiple fished species to climate change may be able to better capture non-linear dynamics in the ecosystem response and could engage a broader range of stakeholders in risk analyses (i.e., pathway “b” or “c” in Fig. B-2).

scope next steps and information needs. Because different tools map to different level-class combinations (e.g., single-species population viability analyses vs. end-to-end ecosystem models), our framework provides guidance to scientists about how to conduct research to best to address and inform management questions and challenges. Using the framework to classify a management question can also help managers/stakeholders identify additional sectors and stakeholders that need to be included in decision making and which other ecosystem components are essential for adequately assessing cumulative ecosystem risk.

Considerations for Risk Assessments of Coupled Natural-Human Systems

One of the challenges in conducting ERAs to address tradeoffs and cumulative risks across multiple management sectors is the degree of explicit consideration of

dynamic feedbacks between natural and human systems (Liu et al. 2007, Ostrom 2009). With few exceptions, ecosystem risk assessments have been conducted in the context of natural systems (as modified by human activities) or human well-being (as modified by environmental disturbances). Much less work has evaluated risk to human and natural systems simultaneously using CNH system conceptual models (Fig. 2; Liu et al. 2007). Both human and natural components of complex systems have rich theoretical foundations, which considered in concert can provide insight to potential management action feedbacks and compensatory dynamics (Janssen et al. 2006, Ostrom 2007, 2009, Bodin and Tengo 2012, Anderies et al. 2013, Ban et al. 2013, Cinner et al. 2016, Cumming et al. 2015). For decades, researchers have contended with how best to couple empirical data from the natural sciences with social science knowledge and data (Haberl et al. 2006, Ostrom 2007, 2009, Bodin and Tengo 2012, Schlüter et al. 2012, 2014). Tractable approaches to move

CNH systems theory into practice for assessing risk in marine ecosystems are nascent, but developing (see Ostrom 2007, 2009, Shackeroff et al. 2011, Kittinger et al. 2014).

Perhaps the key ingredient to integrating social and ecological risk assessments is to level the playing field by addressing both human and natural system endpoints within a single analysis and similar, or at least comparable, units of measure. Indeed, there is an emerging consensus on the utility of adopting a holistic framework for understanding multiple direct and indirect interactions and feedbacks between human and natural system components (Fig. 2; Eakin and Luers 2006, Schlüter et al. 2012, Bennett et al. 2015, Cinner et al. 2016, Cumming et al. 2015). Under such a reciprocal framework, human components are considered to exert pressure(s) on the natural components of the system and themselves, and to respond (often non-linearly) to pressure(s) from the natural system (or vice versa). Thus, a pressure posing risk to an ecological component (e.g., impacts of fossil fuel emissions on calcifying marine organisms) may also represent a benefit accrued to a social component of the system (e.g., manufacturing, energy, or transportation industries). The inverse may also be true: A pressure posing risk to a social component (e.g., a climate shift favoring groundfish fisheries rather than crab fisheries) may represent a benefit accrued by an ecological component (e.g., groundfish).

One approach to making the analysis of risk due to CNH interactions tractable is to conduct social and ecological risk assessments sequentially, and then consider the individual and joint risk to the human and natural components of the system (Fig. 2a). In such a conceptualization, an estimate of the risk to the natural system due to a pressure (e.g., an environmental disturbance) underpins estimates of the exposure of the human system to the same pressure. An example of this approach has been applied to evaluate climate change vulnerability of species and dependent human communities in the NW Atlantic (Box 1; Hare et al. 2016, Colburn et al. 2016). Similarly, Barange et al. (2014) coupled model-derived biological impacts with socio-economic dependency metrics to evaluate global patterns in vulnerability and adaptive capacity of fishery-dependent communities to climate change. While these analyses represent strong advances toward CNH risk assessment, they do not capture dynamic feedbacks between social and ecological components of the system.

Analyses that explicitly incorporate the dynamics of CNH systems thus represent the future of ERAs. In such analyses, drivers of change in the CNH system have the possibility of creating both positive and negative feedbacks between social components, between ecological components, and between social and ecological components (Fig. 2b). For example, Horan et al. (2011) used a bioeconomic model to demonstrate that human responses to, and influences on, species interactions can generate

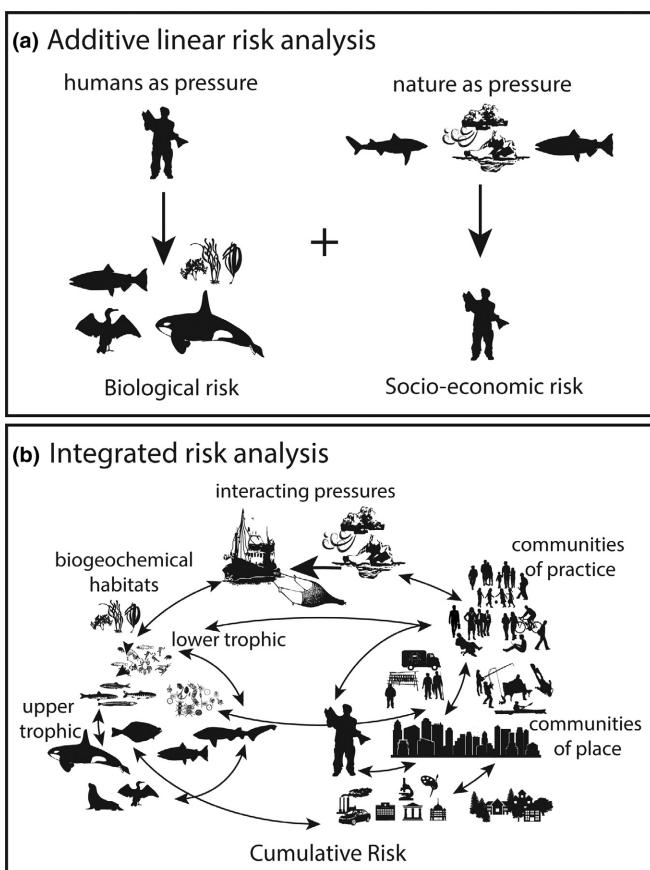


Fig. 2. Conceptualization of environmental risk via (a) linear impact risk analysis and (b) integrative coupled natural–human system risk analysis. Traditional, linear risk analyses (a) reflect an oppositional tension between humans and nature. Within this relationship, humans exert pressure(s) on the environment (left) or the environment impacts humans (right). In this approach, the cumulative biological and socio-economic impact of a change in a pressure (e.g., climate) might be through the sequential linear impact of humans on the environment and then climate on humans. More recent conceptualizations (b) focus on the expanding domain of coupled natural–human systems, with reinforcing feedbacks that might amplify or attenuate risks from a given pressure.

threshold changes in a CNH lake ecosystem. Thus, these authors quantified the risk of producing undesirable system states under alternative management scenarios and historical contingencies, and identified the structural ecological and socio-economic feedbacks that can mitigate risk by creating stability within the desirable state of the CNH system. Importantly, a full assessment of risk to the CNH system would not have been complete without considering potential changes across all components simultaneously.

As the examples above make clear, while CNH system problems are complex, tractable methods for analyzing risk to them need not be. One area ripe for advancement along these lines is the potential adaptive capacity of CNH systems. Natural systems will not simply absorb pressures posed on them by the human system; rather, they are likely to respond, adapt, and exert pressures

back on the human system as well as other components of the natural system (the inverse is also true for human systems responding to natural pressures). Further, because risk is not distributed equitably among the human or natural components of the system, there is an asymmetry in the benefits and costs between different stakeholders in the community (Cook and Heinen 2005). Capturing such potential responses is essential for an accurate assessment of risk. In the context of climate change, Metcalf et al. (2015) introduced a method to quantify socio-economic feedbacks that can facilitate human adaptation to natural system pressures and, in general, the capacity for human adaptation to change is enormous. Similarly, Gattuso et al. (2015) review examples of empirical demonstrations of the capacity of natural system components to respond to a changing climate, which suggests that adaptation occurs rapidly, is non-uniform, and is worth considering in future vulnerability assessments. We are not aware, however, of many studies that assess risk to both human and natural system components while allowing for adaptation within both systems. Encouragingly, the analytical tools for doing so are emerging from the world of complex adaptive systems (Levin 1998, 2002, Levin et al. 2013) and related products are slowly beginning to be applied in the context of marine ecosystem-based management (McDonald et al. 2008).

Conclusion

Given the uncertainty inherent in complex marine social–ecological systems, it is important to clearly define the focal components of an ecosystem risk assessment. Assessments that start with rapid screening via qualitative expert opinion ERAs (Level 1) and high system complexity (e.g., Class 3) and then progress toward slightly lower complexity as they increase to more quantitative approaches, may represent a parsimonious approach (i.e., progression from lower right to upper-middle of Fig. 1). This is the approach taken by the few examples we provide of multi-level assessments (Table 1). For example, Hobday et al. (2011) detailed a progression from Level 1 to 2 of a Class 2 analysis (i.e., fishing effects on multiple ecosystem targets), but then suggested Level 3 analyses would be for the direct impact of fishing on individual species identified in the Level 2 assessment (i.e., Class 1). Similarly, results of regional rapid climate vulnerability assessments (arguably Levels 1 through 2, Class 2 or 3), might initially lead to quantitative analyses (Level 3) with slightly less ecologically complexity than semi-quantitative analyses. For example, the effect of climate change on a full suite of natural and human system targets might be considered for semi-quantitative analyses, but fully quantitative projections of risk might be considered only for a small subset of species where data are available for climate through socio-economic impacts. In this example,

complexity might increase laterally (from left to right) as additional data and resources become available or in response to emergent climate-related research. In particular, growing acknowledgment of CNH systems and a willingness to embrace their complexity in risk analyses will require approaches other than the linear deterministic methods that have been the predominant tools to date (Waltner-Toews et al. 2008). Yet, if conducted with ample stakeholder input, progression from rapid assessments to quantitative analyses is tractable and may help create a conceptual model of the CNH that best captures the understanding of scientists, managers, and resource users of the dynamic modulating and reinforcing connections between both systems.

One objective of EBM (and IEAs) is to characterize trade-offs in order to understand how management actions, when considered jointly, might strike a balance between negative and positive pressures for both human and natural components of the system (Link 2010). Central to this objective is understanding the risk associated with potential management actions and future scenarios, especially in terms of actions that prioritize social over ecological components (or conversely, ecological over social components). The ERA framework outlined here can help to identify potential areas for compromise and ultimately facilitate stakeholder consensus on tenable EBM strategies and solutions (Link et al. 2011, Ban et al. 2013, Bennett et al. 2015).

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