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Integrated Risk Assessment for the Blue Economy

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With the anticipated boom in the 'blue economy' and associated increases in industrialization across the world's oceans, new and complex risks are being introduced to ocean ecosystems. As a result, conservation and resource management increasingly look to factor in potential interactions among the social, ecological and economic components of these systems. Investigation of these interactions requires interdisciplinary frameworks that incorporate methods and insights from across the social and biophysical sciences. Risk assessment methods, which have been developed across numerous disciplines and applied to various real-world settings and problems, provide a unique connection point for cross-disciplinary engagement. However, research on risk is often conducted in distinct spheres by experts whose focus is on narrow sources or outcomes of risk. Movement toward a more integrated treatment of risk to ensure a balanced approach to developing and managing ocean resources requires cross-disciplinary engagement and understanding. Here, we provide a primer on risk assessment intended to encourage the development and implementation of integrated risk assessment processes in the emerging blue economy. First, we summarize the dominant framework for risk in the ecological/biophysical sciences. Then, we discuss six key insights from the long history of risk research in the social sciences that can inform integrated assessments of risk: (1) consider the subjective nature of risk, (2) understand individual social and cultural influences on risk perceptions, (3) include diverse expertise, (4) consider the social scales of analysis, (5) incorporate quantitative and qualitative approaches, and (6) understand interactions and feedbacks within systems. Finally, we show how these insights can be incorporated into risk assessment and management, and apply them to a case study of whale entanglements in fishing gear off the United States west coast.

Keywords: ecosystem management, sustainability science, risk management, social-ecological systems, risk analysis, blue economy

INTRODUCTION

Competition for use of the ocean is intensifying. As governments and private investors look to the sea as the next economic frontier (the "blue economy"), the number and variety of ocean uses is climbing and investments in ocean development and infrastructure are rising (European Commission, 2019; Voyer and van Leeuwen, 2019). The expansion of economic development activities, including bioprospecting, aquaculture, marine tourism, offshore renewable energy, mining, shipping and oil and gas development, means that there will be new and complex threats to both the natural environment and to coastal populations and other groups who currently depend on marine resources for their livelihoods. Offshore energy (Arbo and Thủy, 2016) and aquaculture operations (Gentry et al., 2017), for example, may cause both environmental impacts and spatial conflicts with traditional resource users. More broadly, ocean development activities have already resulted in increasing cumulative impacts in the oceans (Halpern et al., 2008), rising threats to valued marine life (Davies and Brillant, 2019), and intensifying risks to the livelihoods of individuals employed in the maritime economy. With a push for more transparent, sustainable and equitable decision-making in the oceans (Lubchenco et al., 2016; Golden et al., 2017; Bennett, 2018; Lester et al., 2018) we need to understand the impacts of the blue economy on both the environment and people. Integrated risk assessments can inform that understanding and provide the insights required to manage activities and mitigate undesirable outcomes.

We are therefore in a vital time to assess what we know about risk assessment in ocean ecosystems, and to evolve our learning and methodologies to contend with a large suite of ongoing and emerging activities that bring with them new threats. Theory and concepts around risk research have a long history across many disciplines (Renn, 1998). However, because of the siloed nature of science (Levin and Anderson, 2016), some biophysical scientists are likely unaware of the vast research on risk beyond the environmental sciences, creating an opportunity for forging stronger connections between disciplines. If we are to move toward more integrated decision-making, as called for by many writing about the blue economy and ecosystem-based management (EBM) (Keen et al., 2018; Klinger et al., 2018; Link et al., 2018), we need these balanced approaches based on shared understanding. Thus, we believe that an improved understanding of risk as a foundational concept will enhance the quality of research to support EBM in the ocean. In this paper we argue that this broader understanding of risk will facilitate the use of a diverse array of knowledge in making conservation and management decisions, as a step toward balancing trade-offs when managing ocean resources. To that end we present a primer on risk assessment from diverse disciplinary frameworks, both for those entering the field of marine ecosystem management from other contexts, as well as for those long familiar with the marine environment who are now tasked with evaluating the risks of new technologies and enterprises. This primer is intended to provide a critical step toward the application of interdisciplinary risk assessment in practice.

Risk is a boundary concept with established roots across social and biophysical sciences (Renn, 1998), and is a focal component of decision support for EBM (Burgman, 1993; Levin et al., 2009). Risk research has been applied across an incredibly diverse set of disciplines from medicine, behavioral psychology, ecology, public health, business, economics and many more. Specifically, "[r]isk refers to uncertainty about and severity of the consequences (or outcomes) of an activity [or decision] with respect to something that humans value" (Aven and Renn, 2009, p. 2). Risk analyses include measurements of both losses and gains, as well as sensitivity and uncertainty in outcomes (Fischhoff et al., 1984; Aven and Renn, 2009; Mahmoudi et al., 2013). Given the magnitude of uncertainty in ecosystem responses, risk analyses are ideally suited for EBM (Carpenter, 1995; Aven and Renn, 2009). Thus, risk frameworks have the potential to serve as a unifying concept and bring disciplines together.

Effective generation and application of interdisciplinary research and policy requires a better understanding of how different disciplines address similar problems (Castree et al., 2014; Levin and Anderson, 2016). However, to a large degree, the peer-reviewed literature on risk in the biophysical and social sciences constitute distinct spheres (Renn, 1998) with limited communication across disciplines (Hoffmann, 2011). For instance, while the fisheries literature has well-established and effective frameworks for risk assessments rooted in modeling, statistics and application of the exposure–consequence method (e.g., Hobday et al., 2011; Samhouri and Levin, 2012; Hodgson et al., 2016), these approaches presume that risk can be assessed objectively, is knowable and that decision-making involves optimizing expected benefits against net losses. This interpretation of risk may leave out important but intangible cultural losses (Turner et al., 2008; Poe et al., 2014) and neglect social perceptions of risk, which have long been recognized by social scientists as a fundamental component of informing environmental management decisions (Renn, 1998).

In addition to a lack of cross-pollination among disciplines on the topic of risk assessment, within ecological research there is substantial variability with use of the term "risk" in terms of scope and the level of connection to management outcomes. In an informal review of the literature, we found that across 20 recent publications (including our own) the term "risk" was used quite variably. Some authors used it to mean general threat, i.e., evaluating the risks to the ecosystem rather than linking risk to the delivery or maintenance of an outcome or some valued state, while others used the term risk to mean vulnerability, i.e., what is the expected impact, or probability, of a current or future threat. Finally, relatively few factored in the social components and perspectives on risk, or implicitly linked risk assessment to the broader risk management framework that considers risk to other parts of the system.

As a group of multi-disciplinary collaborators who have employed risk assessments ourselves, we have each come to understand that a broader, more holistic and integrated understanding of risk and risk assessment could improve our work individually and collectively. We thus identify and present insights that aim to move EBM scientists and practitioners toward this deeper understanding. Our hope is that, moving forward, when practitioners and researchers implement risk frameworks, a more complete picture of the system will emerge, enabling the enactment of the calls for social justice and inclusion in oceans management (Bennett, 2018; Cohen et al., 2019). We envision increased collaboration such that biophysical and social scientists jointly conduct connected risk assessments that are useful in decision-making. The paper is organized in three parts. First is a brief review of risk assessment in the peer-reviewed ecological literature. Building on this, we review insights from the social sciences that can be leveraged to achieve a more holistic understanding of the broader risk context when conducting a risk assessment. Finally, to put these insights into context, using a case study we characterize how they pertain to an ongoing management challenge regarding whale entanglements in fishing gear along the United States west coast.

WHAT IS ECOLOGICAL RISK ASSESSMENT, HOW IS IT USED AND HOW IS IT CONDUCTED?

Ecological risk assessment (ERA) has its roots in hazard and disaster management (Adger, 2006) and eco-toxicological hazard and risk (De Lange et al., 2010), and has been applied to a wide range of contexts for populations, species and ecosystems (Adger, 2006; Astles et al., 2006; Teck et al., 2010; Chen et al., 2013; Fletcher, 2014). Much of the research on ERA developed as a result of legislation requiring risk assessment as part of environmental policy and management processes. In the United States the passing of the National Environmental Policy Act (NEPA, 1969) established the requirement for risk assessment. In 1983 the National Research Council published the Red Book, *Risk Assessment in the Federal Government* (NRC, 1983; Hoffmann, 2011) followed by several additional guidance documents, including Understanding Risk (NRC, 1996), the more recent Silver Book, *Science and Decisions; Advancing Risk Assessment* in 2009 (NRC, 2009) and US EPA guidance (e.g., United States, Environmental Protection Agency, 2010). Beyond the United States, ERA has been applied in a diversity of global contexts. Risk assessment guidelines have been developed by many nations for managing natural resources or at minimum ensuring safe management strategies [e.g., South Africa (Claassen et al., 2001), India (Ministry of Environment Forst and Climate Change, 2016), Philippines (Environmental Management Bureau, 2007)] and their implementation is often supported by international organizations, such as the United Nations. This highlights that although ocean-focused risk assessment may not be broadly used, elements of this process are already employed in countries across the globe, which we hope will help to enable further adoption of these processes in the context of the blue economy.

Risk assessment, in turn, is a component in a larger process termed *risk management.* That process is made up of a series of steps, including communication, consultation, monitoring and review that is common to many decision-making processes (**Figure 1**; ISO, 2009). Importantly, risk management first establishes the context for risk assessment. That is, knowledge of the relevant threats, states of nature and social circumstances that are preferred or to be avoided, the management context and the scale (individual, community, local, regional) are critical before proceeding with assessment. Once this context is established, risk assessment quantifies the consequences of exposure of individuals or populations to hazards (Burgman, 2005). The products of a risk assessment are then used for weighing policy and management alternatives and selecting the most appropriate regulatory action (Jasanoff, 1987). Essential to this process is that outputs are defined and generated in a way that is useful to decision makers (Kienast et al., 1998).

Current risk assessment methods range from those that are qualitative (Astles et al., 2006; Fletcher, 2014), to those that are highly quantitative (Zhou and Griffiths, 2008; Chen et al., 2013) but applied to questions of limited scope, to finally those that integrate qualitative and quantitative knowledge to achieve an interdisciplinary characterization of risk (Cullen and Small, 2003). Each of these is applicable in different contexts (see methods reviewed in Barnthouse, 1992; Burgman, 1993; Dale et al., 2008; Hobday et al., 2011; Chen et al., 2013; Suter, 2016). There is thus no single "correct" approach, but rather the breadth and type of information used will depend on a decision or management context external to the risk assessment.

Ecological risk assessment can be a stand-alone product, or increasingly, can be linked to broader socioeconomic considerations as a move toward social-ERA. This integrated approach is a core tenet of management in the era of the blue economy (Klinger et al., 2018), yet multi-faceted approaches have yet to be developed and adopted (Link et al., 2018). Some have argued that monetizing ecological benefits, e.g., by expressing them in the consistent unit of dollars, makes it possible to quantify trade-offs between economic and ecological considerations (Chan et al., 2012; Fischer et al., 2016). Broader use of combined approaches include ecosystem services (Chan et al., 2012), using ecological and economic objectives in decision frameworks (Cullen et al., 2007; Fischer et al., 2016) and factoring human behavior into scenario analyses (Wilen et al., 2002; van Putten et al., 2012). However, some economists have argued that economic considerations are frequently relegated to the cost-benefit factors used in decision-making, *post hoc* and separate from risk *assessment* (Williams and Thompson, 2004; Hoffmann, 2011).

While there has been a growing push for environmental management to incorporate social considerations (Liu et al., 2007; Kittinger et al., 2014; Bennett et al., 2016; Hicks et al., 2016), existing environmental decision-making processes most often focus on the social aspects that can be more readily quantified. For example, assessments may include access to fishing, recreation and aquaculture (Kittinger et al., 2014). However, aspects of social-ecological systems that are less easily accounted for such as social cohesion, identity, self-determination, and traditional practices are also important and contribute to environmental management (Poe et al., 2014). People have diverse connections with the ecological systems to which they belong (Satterfield et al., 2011; Biedenweg et al., 2016; Breslow et al., 2016). Although these connections are not easily rendered into monetary units they are no less important in risk

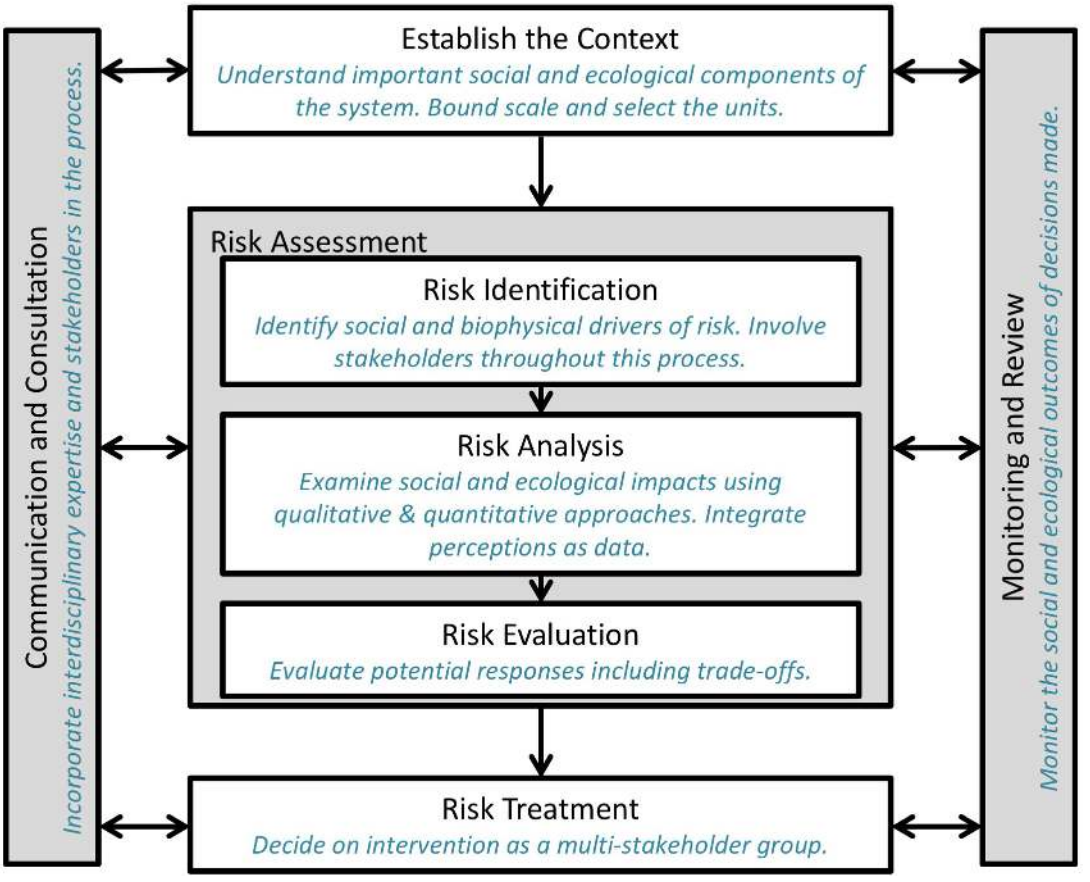

FIGURE 1 | Adapted from ISO Risk Assessment Standards (ISO, 2009), the traditional risk management framework. Text in italics has been added, and refers to the ways in which changes to this traditional process incorporate the insights from this work.

management. Across the globe as we move toward increasingly diverse uses of ocean ecosystems, ensuring inclusion of an array of social dimensions and needs of local communities in assessment and decision-making is critical (Bennett, 2018).

IMPROVING ECOLOGICAL RISK ASSESSMENT BY ADOPTING INSIGHTS FROM SOCIAL RISK RESEARCH

While most practicing ecologists do research that could be useful for management and decision-making, fewer conduct work for the direct purpose of guiding a particular decision. We argue that engaging in risk research that recognizes the multiple dimensions of management systems (including both the ecological and social) will ensure that outputs are more likely to be used. Moving beyond an ecological focus requires consideration of social dimensions such as: social connections to the environment, including hunting and fishing, ceremonial use of species, subsistence harvests and sense of place (Satterfield et al., 2011); economic factors, such as revenue variability and income diversification (Kasperski and Holland, 2013) and dependence on natural resources (Jacob et al., 2010); physical and psychological well-being (Pfeiffer and Gratz, 2016); and legal considerations (Kelly et al., 2017). This broader consideration does not require new risk management frameworks, as many already exist, including the ISO risk management loop (**Figure 1**; ISO, 2009), the Red Book risk management approach (NRC, 1983), iterative management procedures (Kates and Kasperson, 1983) and adaptive management cycles (Essington et al., 2016; Kaplan-Hallam and Bennett, 2017). Rather, it requires the incorporation of systems thinking and intentional efforts to achieve interdisciplinary collaboration (Holsman et al., 2017).

Below, we identify and characterize six key insights from risk research in the social and interdisciplinary sciences that could be applied in an ocean resource management context and would be useful for researchers and practitioners with a diversity of backgrounds (**Figure 2**). We have integrated these insights into the adapted ISO risk assessment process shown in **Figure 1**.

Subjectivity Underlies Decision-Making

Many scientists are often taught to view their work as a "value-free" endeavor through which they conduct objective measurement and analysis. This leads to the impression that ERA is itself value-free (Douglas, 2000), and the belief that scientists conducting risk assessments can determine the 'true'

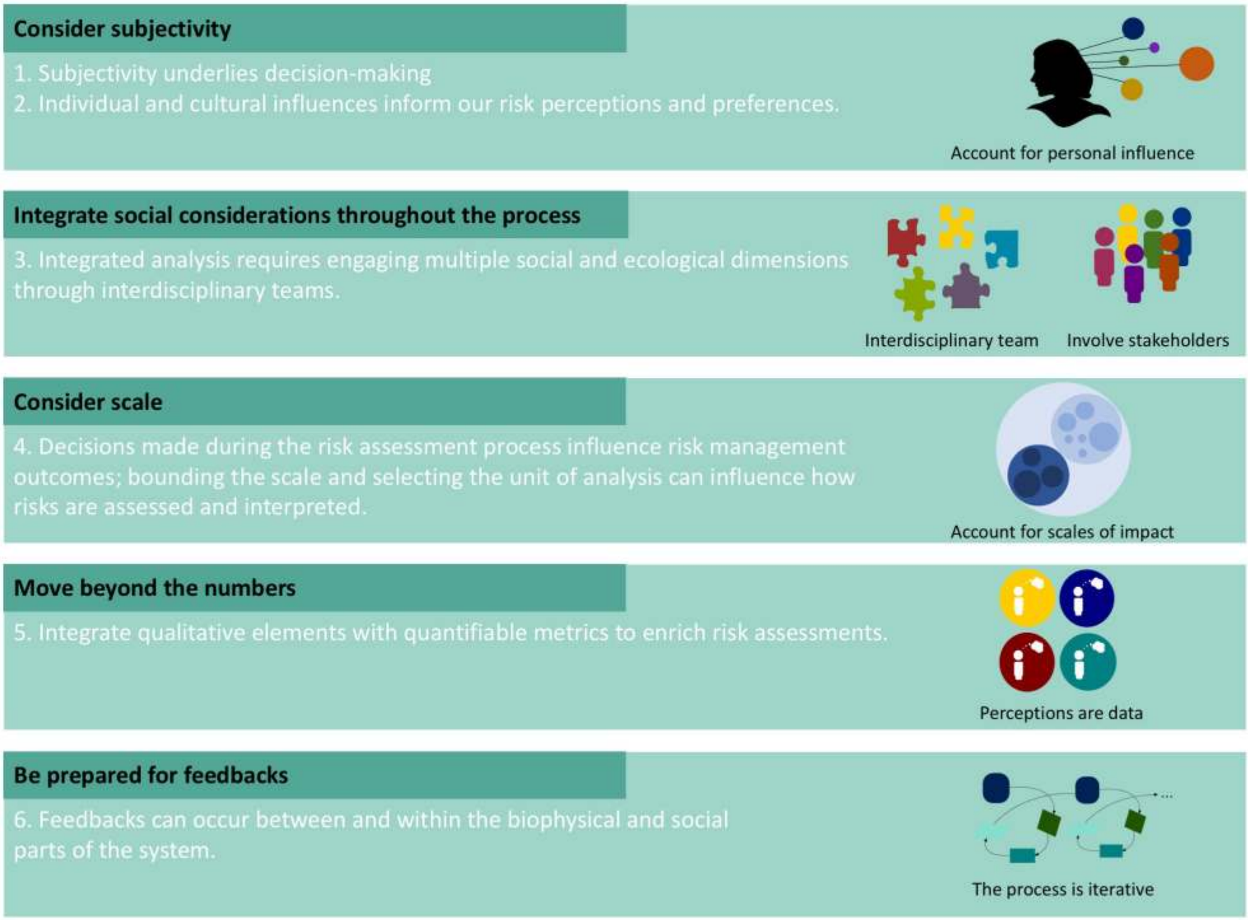

FIGURE 2 | Fundamentals for an integrated approach to risk assessment, our six insights and how to begin to account for them.

risk associated with an action (Fischhoff et al., 1984; Hermansson, 2012). This belief is not entirely untrue. Many risk outcomes are objective, for example, it is a fact that harvesting fish kills them and has the potential to put fish populations at risk of decline. Nevertheless, determining which outcomes to assess as potentially harmful is necessarily subjective. As scientists we make decisions in the research process (such as level of statistical significance), often based on expertise, past evidence and disciplinary norms, but these also have subjective influences. As noted in the Silver Book (NRC, 2009), choices at different decision points can shape the prediction of risk and the credibility of risk assessments.

In contrast, social science-informed approaches acknowledge that risk assessment is not a value-free endeavor (Fischhoff, 1995; Renn, 2008). Many social sciences acknowledge subjectivity with an understanding that information is filtered through one's personal and cultural perspective (Hermansson, 2012; Renn and Benighaus, 2013) and across types and levels of expertise (Barke and Jenkins-Smith, 1993; Bostrom, 1997). Risk judgments – including the selection of endpoints to observe in a risk assessment – are demonstrably influenced by additional factors, such as who has control over the risk and the potential for catastrophic outcomes (Barke and Jenkins-Smith, 1993; Slovic, 2000). The risk judgments and subjectivities of scientists and decision makers become topics of research and risk evaluation. Here, we provide some insights into research in the social risk sciences that can help in the integrated risk assessment process to understand where human perceptions, preferences and reactions may come from.

Even among experts, cognitive biases can influence risk perception, which in turn can influence the conduct of risk assessments (Kahneman and Tversky, 1979; Renn, 1998, 2008). These cognitive biases are now fairly well-recognized (Kahneman and Tversky, 1979), and include availability bias (events that come more easily to mind are thought to be more probable), anchoring bias (previously received information influences perception of subsequent information); representativeness bias (assuming that events experienced by an observer are representative of all related events); and finally a collection of biases that together allow individuals to avoid cognitive dissonance (where information that challenges one's belief system is down-played). These personal biases play a role both within the assessment process itself, as well as the context setting and use of information that is derived from these assessments. For example, Wilholt (2009) discusses multiple examples within biomedical research of biases influencing experimental designs all the way through to results interpretations. Perhaps the simplest bias that most researchers know of is "publication bias" (Wilholt, 2009); our tendency to publish only significant results biases our resulting understanding of potential risks from a particular activity or decision. There is therefore an opportunity to improve risk assessment outputs by both being aware of personal biases and anticipating the way that information will be perceived by decision makers.

Risk assessment ultimately requires subjective judgments (NRC, 1983, 1996). Conducting any scientific analysis requires framing the problem and choosing the methods and unit of analysis, which are to some extent subjective choices; such decisions are also required in technical risk assessments (Douglas, 2000). Although researchers are trained to remove personal bias from their work, recognizing where personal perspectives and preferences enter into risk assessment can help reconcile the assessments of those with diverse training and backgrounds across the sciences. Failure to recognize the inherent subjectivity in ERA means, minimally, that an individual's work will ultimately be less useful in practice because information is not presented in a way that aligns with the way the people receive and process information. At worst, failing to recognize these biases leads to misdirected guidance because the values that underlie even seemingly subtle decisions are not highlighted. Risk assessments are stronger when scientists simply acknowledge where subjectivity has played a role and provide justifications behind associated decisions.

Individual and Cultural Influences Inform Our Risk Perceptions and Preferences

Perception of risks is influenced by both social upbringing and individual worldviews (Douglas and Wildavsky, 1983). Renn and Benighaus (2013) proposed a hierarchical framework for how individuals perceive risk as it filters through their cultural background at the broadest scale, the social-political institutions in which they exist, cognitive and affective factors and individual information processing. In addition to perceptions of risk, risk orientation, or degree of risk aversion or tolerance (Arrow, 1971; Pratt, 1975), also influence decision-making. Loss aversion and reference-dependent preferences are common, indicating that often individuals will prefer to avoid a loss rather than acquire an equivalent gain, which can in turn influence the course of action they will prefer (Tversky and Kahneman, 1991).

Loss aversion plays out in our interpretation of different options which might be placed before us and even at times in the metrics used for identifying possible courses of action. For example, in fisheries management, metrics of risk may entirely focus on risk to livelihoods of fishers or communities (Essington et al., 2018), where these may be communities writ large, or specific communities or sectors. Alternatively, metrics may focus on ecological endpoints intended to reduce risk to fish populations (Hobday et al., 2011) or may consider both simultaneously (Siple et al., 2019). To ensure a comprehensive set of metrics requires a careful process of context setting in the risk management process and inclusion of a diversity of stakeholders (see insight 3).

Integrated Analysis Requires Engaging Multiple Social and Ecological Dimensions Through Interdisciplinary Teams

It follows from the first and second insights and considerable research on participative environmental assessment and decision-making (e.g., NRC, 2008) that achieving an effectively integrated assessment of risk to a social-ecological system requires a diverse team. This includes stakeholders, practitioners and researchers from multiple disciplines. Each stakeholder will bring their own perspectives and interests; and incorporating these differences can lead to an improved understanding of the system and what is at risk (Grimble and Wellard, 1997; Hermansson, 2012). For example, stakeholders may identify social or cultural aspects of the system not addressed in more disciplinary-specific impact assessment frameworks (Satterfield et al., 2011). When they are part of decision-making, stakeholders can contribute to conflict-resolution and steer the process toward consensus (Grimble and Wellard, 1997). Engaging a diverse group helps ensure that individual biases or perspectives will not disproportionately influence the risk assessment process, when the processes are facilitated and implemented effectively (Smith and Hou, 2014). This stakeholder engagement has been noted as one of the five key "rules" for growth in the blue economy (Burgess et al., 2018). In addition to stakeholders, rigorous incorporation of multiple sources and types of information to identify and assess risk requires researchers with diverse expertise, across the social and biophysical sciences. That is, separate from stakeholder input, rigorous social science research on risk is required, in equal manner to rigorous ERA. Integrated interdisciplinary teams can afford insights that are otherwise inaccessible (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, 2005; NRC, 2014, 2015).

It has been our experience that these risk assessment processes are intended to engage and incorporate diverse teams and expertise, but in reality, this is most often not the case. For example, it is often a single person who is brought in to represent an entire diversity of social science disciplines, whereas biophysical scientists are well-represented in the process. This is partly because within many government agencies, there is inadequate social science capacity. For example, the National Oceanic and Atmospheric Administration's National Marine Fisheries Service in the United States is the organization responsible for Integrated Ecosystem Assessments, which factor in social dimensions and use risk assessment as a framework. Yet, currently ca. <1% of employees are non-economic social scientists. In addition, while there may be interest in interdisciplinary views from the decision maker, they may ultimately implicitly rank particular elements higher than others. These issues can be addressed by intentionally balancing representation of disciplines and stakeholders on risk assessment teams (**Figure 2**) and working to achieve consensus on the most appropriate way to rank risks.

Decisions Made During the Risk Assessment Process Influence Risk Management Outcomes; Bounding the Scale and Selecting the Unit of Analysis Can Influence How Risks Are Assessed and Interpreted

Experiences and realizations of risks vary and are distributed across space and time (Boer et al., 1997; Shapiro, 2005; Cullen and Anderson, 2016; Hodgson et al., 2016). Furthermore, management decisions do not impact all groups in the same manner (Checker, 2007). Populations can be more or less vulnerable due to different socio-cultural, economic, or political factors (Arquette et al., 2002; Cutter et al., 2003; Allison et al., 2009). For example, climate change can differentially and inequitably affect some socioeconomic and ethnic groups and genders (Ajibade et al., 2013; Cullen and Anderson, 2016; Davies et al., 2018). Frequently, risk assessments rely on statistics based on majority populations – such as results from males alone, or particular socioeconomic communities – or averages across groups (Hermansson, 2012). These majority and aggregated metrics may obfuscate the fact that some individuals and communities are at higher risk.

Addressing this challenge requires awareness of how the selection of bounds and units (e.g., individuals, landscapes) and scale(s) of analysis (e.g., spatial, temporal, organizational) may influence outcomes. Units in social systems range from individuals, to households, to industrial sectors, to communities (of place or of practice, defined by social activities) and to political jurisdictions. When considering metrics, it is vital to address how risk is distributed among units and across scales of analysis. Using multiple units of analysis is one approach to addressing this concern. For example, it has long been recognized that within fisheries management different approaches may benefit or disadvantage particular groups (Guyader and Thébaud, 2001), such that small-scale fishers may be disadvantaged by approaches such as individual-transferable quotas as compared to large scale producers. While this is not necessarily always the case (Brandt, 2005), small scale fishers are a prime example of a user group that needs to be factored in decision-making as we face a time with increasing competition between ocean uses, and large asymmetries of power between those users and their ability to mobilize knowledge (including risk assessments) to advance their case for use of ocean and coastal space (Cohen et al., 2019).

Integrate Qualitative Elements With Quantifiable Metrics to Enrich Risk Assessments

Risk is defined and measured in a variety of ways in both the social and biophysical sciences. Approaches in the economic sciences are closely related to those prevalent in ERA. Insurance and actuarial risk determination (Zinn and Taylor-Gooby, 2006; Renn, 2008), financial credit risk (Chen et al., 2016), investment risk (Markowitz, 1952) and specific methods such as risk from catch variability in fisheries (Kasperski and Holland, 2013) focus on probabilities of potential (often economic) losses to persons, institutions or industries. How the probabilities and losses are assessed and combined vary.

One example approach to risk assessment within the social sciences is social impact assessment (Vanclay, 2003; Mahmoudi et al., 2013). Social impact assessment "is [the process of] analyzing, monitoring and managing the social consequences of development" (Vanclay, 2003). Social impact assessments can involve narrative, explanatory and interpretive elements with both qualitative and quantitative approaches. One of the goals is to understand socioeconomic risks – such as impacts to employment, household income and infrastructure – from a management decision, which are defined by what individuals perceive as risks. Social impacts can be diverse; individuals may be concerned about their well-being, inclusion in decision-making, property rights and/or their culture (Vanclay, 2003; Biedenweg et al., 2016; Bennett et al., 2017; Kaplan-Hallam and Bennett, 2017). Assessing risk to the social parts of social-ecological systems will be aided by engaging with those implicated in the risk identification and assessment processes.

Complementing quantitative analyses with qualitative analyses can build more robust understandings of risk, including how impacts of risk vary, as well as what is at stake for whom, why it matters and what priority actions are possible for responding (Bennett et al., 2016; Charnley et al., 2017). Qualitative research is generally viewed as useful for exploring and understanding the meaning individuals or groups ascribe to systems and risks (Creswell, 2014), whereas at the most basic level, quantitative research is more often used to assess covariation and model fit (Gerring, 2017). Tools that can factor in both quantitative and qualitative elements provide one approach to joining them. Many social and interdisciplinary scientists employ mixed methods, using both qualitative and quantitative elements (see Parker and Kozel, 2007; Creswell, 2014) and multi-criteria decision analysis (Mendoza and Martins, 2006). Qualitative and mixed methods approaches can afford a broader perspective on risk and risk assessment.

Feedbacks Can Occur Between and Within the Biophysical and Social Parts of the System

Social-ecological systems are complex and interconnected, and consequently unexpected feedbacks can result from changes within the system (Liu et al., 2007; Horan et al., 2011; Holsman et al., 2017; Tekwa et al., 2019). Unintended interactions can occur when management decisions do not account for social responses to an ecological problem, and vice versa, if they do not consider ecological changes that result from social processes (Horan et al., 2011; Tekwa et al., 2019). For example, wildlife conservation can bring attention to a species of concern which may result in increased demand for the species in trade (Larrosa et al., 2016).

Three types of social feedbacks can influence social-ecological systems, but are infrequently included in ERAs: stabilizing, amplifying, and adapting (Kaplan-Hallam et al., 2017). Stabilizing feedbacks occur when the management decision made results in a mitigation of undesired outcomes. Amplification results from the filtering of risk assessment and communication through social structures (individuals, communities, and institutions) whereby responses of those structures can contribute to exacerbating consequences (Cullen and Small, 2003; Pidgeon et al., 2003). These reactions and amplifying feedbacks within social structures can have disproportionately large consequences for both the social and ecological parts of the system. For example, this may occur when fear of a potential impact leads to behavioral changes with a negative feedback on the economy; for example, fear of the marine microorganism *Pfiesteria* led to reduced fish consumption, with multimillion dollar economic consequences (Kempton and Falk, 2000). In this way, the process of identifying risks can lead to further societal changes (Kasperson et al., 1988). Kaplan-Hallam et al. (2017) describe adaptive feedbacks as those that result in a desired change. Accounting for feedbacks is part of ongoing management and iterative assessment cycles (**Figure 2**).

LEVERAGING INTERDISCIPLINARY INTEGRATIVE RISK ASSESSMENT: THE EXAMPLE OF WHALE ENTANGLEMENTS IN FISHING GEAR IN CALIFORNIA

In this concluding section, we explore the recent management challenge of whale entanglements in fishing gear on the United States west coast, an example of conflicts in an increasingly crowded ocean. Both whale watching and crab-fishing are significant elements of California's 'blue economy.' This case study is used to demonstrate how approaching risk from an integrated perspective can reveal the contributions of ecological considerations relative to other factors, allowing decision makers to account for different influences in a transparent manner. By broadening the perspective of risk, this example is also intended to help those involved in ecosystem assessment and management understand cases where the scope is beyond a particular ecological concern, and may include risks to other factors including political risk, financial risk, legal risk, etc.

In spring of 2014, reports of increasing numbers of whale entanglements in fishing gear on the United States west coast resulted in a public outcry because of concerns for the whales (e.g., Shahagun, 2015). The number of reported whale entanglements were substantially higher than the historical average of 10 per year: 61 (48 confirmed) in 2015, 71 (48 confirmed) in 2016, 41 (30 confirmed) in 2017, and 57 (46 confirmed) in 2018 (NOAA, 2016, 2017, 2019). Dungeness crab trap lines accounted for 31% of all reported entanglements in 2016 (22 of 71) and 22% in 2017 (9 of 41), more than any other fishing method (personal communications, NOAA).

There was a series of responses to these entanglements. In 2014 a Dungeness crab working group formed, composed of crabber, government, and non-profit representatives[1]. Recommendations from the working group, made in 2016 included gear modifications, enhanced reporting and lost gear recovery. The California state legislature passed a law (Senate Bill No. 1287) in 2016 to incentivize the removal of derelict gear both during and after the crabbing season. In October 2017, the Center for Biological Diversity (CBD) filed a lawsuit against the California Department of Fish and Wildlife, over risks to whales and turtles, where they sought "common-sense reforms to the fishery such as restricting the amount of gear in whale hotspots like Monterey Bay and reducing the amount of rope running through the water" (CBD, 2017).

Despite the actions taken by the state of California and the fishing industry, public concerns made it clear that additional management measures should be considered (Lebon and Kelly, 2019). A variety of management actions have been proposed, such as spatio-temporal management, entanglement caps and technological innovations. Each poses risk in different ways. In 2019 as part of their settlement agreement with the CBD and the Pacific Coast Federation of Fishermen's Associations, the California DFW decided to close the fishery statewide beginning April 15th in an effort to reduce entanglements (Center for Biological Diversity v. Bonham et al., 2019). Here we describe how this problem may be approached from two perspectives; first, based on current risk assessment practices that focus primarily on ecological risk. We then illustrate how applying the insights described in this paper better addresses the complexities of the problem to achieve a more integrated risk assessment, and provide a *post hoc* interpretation of why California reached the early closure decision this year (2019).

A Disciplinary Ecological Risk Approach

From a narrow ecological point of view, the focus would be on the risks to individuals and populations of whales and the marine ecosystem (**Figure 3A**). At the individual animal scale, ERA might consider physiological costs of injuries and impacts on survivorship. At the population scale, an ERA would consider risks to whale population abundance and growth rate from increased mortality. Finally, analysis at the ecosystem scale would likely consider ecosystem impacts generated by changes in whale *and* crab abundances. For example, if management measures reduced rates of crabbing, what would be the change to the ecosystem from an increase in crab populations resulting from reduced fishing pressure?

Considering the Interconnected System

Taking an interdisciplinary integrative approach, the risks considered would likely expand to include risks to social institutions. **Figure 3B** illustrates this broader set of risk categories: economic, socio-cultural, legal and physical. This figure is illustrative rather than exhaustive, since a fully integrative approach requires stakeholder input. The insights identified above highlight a number of factors to include in the process of considering risk.

[1] http://www.opc.ca.gov/whale-entanglement-working-group/

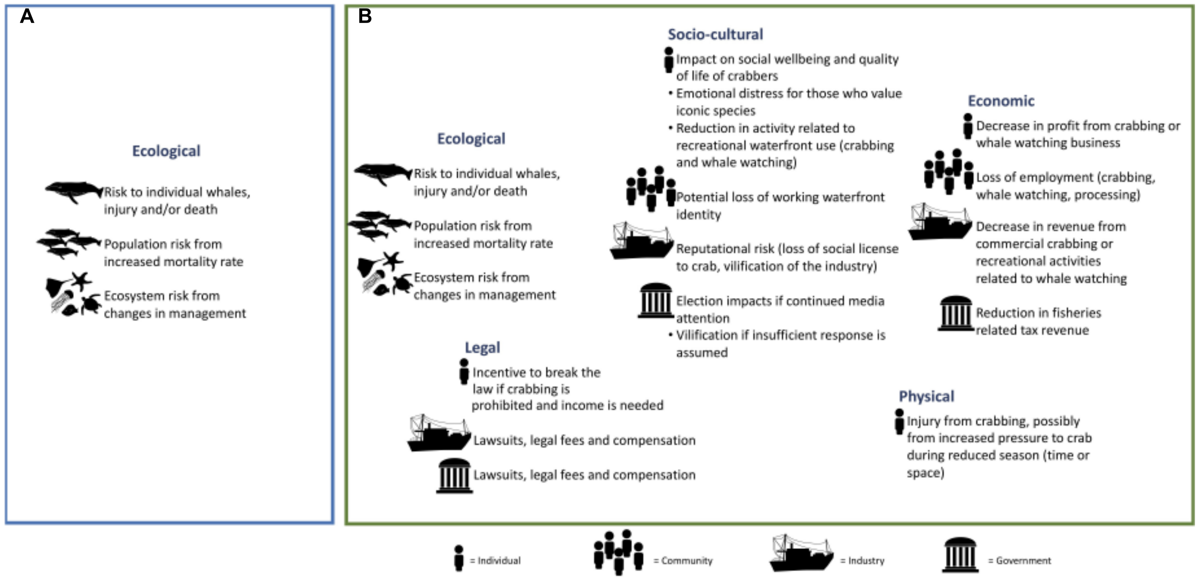

FIGURE 3 | Demonstrating the different elements of the system which may be considered under the current standard of only an ecological focus **(A)**, as compared to a broader perspective, considering economic, socio-cultural, legal and physical risks **(B)**. Within the social institutions, we define scales as follows. *Individuals* are people who may participate in crabbing recreationally or professionally, or individuals who enjoy whale watching, advocate for the protection of whales or are employed by the whale watching industry or conservation organizations. *Communities* are people that live in and around a community center on the coast, in locations where there are crab and/or whale watching industries, they may include people employed by those industries but those individuals represent only a portion of the larger community. *Industries* include the crab and whale watching industries. Finally, *government* includes both elected government bodies and government agencies.

Including a diversity of stakeholders and experts will help to ensure that specific individual biases do not disproportionately influence the risk assessment process or resulting decisions. The Dungeness crab task force has been a mechanism for stakeholder engagement in this particular case study[1]. Members of this task force consisted of multiple groups including fishers (commercial and sport), eNGOs, state and federal agency representatives and government and academic scientists. This task force represents an advance over a disciplinarily focused ERA, and because stakeholders have been involved in the management process from the beginning, the likelihood that the process and outcomes will be trusted and used in future decision-making is higher (NRC, 2008). Nonetheless, broader engagement across stakeholders and experts, including across the social and biophysical sciences, would likely improve the prospects for achieving integrative risk assessment.

As noted in insight 4, the distribution of outcomes across scales is a central piece of integrated risk analyses, as opposed to only considering risk in the aggregate. In the case of whale entanglement, it is evident that a variety of risks might be experienced across social and ecological scales and within different categories of risk (**Figure 3B**). While not all of these elements should necessarily be factored into the decision-making process, identifying an expanded set of potential risks would enable an integrated assessment. In an integrated assessment, the diverse stakeholders involved would deliberate the list of potential risks to be included in the assessment, informed by an interdisciplinary science team.

For example, should a management action reduce crabbing activities, there will likely be economic consequences for the crabbing industry. As a result, the management change may affect individuals participating in those industries, communities where the industries are based and even government institutions that receive tax revenue through landing taxes. Individual crabbers are likely to feel these impacts differently – depending on their catch diversity, vessel size and dependence on crabbing as a primary source of income (Fuller et al., 2017). Where an economic cost-benefit analysis might reveal marginal risks of closing the crab fishery to regional economies, there are profound distributional effects where one segment of the community would bear most of the risk of loss.

By comparison, if activities continue under the current trajectory, and it is found that there is a substantial risk to whale populations from entanglement (which has not been proven), there could be different types of consequences for both whale watching and crabbing industries. If demonstrated, risk to whale population viability from crabbing could be translated to reductions in revenues for the whale watching industry. At the same time, there are non-monetary socio-cultural risks associated with the lived experiences of individuals found in coastal communities or participating in the identified industries, where impacts may be felt through well-being and changes in identity (Pollnac et al., 2001). For crabbers and larger social institutions there are possible reputational risks through vilification of the industry and loss of social license to fish (Lien, 1995). Regardless of risk to whales or not, reputational risks to different stakeholders are possible as there is a strong perception of impacts from crabbing.

In addition, there are potential legal risks associated with different management actions. At the larger scale, industry or government may face legal action, such as the CBD lawsuit citing that entanglements of certain species of whales is in violation of the Endangered Species Act (CBD, 2017). Alternatively, should management enforce measures to reduce crabbing pressure, individuals may break the law in order to make a necessary income. Finally, it is important to consider the risks to physical well-being; fishing is a dangerous job, and other crabbing industries have experienced management changes, in part, to increase safety (e.g., NIOSH, 2016).

Following risk identification, multiple methods can enhance the risk assessment process. Some aspects of risk to this social-ecological system are conducive to quantification: population impacts for whales and economic impacts from management strategies. This type of quantification is common. However, risks to other aspects of the system are likely to require qualitative assessment, at least initially, such as reputational risk to the crabbing industry or the emotional distress stemming from the reductions in opportunities to crab and/or sightsee for whales. Thus, mixed methods approaches can contribute to more holistic understanding of risk and can be applied to assess diverse management options. **Figure 2** illustrates the importance of *moving beyond the numbers* and leveraging the use of perceptions as data, to achieve integrated risk assessment.

The decision to close the Dungeness crab fishery early this year is a case in point. The legal and reputational risks to California and the fishery (Pacific Coast Federation of Fishermen's Associations and Institute for Fisheries Resources), combined with perceived ecological risk to whales under *status quo* fishery management, seems to have made a disproportionate contribution (Center for Biological Diversity v. Bonham et al., 2019). The perception of some stakeholders was that decision makers felt it was more important to act immediately to avoid the high reputational and legal risks associated with continuing to fish for crab in the spring than to follow the stakeholder-driven working group process (French, 2019). Although the settlement agreement clearly leaves open the possibility of identifying less stringent management measures that will reduce ecological risk sufficiently to avoid early closures in the future, the presumption of high ecological risk until alternative evidence emerges is clear. Indeed, exchanges in the literature underscore the need to define "risk to what?," to which we propose an answer, inclusion of risk to human well-being defined quite broadly.

As described above, ongoing monitoring and iterative analysis is essential to discover unanticipated interactions in social-ecological systems. This could include further research into the causes of whale entanglements, in order to inform adaptive management and policy adjustments. It could also include additional scoping and engagement to ensure that a sufficiently broad group of stakeholders and experts were engaged in the risk assessment, as different mitigation efforts are implemented and the realizations and perceptions of risk change. Leveraging ongoing monitoring and iterative analysis creates a form of adaptive management that has the potential to factor in a much broader sweep of ecologically and socially relevant aspects of the system, by taking into fuller consideration the social and ecological repercussions of the decision. In the case of whale entanglement, this is already envisioned, as those involved in the Dungeness crab working group are well aware of the need for ongoing monitoring and management. What is less clear is how to incorporate this broader vision and these fuller considerations into future decisions, given ever-changing ecological conditions, legal context and pressures to take action.

CONCLUSION

In the era of increasing competition for ocean resources, any environmental management decision has implications for multiple components of linked social-ecological systems. Although benefits of EBM have long been recognized, implementation has been slow and modest in most places (Link et al., 2018). Working to better ensure that social and biophysical sciences contribute to risk assessments in a rigorous and independent way is a prerequisite for achieving integrated risk assessment. With the growing recognition of the importance of interdisciplinary approaches (Liu et al., 2007; Bennett et al., 2017), we offer practical steps toward these challenging goals (**Figure 2**). In the era of increasing competition for ocean space, this approach will help in the process of identifying and minimizing risks, managing impacts and trade-offs across domains and mitigating undesirable and unavoidable negative consequences.

Given that this approach builds from existing risk management frameworks (NRC, 1983, 2009; ISO, 2009; see **Figure 1**), this change does not require novel methods. Drawing insights from research on risk perceptions, judgments and decision-making from across the social and natural sciences, the approach presented here requires more collaboration, reflection and integration. Improved understanding and collaboration between researchers form the biophysical and social sciences is necessary to achieve the type of interdisciplinary and integrative risk assessments that we are advocating. A key element is factoring in the many forms that risk can take and evaluating them in decision-making and management. This needs to be done through an explicit, transparent, open, transdisciplinary risk assessment approach to obtain durable outcomes for a sustainable blue economy (**Figure 2**).

AUTHOR CONTRIBUTIONS

EH, TE, JS, NB, AB, SK, PL, and MP participated in a 1-day workshop discussion on risk across disciplines. EA and AC contributed written insights for this discussion. Collectively, all authors conceptualized the manuscript. EH led the writing of the manuscript, with input from all authors at different points and based on different author's subject area expertise.

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