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Table of Contents

List of Figures

List of Tables

Abbreviations

ABC	Acceptable Biological Catch
AFSC	Alaska Fisheries Science Center
AI	Aleutian Islands
BKC	Blue king crab
BSAI	Bering Sea and Aleutian Islands
EAFM	Ecosystem approaches to fishery management
EBFM	Ecosystem-based fisheries management
EFH	Essential fish habitat
ERA	Ecosystem-level risk assessment
ESA	Endangered Species Act
FEP	Fishery ecosystem plan
Gfish	Groundfish
LME	Large marine ecosystem
LMR	Living marine resource
MAFMC	Mid-Atlantic Fishery Management Council
MSE	Management strategy evaluation
NEFSC	Northeast Fisheries Science Center
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPFMC	North Pacific Fishery Management Council
NWFSC	Northwest Fisheries Science Center
OA	Ocean acidification
OFL	Overfishing limit
PFMC	Pacific Fishery Management Council
PS	Puget Sound
RKC	Red king crab
SoCal	Southern California Bight
SSL	Stellar sea lion
WCRO	West Coast Regional Office

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Executive Summary

Managing U.S. federal fisheries often requires considering complex interactions among fisheries, protected species, habitats, and other ecosystem components, including humans and climate. In addition, management that focuses on individual species can experience undesirable and unexpected changes due to unaccounted for impacts of climate or other ecosystem factors. Regional fishery management councils (Councils) need ways to efficiently process these interactions and the potential impacts they may have on meeting Council management objectives. One tool that can help with this is the ecosystem-level risk assessment (ERA), also called ecological risk assessments or vulnerability assessments. ERAs are management decision tools that can assist Councils in integrating large amounts of ecosystem information in a standardized, yet flexible and transparent way to help identify issues to prioritize in science or management. The purpose of this document is to share applied results from five regional case studies of ERA. The case studies cover different geographies illustrate how Councils can systematically approach ERA to help address current challenges and advance ecosystem-based fisheries management. To demonstrate the versatility of this tool, we organized the case studies by three different applications in the adaptive fishery management process: screening, prioritization, and evaluation. We emphasized broader ERAs that analyzed a number of different ecosystem drivers in one assessment. To improve the process of incorporating ecosystem information into fishery management decisions, we summarize key takeaways from the case studies. Finally, we provide additional recommendations for optimizing ERA use at the end of this report.

1. Introduction

Managing U.S. federal fisheries often requires considering complex interactions among fisheries, protected species, habitats, and other ecosystem components, including humans and climate. Regional fishery management councils (Councils) need ways to efficiently process these interactions and the potential impacts they may have on meeting Council management objectives. While the number of potential risks associated with ecosystem interactions affecting Councils' living marine resources (LMRs) seems ever-growing, the resources to manage LMRs are finite. Councils are faced with emerging issues that divide their time and prevent progress on core mandates. In a changing climate, the uncertainty surrounding these potential impacts (e.g., next heat wave, disease outbreak, or algal bloom) further challenges Councils in prioritizing management and scientific needs.

Given these challenges, the National Marine Fisheries Service (NMFS; herein referred to as NOAA Fisheries) and the Councils have recognized the importance of implementing ecosystem-based fisheries management (EBFM). EBFM acknowledges the physical, biological, economic, and social interactions among LMRs and the fisheries that depend on them, and seeks to optimize benefits among diverse goals for those LMRs. NOAA Fisheries formalized its commitment to EBFM through the development of an EBFM policy (NMFS 2016a) and roadmap (NMFS 2016b). Both documents follow a hierarchy of six guiding principles to support the effective implementation of EBFM: ecosystem-level planning, foundational science, prioritizing vulnerabilities and risks, exploring trade-offs, incorporating ecosystem considerations into management advice, and maintaining resilient ecosystems. This structure aligns with the adaptive management cycle of Councils and offers a suite of ecosystem-based tools in support of the guiding principles.

One such tool is the ecosystem-level risk assessment (ERA). ERAs, also called ecological risk assessments or vulnerability assessments, are management decision tools that integrate information on individual and cumulative pressures to estimate the relative probability and magnitude of an undesirable ecological response (Holsman et al. 2017, Suter and Norton 2019). They provide a standardized, yet flexible and transparent framework that can assist in assessing tradeoffs and prioritizing conservation and management actions (Holsman et al. 2017, Gaichas et al. 2018). ERAs can analyze relative risk broadly or in response to a small number of drivers (Holsman et al. 2017) and are a core component of NOAA's Integrated Ecosystem Assessment Program (NOAA, n.d.). For the purposes of this paper, we are focusing on ERAs that assess multiple ecosystem pressures and risks, including where possible the cumulative impacts to the ecosystem and its fisheries. For a table of additional examples of ERA approaches, see Holsman et al. 2017.

Using a systematic approach, like ERA, can help organize information in an objective way to estimate relative risk and associated uncertainties. This allows Councils to focus on risk elements affecting the greatest number of stocks or on fisheries that have a larger number of high-risk interactions. Furthermore, making ERAs a regular part of the Council process demystifies risk and builds trust and a common understanding of uncertainty by improving transparency, and in some cases, collaboration. ERAs can also link to and assist in achieving other guiding principles of EBFM and their associated tools. These principles include understanding ecosystem processes through the development of ecosystem status reports, exploring trade-offs via management strategy evaluations (MSEs), and incorporating ecosystem considerations into management advice through stock assessment and allowable biological catch recommendations.

The purpose of this document is to share applied results from five regional case studies of ERA covering different geographies to illustrate how Councils can systematically approach ERA to help address current challenges and advance EBFM. To demonstrate the versatility of this tool, we organized the case studies according to three different applications in the adaptive fishery management process:

- As a screening tool during early scoping,
- As a prioritization tool for management focus, and
- As a decision-support tool to incorporate ecosystem information into decision-making and/or evaluate potential impacts of certain management strategies and reference points.

2. Case Studies

2.1 As a Screening Tool

An ERA can be a useful tool for management scoping. For example, it can be used to develop a new fishery management plan or as an initial step in other management tools like scenario planning. ERA can also be used to quickly screen out low-risk elements and identify key pressures that may be affecting a wide range of species, habitats, or communities and warrant additional analyses or monitoring (Holsman et al. 2017). As a transparent process, ERA is a helpful tool for engaging diverse stakeholders during a scoping phase (Mikkelsen et al. 2022).

2.1.1 Case Study 1: Aleutian Islands Fishery Ecosystem Plan

Overview: The North Pacific Fishery Management Council (NPFMC) completed its first fishery ecosystem plan (FEP) for the Aleutian Islands region (NPFMC 2007). The goal of the FEP was to "provide enhanced scientific information and measurable indicators to evaluate and promote ecosystem health, sustainable fisheries, and vibrant communities in the Aleutian Islands region." As one of the first FEPs developed by a Council, the NPFMC set an example of how to carry out an ecosystem approach to fisheries management. As part of the FEP, the NPFMC included an ERA as an "interim step towards developing a comprehensive ecosystem assessment for the Council." The ERA helped the NPFMC identify and prioritize issues of concern to develop a warning system to monitor ecosystem changes in the region. However, the NPFMC did not design the ERA to be a decision-making tool.

Process: The NPFMC's Aleutian Islands Ecosystem Team used expert opinion to qualitatively compare important ecological, human, and institutional interactions with the fishery ecosystem and economy. An interaction was defined as a component (or group of components) that has an impact on another component or group. The categories of interactions evaluated included climate and physical, predator-prey, fishing, regulatory, and other socioeconomic factors. Experts ranked the probability of interactions or results of interactions occurring (e.g., changing water temperature or fishing and predation mortality) as high, medium, or low. They also ranked ecological and economic impacts as high, medium, or low, considering the time and geographic scale of the potential impacts.

The ERA authors included a section on the implications for management, including what the NPFMC was currently doing to address the potential risk of each interaction as well as recommendations on additional actions the NPFMC could take. Interactions were cross-referenced to fishery management plans with a corresponding management objective and identified whether the interaction was within the NPFMC's control. The authors also identified candidate indicators for tracking interactions of concern divided across three categories: interactions that were currently included in the stock assessment and fishery evaluation reports, interactions for which data was available, but not tracked by the NPFMC, and interactions for which data was not available yet. Data gaps and needed research were also discussed. Connections among interactions were illustrated in a conceptual model called a cognitive map, including the direction and strength of the interactions (Prigent et al. 2008).

Results and Initial Outcomes: The resulting product was a comprehensive table of all the interactions and their rankings as risk assessment priorities, whether they are addressed in the groundfish or crab fishery management plans, whether they are within NPFMC control, if the Council is currently addressing the risk, and potential options for what NPFMC might do to address them (for an excerpt of high priorities see Table 1).

Table 1. Adapted from NPFMC 2007: Summary of the high priority risk assessment interactions. The table includes the risk assessment on each interaction, and the implications for management of each assessment. For each interaction, the Fishery Ecosystem Plan has identified specific actions that the Council may wish to consider, either to obtain a better understanding of the interaction, or to mitigate the risk associated with that interaction. gfish = groundfish, SSL = Stellar sea lion, BSAI = Bering Sea and Aleutian Islands, AI = Aleutian Islands, AFSC = Alaska Fisheries Science Center

Interaction	Risk assessment priority?	Fishery management policy priority?	Within Council control?	What is the Council currently doing to address this risk?	Possible short-term Council actions	Possible long-term Council actions
Fishing and predation mortality on managed species	high	yes (gfish)	yes	Ad hoc, species by species. SSL protection measures are best example.	Focus on species with the most important predator-prey interactions. Use food web model and mortality source estimates to characterize commercial species as primarily "prey" or '"predator", and consider these differently.	Task new or existing management body to provide ecosystem-level advice, rather than species-by-species. Develop framework to "assign" an amount of a species' productivity to its predators, when setting fishery catch levels. Implement mechanisms which more explicitly integrate ecosystem considerations into the allocation process.
Total removals	high	yes (gfish)	yes	Total removals are well managed for the BSAI groundfish, but not necessarily specific limits for AI specifically.	Evaluate AI framework of indicators for evidence of a distinct system, particular with regard to genetic flow and trophic linkages.	Evaluate need to develop an AI-specific groundfish cap.
Stock structure	high	no	yes	Some research for certain AI species to look at whether AI population is distinct from EBS population.	Encourage tagging and genetics studies, research into the interaction between physical and biological characteristics.	Modeling studies to determine biological impact of various scales of spatial management.

Interaction	Risk assessment priority?	Fishery management policy priority?	Within Council control?	What is the Council currently doing to address this risk?	Possible short-term Council actions	Possible long-term Council actions
Vessel traffic	high	yes	somewhat	NOAA Fisheries/U.S. Coast Guard require and enforce vessel safety standards for fishing vessels.	Engage with the State of Alaska/U.S. Coast Guard's vessel traffic risk assessment (through Alaska Marine Ecosystem Forum).	Prepare contingency plan for a response to AI accident scenarios.
Bottom up productivity changes	high	yes (gfish)	somewhat	Some indices presented as part of Ecosystem Considerations chapter, but AI not well represented.	Consider species' roles as prey and predator when assessing harvest levels. Encourage AFSC "Fisheries Interactions in Local Ecosystems" initiative, and include study for AI.	Consider estimating a measure of optimum yield for the AI ecosystem that is updated on a periodic timeframe. Develop framework to adjust management for species with shared prey fields.
Change in water temperature	high	no	no	Some Alaska research, not specific to AI.	Monitor for big changes (need to define 'big').	Encourage funding for physical data collection in the AI. Encourage research into biological-physical linkages.
Ocean acidification	high	no	no	NOAA program is investigating.	Interact with NOAA program to encourage monitoring and investigation in the AI ecosystem.	Develop an ocean acidity monitoring program in AI. Encourage research into the threshold effects of acidification on different parts of the ecosystem.
Oil and gas	high	no	no	Dialogue with Minerals Management Service through the Alaska Marine Ecosystem Forum.	Monitor lease sales and participate in development of analyses and mitigation for potential impacts on fish stocks and fisheries.	Identify sensitive areas where oil and gas development are not compatible with existing uses/habitat needs, and proactively seek to exclude oil and gas development where it might affect these areas.

The Ecosystem Team ranked the following interactions with a high probability of occurrence and high ecological impact: changing water temperature, increasing ocean acidification, and vessel traffic (Fig. 1). The following high probability interactions were also ranked high for economic impact: increasing ocean acidification and vessel traffic (Fig. 2). Other interactions were ranked high as a risk assessment priority because they had high potential ecological and/or economic impacts and medium or unknown likelihood. These interactions include fishing and predation mortality, bottom-up productivity changes, total removals, stock structure, and oil and gas development. Interactions with unknown likelihood and/or magnitude included other biota habitat impacts and changes in nutrient transport. Understanding these interactions was considered a high priority for further research or analysis.

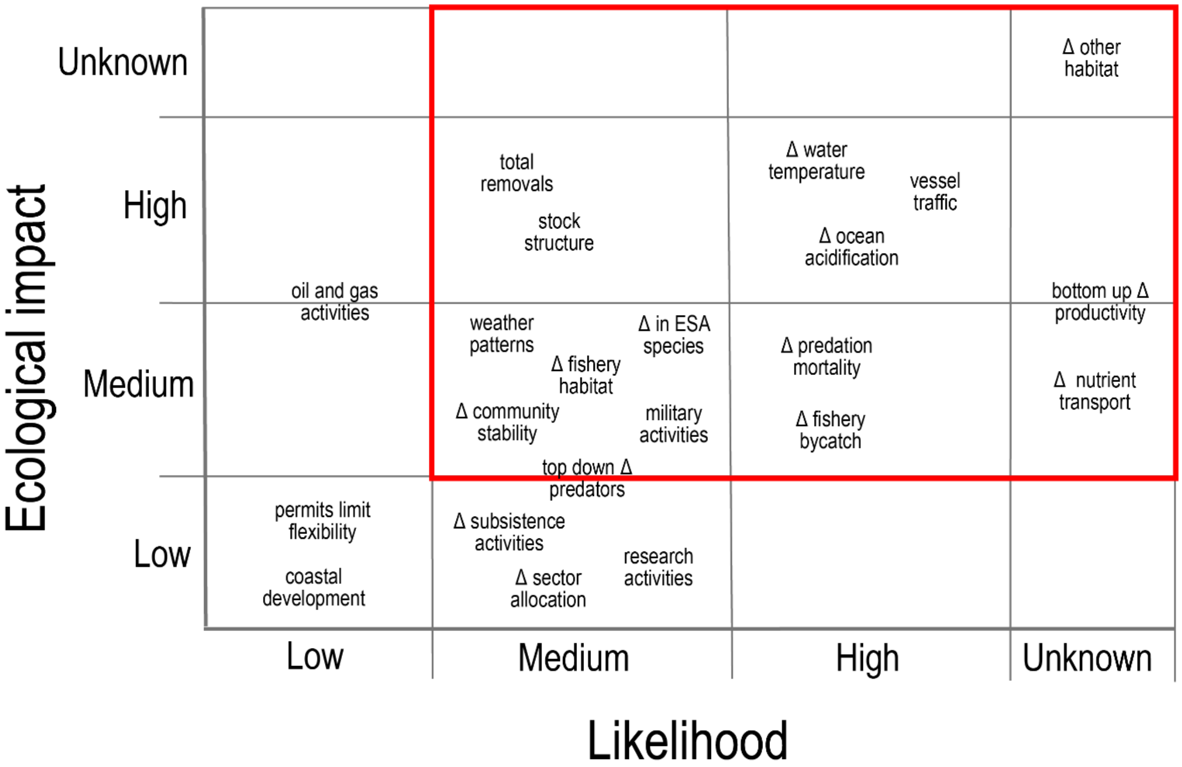

Figure 1. Likelihood of occurrence and ecological impact assessment of interactions. Based on the professional judgment of the Aleutian Islands Ecosystem Team (NPFMC 2007). Note that the red box in the upper right quadrant highlights those interactions with a medium to high or unknown likelihood of occurrence and impact. Δ symbol = change.

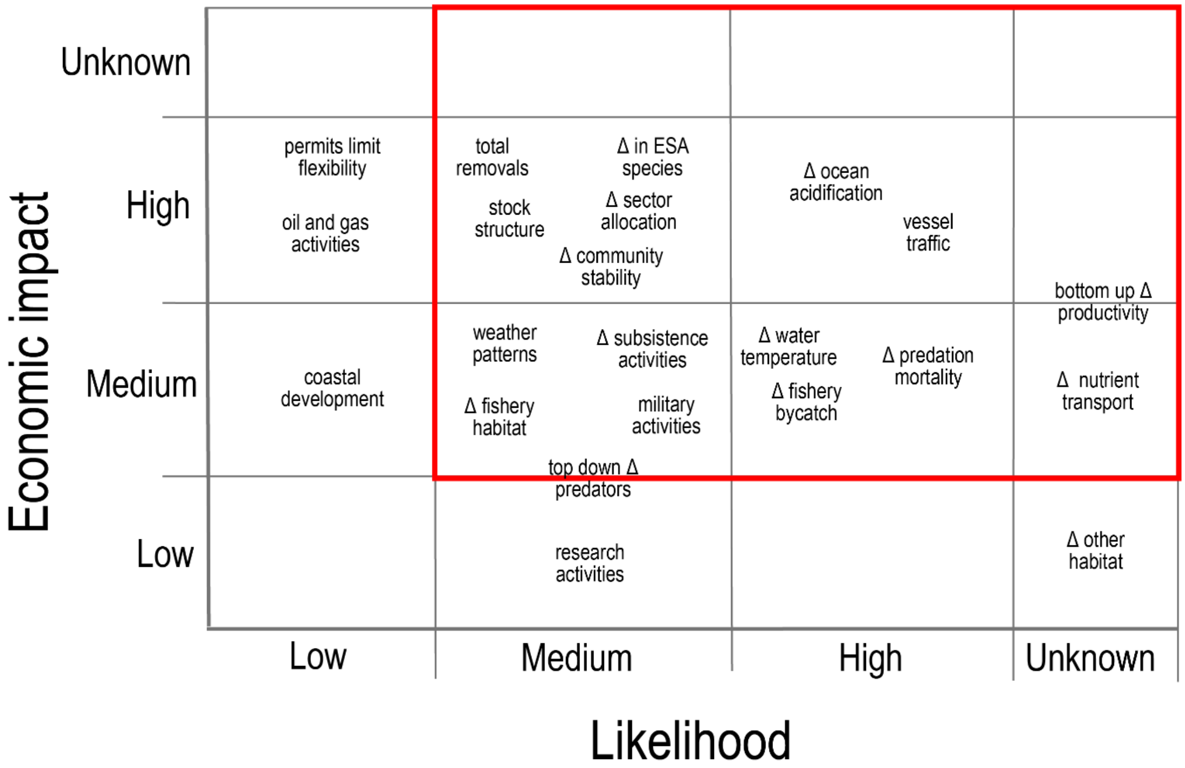

Figure 2. Likelihood of occurrence and economic impact assessment of interactions. Based on the professional judgment of the Aleutian Islands Ecosystem Team (NPFMC 2007). Note that the red box in the upper right quadrant highlights those interactions with a medium to high or unknown likelihood of occurrence and impact. Δ symbol = change.

NOAA Fisheries' Alaska Regional Office used some of the indicators within National Environmental Policy Act analyses, such as the programmatic Environmental Impact Statement for the groundfish fishery management plan.

Challenges and Further Applications: While the NPFMC did not use the ERA in a systematic way, stock assessment scientists began incorporating information from the ERA into stock assessment recommendations on an ad hoc basis. This led to the eventual development of stock-specific risk tables, which we will discuss in Section 2.3.1. The NPFMC learned that having a procedure for how to use the results of the ERA might have increased its application. Thus, the NPFMC included a process through action modules outlined in the Bering Sea FEP (NPFMC 2019). A full risk analysis for the Bering Sea FEP was not prioritized by the NPFMC. However, analyses specific to climate risk, such as assessments of the vulnerability of commercial fishing stocks to climate change (Spencer et al. 2019), are ongoing through the Bering Sea FEP team's climate change action module and task team. The goal of these analyses are to provide climate-resilient management tools to summarize key risks, climate adaptation actions, and where possible, residual risk exists (remaining risk after adaptation; NPFMC 2021).

2.2 As a Prioritization Tool

ERA evaluates relative risk to fisheries, species, and other ecosystem components. This evaluation can help assess potential management actions and identify management or science priorities. Therefore, Councils can use ERAs to focus limited resources on high-risk species or issues in an objective and defensible manner.

2.2.1 Case Study 2: West Coast Fishery Specific Habitat Objectives Pilot

Overview: When the abundance of a fish stock drops below the minimum stock size threshold, managers determine the stock to be overfished and it enters a formal rebuilding program. This approach assumes the reason for low abundance is overfishing. However, some stocks are slow to rebuild because they are habitat-limited, and depend on particular habitats during critical life stages. By identifying, prioritizing, and quantifying conservation activities, NOAA Fisheries can more effectively use its resources on stocks that are particularly dependent or vulnerable to habitat degradation, and are not rebuilding through reductions in fishing mortality alone.

Thus, NOAA's Northwest Fisheries Science Center (NWFSC) led the development of a process for creating species-specific habitat conservation objectives to support rebuilding and maintaining selected stocks managed by the Pacific Fishery Management Council (PFMC). The development of qualitative objectives for four groundfish species drew from a combination of conceptual models and a semi-quantitative risk assessment to evaluate the relative risk of 17 non-fishing-related anthropogenic stressors present in the California Current Large Marine Ecosystem (Halpern et al. 2009). The NWFSC's intent of identifying habitat conservation objectives and high-priority stressors was to guide targeted implementation of strategies, such as habitat restoration and Essential Fish Habitat (EFH) and Endangered Species Act (ESA) consultations that could best support stocks at risk.

Process: A multi-agency team led by NWFSC carried out the risk assessment in two phases[1]. The first phase was a proof of concept that set habitat objectives across the entire West Coast, making use of coarse spatial data. The second phase focused on two regions with fine-scale data: Puget Sound and the Southern California Bight.

For both phases, the team calculated relative risk for each stressor by species, life stage, and geographical area by adapting the Productivity and Susceptibility Analysis Framework (Patrick et al. 2010, Andrews et al. 2011), where the two axes of risk assessed were exposure-habitat vulnerability and sensitivity. The exposure-habitat vulnerability axis incorporated information about the species' exposure to stressors at different life stages, and the vulnerability of the habitat types used by the species.

Exposure and vulnerability information relied on Habitat Suitability Probability scores from the NOAA Fisheries EFH Environmental Impact Statement (NMFS Northwest Region 2005), the Habitat Use Database, and information on the relative intensity of stressors across the coast. Stressor data was taken from Halpern et al. (2009) in Phase 1 and finer-scale stressor data from sources like individual states and the Bureau of Ocean Energy Management, as available, in Phase 2. Stress values were calculated by multiplying the presence/absence of the stressor in a given location by its extent.

The sensitivity axis incorporated information about the species' resistance (based on mortality, behavioral response, and physiological response information) and their ability to recover from those stressors (based on life history characteristics). Once risk scores were calculated for each life stage, life cycle models were used to weight risks by life stage. The weighting accounts for the elevated population-level impacts of risks to older life stages due to their higher reproductive value.

Stressors were further ranked based on overall risk and contribution of exposure-habitat vulnerability to that risk score. This approach prioritized stressors that NOAA Fisheries and the PFMC can address through habitat conservation efforts. NOAA Fisheries can limit the exposure of species and habitats to some stressors, but it cannot reduce the sensitivity of a species to those stressors. Based on this reasoning, high-priority stressors are those that have high overall risk and

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[1] From: Yergey, M., Sherman, K., Greene, C., Schaeffer, K., Stadler, J., Wakefield, W., Walton, R., Hilgart, M., Lederhouse, T., Latchford, L., Phillis, C., Rice, J., Lawson, P., & Griffin, K. (2016). Fishery Specific Habitat Objectives – West Coast Pilot Draft Report. *Unpublished manuscript.*

high exposure-habitat vulnerability. In Phase 1, the stressor data from Halpern et al. (2009) was not at a fine enough spatial resolution and did not allow realistic prioritization of stressors and their risk to groundfish. The Phase 2 analysis produced more realistic results using the available fine-scale data for the two smaller areas.

Results and Initial Outcomes: In Phase 1, three of the four species had ocean acidification (OA) as the highest risk score, whereas the fourth species, black rockfish, had risk from invasive species as the highest. Other stressors were sea surface temperature and atmospheric pollution deposition.

Phase 2 risk scores differed from Phase 1, most notably in that large-scale climate-related stressors did not dominate the high-risk stressors anymore. Bottom trawling and derelict fishing gear had consistently high-risk scores across all five species and both regions. After ranking stressors based on both the overall risk score and contribution of exposure-habitat vulnerability, high-priority stressors for all four groundfish species included derelict fishing gear, oil spills, bottom trawling, and invasive species. Submarine pipeline cable and coastal development were high priorities for all species except English sole (Table 2[2]).

Table 2. Summary Phase 2 risk score results of stressor prioritization for the four focal species and two geographic areas. SoCal = Southern California Bight, PS = Puget Sound, H = high priority, M = medium priority, L = low priority, and NA = not applicable or insufficient data.

	Black Rockfish		**Boccacio**		**Lingcod**		**English Sole**	
Stressor	SoCal	PS	SoCal	PS	SoCal	PS	SoCal	PS
Derelict fishing gear	H	H	H	H	H	H	H	H
Oil spills	H	H	H	H	H	H	H	H
Bottom trawling	H	H	H	H	H	H	H	H
Invasive species	H	H	H	H	H	H	H	H
Submarine pipeline cable	H	H	H	H	H	H	M	M
Coastal development	H	H	H	H	H	H	M	M
Marine debris	H	NA	H	NA	H	NA	M	NA
Storm/wastewater discharge	M	M	M	M	M	M	M	M
Overwater structures	M	M	M	M	M	M	L	L
Aquaculture	M	M	M	M	M	M	L	L
Commercial shipping	M	M	M	M	M	M	L	L

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[2] From: Yergey, M., Sherman, K., Greene, C., Schaeffer, K., Stadler, J., Wakefield, W., Walton, R., Hilgart, M., Lederhouse, T., Latchford, L., Phillis, C., Rice, J., Lawson, P., & Griffin, K. (2016). Fishery Specific Habitat Objectives – West Coast Pilot Draft Report. *Unpublished manuscript.*

	Black Rockfish		Boccacio		Lingcod		English Sole	
Stressor	SoCal	PS	SoCal	PS	SoCal	PS	SoCal	PS
Dredging	M	M	M	M	L	L	L	L
Recreational boating	M	M	M	M	L	L	L	L
Oil and gas exploration	M	NA	M	NA	M	NA	M	NA
Beach nourishment	M	NA	M	NA	M	NA	M	NA
Altered freshwater flow	L	M	M	M	L	L	L	L
Water intake structures	L	L	L	L	L	L	L	L

The qualitative results and diverse list of high-risk stressors led to the development of a generic habitat objective that NOAA Fisheries and the PFMC can use to address stressors that contribute to the risk to the four groundfish species. The resulting objective was to "decrease exposure to priority stressors (those ranked high and medium) to recover degraded focal species habitat, protect high-functioning focal species habitat, and decrease overall risk to focal species."

The team intended for the habitat objective and risk assessment results to guide EFH consultations and restoration efforts. It is not clear to what extent that occurred; however, coordination between NOAA's West Coast Regional Office (WCRO) and the PFMC on consultations of interest did increase following this project.

Challenges and Further Applications: Similar to the first case study, the PFMC and WCRO did not have a procedure or framework to use the results for decision-making. However, this pilot effort illustrates how using habitat to define a spatial scope for risk exposure can help target actions where they will be most effective. This was a strength of the project, but also a challenge; as higher-level EFH data was limited, the spatial extent of stressors was not well delineated, and habitat use data had not been updated since 2005. EFH-related data is organized across four levels, with Level 4 being the highest level of information that describes EFH. One of the main recommendations from this effort was to collect higher level EFH-related data, such as habitat-related densities (Level 2), growth, reproduction, or survival rates (Level 3), and habitat-specific production rates (Level 4). These data would enable the development of more quantitative habitat objectives (e.g., number of acres of a specific habitat necessary for a sustainable fishery) for these species.

2.2.2 Case Study 3: Mid-Atlantic Fishery Management Council's Ecosystem Approaches to Fishery Management

Overview: For the Mid-Atlantic Fishery Management Council (MAFMC), risk assessment was the first step in implementing their Ecosystem Approaches to Fishery Management (EAFM) guidance document (MAFMC 2019). The EAFM guidance document grew out of a stakeholder-driven process, in which food web and ecosystem interactions were identified as important areas of management focus for the future of marine fisheries (Muffley et al. 2021). The MAFMC became interested in how interactions among species, fleet, habitat, and climate could be integrated into its management and science programs. As a starting point, they opted to use risk assessment to narrow down the number of ecosystem interactions. This allowed more in-depth quantitative analyses to be focused on the highest-risk threats to achieving ecosystem goals (Muffley et al 2020). The result of this risk assessment project was a set of color-coded tables that show levels of risk at the individual species level, the species level by sector, and the ecosystem level. The MAFMC then chose a high-risk stock as the subject of further analysis and planning under the EAFM framework. In addition, the tables are updated annually to reflect changes in risk levels, and are used in various other ways by MAFMC members and staff.

Process: The risk assessment combined qualitative and quantitative information drawn from the Mid-Atlantic State of the Ecosystem Report (NEFSC 2018), a climate vulnerability assessment of northeastern fish species (Hare et al. 2016), and several other sources, including expert opinion. Managers and scientists together identified five categories of objectives, which they termed "risk elements": ecological, economic, social, food production, and management. They then chose potential indicators for each risk element, and defined criteria to rank each indicator on a qualitative scale from low to high.

This process resulted in a list of 25 risk elements with associated risk criteria. For example, for the risk element "ecosystem productivity", low risk was defined as "no trends in ecosystem productivity", and high risk was defined as "decreasing trends in ecosystem productivity, by all measures." Depending on the risk element, these criteria were applied to each species, to each species by fishing sector (commercial and recreational), or to the ecosystem as a whole (Gaichas et al. 2018).

Results and Initial Outcomes: The MAFMC's goal for this analysis was to identify which fisheries carried the most risk across elements, and to do further analysis and planning around its management goals for those fisheries. They selected summer flounder (*Paralichthys dentatus*), an economically important commercial and recreational fishery that scored high across the most risk categories, as their first target for more analysis (Gaichas et al. 2018). The Council convened a workgroup over the course of a year to identify system linkages, available data sources, and draft management questions relevant to summer flounder and the associated fisheries. The workgroup developed a conceptual model to further consider the key risk factors affecting summer flounder and the fisheries that target it (DePiper et al. 2021). The Council used the conceptual model to identify the focus of a MSE for summer flounder (MAFMC 2023, Muffley et al. 2021). The ongoing MSE is a collaborative process using a simulation model to test the performance of proposed management measures for achieving stakeholder-defined fishery objectives.

Challenges and Further Applications: Council staff and analysts collaborate to update the risk assessment every year as new data becomes available. Interestingly, summer flounder improved on a number of risk elements, including overfishing status (F status), regulatory complexity of recreational fishery, and spatial distribution of stocks to commercial allocation due to actions the Council has taken (Tables 3 and 4; NEFSC 2022).

The MAFMC's Science and Statistical Committee has recently begun exploring whether the risk assessment and other ecosystem indicators could help them more transparently set Acceptable Biological Catch (ABC) limits, by providing an objective measure of ecosystem uncertainty that can be applied to the Overfishing Limit (OFL).

Table 3. Mid-Atlantic Fishery Management Council species level risk analysis results from 2022 (adapted from Table 5 in NEFSC 2022). L = low risk (green), lm = low to moderate risk (yellow), mh = moderate to high risk (orange), h = high risk (red). Assess = assessment performance, Fstatus = fishing mortality limit status, Bstatus = stock biomass target status, FW1 Pred = food web interactions as a predator of managed species, FW2 Prey = food web interactions as prey for managed species, FW3 = food web interactions as prey for protected species, Climate = climate vulnerability, Dist Shift = distribution shift potential, EstHabitat = dependence on estuarine habitat.

Species	Assess	Fstatus	Bstatus	FW1 Pred	FW1 Prey	FW2 Prey	Climate	Dist Shift	EstHabitat
Ocean Quahog	l	l	l	l	l	l	h	mh	l
Surfclam	l	l	l	l	l	l	mh	mh	l
Summer flounder	l	l	lm	l	l	l	lm	mh	h
Scup	l	l	l	l	l	l	lm	mh	h
Black sea bass	l	l	l	l	l	l	mh	mh	h
Atl. mackerel	l	h	h	l	l	l	lm	mh	l
Chub mackerel	h	lm	lm	l	l	l	na	na	l
Butterfish	l	l	lm	l	l	l	l	h	l
Longfin squid	lm	lm	lm	l	l	lm	l	mh	l
Shortfin squid	lm	lm	lm	l	l	lm	l	h	l
Golden tilefish	l	l	lm	l	l	l	mh	l	l
Blueline tilefish	h	h	mh	l	l	l	mh	l	l
Bluefish	l	l	h	l	l	l	l	mh	h
Spiny dogfish	lm	l	lm	l	l	l	l	h	l
Monkfish	h	lm	lm	l	l	l	l	mh	l
Unmanaged forage	na	na	na	l	lm	lm	na	na	na
Deep-sea corals	na	na	na	l	l	l	na	na	na

Table 4. Mid-Atlantic Fishery Management Council species and sector (C = commercial and R = recreational) level risk analysis results from 2022 (adapted from Table 7 in NEFSC 2022). l = low risk (green), lm = low to moderate risk (yellow), mh = moderate to high risk (orange), h = high risk (red). MgtControl = fishing mortality control, TecInteract = technical interactions, OceanUse = other ocean uses, RegComplex = regulatory complexity and stability, Discards = amount of discards, Allocation = allocation optimization.

Species	MgtControl	TecInteract	OceanUse	RegComplex	Discards	Allocation
Ocean Quahog-C	l	l	lm	l	mh	l
Surfclam-C	l	l	lm	l	mh	l
Summer flounder-R	mh	l	lm	mh	h	h
Summer flounder-C	lm	mh	lm	mh	mh	l
Scup-R	lm	l	lm	mh	mh	h
Scup-C	l	lm	mh	mh	mh	l
Black sea bass-R	h	l	mh	mh	h	h
Black sea bass-C	h	lm	h	mh	h	l
Atl. mackerel-R	lm	l	l	lm	l	l
Atl. mackerel-C	l	lm	mh	h	lm	h
Butterfish-C	l	lm	mh	mh	mh	l
Longfin squid-C	l	mh	h	mh	h	l
Shortfin squid-C	lm	lm	lm	mh	l	h
Golden tilefish-R	na	l	l	l	l	l
Golden tilefish-C	l	l	l	l	l	l
Blueline tilefish-R	lm	l	l	lm	l	l
Blueline tilefish-C	lm	l	l	lm	l	l
Bluefish-R	lm	l	l	lm	mh	h
Bluefish-C	l	l	lm	lm	lm	l
Spiny dogfish-R	l	l	l	l	l	l
Spiny dogfish-C	l	mh	mh	mh	lm	l
Chub mackerel-C	l	lm	lm	lm	l	l
Unmanaged forage	l	l	mh	l	l	l
Deep-sea corals	na	na	mh	na	na	na

The risk assessment authors believe that their iterative process of annual updates has been key to the success and continued use of the risk assessment. Because they see the risk assessment as an ongoing project, the MAFMC can ask for updates or changes to fit their current management needs. It was also important to the MAFMC to have a plan for using the risk assessment at the outset of the project; they outlined its purpose and use in their EAFM guidance document before starting the ERA process. While the ERA's eventual uses have gone beyond the MAFMC's initial purpose, having an application in mind for the ERA and keeping the MAFMC involved throughout helped make the project more useful for management.

2.3 To Incorporate Ecosystem Considerations into Decision-Making

There is broad recognition that single-species models and stock assessments must include simplifying assumptions about the species and ecosystem to produce reliable outputs. Stock assessment scientists continue to make incremental progress on incorporating ecosystem factors to better account for environmental impacts on the stock. However, this process can be data-intensive and time-consuming. ERA is a less data-intensive, more transparent, and quicker option for including considerations of risk and/or uncertainty, and non-intuitive interactions, into management advice.

2.3.1 Case Study 4: Risk Tables for Stock Assessment Advice in the North Pacific Fishery Management Council

Overview: Councils use stock assessments to recommend the OFL and ABC for the stocks in their jurisdictions. The ABC can be the same as the OFL, but scientists may recommend that it be reduced relative to the OFL to account for uncertainty in the data or in the stock assessment itself. When recommending a reduction in the ABC, scientists are required to explain the conditions or uncertainties that warrant the reduction.

Scientists working with the NPFMC recently noted their need to standardize the incorporation of ecosystem information used in recommending or not recommending a change in ABC, as well as the criteria for determining how large the change should be (Dorn and Zador 2020). The risk tables were created in part to allow scientists to be responsive to novel conditions in the environment, such as the 2014–2016 marine heat wave in Alaska.

Because of the lag time in stock assessment modeling, scientists were not always able to incorporate novel conditions into the stock assessment that had been used to set an OFL and ABC for the next year. In addition, some ecosystem impacts on stocks are difficult to quantify, and therefore difficult to include in stock assessment models. They determined that information not explicitly addressed in the stock assessment model should be incorporated into these criteria, and created risk tables for each stock, which are used to help stock assessment experts qualitatively evaluate each type of consideration based on information not accounted for in the stock assessment model (Fig. 3). These risk tables have been used for several years to help scientists transparently recommend ABCs in a standardized way.

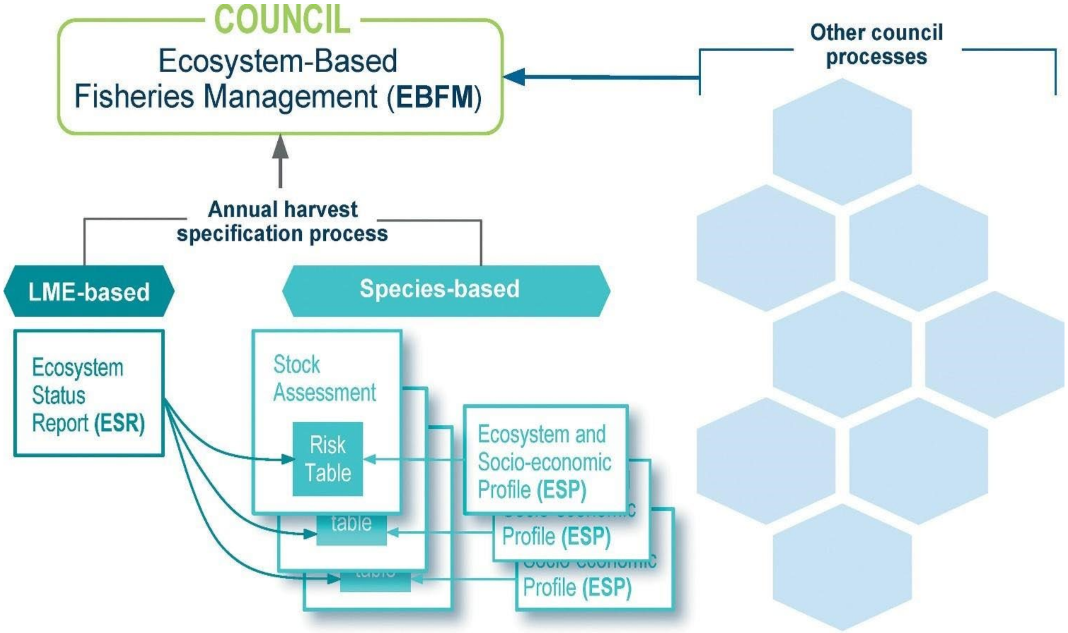

Figure 3. From Dorn and Zador 2020: Flow of ecosystem information in the North Pacific Fishery Management Council's annual harvest specification process. Risk tables are produced for each stock assessment using information from both the ecosystem-level ecosystem status report and from the stock-specific ecosystem and socio-economic profiles. LME = large marine ecosystem.

Process: Scientists identified three categories of considerations—assessment-related, population dynamics, and environment/ecosystem—that could be used to support the decision to reduce or not reduce the ABC relative to the OFL. For each type of consideration, they described four levels of concern (Table 5). When recommending an ABC, stock assessment authors now qualitatively describe the level of concern for each category of consideration. The risk levels are then peer-reviewed and adjusted along with the stock assessment itself. They took information from ecosystem status reports and species-specific ecosystem and socio-economic profiles to create the risk tables (Fig. 3; Dorn and Zador 2020). This process allows stock assessment scientists to translate ecosystem-level information to stock-specific information that can be utilized in the stock assessment process.

Table 5. Adapted from Table 1 in Dorn and Zador 2020: Risk table classification levels and descriptions for assessment, population dynamics, and environmental/ecosystem considerations.

Level	Assessment-related considerations	Population dynamics considerations	Environmental/ ecosystem considerations	Fishery performance
Level 1: Normal	Typical to moderately increased uncertainty/ minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental and/or ecosystem concerns.	No apparent fishery/ resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently or recruitment pattern is atypical.	Some indicators show adverse signals relevant to the stock but the pattern is not consistent across all indicators.	Some indicators show adverse signals but the pattern is not consistent across all indicators.
Level 3: Major concern	Major problems with the stock assessment; very poor fits to data; high level of uncertainty; strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level as the stock, and/or b) up or down trophic levels (i.e., stock predators and prey).	Multiple indicators showing consistent adverse signals a) across different sectors, and/or b) different gear types.
Level 4: Extreme concern	Severe problems with the stock assessment; severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented. More rapid changes in stock abundance than have ever been seen previously or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock. Potential for cascading effects on other ecosystem components.	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock.

Results and Initial Outcomes: During 2018, the pilot year, stock assessment scientists completed five stock-specific risk tables in collaboration with ecosystem scientists. NPFMC's scientific committees reviewed these tables. These stocks were selected for trial risk assessments as their assessments had supported ABCs below the maximum in past years.

A risk table for an additional stock was completed during the first level of review of the assessment, for a total of six stock-specific risk tables. Five of the risk tables supported the stock assessment scientists' recommendation for a reduction in ABC relative to the OFL, including for one stock (eastern Bering Sea Pacific cod; *Gadus macrocephalus*) for which the stock assessment alone had recommended that the ABC be set equal to the OFL. The remaining stock was determined to be low-risk and was recommended to have its ABC set equal to the OFL. In subsequent years, the NPFMC requested that risk tables be used for all fully-updated stock assessments in its jurisdiction, including 29 stocks in 2020. Most risk tables result in supporting the stock assessments' ABC without reductions.

Challenges and Further Applications: Scientists update the risk tables annually along with the stock assessment for that species and incorporated into the stock assessment review process. Initially, the NPFMC Advisory Panel, which is made up of representatives from the fishing industry, was concerned about the use of risk tables due to their belief that they would lead to more stocks with lowered ABCs. Scientists reviewed ABC recommendations before and after the use of risk tables and did not find that to be the case. They worked with the NPFMC to communicate that the risk tables organize and communicate a process that already exists.

The stock assessment authors believe that the transparency of the risk tables ultimately helps build trust with stakeholders. Additionally, the risk tables can help communicate the reasoning behind a decision to lower or not lower the ABC relative to the OFL. While it is difficult to create risk tables for stocks for which there is already very little information, the tables allow for the incorporation of the best and most recent qualitative and quantitative scientific information available.

2.3.2 Case Study 5: Evaluating Management Interventions for Rebuilding a Data-Poor Stock of Blue King Crab in the Eastern Bering Sea

Overview: The NPFMC manages the Pribilof Islands stock of blue king crab (BKC; *Paralithodes platypus*) in the eastern Bering Sea. The fishery for this stock has remained closed since 1999 despite additional gear and effort restrictions aimed at reducing bycatch mortality. Other management interventions may promote recovery, and the NPFMC was interested in exploring out-of-the-box ideas and understanding their efficacy in light of climate change. NOAA's Alaska Fisheries Science Center led the development of a conceptual model to describe the life cycle of BKC, key ecological interactions with other stocks, and potential climate impacts.

A team of scientists carried out simulations under different management interventions and climate (warming and ocean acidification) scenarios and performed sensitivity analyses to identify key sources of prediction uncertainty. The resulting simulations highlight how qualitative models can elucidate non-intuitive interactions and identify where to focus future research efforts.

Process: The team started by developing a conceptual model of the Pribilof Islands BKC life cycle, interactions within the benthic community, and potential management interventions and climate scenarios based on a detailed literature review and participatory stakeholder workshops. Interactions were represented by linkages between elements in the model, including information on the direction of the interactions. Links were categorized as certain if they were known to occur with high confidence based on available data and expert opinion and uncertain if data was limited or opinions varied. The resulting conceptual model was converted to a community matrix, or qualitative network model, to run different scenarios and uncertainty analyses. Qualitative network models are graphs that qualitatively represent a matrix of interactions using signs. In this case, they can be used to visualize complex ecosystem interactions in data-limited situations (Fig. 4, Reum et al. 2019).

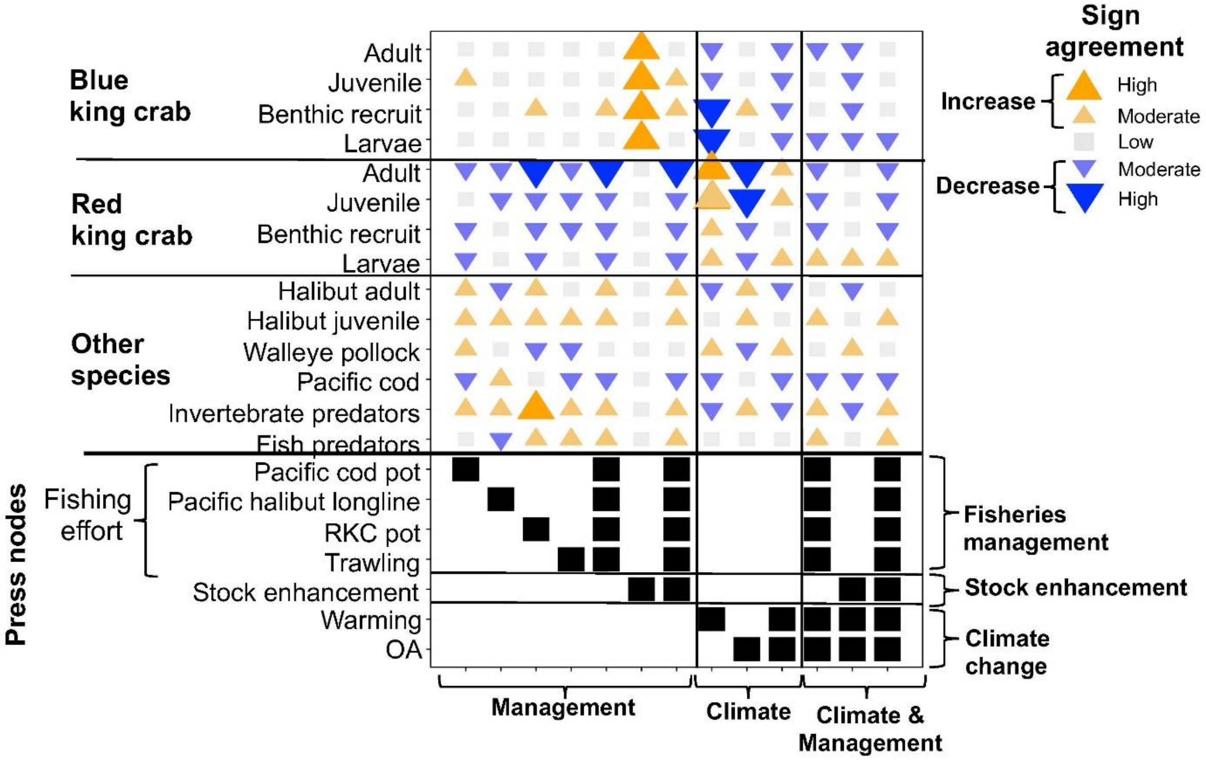

Figure 4. From Reum et al. 2019: Predicted simulated response of variables in the blue king crab network to management and climate scenarios. White open squares indicate no predicted change in response of a node to perturbation. Black squares indicate nodes positively pressed in a given scenario. RKC = red king crab and OA = ocean acidification.

The team evaluated the response of BKC to individual and simultaneous effects of five different management intervention scenarios, including increasing fishing effort or reinitiating fisheries that were excluded to reduce BKC bycatch for stocks that are also predators of BKC (i.e., Pacific halibut longline, Pacific cod pot, red king crab pot, and groundfish trawl) and enhancing the BKC through a hatchery program. They also ran the analyses under three climate scenarios (ocean warming, ocean acidification, and both) separately and with the management scenarios (Reum et al. 2019).

Results and Initial Outcomes: The team observed positive effects for BKC benthic recruit or juvenile stages in scenarios that included Pacific cod pot or red king crab pot fisheries. These effects were due in part to modeled declines in red king crab, which are predators of BKC recruits when they are juveniles Fig. 4, Reum et al. 2019). All life-history stages of BKC responded positively to the stock enhancement scenario, with no predicted changes to the other species.

However, when stock enhancement was combined with fishery interventions, the strength of positive adult BKC responses decreased, suggesting counterbalancing interactions (via predation and competition) among species under those scenarios. The probability of positive outcomes for BKC life-history stages decreased further when climate change was considered with the interventions and was usually predicted to be negative.

Overall, when uncertain links were present, the probability of positive adult BKC outcomes increased. This was especially true for a negative effect by adult red king crab on adult BKC, which has been hypothesized by researchers but has not been validated by experiments. The analysts recommended additional research to test this hypothesis based on the model results.

Challenges and Further Applications: This was a pilot effort with only one year of funding. Thus, results were preliminary, and the NPFMC has not used them in decision-making to date. In addition to identifying research gaps, the results could help inform an updated rebuilding plan for BKC and/or develop indicators for ecosystem status reports and ecosystem socioeconomic profiles. One challenge to wider adoption may be other factors regarding spatial management in the region that were not evaluated in the study (i.e., around groundfish resources in the area). However, a strength of this approach is the visual and collaborative way of developing the qualitative network model, which is accessible to a wide range of stakeholders.

3. Discussion

3.1 Summary

These case studies illustrate a number of different ways that Councils and researchers can carry out ERAs and use the results. While each Council has unique fishery, stakeholder, and ecosystem issues, they also have a number of common challenges that ERAs can help address, especially the challenge of synthesizing diverse and complex ecosystem information in an organized way. These case studies demonstrate a few different approaches for packaging that information for experts and/or stakeholders.

We chose each of these case studies to illustrate how fully qualitative or a combination of qualitative and quantitative information can be used to inform management decisions when Councils lack extensive data or sophisticated models. Councils also grapple with the additional challenge of when and how to more fully incorporate ecosystem information into management decisions. We show how ERAs can help incorporate ecosystem information at three different stages of the adaptive management cycle:

- Screening out low risk factors of less importance for the Council to address while assessing baseline conditions,
- Identifying science or management priorities, and
- Incorporating ecosystem information when evaluating management options or providing management advice.

Each case study was a pilot effort that provided the ERA authors with key takeaways on how to improve the process to enhance the uptake of ecosystem information into fishery management decisions. Below are some of the more notable takeaways.

Collaborative process to engage stakeholders: Several of the case studies had transparent, participatory processes that engaged multiple stakeholders in the development of the ERAs. ERA authors noted these processes as an important factor in the success of the ERA process. Collaboration allows for more sources of information to be used in the evaluation of risk, as well as potentially leading to greater collective understanding, and in some cases, consensus. However, consensus is not necessary for conducting an ERA or using the results (Mikkelsen et al. 2022).

Similarly, engaging stakeholders and documenting the process can help those stakeholders to understand some of the complexities of the many ecosystem interactions that are evaluated. Consequently, it can engender trust in the results and how they are being used, facilitate multiple perspectives and greater equity in decision-making (New et al. 2022), and promote buy-in and support for emergent policy recommendations.

Framework for using ERA results: Taken as a whole, the case studies showed that it is necessary to develop a framework or procedure for how ERA results will be used. New tools like ERA are often developed as proof of concept, but the benefits may not become fully realized without proper planning for how the information will be used. The MAFMC planned for the use of their ERA results from the beginning of the project and was able to incorporate the results into an MSE. While the NPFMC and PFMC initially lacked a similar framework, the NPFMC later began to incorporate information from the ERA into ABC recommendations through their use of risk tables.

Clear management objective to evaluate risk against: The case studies also show that having clear management objectives against which to evaluate risk can be key to the successful use of an ERA. The MAFMC used management objectives primarily drawn from the Magnuson–Stevens Fishery Conservation and Management Act. However, when a Council can be very specific in stating its management objectives, it can more effectively use the ERA to evaluate the risk factors of greatest concern. It is important to identify objectives that managers, the fishing industry, and other stakeholders can agree on and that scientists can quantify and assess. Analysis of management objectives should be limited to those that are exposed to the risk factors.

Alternatively, the West Coast pilot used an ERA to develop habitat conservation objectives that did not already exist for the PFMC. Through this approach, EFH that is at the highest cumulative risk and/or stressors that contribute to the greatest overall risk to EFH for specific stocks were identified to develop conservation objectives to guide Council and NOAA Fisheries efforts.

Clear definitions of risk and uncertainty: Most ERAs that use at least some qualitative information are evaluating relative risk among the factors examined rather than estimating the probability that an undesired outcome will take place. Thus, uncertainty is often estimated as the level of confidence in the available information and/or agreement among experts. Clear definitions of risk and uncertainty are necessary to specify how the information can be used. Additionally, the experts need to fundamentally understand what sources of uncertainty have already been accounted for within analyses to avoid double-counting them (e.g., in the stock assessment model and risk table). A collaborative approach between experts (in this case the stock assessment and ecosystem experts) helps ground truth where sources of uncertainty are being captured.

Indicators drawn from existing tools: While comparatively less data and labor-intensive than more quantitative approaches, ERAs can still take months to more than a year to complete and can engage numerous stakeholders. However, once an approach is agreed upon, updating an ERA can be a much more streamlined process. This is particularly true if indicators are drawn from existing and publicly accessible tools, such as ecosystem status reports, stock and fisheries evaluation reports, vulnerability assessments, etc.

The NEFSC has integrated the MAFMC's ERA into the Mid-Atlantic State of the Ecosystem Report and updates it annually as part of producing the report. This allows them to track changes in risk and uncertainty around their stocks and management objectives. Similarly, the NPFMC uses information from their annual Ecosystem Status Report to create annual ecosystem and socioeconomic profiles for each stock. They incorporate the information into a risk table each time they conduct a stock assessment.

3.2 Additional Recommendations for using ERAs to optimize EBFM

While ERAs are useful decision-support tools on their own, the benefits can be maximized when they are used in conjunction with other EBFM-related tools. Here are some suggested links with other EBFM tools:

1) Pairing an ERA with a conceptual modeling exercise can help participants visualize interactions among ecosystem components to get a sense of trade-offs and cumulative risks. Conceptual modeling with stakeholders can provide a collaborative, interactive process that helps promote common understanding (see Case Studies 1, 2, 3, and 5, and Harvey et al. 2016).
2) Results of an ERA can be used to develop and/or refine indicators to track in the long term, such as through an ecosystem status report. This approach ensures that

indicators are tied to interactions and/or processes important to the Council and that the indicators will provide a quantitative way to reassess risk in the future (see Case Study 3).

3) Comprehensive ERAs should include elements of community resilience and well-being to evaluate the full extent of risk and help inform selection of community health and well-being metrics to track and evaluate (sensu Szymkowiak 2021).
4) Once risks have been identified through ERA, priority trade-offs can be further evaluated through ecosystem simulations, like those used in MSE (Holsman et al. 2017, 2019). Ecosystem-level analyses carried out through an MSE will help translate the trade-offs observed in the ERA into management alternatives that can be tested and result in more robust management advice (see Case Study 3).
5) For high-risk and/or high-uncertainty activities that fall under the authority of other agencies or jurisdictions, Councils can consider developing policy statements that trigger an action by the Council, such as engaging in an EFH consultation or coordinating with another agency or interagency body when the activity occurs. These policy statements could be included in a fishery ecosystem plan.

Conducting ERA as an iterative process allows Councils to refine many of these elements over time, increasing the utility of the tool in different applications. No matter at what stage a Council is at in implementing EBFM, it is our intention to demonstrate the flexibility of ERA as a tool to assist Councils in explicitly considering ecosystem risk as part of their management process.

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