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Linking knowledge and action for climate-ready fisheries: Emerging best practices across the US

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ABSTRACT

Despite progress in understanding and predicting climate change impacts and possible responses for US marine fisheries, use of climate-related information in federal fishery management decisions remains limited. One barrier to progress in linking climate knowledge to management action is that individual management bodies' efforts tend to be isolated, with few opportunities to coordinate or communicate about successes and shared challenges. To promote cross-regional learning, we distill eight best practices from emerging climate-focused efforts, drawn from a collaborative workshop, literature, and authors' experiences. We conceptualize these

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best practices as interrelated—and incomplete—pieces of a knowledge-to-action "puzzle" that could be adopted based on regional context. One best practice, mapping out management processes and structure to identify "on-ramps" for climate information (3.1), represents a foundational centerpiece that enables other best practices. Three practices apply primarily to internal management processes: frame climate initiatives within existing management mandates and processes (3.2); strategically incorporate qualitative information to deal with uncertainty (3.3); and pilot initiatives with healthy or lower-risk stocks (3.4). Another set pertains to efforts that include broader stakeholders: engage stakeholders early and often (3.5), emphasize local priorities (3.6), employ structured processes to keep initiatives on track (3.7), and leverage collaborative research to build trust and overcome capacity constraints (3.8). We highlight emerging initiatives that demonstrate how these practices were implemented, discuss continued challenges, and identify opportunities where these practices could be expanded in support of climate-ready fisheries.

1. Introduction

Climate change creates new challenges and opportunities for marine fisheries and fisheries management. In the United States (US), long-term changes and increasing variability in ocean temperature, salinity, dissolved oxygen, and acidification are impacting fish stock productivity and distribution, and these changes and impacts are projected to persist [38,46,60,86,91]. Increasingly, extreme events, such as marine heatwaves and harmful algal blooms, are causing unprecedented fishery closures and formal federal fishery disasters [6]. Although most communities and fisheries are negatively impacted [47,67,79], shifting distributions may also create expanded harvest opportunities (e.g., blueline tilefish in the Mid-Atlantic or market squid in California; [63, 11,77]). In this paper, we focus on challenges and opportunities for fisheries management in response to climate change in the US, while drawing lessons that could be applicable in other regions.

In US federal waters (3–200 nm from the coast), fisheries management is implemented by the National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) and eight Regional Fishery Management Councils (hereafter, Councils), based on legal mandates of the Magnuson-Stevens Fishery Conservation and Management Act (MSA), Endangered Species Act, Marine Mammal Protection Act, and other national policy commitments such as implementing Ecosystem-Based Fisheries Management (EBFM; [41]). These bodies coordinate with Interstate Marine Fisheries Commissions as well as state and territory partners that govern waters closer to shore under additional state laws and mandates. Science-based management is a core tenet of US federal fisheries policy, and NMFS Science Centers deliver scientific information in support of Council decision making. In the face of climate change and uncertainty, NMFS developed a Climate Science Strategy in 2015 to identify climate-informed reference points, design robust decision processes, and track ecosystem trends at multiple scales, among other objectives [50]. Since then, NOAA scientists have made progress in monitoring ecosystem change, developing products and tools to deliver climate-related information, expanding the mechanistic understanding of climate impacts, and projecting future conditions [71].

Despite this progress in generating climate-related information, use of this information in fishery management remains "limited" according to the Government Accountability Office [27]. Barriers to incorporation of climate-related information include data and modeling limitations – particularly the lack of clear, mechanistic links between environmental variables and fish populations [27,71], resource and capacity limitations [16,27,71], mismatches in timelines, objectives, and priorities between scientists and managers [16,19,27], and management rigidity [27,68], among others. Recently, as climate impacts have grown more consequential and unequivocal, climate change has gained prominence on fisheries management agendas (e.g., https://www.fisheries.noaa.gov/event/2022-council-training; [73]), and regional management bodies are increasingly exploring approaches to incorporate climate-related information into decision making. However, these tend to be region-specific initiatives with few opportunities or incentives to communicate or coordinate across regions [27], slowing shared progress when rapid and concerted action is needed.

To promote cross-regional learning in support of overcoming these challenges regionally and nationally, we distill best practices and lessons learned from emerging US efforts to incorporate climate-related information into fisheries management. We highlight ongoing work demonstrating these best practices, discuss continued challenges, and identify opportunities for implementing or expanding these best practices. We primarily focus on federally-managed fisheries and highlight one innovative state-managed example. Finally, we suggest greater coordination among Councils to learn from one another, minimize barriers to novel solutions, and maximize the transferability of successes.

2. Methods

We organized a collaborative virtual workshop over two days in August 2022, hosted by the Environmental Defense Fund (EDF). Thirty-five individuals participated in the workshop, representing six Regional Fishery Management Councils, six NMFS science centers, two NMFS regional offices, two NMFS headquarters offices (Office of Sustainable Fisheries, Office of Science and Technology), four universities, two non-governmental organizations (NGOs), and a private consulting firm (see Appendix H for a list of institutions). The aims of the workshop were to share experiences from the diverse approaches these groups are taking to incorporate climate-related information into fisheries management processes, identify factors that have enabled successes, and discuss their applications to shared challenges.

The workshop included presentations of eight examples of regional approaches to incorporate climate-related information into management, followed by discussions of challenges faced and factors that contributed to success (see Appendix for narrative summaries of these presentations including takeaways from discussions). Examples were selected based on participant willingness and intended to showcase diverse regions, project stages (from proposed to completed), and management processes. Participants discussed unresolved challenges in their regions, brainstorming applications of lessons learned from other regions and potential new approaches. Participants shared key takeaways and indicated approaches or ideas they found most compelling or applicable.

Following the workshop, the authors distilled best practices from the lessons that participants identified as compelling and promising, or that were identified in multiple contexts, including in published literature. We illustrate these practices with examples presented in the workshop as well as insights from the literature and authors' experiences. These represent initial takeaways from ongoing work but are not intended to be a comprehensive catalog of the workshop and broader literature, and do not constitute collective advice or recommendations from the workshop participants.

In the subsequent text, we discuss efforts conducted in various offices and roles across the US, including NMFS and academic scientists, Council staff, NMFS management officials, NGOs, and state agency officials. Given the regional organization of US fishery management, we refer to these groups collectively as "regions," meaning the people whose work impacts decision-making for fisheries in a given place. We also use the term "stakeholders" to refer to fishermen, community

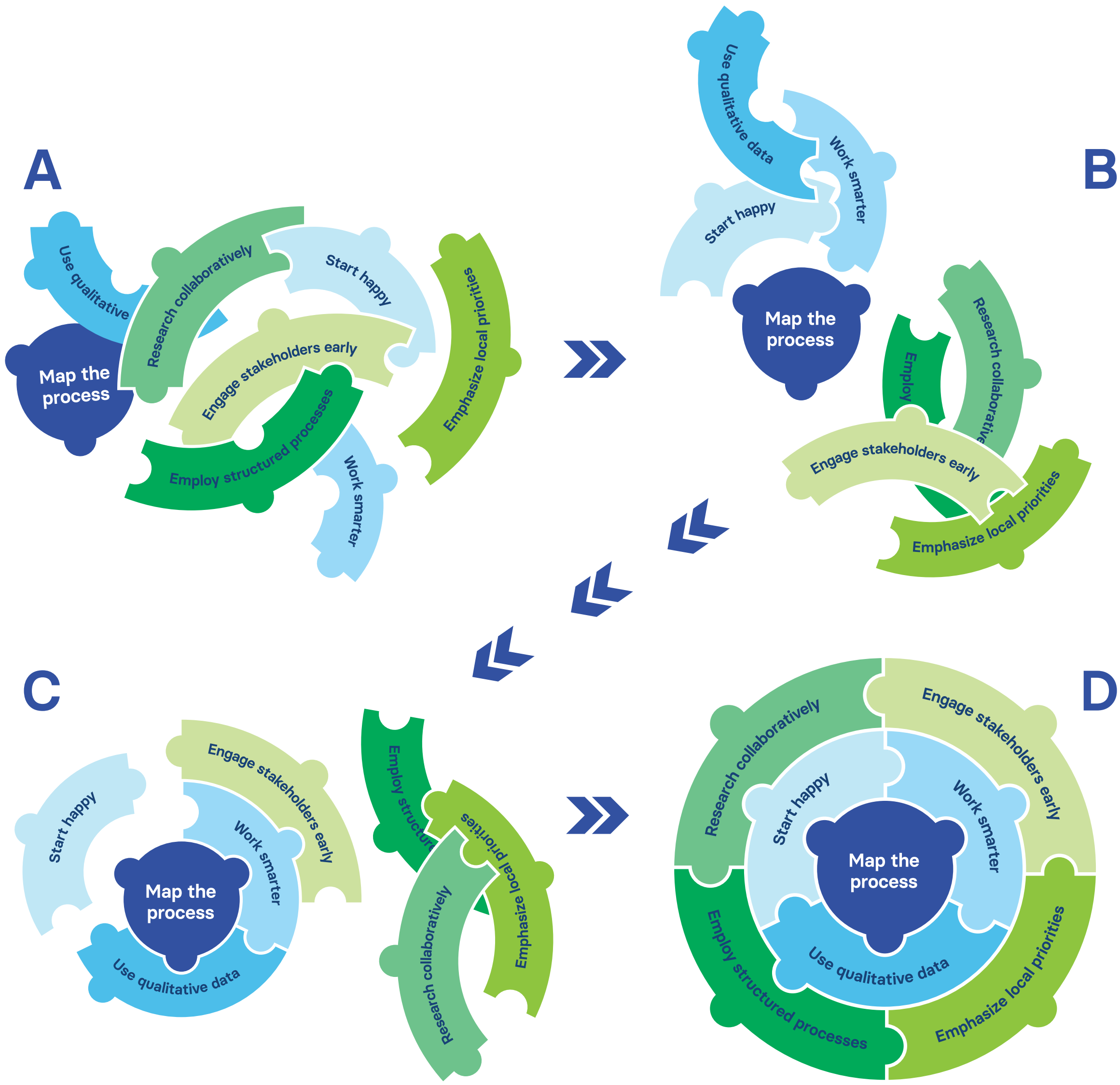

Fig. 1. (A) Eight best practices represent interrelated pieces of the knowledge-to-action "puzzle." (B) We identified practices that are more applicable to internal management processes within regions (light blue), while others apply to initiatives involving broader stakeholders (green). (C) Mapping out management processes and structure emerged as a key enabling step—the "centerpiece" that helps other pieces fall into place effectively and efficiently. But just like a real-world puzzle, there is no singular or correct sequence to fitting the pieces together – how the puzzle is solved is highly variable and context-specific. (D) These pieces, tailored and put together in combinations that work for different regional contexts, can help link knowledge and action to promote climate-ready fisheries. Best practices related to internal processes are represented visually as an inner loop; those extending beyond to include stakeholders form an outer ring. But even with all these best practices, the puzzle is incomplete—more elements are needed and more challenges need to be overcome for effective climate-ready fisheries management. This depiction is intended as a visual metaphor and not instructive as to how practices might be selected, sequenced, and linked.

members, and anyone whose livelihoods and well-being might be affected by fisheries decision-making. Indigenous Peoples hold fisheries-related rights, and thus are more appropriately described as rightsholders–and in some contexts, co-managers–than as stakeholders [74,90,92,94]. We recognize the rights and roles of Indigenous Peoples as resource stewards, but within the context of this paper's aims we have included them in our stakeholder category for concision, not out of disrespect.

3. Results

The eight best practices identified here can be thought of as interrelated and interlocking pieces of a knowledge-to-action "puzzle," which regions might prioritize depending on their context, capacities, and progress in incorporating climate-related information (Fig. 1). However, workshop participants identified the best practice of mapping and understanding management processes and structures as a key enabler of other best practices: a foundational "centerpiece" of the puzzle that helps reveal how the other pieces fall into place (Fig. 1c). We thus present that practice first (3.1), as an overarching method that not only facilitates incorporation of climate-related information but can also illuminate when and how to implement the other best practices. The remaining best practices are clustered into a set that are most applicable to internal processes within regions (3.2–3.4), and those that apply to initiatives that include broader stakeholders (3.5.–3.8) (Fig. 1b).

3.1. Centerpiece: map management processes and organizational structure to identify climate-related information on-ramps

One overarching challenge to linking climate knowledge and management action is navigating the complex US fisheries management process and structure. Each management body has unique procedures for incorporating scientific information and launching new initiatives. Council discussions follow set schedules to accommodate participating stakeholders and scientific reviews, and often particular topics such as climate change initiatives or Ecosystem Status Reports are addressed only annually or biennially. Thus, policy windows for climate-related information to inform management action are narrow [4]. Siloed processes and interlacing jurisdictions may obscure bigger-picture opportunities for flexibility and adaptation. When, where, and how to incorporate climate-related information into both the science advice and decision making process can thus be opaque to outsiders and insiders alike.

The North Pacific Council's Climate Change Task Force addressed this challenge by mapping out the management process to identify "on-ramps'' for climate-related information. The purpose of the Task Force was to facilitate the Council's work towards climate-ready fisheries management that helps ensure both short- and long-term resilience for the Bering Sea [18].[1] They worked iteratively with Council members to evaluate where management processes were already incorporating climate-related information and identify gaps where necessary on-ramps did not yet exist [18]. They identified three on-ramps for delivery of climate-related information for decision making: 1) near-term (<2 year) tactical advice such as revising stock catch limits based on climate forecasts; 2) near-term strategic advice such as using species distribution projections to evaluate protected area boundaries; and 3) long-term (>2 year) strategic advice such as revising essential fish habitat designations or experimenting with adaptive management approaches. This third category also involves developing new on-ramps to enhance delivery of climate-related information and fill gaps [18]. The on-ramp framework clarified what kind of information to deliver and how to coordinate delivery with appropriate decision-making timelines. For example, emergent climate issues relevant to stock assessments are communicated during spring and fall Council meetings via their existing Ecosystem and Socioeconomic Profile (ESP) indicator development process ([83]; Appendix G), thus minimizing the time to incorporation into stock assessments [18]. We find this "on-ramp" metaphor useful and adopt it throughout this text to refer to any opportunity to incorporate climate-related information in Council decision-making processes, and highlight examples in boxes that roughly correspond to each of the three on-ramps (Boxes 1–3).

Similar efforts in other regions could identify the on-ramps in their respective Council processes, as well as any gaps or barriers for making management more climate-ready. The Pacific Council recently launched an initiative (Ecosystem Initiative 4) to this end, which calls for the incorporation of ecosystem and climate information into fisheries decision making (either stock-specific or across multiple Fishery Management Plans, FMPs), identifying where and when additional ecosystem and climate-related information is needed, and identifying existing or potentially developing relevant pathways for that information to be used in harvest-setting processes (https://www.pcouncil.org/actions/ecosystem-and-climate-information-for-species-fisheries-and-fmps/). This final component of Ecosystem Initiative 4 is key, as some climate and ecosystem information has been delivered to the Pacific Council for a decade but has lacked formal pathways for use in decision making.

One promising tool for mapping complex management processes is conceptual modeling [34]. Many regions already use conceptual models–tailored, qualitative summaries of the key relevant components and relationships in a system–to characterize and communicate ecosystem and fishery dynamics (Appendix A), but these models often stop short of including governance processes. Conceptual models of fisheries management processes can illuminate when, how, and to whom to deliver climate-related information effectively, identify choke points, and reveal opportunities to develop new on-ramps. Scientists and managers may mutually benefit from co-creating these governance conceptual models; the creation process could identify individuals' or groups' needs, build relationships to bridge siloes, and give participants a sense of ownership in the outcomes [1,29]. Such collaborative mapping efforts could be a way to implement the Government Accountability Office's (GAO) recommendation that NMFS and Councils work together to identify and prioritize opportunities to enhance climate resilience of federal fisheries [27].

3.2. *Work smarter, not harder: frame climate considerations within existing Council mandates and processes*

Councils already have myriad mandates and priorities, and limited resources with which to meet them. Thus, efforts to incorporate climate-related information or address climate-related concerns tend to get traction when they support existing mandates and/or align with established processes. While new on-ramps and more transformative change to management processes may be necessary for fully implementing climate-ready fisheries, working "smarter, not harder" within existing structures is essential to interim progress and can help inform which changes may be most beneficial. This transitional approach allows the Councils to develop and address climate priorities that work within the existing management framework while also building capacity that evolves along with the science needed to support a more transformative management approach ([23,7]; also see Appendix C).

Councils' annual stock assessment and subsequent quota or harvest rule setting processes are core components of US fisheries management pursuant to legal mandates to achieve optimum yield and prevent overfishing. These provide a well-defined on-ramp (on-ramp 1, near-term tactical advice, in the above-described North Pacific Council framework). The New England and Mid-Atlantic Councils have launched a new "research track" stock assessment process that provides an opportunity to incorporate environmental covariates in stock assessments (Box 1, Appendix E). Councils can also incorporate or consider climate-related information when setting precautionary buffers. The North Pacific Council incorporates environmental and ecosystem considerations along with model uncertainty and population dynamics in structured risk tables to adjust catch buffers for its groundfish stocks ([20]; see Appendix G for how these link to ESPs), and the Pacific Council is exploring a similar approach through Ecosystem Initiative 4 (highlighted above). Another tactic is dynamic harvest control rules (HCRs): these allow biological parameters to vary over time, which can help match harvest levels to fluctuating stock abundance, even when the mechanisms driving observed changes are unclear [15]. A recent inventory of the HCRs used for all 507 federally-managed stocks and their dynamism and/or incorporation of environmental information [24], could provide a "map" (3.1) of opportunities to enhance climate-informed HCRs.

Another clear on-ramp is Council Fishery Ecosystem Plans (FEPs), which are a common means by which Councils implement NOAA's policy commitment to Ecosystem-Based Fisheries Management (EBFM; [41]). In fact, the NOAA Fisheries Climate Science Strategy and EBFM Road Map provide recommendations for delivery and incorporation of environmental information, including climate-related information, in support of EBFM implementation [42]. For example, the Road Map recommends that Science Centers regularly deliver Ecosystem Status Reports (ESRs) to Councils, and several Science Centers include climate-related information in these reports ([34,32]; https://www.

[1] The Climate Change Task Force (CCTF) is working to collate and synthesize existing North Pacific Climate Change information and to develop recommendations for increased resiliency in fisheries management in the future. The CCTF has compiled a Climate Readiness Synthesis [https://meetings.npfmc.org/CommentReview/DownloadFile?p=8b9a215d-57bd-4cdc-976e-3f3ca44ccdb8.pdf&fileName=D6%20Climate%20Readiness%20Synthesis.pdf] ranking various aspects of fishery management in the North Pacific in response to resiliency to climate change and in 2024 will move towards providing the Council with management recommendations.

Box 1
Climate-informed stock assessments and harvest rules.

Approach: Multiple regions are exploring methods to incorporate climate-related information into annual stock assessment and harvest rule setting processes. The New England and Mid-Atlantic Councils have launched a new research track stock assessment program that facilitates incorporation of environmental covariates in stock assessment models. While we focus on federally-managed fisheries in this text, we highlight here a state-managed example that demonstrates a new on-ramp for bringing ecosystem and climate considerations into a single stock harvest framework, beyond the stock assessment process: A recent proposal for the California state herring management plan developed a structured, ecosystem-based framework to adjust a temperature-linked herring quota level based on qualitative indicators of predator health and alternate prey availability.

Relevant on-ramp(s):

Near-term tactical (1)

Best practices illustrated:

BEST PRACTICE 3.2: These approaches directly inform Councils' routine processes and mandates.

BEST PRACTICE 3.3: Some regions are incorporating qualitative data and indicators into risk tables and harvest rules, but the herring example illustrates a need for more on-ramps for qualitative information.

BEST PRACTICE 3.4: In the New England/Mid-Atlantic research track example, starting with a healthy stock alleviated pressure and controversy that might have accompanied a higher-risk stock. Whereas in the California herring example, perceptions that the framework would generally result in unpopular quota reductions were one barrier to adoption.

BEST PRACTICE 3.5: In the New England/Mid-Atlantic example, stakeholder meetings helped fill knowledge gaps and streamline the modeling process.

Detail: The New England and Mid-Atlantic Councils' research track stock assessments involve a multi-year process, where a working group of scientists including NMFS stock assessment scientists, academic, and research partners produce a stock assessment model. This model is externally peer reviewed and presented to the Council. In one of the first completed research track assessments, which was for American plaice (*Hippoglossoides platessoides*), the team identified ecosystem and climate influences on stock dynamics from a combination of scientific literature review and stakeholder meetings and evaluated how to integrate this information into the assessment. The team did not ultimately include environmental covariates in the model due to time constraints and diagnostic challenges, but was successful in transferring the assessment to a more flexible model that has this capacity for future assessments and in incorporating time-varying parameters to account for non-stationarity. The team found that eliciting fishermen's knowledge at an early stage helped prioritize key covariates and stock responses, which reduced modeling load and ensured that the process would be more relevant to managers and fishermen. Further, individuals in the working group who could translate climate information to stock-assessment-relevant timescales and indicators were crucial to ensuring uptake. Finally, plaice turned out to be a good test case because it is a healthy stock that has been doing well in recent years. This not only reduced complexity because researchers did not have to disentangle the impacts of environmental covariates from impacts of overfishing, but also alleviated pressure and controversy that might have accompanied a higher-risk stock. Plaice thus paved the way for ongoing work in more controversial stocks.

A recent proposal for the California state management plan of the highly climate-sensitive key forage species San Francisco Bay Pacific herring (*Clupea pallasii*) sought to develop an on-ramp for adjusting quotas via a structured, ecosystem-based framework. The framework included a temperature-linked herring quota that could then be adjusted based on indicators of predator health and alternate prey availability. These indicators were summarized across the forage complex as qualitative "stoplight" indices: red (reduce or round down quota), yellow (caution; moderate quota reductions may be needed), or green (maintain or round up quota; harvest may be increased with good ecosystem conditions) [87]. The final management plan incorporated limited flexibility in its harvest rule (+/- 1%) compared to the original proposal. While this still represents a climate-informed approach, it is unlikely to adequately address ecosystem change.

Managers were reluctant to adopt flexible rules linked to ecosystem change due to concerns about controversy over how much to adjust quota based on qualitative indicators. These concerns were exacerbated by perceptions that the framework would generally result in unpopular quota reductions: in a retrospective analysis of past quota adjustments, only one of 26 years had a quota increase indicator; the rest were yellow or red [87]. This demonstrates a counter-example to the "start happy" strategy, where a proposal for a healthier species and ecosystem may have been more likely to get the "green light."

Status: Plaice research track assessment completed in 2022; other stocks including Atlantic Cod (*Gadus morhua*), black sea bass (*Centropristis striata*), and yellowtail flounder (*Limanda ferruginea*) are ongoing in 2023. California herring FMP amendment adopted in 2020.

fisheries.noaa.gov/new-england-mid-atlantic/ecosystems/state-ecosystem-reports-northeast-us-shelf). Building upon the Climate and Communities initiative, the Pacific Council has since requested a specific climate appendix to its ESR.

However, while this information can help increase awareness and understanding of ecosystem and climate processes, in many regions there remains no direct link between ESRs and management action. FEPs can serve as more concrete on-ramps when they include structured mechanisms for Councils to adopt climate-related initiatives, such as the Pacific Council's FEP Ecosystem Initiatives or the North Pacific Council's Bering Sea FEP "Action Modules" process (https://www.pcouncil.org/fep-initiatives/; [66]). The North Pacific Council has formally incorporated ESRs into their decision-making process as part of efforts to increase consideration of climate-related information. The Mid-Atlantic Council includes climate as one of several interactions in the structured risk assessment process built into its stepwise Ecosystem Approach to Fisheries Management (EAFM; [26]).

Incorporating climate information directly into tactical Council decisions requires skilled translation to align climate and ecosystem variables with the appropriate indicators and spatiotemporal scales of management processes. The New England and Mid-Atlantic Councils' research track process has opened collaboration among ecosystem and stock assessment scientists, where team members who could communicate climate variables as stock-relevant indicators were key to ensuring that climate-related information was valued and incorporated (Box 1, Appendix E). Such translation may require specialized training, and sustained positions for these skilled boundary-spanning individuals.

3.3. Strategically incorporate qualitative information to deal with uncertainty and stochasticity

Qualitative assessments can deliver information to Councils on how climate change may affect managed species, habitats and resource-dependent communities – often more rapidly than quantitative approaches that require lengthy development and review. Additionally, qualitative assessments can flexibly incorporate and weigh new sources of data [96], including climate information. They thus represent a critical tool for climate-readiness, especially in data-poor regions and for responding to extreme, "no-analog" climatic events such as the unprecedented 2014–2016 marine heat wave in the North Pacific [3]. While NMFS has made substantial progress in conducting qualitative assessments such as Climate Vulnerability Assessments (CVAs; [31,28,57,71,85]), their applications to decision making tend to be more strategic or contextual, such as for prioritizing stock assessments [27]. The North Pacific Council's groundfish risk tables are a more direct application of qualitative data to adjusting catch buffers for groundfish stocks, but use is limited to justifying adjustment, with no systematic link between qualitative indicators and the level of adjustment [20]. However, progress toward increased uptake of ecosystem information has been made within the risk tables when both the ESP and ESR frameworks are integrated because the stock-specific and overarching ecosystem status provide context for the model and population dynamics concerns. Further development and wider use of these existing frameworks are needed for rapid and rigorous incorporation of qualitative information in more tactical decision-making.

One barrier is discomfort with qualitative data. Quantitative rules–even if based on models with high uncertainty–are often treated more favorably in fishery management processes than qualitative rules [35,78]. For example, a recent innovative proposal for California herring (*Clupea pallasii*) harvest quota adjustments based on qualitative ecosystem information was rejected in favor of a far less flexible approach, in part due to concerns about possible controversy over how much to adjust quotas based on the qualitative indicators (Box 1, Appendix F). Critically, quantitative approaches like the above-described dynamic HCRs also incorporate a great deal of uncertainty, but regions have accepted ways to account for it, such as model selection procedures and peer review. Moving forward, it will be critical to design similar procedures to account for uncertainty and build trust in qualitative assessments.

3.4. Start happy: pilot initiatives with healthy or lower-risk stocks

In some contexts, past controversy over fisheries management or perceptions of regulatory burden can lead to concerns that adding new considerations to management processes will face backlash. This may stymie initiative and momentum for efforts to incorporate climate-related information in management. Thus, piloting new climate-informed management initiatives with lower-controversy issues and lower-risk stocks, or even areas that could expand harvest opportunities (e.g., [37]), may be a useful strategy for improving buy-in (Box 1). This is akin to financial advice to pay off a small loan first, even if it has a lower interest rate and would traditionally be considered a lower priority, because early success builds momentum and catalyzes sustained behavior change.

The "start happy" strategy is not intended as a departure from the precautionary approach, nor a recommendation to downplay potentially controversial findings. Addressing climate impacts on high-risk stocks is necessary to prevent overfishing and potential stock collapses [70]. But if controversy reduces community buy-in or blocks new approaches, it may diminish the ability to develop climate-informed management strategies to the detriment of all managed stocks.

3.5. Engage stakeholders early and often

The importance of engaging diverse stakeholders early and often has been articulated for various marine science policy contexts (e.g., [48,44,76,82,89]), but bears repeating here. Trust and ownership built early and maintained through iterative engagement can promote uptake of climate-related information in decision-making processes, and stakeholder acceptance of climate-informed management [17].

Engaging stakeholders can fill knowledge gaps while steering research toward management and industry-relevant questions (Box 1). For example, the Caribbean Council and South Atlantic Council, in partnership with the Southeast Fisheries Science Center, have used participatory conceptual modeling workshops to identify key ecosystem and climate impacts on fisheries in data-poor contexts [48,59]. In the more data-rich California Current context, practitioners found that co-developing conceptual models via participatory workshops or interviews identified additional connections and built a more holistic understanding of the fisheries system and climate impacts (Appendix A).

Ongoing stakeholder engagement also ensures continued coordination and knowledge exchange (as does collaborative research, discussed in Section 3.8). The Western Pacific Council uses its Regional Ecosystem Advisory Committees as a forum for the Council, government agencies, NGOs, and other interested parties to identify emerging climate-related issues of concern relevant to each managed state and territory, share information on programs and activities, and establish partnerships to coordinate efforts and resources. These Committees provide frequent and much-needed opportunities to communicate across the Western Pacific Council's vast jurisdictional region.

Extensive stakeholder engagement requires substantial resources and time, and developing truly inclusive and participatory processes that can reach diverse stakeholders remains a challenge. Recent pivots to web-based participation in response to the COVID-19 pandemic may provide helpful lessons. The Southeast Fisheries Science Center found that participation increased when they moved their conceptual modeling workshops to webinars and individual phone calls; they plan to carry these methods forward [59]. The Pacific Council and joint East Coast Councils sought inclusive processes for their Climate Change Scenario Planning Initiatives by providing multiple options for participation opportunities at several stages of the process, as well as several communication formats in their outreach efforts (Box 3, Appendix B).

3.6. Emphasize local priorities: communicate climate considerations in terms of stakeholders' experiences

Climate-related information becomes more usable when managers and stakeholders see it as salient, timely, credible, and legitimate [13]. In fisheries, climate-related information focusing on subregional and near-term time scales–events that fishermen directly experience, such as red tides or extreme storms–enhance salience and timeliness. Credibility and legitimacy are bolstered by participatory processes that allow stakeholders to share climate-related priorities based on their own observations and needs. Particularly in contexts where climate change is politicized, a participatory approach emphasizing stakeholders' on-the-water experiences is likely to have more buy-in than one described as addressing climate change. The Gulf Council's proposed Fishery Ecosystem Issues (FEIs) seek to "meet people where they're at" by soliciting ecosystem initiatives as defined by stakeholder priorities and experiences, rather than imposing a climate framing (Box 2, Appendix D). In another example, the Pacific Council recently framed an amendment to its salmon FMP that triggers management action when

Box 2
Stakeholder-driven identification of Fishery Ecosystem Issues in the Gulf of Mexico.

Approach: The Gulf of Mexico Fishery Management Council is considering stakeholder-proposed Fishery Ecosystem Issues (FEIs) as the operational unit of an actionable Fishery Ecosystem Plan.

Relevant on-ramp(s):

Near-term Strategic (2)

Long-term Strategic (3)

Best practices illustrated:

BEST PRACTICE 3.6: Instead of imposing a climate or ecosystem framing, FEIs allow issues to come from stakeholders.

BEST PRACTICE 3.5: FEIs engage stakeholders early by design, and provide regular mechanisms for engagement.

Detail: The Gulf of Mexico Council is considering a proposal for Fishery Ecosystem Issues (FEIs) as the operational unit of its developing Fishery Ecosystem Plan (FEP). The key innovation of FEIs is that they would be proposed by stakeholders, including active fishermen, based on their own observations and experiences. The FEI process would begin with stakeholder submissions of potential FEIs, where a designated "FEI Champion" would work iteratively with the Council to build a standardized proposal including a conceptual model of issue bounds, drivers, and relevant stakeholders; potential indicators; and possible management recommendations. The Council would select priority FEIs and appoint a dedicated task force to develop a work plan and actionable management guidance [49]. For example, fishermen experiencing increased bycatch might propose an FEI, and the champion and task force would work with them and Science Center researchers to understand fleet behavior and climate impacts on species distribution, evaluate management options, and recommend a preferred option (e.g., dynamic time-area closures) along with indicators for evaluating success.

The FEIs thus create an on-ramp for climate-related information in the Council's Ecosystem-Based Fishery Management process, while providing a mechanism for stakeholder engagement. They do not impose a climate framing, but rather allow issues to come from stakeholders. This helps develop actionable management processes suited to the Gulf's regional context, including its uniquely large recreational sector, interaction with issues outside the Council's jurisdiction such as upland pollution, and relatively low prioritization of or acceptance of climate change. This locally-driven framing also helps ensure that climate and ecosystem issues can be addressed at appropriate subregional scales.

Status: Proposed in 2021.

Chinook salmon (*Oncorhynchus tshawytscha*) abundance falls below a threshold as maintaining prey availability for endangered Southern Resident killer whales (*Orcinus orca*). Although climate and environmental drivers also affect salmon abundance, the plight of killer whales is a shared concern across regional and national stakeholders and likely helped provide a sense of urgency and garner broader support [72].

Devising appropriate framing requires engaging stakeholders early to build trust between regions and stakeholders (3.5). A bottom-up, localized approach also requires resources and staff–such as the dedicated champions and task forces for FEIs (Box 2)–to translate issues to management actions. Another challenge is the potential for conflict among stakeholder priorities, or between stakeholder priorities and long-term management goals. In regions with low perceived climate urgency, emphasizing the most salient issues for stakeholders may tend to prioritize reactive over proactive actions, such as recovering from disasters rather than preparing for long-term changes [33,81]. Pairing stakeholder-driven framing with longer-term strategic climate-related information on-ramps and finding opportunities for engagement with broader stakeholder interests may be needed to ensure proactive as well as reactive management actions.

3.7. Employ structured processes to keep initiatives on track

Without structured and sequential processes, clear goals, and ground rules, initiatives to incorporate climate-related information and engage diverse stakeholders may get mired in complexity, be derailed by politics, or become too abstract to be management-relevant. The Mid-Atlantic Council was successful in its transition to EAFM in part because they laid out a clear, structured approach for defining challenges, prioritizing species, and monitoring outcomes. A transparent process and ground rules helped maintain focus and momentum as the council worked through this stakeholder-initiated approach (Gaichas, 2016; Appendix C). Similarly, both the Pacific and East Coast Council-related Climate Change Scenario Planning Initiatives relied on structured processes to engage diverse stakeholders and achieve their goals, which required substantial staff investment in planning. A trained neutral facilitator was a key enabling factor for defining the questions, guiding participants through the process, and ensuring outputs would be usable (Box 3, Appendix B).

Because of the appeal of a structured and participatory process for climate planning that can be used even in low-data settings, several other regions have expressed interest in scenario planning. Moving forward, engaging managers throughout such processes and developing structured pathways for scenario planning to inform decision-making could help ensure that recommendations are actionable. The utility of scenario planning can be enhanced by prioritizing existing governance pathways, or developing new ones, that are proactive and responsive to one or more of the plausible futures.

3.8. Leverage collaborative research to build trust and overcome capacity constraints

Cooperative research approaches that invite fishermen and other stakeholders to participate in scientific research help address two fundamental challenges of fisheries management exacerbated by climate change: (1) filling knowledge gaps, and (2) navigating conflicting stakeholder needs [30,8]. Many regions have partnered with fishing fleets or launched collaborative science programs to overcome capacity constraints and build trust with stakeholders ([45,8]; www.fisheries.noaa.gov/sustainable-fisheries/national-cooperative-research-program). While not necessarily climate-focused, these initiatives can generate

Box 3
Climate change scenario planning Initiatives.

Approach: The Pacific Council and a joint initiative across the East Coast Councils and Atlantic States Marine Fisheries Commission have both used scenario planning to engage stakeholders in exploring plausible scenarios for how climate change might impact fisheries over the next 20 years, and to develop tools and processes for building resilience and navigating uncertainty.

Relevant on-ramp(s):

Long-term Strategic (3)

Best practices illustrated:

BEST PRACTICE 3.7: Structured, stepwise processes led by a professional facilitator were critical to keeping the initiatives on track.

BEST PRACTICE 3.5: Both initiatives built in multiple opportunities for stakeholder engagement via webinars and in-person workshops. The Pacific Council communicated interim outputs in multiple formats (reports, videos) to engage a broader audience throughout the process.

Detail: Scenario planning is a tool used by many sectors to navigate uncertainty by envisioning plausible future scenarios and how management strategies may need to change to prepare for them [25]. The Pacific Council launched its scenario planning process as part of the Climate and Communities Initiative, a module adopted via its FEP. The East Coast joint initiative was subsequently launched through the Northeast Region Coordinating Council. Both initiatives entailed a stepwise process of gathering information of drivers of change in fisheries over the next 20 years, collaboratively developing scenarios of what fisheries might look like in 2040, validating and deepening the scenarios, and identifying potential management actions.

Both initiatives were led by the same experienced, neutral facilitator, who oriented participants to the concept and goals of scenario planning and was critical for keeping the initiatives on track. In the earlier Pacific Council initiative, the facilitator crucially helped participants narrow the vague and seemingly insurmountable problem of climate change to the specific challenge of changing stock availability and distribution. The East Coast initiative subsequently adopted a similar specific framing. The facilitator was also critical for maintaining progress toward actionable scenarios, particularly when enthusiasm for proposing solutions before the scenarios and underlying uncertainties had been defined may have caused the project to veer in unintended directions or fail to solve the underlying challenges. Additionally, both initiatives had dedicated teams who devoted substantial time and effort at the outset to carefully plan the entire process. Funding and resources from an outside partner (The Nature Conservancy) to sponsor scoping and scenario development workshops was another key enabler for both initiatives.

For the Pacific Council, the key contribution of the scenario planning process was to more formally raise climate change as a pressing issue for the Council and to open up conversations about different stakeholders' concerns and values. However, there were no obvious on-ramps for the Council to incorporate the scenarios in decision-making identified at that time. Maintaining momentum and encouraging Council action on the recommendations from the process took considerable time and effort and is still ongoing. On the East Coast, where the impacts of climate-driven stock shifts on the fishing industry have been more apparent, participants were eager for management action. Learning from the Pacific initiative, the East Coast initiative has developed a more structured process to identify the issues and possible management actions, including a summit with managers from all four management bodies and NMFS to identify near term management priorities and longer-term governance needs based on the scenarios.

Status: Pacific Council: initiated in 2019; recommendations submitted to the Council in September 2021; East Coast Councils: initiated in 2020; completion expected in 2023.

climate-related information (e.g., the New England Fisheries Science Center/Gulf of Maine Lobster Foundation eMOLT program that places oceanographic sensors on lobster gear; [56]), contribute to mechanistic understanding of climate impacts on stocks and ecosystems (e.g., the Commercial Fisheries Research Foundation-led and NOAA-funded Lobster and Jonah Crab Research Fleet collecting temperature and fishery data to inform these species stock assessments and FMPs; www.fisheries.noaa.gov/feature-story/noaa-supports-american-lobster-and-jonah-crab-research-fleet-led-fishermen), and inform management recommendations that confer broader climate resilience (e.g., protecting fish spawning aggregations based on fishermen's knowledge; [36]). Collecting data aboard fishing vessels is also more nimble, more frequent, and allows for widespread distribution of data collection efforts. However, these efforts can only support climate-ready management with appropriate on-ramps for collaborative data to inform decision-making.

While cooperative research projects primarily engage fishermen in onboard data collection, best practices in community-based participatory research dictate including non-traditional researchers in *all* project stages, from question development to data interpretation to generating management advice [2]. Data should not simply flow one way, from fishermen to scientists. Such partnerships are most effective when objectives and roles are formalized [53], as exemplified by the South Atlantic Council's structured citizen science program [8]. Further, although cooperative research is often less expensive than traditional data collection, fishermen should be appropriately compensated for their time and resources. Funding and time must also be invested in training fisheries scientists in community-based research practices and building relationships to support sustained partnerships, which could include spending time aboard fishing vessels [53].

4. Discussion

The best practices described here illustrate promising approaches for linking climate-related information to management action. They are interrelated and complementary pieces that can be tailored and linked together, as contextually appropriate across regions, in order to accelerate fisheries scientists', managers', and stakeholders' efforts to prepare for and respond to rapidly changing conditions. These practices are broadly consistent with other documents that provide guidance for achieving climate-ready fisheries management or linking knowledge and action for climate-informed fisheries management (e.g., [5,42,27,43,51,75]). The examples and success stories described here provide illustrations of how some regions are implementing that guidance in the US. However, the best practices we summarized here have relevance in other regions across the world, even though the details of the management systems are highly variable. This relevance is brought into sharp focus from IPCC syntheses, including their recognition that static management systems may be less effective under climate change [64]. These concerns are further evident in case studies from across the globe (e.g., Southern Ocean, [12]; Australia, [88]; South Africa, [40]; Europe, [52]).

In highlighting promising approaches, we do not wish to downplay unresolved challenges and remaining needs. Even with idealized use of all the above best practices, the puzzle is incomplete–there are many key pieces needed for effective climate-ready fisheries management. Below we identify several additional shared challenges and potential solutions that emerged from our workshop and other national-level assessments [27,48].

4.1. Limited resources, capacity, and staff

Incorporating climate-related information into fisheries management processes will require operational delivery of climate-informed advice and the staff, expertise, time, relationships, and coordination needed to apply that information over short- and longer-term timeframes. Additional resources will be needed to meet these requirements. Partnerships with academia, NGOs, and private industry can provide resources and relationships across the knowledge-to-action continuum ([53]; Appendix E for academic time and expertise; Appendix B for NGO funding), but external partnerships cannot provide the full and permanent solution to staffing shortfalls. While several of the above best practices can help increase efficiency (3.2, 3.8), serious effort is needed to help fisheries Councils and NOAA prepare for rapid change, including investments in both the science and management infrastructure necessary for climate-informed decision making [27,71].

In order to provide fisheries managers and stakeholders with robust information about changing conditions, it will be critical both to maintain in situ data collection and provide funds for additional sampling efforts to more nimbly respond to extreme climate events. To get the most from these and other information systems–existing datasets, new alternate datasets, and collaborative data collected onboard fishing vessels–it will be important to develop tools that allow for ready use of robust, climate-informed products, services, and advice for Councils. These will also require dedicated staff to translate information to the appropriate contexts and promote uptake and implementation. Unfortunately, there are currently only limited operational systems in place to provide fisheries decision makers with actionable information on current observations, future projections, and assessment of management options. NOAA's Climate, Ecosystems and Fisheries Initiative (CEFI) would develop an end-to-end, operational decision support system to provide fisheries decision makers with robust information and advice they need to support climate ready fisheries management and fishing community adaptation. Recent funding of this initiative provides a timely opportunity to accelerate climate-ready fisheries management if successfully applied (https://www.fisheries.noaa.gov/national/climate/helping-america-prepare-and-respond-climate-change-under-inflation-reduction-act).

4.2. Aligning timescales

The disconnect in time scales of the scientific and management processes is a widely shared challenge, where lengthy and often misaligned procedures for scientific rigor (e.g., replication, peer review) and for management action (e.g., 3–5 year planning cycles, set schedules for considering issues) can result in yearslong separation between initial data collection and policy windows for management action. Additionally, until recently the temporal resolution of available climate-related ocean models and information tended to be too coarse and far in the future to be immediately relevant for industry and management needs. These mismatches are particularly problematic for responding to extreme events and may threaten effective management as such events grow increasingly common. There is also the challenge of finding the right balance in recognizing the urgency to appropriately address and quickly respond to the climate effects on fisheries resources, while also supporting the Councils' continued incremental transition to a more adaptive, robust, and transformative management framework.

One potential approach for improving fisheries responses to near term extreme events could be a tiered information delivery system analogous to the National Weather Service's weather-ready nation initiatives. These provide day-to-day forecasts based on robust models, but have operational warning and rapid response systems for urgent but uncertain events like hurricanes. A similar system for fisheries management could identify criteria for "rapid response" extreme events and create systematic and iterative mechanisms to deliver nowcasts and model ensembles with associated uncertainty estimates, providing urgent information without losing the rigor of peer review and other validation processes.

4.3. Cross-jurisdictional challenges

Climate-related stock distribution shifts pose new transboundary and cross-jurisdictional management challenges. While there are several possible approaches for cross-jurisdictional fisheries management in the US, regions presently lack guidance for determining or adapting governance to account for species shifts [93]. Along the East Coast, where cross-boundary stock shifts are already generating controversy over how to adapt quota allocations [22], various groups are collaboratively developing tools and principles for allocation options [65,69]. The East Coast Climate Change Scenario Planning Initiative that brings together multiple regional management bodies around a common goal is a promising step forward for cross-jurisdictional collaboration, although the Councils' different timelines and structures remain a challenge for implementation (Box 3, Appendix B). In international and highly migratory fisheries, climate-driven stock shifts exacerbate already challenging management processes, where decision-making tends to be slow and domestic actions can have limited impact. Scenario planning or other structured visioning processes to build common understanding could show promise for global or basin-scale management bodies, particularly if NGOs and other outside partners provide support and facilitation.

4.4. Integrating social science information to promote social-ecological resilience as initiatives move from concept to implementation

Fisheries are linked social-ecological systems, and US fishery managers are required under the MSA to account for social and economic impacts. However, social science also faces bottlenecks for incorporation into management processes. Parallel processes of identifying and creating on-ramps are needed for social science efforts such as NOAA's social vulnerability indicators and community evaluations [14,39], work examining adaptation in fishing communities [21,77,84], and other relevant sources of social information [10]. Incorporating social science in management processes will be increasingly important to promote stakeholder buy-in and equitable outcomes as new management initiatives to build climate resilience move from conceptual discussions to on-the-ground implementation that impacts stakeholders' livelihoods and interacts with differing values and beliefs. Critically, fisheries adaptation interventions focused on climate change tend to emphasize ecological resilience over social stressors and adaptation [95], so integrated framings are needed at the outset to ensure that climate adaptation interventions can balance social, economic, and ecological objectives.

Several regions have made progress in incorporating social science information. The Mid-Atlantic Council's EAFM framework takes an explicit social-ecological approach, including fleet interactions alongside climate, habitat, and ecosystem interactions in its risk assessment and Management Strategy Evaluation (MSE) processes [26]. Its recent recreational summer flounder MSE linked biological and economic models to evaluate economic, social, and behavioral implications of changing regulations [55]. Similarly, ESPs explicitly provide economic and community information relevant to stocks (Appendix G). Both Scenario Planning Initiatives allowed exploration of social and economic outcomes and drivers (Box 3, Appendix B). However, as with climate-related information, additional and more systematic links to incorporate social science information to decision-making will be needed. Progress toward incorporating qualitative information in management processes (3.3) may also facilitate uptake of social science.

Greater engagement and collaboration with social scientists in initiatives to promote climate-ready fisheries–at every step of the process, not just as a final "add-on"–will be necessary to ensure such initiatives appropriately incorporate social information and promote more equitable and holistic interventions [54,58]. Collaboration with social scientists who have training and skills in community-based participatory research would also enhance sustained collaborative research projects with fishing communities (3.8). More generally, the best practices described above are primarily strategies to address social challenges–navigating institutions, building trust, understanding motivations and fears. Thus, greater collaboration with social scientists could also improve efforts to map management processes (3.1), develop governance structures to integrate social information, and effectively implement the above best practices.

5. Conclusions: key findings and opportunities moving forward

Advancing climate resilience in fisheries in the face of escalating and uncertain climate impacts will require both modifications of existing management processes, and fundamental shifts in how climate-related information and advice are used to shape and inform management decisions. We identify key findings that may be broadly applicable and provide useful pathways to accelerate climate-ready fisheries management (numbered for readability, not priority): 1) Mapping out management processes and structure to identify existing on-ramps and create new on-ramps for climate-related information can ensure that this information is provided at the best time and in a usable format to maximize effectiveness and efficiency. In particular, on-ramps are needed for new and innovative climate-related data sources including qualitative information, collaborative data from fishing vessels, social science, and tiered "rapid response" data for extreme events. 2) Participatory approaches such as conceptual modeling or scenario planning could be valuable across regions to build shared understanding of climate concerns and promote buy-in of management outcomes, but must be paired with structured on-ramps to inform decision-making in order to be actionable. 3) Operational delivery of robust, timely and actionable climate-related advice, along with implementation of decision-support systems such as the NOAA CEFI to make sense of that information, is a must for climate-informed decision making on near and longer time frames, especially in the face of continued ecological surprises that affect fisheries. 4) While continued regional development of climate-informed initiatives will foster innovation and ensure approaches are context-appropriate, national-level policy and investment–including dedicated, sustained staffing–are also critical to maintain progress and move toward a proactive, rather than reactive, approach to climate change. Implementing policy recommendations from Karp et al. [43] and including specific guidance for incorporating climate-related information in national-level mandates and policy documents could spur greater uptake across Councils and unify efforts. NOAA's current review of MSA guidelines for National Standards 4, 8 and 9 and the planned October 2023 review of NMFS' Allocation Policy and EBFM Road Map could represent timely policy windows. Finally, 5) more opportunities for cross-regional coordination and knowledge sharing are needed to accelerate progress and avoid common stumbling blocks. The Council Coordination Committee's 2022 national workshop for Council members to share and discuss EBFM approaches provides a potential model (http://www.fisherycouncils.org/cmod-workshops/2022). The GAO and NOAA have recommended formal tracking of efforts to incorporate climate-related information [27]; workshop participants further suggested a dedicated clearinghouse or other data sharing mechanism to track and communicate climate-change related activities across regions. In the near term, continued collaborative discussions around particular topics or challenges could provide venues for learning and innovation, and grow into informal or formal communities of practice for climate-ready fisheries.

CRediT authorship contribution statement

Julia G. Mason: Conceptualization, Methodology, Writing – original draft, Project administration. **Sarah J. Weisberg:** Conceptualization, Methodology, Writing – original draft, Visualization, Project administration. **Janelle L. Morano:** Conceptualization, Writing – original draft. **Richard J. Bell:** Conceptualization, Writing – original draft. **Mark Fitchett:** Conceptualization, Writing – original draft. **Roger B. Griffis:** Conceptualization, Writing – original draft. **Elliott L. Hazen:** Conceptualization, Writing – original draft. **William D. Heyman:** Conceptualization, Writing – original draft. **Kirstin Holsman:** Conceptualization, Writing – original draft. **Kristin M. Kleisner:** Conceptualization, Writing – original draft, Supervision. **Katie Westfall:** Conceptualization, Writing – original draft, Funding acquisition. **Michele K. Conrad:** Conceptualization, Writing – review & editing. **Margaret Daly:** Conceptualization, Writing – review & editing. **Abigail S. Golden:** Conceptualization, Writing – review & editing. **Chris J. Harvey:** Conceptualization, Writing – review & editing. **Lisa A. Kerr:** Conceptualization, Writing – review & editing. **Gway Kirchner:** Conceptualization, Writing – review & editing. **Arielle Levine:** Conceptualization, Writing – review & editing. **Rebecca Lewison:** Conceptualization, Writing – review & editing. **Sean M. Lucey:** Conceptualization, Writing – review & editing. **Wendy Morrison:** Conceptualization, Writing – review & editing. **Brandon Muffley:** Conceptualization, Writing – review & editing. **Jameal F. Samhouri:** Conceptualization, Writing – review & editing. **Matthew Seeley:** Conceptualization, Writing – review & editing. **S. Kalei Shotwell:** Conceptualization, Writing – review & editing. **Diana L. Stram:** Conceptualization, Writing – review & editing.

Data Availability

No data was used for the research described in the article.

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Appendix: Success stories

A. Conceptual models: Getting us all on the same page

Various Councils have employed conceptual models–broadly defined as ideas, statements, or illustrations of the components, processes, relationships, risks, and attributes in a system–to characterize and communicate complex ecosystem and climate dynamics in their fisheries systems. Conceptual models can facilitate implementation of many best practices described above: by breaking down complex ecological, economic and social information into visual, qualitative summaries of the most important relationships and processes tailored for a particular management context, they can communicate how climate considerations interact with other management mandates (Best Practice 3.2) or identify and match appropriate indicators. When co-designed with stakeholders they provide a means of developing trust and buy-in at the initial stage of defining the system (Best Practice 3.5) and drawing connections between climate change and issues stakeholders directly observe (Best Practice 3.6), while leveraging stakeholder knowledge to fill gaps (Best Practice 3.8).

In data-rich settings, conceptual models are useful for distilling and prioritizing climate-related information–making sense of complex information and honing in on the most important variables. As part of the Pacific Fishery Management Council's (PFMC) Fishery Ecosystem Plan (FEP), the California Current Integrated Ecosystem Assessment (CCIEA) team has used visual conceptual models to succinctly communicate the complex information in their annual Ecosystem Status Report. The conceptual model also serves as a "principles statement" grounding subsequent analyses in the agreed-upon most important relationships and variables and ensuring a holistic approach [34]. In data-poor settings, conceptual models are a valuable tool to generate information about ecosystem dynamics and interactions. The Caribbean Fisheries Management Council (CFMC) conducted workshops with diverse stakeholders to develop comprehensive ecosystem models where little data existed; these could eventually provide the basis for management decisions [48]. In the South Atlantic, a participatory conceptual modeling workshop with fishermen filled in the necessary knowledge on ecosystem effects in order to modify catch limits for wahoo (*Acanthocybium solandri*) and dolphin (mahi mahi, *Coryphaena hippurus*). These were data limited stocks without stock assessments, and the conceptual model process helped gather hypotheses about environmental drivers of stock dynamics that could then be tested ([48]; McPherson et al., 2022).

While conceptual models can be fully developed by "experts," practitioners advise co-developing conceptual models with stakeholders via workshops or interviews to build credibility and develop a more holistic picture of the system [62,80]. Intensive participatory workshops are time, effort, and resource intensive but are more effective at generating engagement, identifying connections, and filling knowledge gaps. One-on-one interviews are also time consuming and may gather conflicting inputs, but are a strong alternative to large virtual meetings where active participation by all attendees is less likely.

While the initial outcomes of bringing people together and building shared understanding are valuable, persistence is critical if conceptual models are to inform management decisions. Practitioners emphasized the importance of regularly revisiting conceptual models to build understanding and to revise the model as knowledge and/or environmental conditions change. In the Pacific, CCIEA scientists found that the initial marginal increase in clarity about ecosystem functions did not immediately garner support for conceptual modeling, particularly when climate change was not viewed as a pressing concern. But, as the Council grew more familiar with ecosystem and climate interactions with repeated presentation, and when an unprecedented heatwave brought climate change to the forefront, they had a shared understanding to draw from and could use the conceptual model to aid decision-making.

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B. Climate Change Scenario Planning Initiatives

The Pacific Fishery Management Council (PFMC) and joint East Coast Climate Change Scenario Planning Initiatives demonstrate how a structured and facilitated process (Best Practice 3.7) effectively engaged diverse stakeholders (Best Practice 3.5) and broke down the highly uncertain and complex challenge of climate change into specific issues and priority action items.

The PFMC launched its scenario planning process as part of the Climate and Communities Initiative, a module adopted through its Fishery Ecosystem Plan (FEP). The East Coast process is a joint initiative with the New England Fishery Management Council, Mid-Atlantic Fishery Management Council, South Atlantic Fishery Management Council, Atlantic States Marine Fisheries Commission, and National Marine Fisheries Service (NMFS). It was launched through the Northeast Region Coordinating Council (NRCC) aimed at exploring management and governance issues related to climate change and shifting fish stocks. In both cases, the goals were to 1) engage stakeholders in exploring plausible scenarios for how climate-driven stock distribution shifts could impact fisheries over the next 20 years and 2) develop tools and processes for building resilience and navigating uncertainty.

For the PFMC, the systematic Ecosystems Initiative process to take up climate issues via its FEP was a key enabler for putting climate change on the Council agenda. Perhaps more importantly, The Nature Conservancy (TNC) provided funding and resources to sponsor scoping and scenario development workshops. A bridging individual at TNC with Council experience knew to pair an additional ask of the Council with the resources necessary to achieve it. TNC also provided substantial funding for the East Coast initiative. For the East Coast's joint efforts, a dedicated core team with membership from participating organizations was critical for coordinating so many groups' timeframes and priorities, although this required substantial time and effort. Both initiatives faced challenges in communicating the concept and goal of scenario planning to participants and keeping the process on track–participants were concerned about existing problems and eager to jump to their favored solutions, which might have created gridlock or detracted from the initiatives' forward-looking objectives. Having an experienced facilitator (the same individual facilitated both initiatives) to guide participants through a stepwise, structured process was paramount for clearly defining the focus of the initiatives, ensuring that the scenarios would be plausible and management-relevant, and helping stakeholders be more open to novel solutions. Additionally, the PFMC communicated interim outputs in multiple formats (reports, videos) to more broadly engage the public throughout the process.

In all such initiatives, moving from recommendations to action is always a challenge and could utilize its own structured process. The PFMC has taken the initial steps through a series of initiatives to increase climate information in individual Fishery Management Plans and the Council process. By including management priorities and policy recommendations as part of the expected outcomes from the East Coast project, the East Coast developed a plan to move the scenarios to action, including through a summit that brought togethers managers from all four management bodies and NMFS. Scenario planning could be a promising tool for application in other regions to identify and refine climate challenges, engage stakeholders, and forge cross-jurisdictional collaborations. It may be particularly useful in data-poor or highly uncertain conditions. However, structured processes and on-ramps for the outcomes of scenario planning to inform decision making are needed from the outset to make these initiatives actionable.

Sources and additional resources

- East Coast Climate Change Scenario Planning website and materials: https://www.mafmc.org/climate-change-scenario-planning
- Narrative of Pacific Council scenario planning process as part of Climate and Communities Initiative, including scenario descriptions and video explainer: https://www.pcouncil.org/actions/climate-and-communities-initiative/
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C. The Mid-Atlantic EAFM experience

The Mid-Atlantic Fishery Management Council's (MAFMC) transition to an Ecosystem Approach to Fisheries Management (EAFM) demonstrates how early stakeholder engagement (Best Practice 3.5), individual champions shepherding a pragmatic stepwise process (Best Practice 3.7), and appropriate framing (Best Practices 3.2 and 3.6) enabled them to develop a framework for incorporating climate-related information into the management process with public buy-in. In developing their approach, the Council faced several challenges: the overwhelming complexity of interactions in marine ecosystems (including climate, habitat, fishing fleet, and species interactions); attempting to make a major change to the Council system; dealing with coordination challenges with many adjacent and overlapping jurisdictions; and maintaining public support, particularly after successful efforts to rebuild stocks but with little perceived benefit to fishing communities.

They used a strategic visioning process to solicit stakeholder input on their 2014–2018 strategic plan (Best Practices 3.5 and 3.6), from which ecosystem and climate change issues emerged as high priorities for stakeholders. This strategic plan was critical for setting expectations, staying on track, and developing common understanding of goals among the public, scientists, and Council members. Additionally, individual champions invested in the EAFM process, both in the New England Fishery Science Center and the Council, were key to seeing the process through, and these champions were able to leverage outside expertise and open-source data to overcome limited resources and tight management timelines [62].

Via a series of public workshops, scientists, managers, and stakeholders worked collaboratively to develop an EAFM framework that breaks down complex climate and ecosystem dynamics into priority interactions and specific management questions. A modular and iterative approach systematically incorporates these interactions into the management process, allowing for a gradual transition to ecosystem management with opportunities to learn and adjust along the way. The structured, stepwise framework combines: (1) qualitative risk assessments to prioritize interactions and break down complexity; (2) conceptual models (Appendix A) to communicate how those priority interactions fit within the larger system, refine management questions and objectives for those interactions, and identify management options and data needs; and (3) formal management strategy evaluations (MSEs) to assess options (see [26] for full details). Finally, framing the process as an ecosystem *approach* to fisheries management (EAFM) has met with less public resistance than more transformative framings of ecosystem-based fisheries management (EBFM), despite having similar goals and outcomes ([61]; Best Practice 3.6).

The MAFMC still faces challenges with jurisdictional issues, especially for addressing distributional shifts. Delivering climate predictions for industry and management-relevant time scales is also a continued struggle, but the EAFM approach is considered a success and can continually update to incorporate new knowledge or new challenges and opportunities.

Sources and additional resources

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D. Fishery Ecosystem Issues in the Gulf of Mexico FEP

Following extensive stakeholder engagement and a review of success and challenges in other regions' Fishery Ecosystem Plan (FEP) processes, LGL Ecological Research Associates (LGL) proposed that the Gulf of Mexico Fishery Management Council (GMFMC) could make an actionable FEP by building in mechanisms for stakeholder engagement (Best Practice 3.5), leveraging collaborative research and outside partnerships (Best Practice 3.8), and devising a structured process (Best Practice 3.7) for taking up ecosystem and climate management concerns as generated and defined by stakeholders (Best Practice 3.6). It was critical that the Council develop processes suited to its regional context, including its uniquely large recreational sector, interaction with issues outside the Council's jurisdiction such as upland pollution, and relatively low prioritization of or acceptance of climate change. LGL thus concluded that subregional, rather than Gulf-wide, initiatives based on stakeholder priorities would be most actionable for the Council.

LGL's proposed Fisheries Ecosystem Issues (FEIs) structure is the primary mechanism by which the GMFMC would take up a new climate or ecosystem initiative. This was modeled from the North Pacific Fishery Management Council's Action Modules and Pacific Fishery Management Council's Ecosystem Initiatives, structured and regular processes by which those Councils consider and adopt ecosystem planning efforts, and modified based on extensive Gulf stakeholder engagement and mapping. The key innovation of FEIs is that they are conceived of by experienced and active fishermen based on their own observations. Fishermen and other stakeholders can propose FEIs, and work with a designated "FEI Champion" to submit a standardized proposal to the Council, with clear system bounds, definition of relevant stakeholders, and a range of management recommendations. The Council filters these for feasibility and an FEI task force defines a workplan and budget, regularly updates the Council, and ultimately provides actionable management guidance. In this manner, specific, subregional ecosystem and climate issues can bubble up from stakeholders in their own terms–from how the issue and system are defined to what the management recommendations could be. The architects of FEIs noted that this allows them to address climate concerns without ever explicitly talking about climate change.

The other pillars of the GMFMC FEP are expanded institutional partnerships with other agencies and organizations to address extra-jurisdictional issues, and an expanded cooperative research program to engage fishermen and enhance data collection. This FEP is still in its initial stages and may face additional challenges and modifications as it is put into practice, but is a promising model for participatory approaches that “meet people where they’re at.”

Sources and additional resources

- Draft Gulf of Mexico Council Fisheries Ecosystem Plan: https://gulfcouncil.org/wp-content/uploads/Q-4b-Gulf-of-Mexico-Fishery-Ecosystem-Plan-2022_03_25-AS-SUBMITTED-2.pdf
- LGL Ecological Associates mid-term project summary presentation to the Gulf of Mexico Council: https://gulfcouncil.org/wp-content/uploads/6_LGL-FEP-Midterm-Progress-Report-and-FEIs-as-submitted-09_07_21.pdf

E. Integrating Ecosystem and Climate Influences on Dynamics of American Plaice into Stock Assessment

The New England and Mid Atlantic Fishery Management Councils’ new research track stock assessments represent a promising on-ramp for new ecosystem and climate science to enter the stock assessment process. Research track stock assessments were developed as part of the Next Generation Stock Assessment strategic framework to make NMFS stock assessments more holistic and ecosystem-based while also more timely and efficient. Research track stock assessments are efforts to revise or expand stock assessment methods, to be conducted in parallel with ongoing operational, or management track, stock assessments. Research track assessments are subject to a review process, and if approved can be incorporated into management track assessments (Lynch et al., 2018). The peer-reviewed assessment for American plaice (*Hippoglossoides platessoides*) is an example of a recent research track process that had a subgroup explicitly focused on identifying and integrating relevant ecosystem and climate influences on stock dynamics into the stock assessment. The process revealed the importance of including individuals who can translate ecosystem information to stock-assessment relevant scales and indicators, the science capacity needed and importance of timing to address ecosystem and climate influences such that information can be incorporated into aspects of the stock assessment, and the value of using a healthy, non-controversial stock to provide proof of concept for a new process (Best Practice 3.4).

In the American plaice process, the team paired a review of the state of science with stakeholder meetings to identify key ecosystem and climate influences on plaice stock dynamics and incorporate fishermen’s observations of distributional shifts. This prioritization with stakeholders helped narrow the scope of indicators assessed, greatly reducing the modeling load and ensuring that the outputs were more management-relevant. The team then evaluated a suite of models using the Woods Hole Assessment Model (WHAM), a state-space-age-structured stock assessment framework that has flexibility to integrate non-stationarity in and environmental effects on stock dynamics. The research track process required substantial staff capacity, and was extremely time intensive. In fact, the team ultimately ran into time constraints along with diagnostic issues that prevented the inclusion of environmental covariates in the final model. However, the team was successful in transferring the American plaice assessment from the previous Virtual Population Assessment process to the more flexible WHAM model and incorporating random effects in the model that allow for time-varying survival. The team also identified promising mechanistic relationships between climate drivers and plaice stock for future study, and demonstrated the value of flexible models that can incorporate non-stationarity. The adoption of flexible models, like WHAM, that allow for time-varying aspects of stock dynamics and integration of climate covariates means advancements in the integration of climate impacts are possible in future management track assessments and is a step toward climate-proofing our stocks assessments for future change.

Key ingredients for success identified by participants included: having a dedicated team working together on this issue, particularly in the early stages of the project such that findings could inform decision-making throughout the assessment process. Academic collaborators who brought postdocs and graduate students helped provide additional capacity, but dedicated staff would be needed to sustain this work. Team members with specific translation skills were critical: individuals who could align the spatial and temporal scale of climate data to stock-assessment relevant indicators made the difference between what climate-related information was considered relevant and useful, and what languished in the academic literature. External, international peer reviewers who were open to a new process also helped facilitate acceptance and assessment of the models. Finally, the fact that the American plaice stock is currently doing well helped the process go smoothly, where there was less resistance to change and experimentation and fewer political complexities than working with more controversial depleted stocks.

Sources and additional resources

- Research Track process description and Terms of Reference: https://d23h0vhsm26o6d.cloudfront.net/NRCC_Assessment_Process_Version-18Feb2022_508.pdf
- Research Track materials - https://apps-nefsc.fisheries.noaa.gov/saw/sasi.php
- Lynch, P. D., Methot, R. D., & Link, J. S. (2018). Implementing a Next Generation Stock Assessment Enterprise. An Update to the NOAA Fisheries Stock Assessment Improvement Plan (NOAA Technical Memorandum NMFS F/SPO) [NOAA Technical Memorandum NMFS F/SPO]. NOAA. https://doi.org/10.7755/TMSPO.183

F. An EBFM approach for California SF Bay Herring

Although we focus on federally-managed fisheries in this text, we highlight here a state-managed example that could be informative: the 2019 update to the California state management plan for San Francisco Bay Pacific herring (*Clupea pallasii*), which demonstrates a new on-ramp for bringing ecosystem and climate considerations into a single stock harvest framework, beyond the stock assessment process (Best Practices 3.1 and 3.2). It also illustrates some possibilities and pitfalls for incorporating qualitative information and approaches (Best Practice 3.3).

Pacific herring are highly climate-sensitive, exhibiting dramatic environmentally-driven population fluctuations, and also serve as key forage species for 83 predators in the California Current. The San Francisco Bay Herring fishery targets the northern edge of the population’s range, leading to greater population fluctuations as well. Therefore, an ecosystem-based and climate-informed management approach for this species is paramount, and ideally would account not only for how climate conditions impact stock size, but also how climate and other variables impact herring predators. During the 2019 management plan review process, a team of scientists put forth a holistic and forward-looking harvest framework to do just that. The multi-step framework started with an environment-linked quota using information on bottom water temperature and pre-recruit production to predict spawning stock biomass. This quota could then be adjusted up or down based on a predator indicator derived from a matrix of 1) availability of alternate forage species for predators and 2) predator population health. These indicators were summarized across the forage complex as qualitative “stoplight” indices: red (reduce or round down quota), yellow (caution; moderate quota reductions may be needed), or green (maintain or round up quota; harvest may be increased with good ecosystem conditions) [87].

One challenge with this approach is translating the qualitative stoplight indicators into actual quota increases or decreases. The initial proposed framework included substantial flexibility, with possible increases in harvest limits up to 100% in good ecosystem conditions or up to a 75% decrease in extremely poor ecosystem conditions. The framework ultimately adopted for Pacific herring management still incorporated post stock-assessment flexibility based on ecosystem conditions, but to a much more limited degree: 1% in either direction [9]. This limited adjustment still represents an ecosystem approach, but it is clear the ecosystem impact will be smaller with less adjustment commensurate with the ecosystem indicators. Revisiting the utility of a 1% adjustment may be necessary to ensure ecosystem considerations are adequately addressed. Evaluations of current and past quotas with the proposed framework were also predominantly yellow or red, which may have also discouraged uptake (Best Practice 3.4).

Ultimately, the final adopted Fishery Management Plan for Pacific herring represents a victory and a promising framework for incorporating ecosystem and climate information to adjust harvest post-stock assessment and providing some flexibility to respond to changing ecosystem conditions. It also identifies a critical bottleneck: lack of standard and trusted mechanisms to deal with uncertainty and qualitative information. Moving forward, it will be necessary to build from the well-designed and accepted processes in place for accounting for uncertainty in stock assessments (e.g., peer review) and socialize them in ecosystem and climate contexts.

Sources and additional resources

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- CA Pacific Herring Fishery Management Plan: https://wildlife.ca.gov/Fishing/Commercial/Herring/FMP

G. Ecosystem and Socioeconomic Profiles to package indicators for individual stocks

Ecosystem and Socioeconomic Profiles (ESPs) are a standardized framework to distill relevant climate, habitat, and ecosystem information for specific stock assessments. ESPs represent a powerful tool to "work smarter, not harder" (Best Practice 3.2) by strengthening and solidifying an on-ramp for climate information to inform stock assessments. The Alaska Fisheries Science Center (AFSC) and North Pacific Fisheries Management Council (NPFMC) developed ESPs in response to a communications gap within the Council process that hindered proactive, climate-informed stock management: stock-specific assessments for quota setting were communicated to the Council via Stock Assessment and Fishery Evaluation (SAFE) reports while comprehensive ecosystem and climate information was communicated through Ecosystem Status Reports (ESRs), with no pathway to integrate the two and understand how the information in the ESRs would translate to stock-specific decision making. Additionally, the Next Generation Stock Assessment framework recommended an early version of ESPs as a standard template for summarizing and communicating stock assessment results (Lynch et al., 2018).

During the ESP process, stocks can be prioritized for developing ESPs based on a number of factors such as council recommendations, regional priorities, and recommendations from national initiatives. For each of these priority stocks, a team is created to generate the ESP and seeks to develop a mechanistic understanding of ecosystem and socioeconomic drivers of stock dynamics, from which they define a suite of stock-relevant indicators to monitor. These trends and their impacts on stock status are then communicated to the Council via a concise standard reporting template within the appendix of the SAFE report as part of the annual stock assessment cycle. The ASFC has also developed a rapid communication two-pager template to collate information on stock status and ESP indicators for scientists, Councils, and stakeholders.

In Alaska, ESPs have been identified as a primary pathway for incorporating climate, ecosystem, and habitat information into the stock assessment process. They are a key input to the risk tables that the NPFMC uses to adjust Acceptable Biological Catch limits for groundfish stocks, which are structured qualitative frameworks to account for additional risk to stocks based on assessment performance and uncertainty, population dynamics not accounted for in the model, and environmental and ecosystem considerations [20]. Additionally, ESPs have been used to set expectations for recruitment in developing rebuilding plans, and to contextualize environmental and economic conditions for setting Total Allowable Catch. The ESPs have also helped prioritize indicators and mechanistic linkages to improve stock assessment models, either via inclusion as covariates or to condition data inputs.

Currently, ESPs have been developed or are in development for Alaska sablefish, Gulf of Alaska pollock, Eastern Bering Sea Pacific cod, Gulf of Alaska Pacific cod, St. Matthews blue king crab, Bristol Bay red king crab, and Bering Sea snow crab at the AFSC (Pers. Comm., Kalei Shotwell, kalei.shotwell@noaa.gov, reports within the Alaska stock assessment and fishery evaluation reports); bluefish, black sea bass, mackerel, and Atlantic Cod at the Northeast Fisheries Science Center (Pers. Comm., Scott Large, scott.large@noaa.gov, within the TOR1 of the research track assessments); and uku at the Pacific Islands Fisheries Science Center (Ayers, 2022, administrative report). While ESPs still represent management in a single-stock context, they represent an important bridging step toward ecosystem-based and climate-resilient management. A national effort is underway to increase the use of ESPs for more stocks and regions, with potential to create a national ESP initiative.

Sources and additional resources

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- Overview of ESPs given as an update to the NPFMC in 2020: https://meetings.npfmc.org/CommentReview/DownloadFile?p = 8f5233fb-3b62-4571–9b49-8bb7ce675916.pdf&fileName=ESP_Shotwell.pdf
- Example of an ESP report card for Eastern Bering Sea Pacific Cod: https://afsc-assessments.github.io/EBS_PCOD/2022_ASSESSMENT/NOVEMBER_MODELS/APPENDICES/Appendix_2.2_-EBS_PACIFIC_COD_ESP_REPORT_CARD.pdf

Appendix H. Institutions represented in the workshop

Regional Fishery Management Councils: Pacific Fishery Management Council, New England Fishery Management Council, Mid Atlantic Fishery Management Council, Gulf of Mexico Fishery Management Council, Caribbean Fishery Management Council, Western Pacific Fishery Management Council.

NOAA Fisheries Science Centers: Alaska Fisheries Science Center, Northwest Fisheries Science Center, Southwest Fisheries Science Center, Pacific Islands Fisheries Science Center, Northeast Fisheries Science Center, Southeast Fisheries Science Center.

NOAA Offices: Greater Atlantic Regional Fisheries Office, Southeast Regional Office. NMFS Office of Science and Technology, NMFS Office of Sustainable Fisheries Highly Migratory Species Management Division, NMFS Office of Sustainable Fisheries Domestic Fisheries.

Other: Cornell University, LGL Ecological Associates, The Nature Conservancy, San Diego State University, LGL Ecological Associates, University of Washington, University of the West Indies.

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