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Harnessing the value of near-term actions for achieving climate-ready fishery management

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Climate change requires managers to bolster long-term resilience of fisheries and concurrently improve short-term responsiveness of management systems to prevailing ecological conditions, all while avoiding unintended harm to stocks in a highly uncertain context. There has been substantial effort dedicated to developing the scientific information and tools needed to inform climate-ready fisheries, yet implementation of these approaches has been limited in the United States management system. Meanwhile, climate impacts on fisheries are already occurring, making fish and fishing communities highly vulnerable to sudden, and often detrimental, changes. There is a need to accelerate adaptation efforts, and near-term action is critical even without the full complement of information and tools in hand. Here, existing climate-ready approaches were compiled and synthesized to offer a comprehensive and structured perspective on priority actions that can be taken in the next 1-2 years to increase the resilience and adaptability of fish stocks and communities that rely on them. From the review there are three main findings: 1) 45% of the management actions can be implemented in this short timeframe, 2) Nearly all actions identified can be implemented in the current fishery and regulatory framework, and 3) While new approaches are needed, managers should proceed with caution to avoid maladaptation and choose a no- or low- maladaptation risk approach wherever possible.

KEYWORDS

climate, fisheries, climate-ready fisheries, fishery management, climate adaptation, fishery management council (FMC)

1 Introduction

1.1 Climate impacts on fisheries

Climate change is expected to disrupt fisheries in a multitude of ways, including the loss of catch potential on a global scale (Cheung et al., 2010; Barange et al., 2018; Free et al., 2019). The productivity of fish stocks worldwide has already declined (Free et al., 2019), many fish stocks are exhibiting substantial shifts in distribution (Lenoir et al., 2020), extreme events have resulted in rapid population declines and fisheries collapse, and ecological interactions and food web dynamics have changed (Griffith et al., 2019; du Pontavice et al., 2020). The realized impacts of climate change on marine fisheries are already substantial (Bellquist et al., 2021; Fisher et al., 2021; Smith et al., 2021). These impacts can manifest in fishery systems suddenly, such as climate-driven disasters and shocks (Fisher et al., 2021; Szuwalski et al., 2023), through long-term trends, like an increase or decrease slowly over time (Pinsky et al., 2013; Free et al., 2019), or as an increased amplitude and frequency relative to the past (Hollowed et al., 2013; Oremus, 2019).

Climate change is causing ocean warming, deoxygenation and ocean acidification (Mathis et al., 2015; Fox-Kemper et al., 2021), sea-level rise (Bigford, 1991; Whitehead et al., 2009), and marine heatwaves (Mills et al., 2013; Cheung and Frölicher, 2020; Smith et al., 2021; Free et al., 2023a; Szuwalski et al., 2023) and is driving loss of biodiversity and ecosystem function (Stige and Kvile, 2017; Weiskopf et al., 2020; Palacios-Abrantes et al., 2022; Viitasalo and Bonsdorff, 2022). These climate-driven changes to the ocean will have far reaching impacts for fisheries and on the production of seafood globally (Cheung et al., 2010; Pinsky and Fogarty, 2012; Young et al., 2019), causing further risk to communities that depend on fish for food security and livelihoods (Colburn et al., 2016; Rogers et al., 2019; Koehn et al., 2022). In addition, marine fisheries provide a multitude of other benefits and services to people, including recreation, opportunity for cultural practice, and sense of place, that are also threatened by climate change (Cooley et al., 2022). Coastal and in-river subsistence-based communities and other resource-dependent communities are particularly vulnerable to the impacts of climate change (Herman-Mercer et al., 2019).

In the United States (U.S.), fishery disasters and losses, attributable at least partly to environmental causes, have increased in the last three decades (Bellquist et al., 2021). There are now a number of examples where inaction has led to the decline or collapse of fishery systems due to the combined effects of overfishing and climate change (Möllmann et al., 2021; Papaioannou et al., 2021; Pershing et al., 2021). Given the impacts of climate change on fisheries, the need for climate adaptation is well-established (Bryndum-Buchholz et al., 2021); within the U.S., a number of recent policies and plans have called for climate-ready fisheries (Executive Office of the President, 2021; Ocean Policy Committee, 2023). Yet, implementation of climate adaptation in U.S. fisheries at the federal and regional levels has been limited. For example, a U.S. Government Accountability Office report found that only a quarter of fishery management plans consider climate or ecosystem information (United States Government Accountability Office, 2022), and fishery managers in the U.S. and elsewhere are still waiting for the delivery of improved climate and ecosystem information to take action (Levin et al., 2018; Link and Marshak, 2021; Sumby et al., 2021; United States Government Accountability Office, 2022).

In the U.S, eight regionally focused Fishery Management Councils (FMCs) are responsible for developing fishery management plans to comply with federal regulations to achieve the optimum yield for each fishery on an ongoing basis. Each FMC is comprised of a diverse set of user groups, including regional fishermen, and industry representatives and federal and state managers; less commonly, FMCs include scientists, Tribal seats and NGOs. Each FMC operates independently from one another to address regionally specific challenges. Each FMC is also advised by several auxiliary groups, including advisory panels, management teams, and a Scientific and Statistical Committee made up of expert scientists. Management decisions made by the FMCs go to the secretary of commerce and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries) for approval and implementation. NOAA Fisheries also provides scientific support to the FMCs, especially through its six regional Fisheries Science Centers. As part of the responsibility to achieve optimum yield for each fishery, the FMCs and NOAA Fisheries develop, test, and evaluate different strategies to accomplish existing and climate specific fishery objectives.

1.2 Management adaptation so far

Climate-ready or climate-resilient fishery management generally does not have a single accepted definition (see Wilson et al., 2018; Holsman et al., 2019). Here, we define climate-ready management as a suite of actions and approaches intended to understand, predict, plan and adapt to the impacts of climate change on fisheries and fishing communities; this is inclusive of actions that broadly support resilience of the fishery social-ecological system. Climate-ready fishery management addresses several principles: it is knowledge-based, adaptive, inclusive and equitable, precautionary, and works to reduce risk and address uncertainty.

Climate change requires managers to improve the long-term resilience of fisheries while concurrently improving the short-term responsiveness of management systems to prevailing ecological conditions and avoiding unintended harm to fish stocks, ecosystem processes, and fishing communities in a highly uncertain context. Resilience can be defined as the capacity of a system, or interconnected systems, to absorb disturbance and reorganize while undergoing change so as to still retain essential function, structure, identity and feedbacks (Bahri et al., 2021). For fishery managers, maintaining resilience is necessary for attaining fishery objectives in the long term.

To date, much of the focus of climate adaptation strategies has been on the production of forecasts of ocean conditions and distributions of fish and other marine life (Busch et al., 2016;

Peterson et al., 2021; Saba et al., 2023). Some efforts have already completed or are close to having operational products (Hollowed et al., 2020; Drenkard et al., 2021; Saba et al., 2023). However, in many regions, these products are likely to take several years or longer to be made and subsequently put into use, are often focused on high-profile species, and any model-based approaches will be subject to steep learning curves and continual revisions; meaning on the water impacts of these efforts may not be felt for up to a decade or more.

Integration of climate information into forecasting tools, such as with climate-informed stock assessments, will be important for fishery adaptation, but this continues to be hindered by low model skill deriving from limited data in many regions and an often incomplete understanding of the relationships between environmental drivers and their impacts on fisheries (Tommasi et al., 2017). Furthermore, despite progress in the development of forecasting tools and data monitoring systems (Punt et al., 2016; Hollowed et al., 2020; Rovellini et al., 2024), there are still obstacles to operationalize the production of highly accurate forecasts of fishery productivity, range shifts, and community impacts into decision-making (Tommasi et al., 2017; Saba et al., 2023).

Regardless of most global emissions scenarios, warming will continue in the near-term; even with deep, rapid, and sustained reductions in greenhouse gas emissions, declines in warming trends will still take decades (Calvin et al., 2023). The need for fishery adaptation will remain, and near-term action is critical even without the full complement of information and tools in hand. To accomplish adaptation, managers need a portfolio of actions to support climate resilience in fish stocks and fisheries (Holsman et al., 2019). A number of studies have identified potential actions for climate-ready fisheries (Bell et al., 2020; Link et al., 2021), frameworks with which to consider possible approaches (Pinsky and Mantua, 2014; Morrison and Termini, 2016), considerations related to partnership and adaptive co-management (Wilson et al., 2018; Lomonico et al., 2021) and best practices with which to do so in ways that build resilience (Mason et al., 2023). Other research has noted a need for management that is proactive, dynamic, and flexible to improve adaptive capacity in response to climate impacts (Golden et al., 2024), though increasing adaptive capacity depends on how the fishery is defined and could require trade-offs (Reimer et al., 2025). Several studies have identified attributes that can contribute to climate resilience in fisheries (Mason et al., 2022), archetypes of resilient fisheries (Eurich et al., 2024), and barriers and enablers of resilience (Maltby et al., 2023). Yet there has been relatively little focus on near-term actions that managers could implement using existing information and tools, and there are relatively few examples of implemented adaptation actions (Bell et al., 2020; Bahri et al., 2021).

2 Study goals and overview

Given these challenges and an urgency for action, we performed a review of climate-ready fishery actions proposed in the literature and by research scientists and fishery managers. Our goal was to identify a core set of actions that have been proposed and then determine which of those actions could reasonably be considered implementable in the near-term. Based on our findings, we identified a set of actions managers could take now to improve the long-term resilience and short-term adaptability of fisheries while the mechanistic links between the environment and fisheries are further identified. We focus on climate adaptation of the fishery management system, rather than in fisheries themselves, which have an additional set of adaptation approaches (e.g., see (Galappaththi et al., 2022) that can be taken in concert with management-specific adaptation (Bahri et al., 2021).

We reviewed literature at the intersection of climate adaptation and fisheries management. We focused on papers that either proposed specific actions to change the fishery management process or derived those actions from model simulation (e.g. the effectiveness of various control rules). A final set of 23 papers (18 peer-reviewed publications and 5 white papers) were used to capture a broad set of proposed actions. Based on our expert judgment, which encompasses several decades of engaging with the FMCs, we extracted the most tangible recommended actions from each paper and characterized each action according to the following criteria: climate impact each action addressed (stock productivity, stock distribution, ecosystem productivity, or other ecosystem aspects); which part of the management process the action would affect (data collection, data treatment, stock assessment, control rules, management options, and communities, as modified from (Link et al., 2021); and the time frame to implement the action (short, or 1-2 years; medium, or 2-5 years; and long, or 5-10 years) (Figure 1). We then focused additional review on the actions that could reasonably be completed in the near term. In our synthesis of actions, we included those that were discrete and that could be clearly implemented at a U.S. FMC through a specific series of steps. For each recommended action, we identified a first step that an FMC could undertake towards implementation. We also reviewed actions that were more general, fell outside the jurisdiction of fishery managers, or could broadly be considered best practices for how climate-ready management could be conducted. Here, we have focused on two criteria; time frame to implement each action, as we are focused on short-term action and the first step managers can take to complete the action. Our characterization of which climate impact each action was expected to address and where the action could be inserted into the management process are discussed in the Supplementary Materials.

3 Results

Our review suggests the nature of the climate challenge necessitates utilizing a range of approaches, including taking opportunities to address climate change in every facet of management from data collection through decision-making.

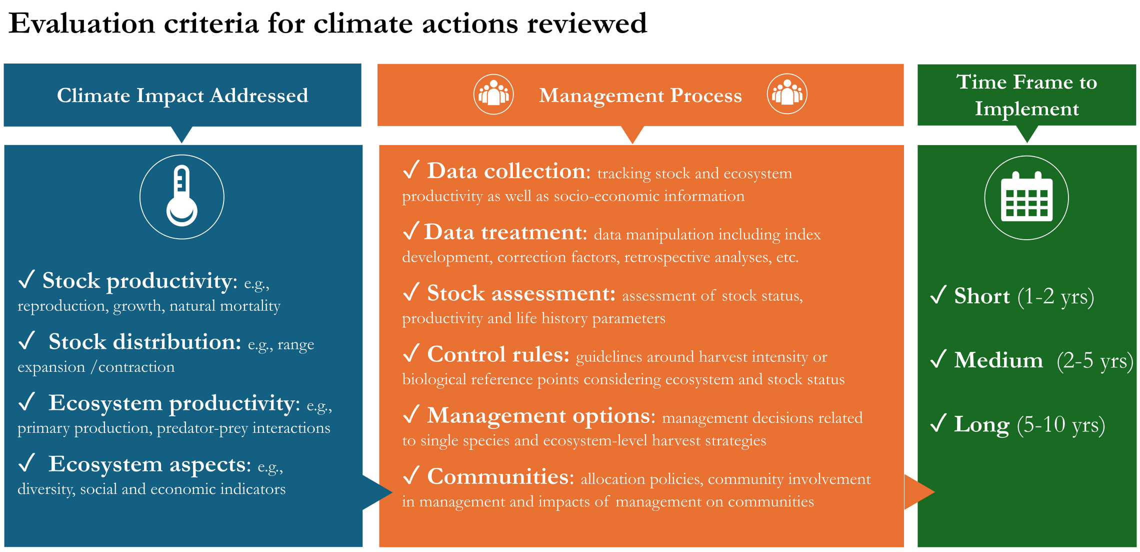

FIGURE 1
Characteristics assigned to each of the climate-ready fishery actions identified in the literature. Those actions that were characterized as short term (1-2 years) are discussed in this paper.

A total of 102 recommended actions from 23 papers were identified, resulting in 60 distinct actions. From those 60 distinct actions, 27 (45%) were identified as short-term actions, 21 (35%) medium, and 12 (20%) were long term (Figure 2; Table 1). The full set of actions and a description of the classifications of each category can be found in the Supplementary Materials.

We grouped the individual actions into nine high-level categories, which are discussed in greater detail below. Not every category was found to have an action for each timeframe. However, every high-level category had at least one short-term action identified, except for the 'restore sensitive habitats' group, which included only one, medium-term action. Three categories (diversify knowledge systems, increase transparency in determining regime shifts, and increase dialogue and identify on-ramps for climate and ecosystem information) only had short-term actions identified.

Many recommended actions fell within three broad groups: 1) actions specifically designed to address climate change impacts (climate-specific), such as those that deal directly with shifting stock distributions. 2) actions more focused on overall fish stock resilience but could also act as a mechanism to address climate (resilience-focused), such as ending overfishing (Pinsky and Mantua, 2014; Sumaila and Tai, 2020); and 3) actions that were directly responsive to climate impacts and resilience-focused (climate-responsive), such as increased reporting and the use of climate and ecosystem information. Many of the climate-responsive actions integrated climate information or considerations into existing tools or frameworks. The authors note that some actions may partially span two or more groups; we focused on primary action intent when delineating group. Most recommended short-term actions (15 of the 27 unique actions) fell into the climate-responsive group (Table 1).

3.1 Actions focused on overall resilience (non-climate specific)

3.1.1 Address systematic scientific issues

The category to address systematic scientific issues included three short-term actions intended to improve stock resilience to climate change and reduce uncertainty from other sources. This included two more explicitly resilience-focused actions, which were considering stock indicators beyond fishing mortality (F) and biomass (B) management targets (Karp et al., 2019) and using indices of stock abundance-based approaches to supplement stock assessments on a more frequent basis (Free et al., 2023b). It also included an action targeted at addressing bias and retrospective patterns within assessments (Karp et al., 2019; Mazur et al., 2023). For example, Mazur et al. (2023) found that addressing stock assessment bias in New England groundfish may be more immediate and important than identifying optimal harvest control rules in a climate context as the harvest control rules were not robust enough to overcome climate biased fishing mortality rates estimated from stock assessment (Figure 3)

The first step for an FMC to take to address systematic scientific issues depends on the short-term action. To diversify indicators beyond *F* and *B*, a first step would be for an FMC to request that the relevant NOAA Fisheries Science Center develop a list of additional indicators of stock resilience, such as age structure and genetic diversity, and report on the status of those indicators. To use stock abundance-index approaches to supplement detailed assessments (Bell et al., 2020; Klibansky et al., 2022; Southeast Fisheries Science Center, 2023; Pacific Fishery Management Council, 2024b), a first step would be for an FMC to identify a candidate index for each stock and create a mechanism to report abundance indices annually

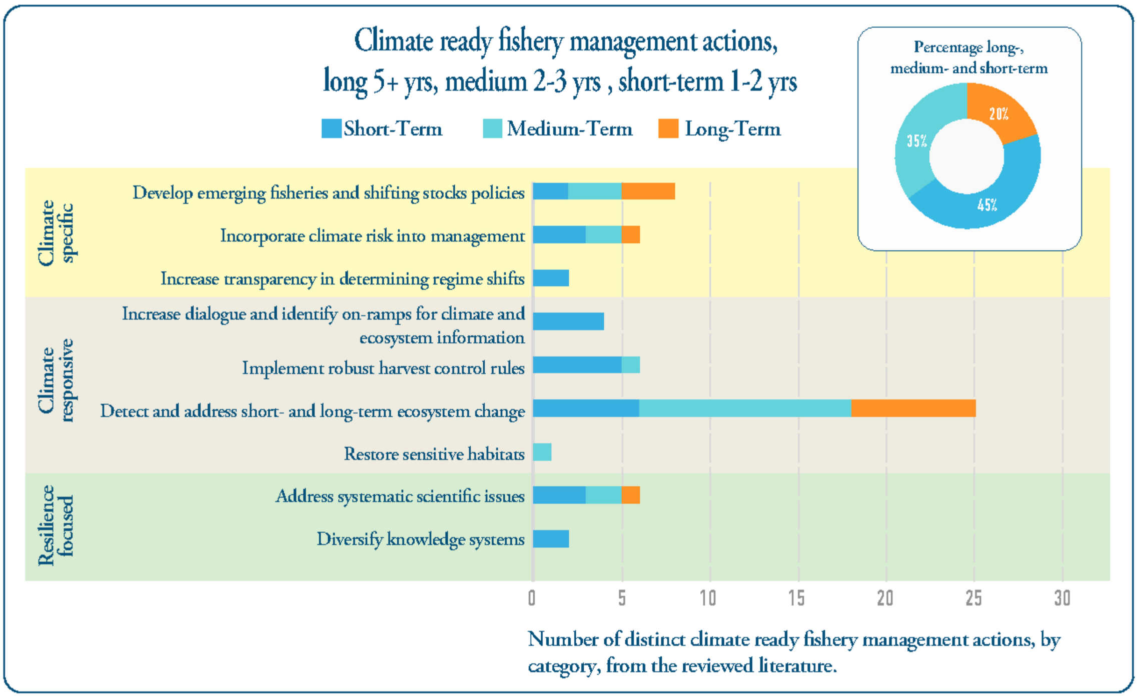

FIGURE 2
Our review of climate-ready fisheries revealed nine categories of recommended actions across three overarching groups: climate-specific (yellow shade), climate-responsive (tan shade), and resilience-focused (green shade). The number short- (blue), medium- (turquoise) and long- (orange) term actions within each category is show in the main figure. The overall proportion of actions falling into each timeframe is in the inset figure, with forty-five percent of the distinct actions identified that could be accomplished in the next 1-2 years.

and evaluate suitability for empirical harvest control rules (HCRs). To address retrospective bias, a first step would be for the FMC to add a term of reference (TOR) to each stock assessment to detect retrospective patterns and if applicable, re-assess model forecasts with and without environmental predictors to determine model skill and develop methods to address unresolved retrospective.

3.1.2 Diversify knowledge systems

The category to diversify knowledge systems included two closely related short-term actions to diversify knowledge systems in management and to do so involving coproduction of knowledge (Raymond-Yakoubian et al., 2017; LKTKS Taskforce, 2023a). Co-production of knowledge (CPK) is generally defined as an iterative and highly collaborative process based on equitable partnerships that bring together diverse knowledge to identify research questions and problems as well as potential management solutions (see (Armitage et al., 2011; Norström et al., 2020; Cooke et al., 2021; Mills et al., 2023). CPK is likely to become an increasingly important tool in the context of climate change and fisheries (Cooke et al., 2021; Mills et al., 2023) as it has the potential to bring together different stakeholders and knowledge systems that can address complex ecosystem and climate challenges. Cooke et al. (2021) described a CPK approach to understand drivers of and potential mitigation solutions for Pacific salmon declines in British Columbia, emphasizing the importance of bringing together researchers, Tribes and community members with broad expertise to tackle a difficult problem. Another strength of CPK is that it can be applied in any region provided a strong partnership base exists to support it. For instance, Divine et al. (2022) used a CPK approach, incorporating both western science and Traditional and Local Knowledge, to explore multifaceted fishing and climate impacts to communities and northern fur seals (*Callorhinus ursinus*) around the Pribilof Islands in the Bering Sea.

The near-term use of CPK and diverse knowledge systems in management could expand understanding of and ability to manage complex social-ecological fishery systems (Aminpour et al., 2021) in the context of climate change. Considering different types of data and ways of understanding in fisheries can enable scientists and managers to evaluate decisions from a more layered perspective that better considers human-environment or species relationships (Johannes and Neis, 2007). Additionally, including diverse knowledge sources can increase participation and stakeholder engagement in management processes (Britton et al., 2021), such as through FMC-associated workgroups or task forces where communities and individuals have the opportunity to utilize their knowledge in science and policy-level decision making. The LKTKS Taskforce is one such example from the Alaska region where Tribal members, fishing industry representatives, Agency and FMC scientists came together to develop a protocol for operationalizing Local Knowledge (LK) and Traditional Knowledge (TK) equitably in fisheries management. The LKTKS protocol has more recently been applied in a few key climate and ecosystem action items at the North Pacific FMC (LKTKS Taskforce, 2023b).

TABLE 1 Summary of near-term climate-ready fisheries actions achievable in the next 1-2 years.

3.1 Actions focused on overall resilience (non-climate specific)	
Address systematic scientific issues (3.1.1)	• Improve stock resilience by considering stock indicators beyond *F* and *B* • Re-assess model forecast skill and address retrospective patterns • Use indices of stock abundance to supplement stock assessments on a more frequent basis
Diversify knowledge systems (3.1.2)	• Diversify knowledge systems in management • Diversify knowledge systems and co-production of knowledge
3.2. Climate-specific actions	
Develop emerging fisheries and shifting stocks policies (3.2.1)	• Evaluate future stock boundaries • Map and report species distributions over time
Incorporate climate risk into management (3.2.2)	• Ecological risk assessment for modifying risk policy and prioritization • Ecosystem indicators to inform catch limits • Adjust P* (buffers)
Increase transparency in determining regime shifts (3.2.3)	• Apply objective approach to determine regime shifts • Truncate time series data to reflect current environmental regime where strong evidence of a transition is present
3.3 Actions focused on overall resilience but responsive to climate change	
Increase dialogue and identify on-ramps for climate and ecosystem information (3.3.1)	• Track and report indicators through ESRs and/or ESPs • Increase FMC dialogue on climate information • Map management processes to identify knowledge on-ramps • Develop Ecosystem and Socioeconomic Profiles
Implement robust harvest control rules (3.3.2)	• Biological reference point adjustment • Environmentally linked harvest control rules (HCRs) • Maintain status quo *B* and *Fmsy* reference points as a default • Phase in or pause increases in catch, especially for shifts in productivity • Apply robust harvest control rules that are resilient to climate change
Detect and address short- and long-term ecosystem change (3.3.3)	• Include ecosystem considerations in TORs • Incorporate changes in stock availability to surveys due to changes in ocean conditions • Implement an ecosystem cap that considers broader ecosystem function and re-evaluate existing caps • Timely detection of and response to changing productivity, as opposed to prediction of climate effects • Develop factors to consider under F-eco • Collect data on population vital rates and report single-species ancillary information, such as vital rates, genetics, and trophic data

It is important to distinguish knowledge types in how they are defined and applied in management. Local Knowledge (LK) is typically defined as the observations and experiences of local people (or fishers) living in or connected to a region, with significant long-term experience in or expertise related to a particular location, species or fishery (St. Martin et al., 2007; Murray et al., 2008; LKTKS Taskforce, 2020; Peterson Williams et al., 2022). LK, in particular, may add value to near-term climate resilience through 'on-the-water' early warnings as well as the collection of novel fishery-dependent data that supplements preexisting fishery independent research platforms (Johannes et al., 2000; Mackinson, 2001). For instance, fishers were the first to report signs of Pacific cod declines in the Gulf of Alaska fishery early in the 2014-2016 marine heatwave (Peterson Williams et al., 2022).

TK is defined a living body of knowledge acquired and utilized by Indigenous communities through long-term socio-cultural and environmental engagement (Raymond-Yakoubian et al., 2017). Especially in regions where climate change is disproportionately impacting food security and culture for subsistence and Native communities, including TK in management may be a foundational way to build equity into climate-resilient fishery management. TK has been included in a few analytical documents presented to the North Pacific FMC to inform decision making, such as the 2022 and 2023 Bering Ecosystem Status Reports, which included TK and community voices to identify cumulative impacts to chum and Chinook salmon (Siddon, 2022, 2023). However, TK and associated Indigenous value systems still do not have equitable standing in most fishery management systems (Raymond-Yakoubian et al., 2017).

As a first step, FMCs can initiate a process to populate a task force to identify protocols and management on-ramps for new types of knowledge similar to the process undertaken by the North Pacific FMC (LKTKS Taskforce, 2023a). Expanding broad stakeholder representation as well as social science capacity on the FMCs and associated FMC bodies and within NOAA Fisheries would also support the action to diversify knowledge systems in the short- and long-term.

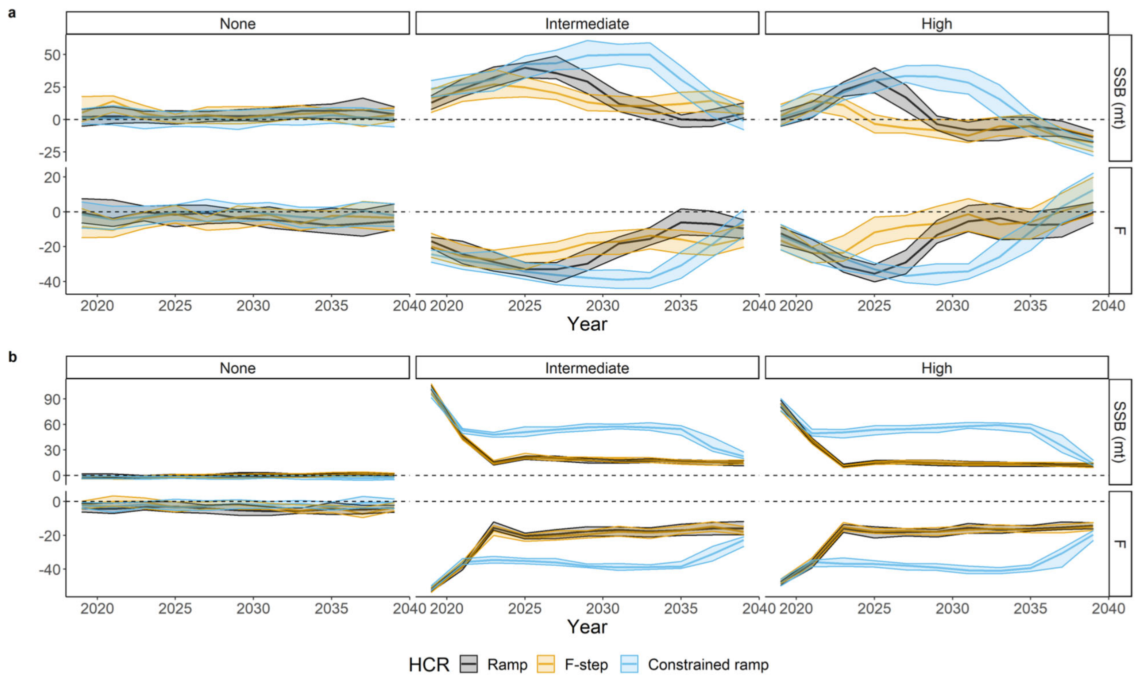

FIGURE 3
Results from Mazur et al. (2023; Figure 6) demonstrating the relative impacts of misspecification of natural mortality (assumed to be related to ignoring climate impacts in the stock assessment) for two stocks, a) Gulf of Maine and b) Georges Bank haddock, and three simulated control rules. When no misspecification is present the relative performance of different control rules (colored lines) are similar (left panel). However, when natural mortality was misspecified, control rules were not robust to the misspecification (center and right panels), which resulted in significant median percent relative error for SSB and F.

3.2 Climate-specific actions

3.2.1 Develop emerging fisheries and shifting stock policies

The category to develop emerging fisheries and shifting stocks policies included two short-term actions: mapping species distributions over time (Link et al., 2021), and identifying future stock boundaries (Karp et al., 2019). These two data-oriented actions could be considered foundational steps for longer-term actions (e.g., making changes to allocations, initiating time and area closures to account for climate-driven shifts, changing surveys to address changes in ocean conditions, or revisiting management authority). Most of the actions in this category were not short-term; (9 of 11 actions) were either in the medium- or long-term timeframes. This is indicative of scale of the challenges associated with shifts in stock distribution, which include data availability and sharing, and governance and institutional barriers to making changes to allocation or to management authority or jurisdiction. As one example, along the East Coast, understanding of shifts from the South Atlantic northward have been complicated by different fishery independent survey methods (trawl vs. pot, trap, and longline) between regions (Golden et al., 2024).

As a first step, individual species distribution maps could be reported to FMCs on a regular basis to passively monitor shifts over time. This reporting could occur via existing management processes such as: ecosystem status reports (ESRs), annual catch limit and rebuilding compliance reviews, or through single-species assessment or catch-setting processes already in place. Both models [e.g., VAST (Thorson, 2019)] and visualization tools [such as DisMAP (NOAA Fisheries, 2024)] have been developed for this very purpose and are broadly used throughout the U.S. Secondarily, FMCs could request NOAA Fisheries Science Centers identify which stocks may shift across extra-jurisdictional boundaries (Figure 4).

3.2.2 Incorporate climate risk into management

The category to incorporate climate risk into management included three short-term actions that identify how to assess climate risk and then use it to inform management decisions, including using it directly in development of scientific catch advice.

The first action was to use risk assessment (Bell et al., 2020; Rankin et al., 2023). Ecological risk assessment can be used by FMCs to focus on key elements of risk for a fishery, understand baseline risk, prioritize management focus, and as a tool to incorporate ecosystem information into decisions (Holsman et al., 2017; Gaichas et al., 2018; Rankin et al., 2023). Risk assessment can also be used to modify risk policies through a risk table approach (Bell et al., 2020; Dorn and Zador, 2020; Peterson Williams et al., 2022). Risk tables can be used to capture and consider ecosystem information, as well uncertainty not captured in the stock assessment, in a structured way that can better inform management decisions (Dorn and Zador, 2020). As a first step to develop risk tables, an FMC could task its Scientific and Statistical Committee, a scientific advisory body, and stock assessors with

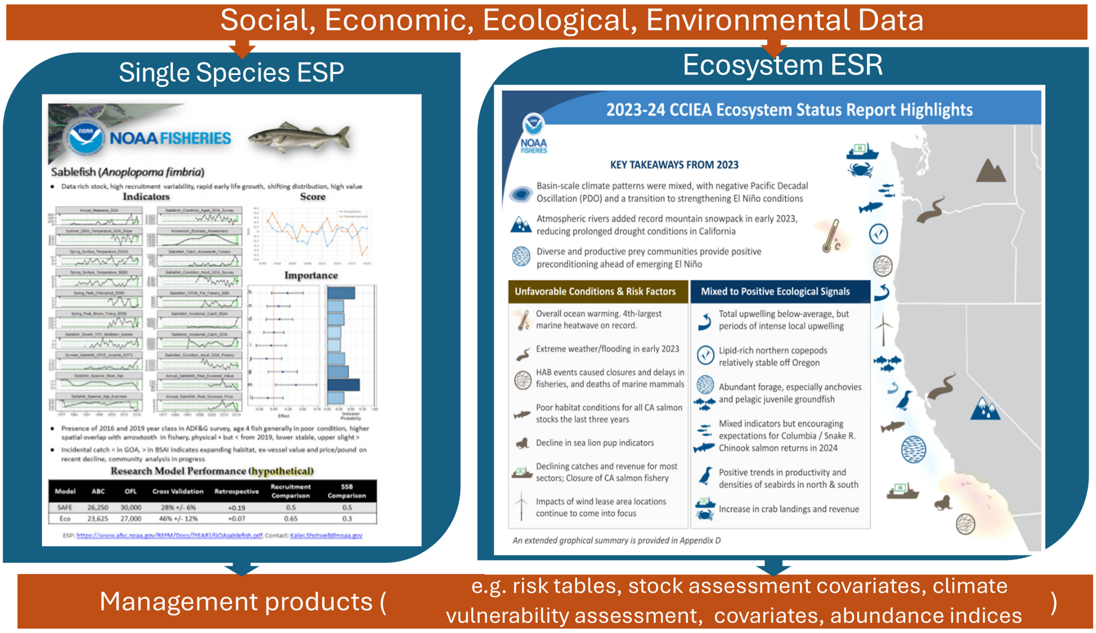

FIGURE 4
Ecosystem reporting tools, such as single-species Ecosystem and Socioeconomic profiles (ESP) and Ecosystem Status reports (ESR), play a central role in assimilating different types of information into the management process. Indicators likewise are important in the development of numerous tactical strategic and tactical management tools. Many indicators may be readily available through existing databases and portals. While ESR and ESPs are important tools to engage with fishery participants, the indicators used in these products can be compiled in different ways for different management purposes. Example management products that can be derived from the ESR and ESP indicators include risk tables, factors used in climate vulnerability assessments, and stock assessment covariates to name a few. Here, we show how an ESP for sablefish (Shotwell et al., 2017) and an ESR for the California Current (Leising et al., 2024) both integrate social, economic, ecological and environmental data and could be used to inform a range of management products.

developing a risk table process. An FMC may first want to initiate a review to identify stocks that would be priority candidates for risk tables. To be relevant for climate-ready management, the incorporation of ecosystem and climate components should be considered from the outset in risk tables (Figure 4).

FMCs generally have risk policies that adjust the acceptable probability of overfishing based on scientific uncertainty and factors related to data quality (Bell et al., 2020). FMCs can adjust risk policies to establish buffers that account for climate risk in a variety of ways. For example, FMCs can make adjustments to P* to respond to productivity changes, range shifts, or environmental variability (Gaichas et al., 2018; Bell et al., 2020; Link et al., 2021; Free et al., 2023b). Climate can impact both scientific and management uncertainties and the interplay of buffers across all of the components of establishing catch limits should be considered. The first step to account for climate risk could be to initiate a review of an FMC's risk policies with the intent to identify how to adjust in response to climate considerations—either by adding a buffer to P* or through the use of ecosystem indicators or other information using a tiered approach. For example, an FMC could use climate vulnerability assessments, which use a trait-based approach to assess the sensitivity and exposure, to rank overall vulnerability of a fish stock (Frawley et al., 2025), when setting risk policy tiers, such that more vulnerable stocks have a larger buffer to avoid exceeding the annual catch limit, or directly in the estimation of scientific uncertainty around the estimated catch limit. At least two FMCs, New England and Pacific, are undergoing a review process that includes a TOR or directive to consider how to best integrate ecological or environmental factors when considering changes to the risk policy (Nies, 2023; Pacific Fishery Management Council, 2024a).

If the linkages between the environment and stock productivity are well understood, then another action is that the FMCs may consider the ecosystem indicators to inform catch limits for single species (Haltuch et al., 2019; Bell et al., 2020) For example, Haltuch et al. (2019) were able to leverage a well-established link between young of the year sablefish and hake abundance and well-established mechanistic relationships to ocean conditions (Tolimieri et al., 2018; Haltuch et al., 2019, 2020; Tolimieri and Haltuch, 2023) for inclusion into a regularly occurring stock assessment. The incorporation of this relationship had a number of impacts including: 1) reduced near-term forecasting uncertainty in the young of year estimates which in turn impacts catch forecasts based on current ocean conditions, 2) allowed research to explore the long-term implications of climate change to stock productivity, and 3) use historical ocean conditions to further refine the estimation of reference points. Indicators can also be leveraged to inform the allocation of quota under a multispecies system level cap; see section 3.3.3 (Cieri, 2023; Jiao, 2023; Montón, 2023).

3.2.3 Increase transparency in regime shifts

The category to increase transparency in regime shifts included two short-term actions that represent differing approaches to handling stock regime shifts. The first is to apply an objective approach to determine a regime shift (Klaer et al., 2015; Bell et al., 2020). Klaer et al. (2015), propose a weight-of-evidence approach and establish four criteria to assess whether a regime shift has occurred. Alternately, another action was to truncate time series data to reflect current environmental regime where strong evidence of a transition is present (Link et al., 2021). The approach of truncating the time series should be used with caution, and Link et al. (2021) suggest it only be used when there is clear evidence that the stock will not return to the previous productivity regime before the next benchmark assessment.

Changing fishery reference points or stock assumptions, such as recruitment trends, will have significant downstream and direct impact to management reference points, catch, and future assumed productivity potential. As a first step, an FMC could add a TOR to its stock assessments to apply four criteria in Klaer et al. (2015) to assess whether a regime shift has occurred. If those criteria suggest that a regime shift has occurred for a particular stock, a sensitivity run could be added to the stock assessment TORs that truncates the time series and explores the implications to future stock abundance, productivity, and resilience and ultimately for management.

3.3 Actions focused on overall resilience but responsive to climate change

3.3.1 Increase dialogue and identify on-ramps for climate and ecosystem information

The category to increase dialogue and identify on-ramps for climate and ecosystem information included four short-term actions, most of which related to the use of ecosystem and climate-informed tools.

Two actions related to products developed by the NOAA Integrated Ecosystem Assessment (IEA) program to meet ecosystem-based fisheries management objectives. These were to track and report on indicators using standardized templates, including Ecosystem Status Reports (ESRs) (Karp et al., 2019; Bell et al., 2020; Link et al., 2021) and to develop species-specific Ecosystem and Socioeconomic Profiles (ESPs) (Peterson Williams et al., 2022; Shotwell et al., 2023). Other actions were focused on finding and leveraging FMC mechanisms to incorporate ecosystem and climate information and indicators, such as mapping management processes to identify knowledge on-ramps (Mason et al., 2023), and increasing FMC dialogue on climate information (Karp et al., 2019), including within the stock assessment process.

A prerequisite for successful application of these actions is to secure access to ecosystem and climate information. For FMCs without access to regular tracking of ecosystem and climate indicators, a first step could be to request production of an ESR by the relevant regional NOAA IEA program that includes climate-relevant indicators. An ESR or other standardized reporting template can, in turn, provide information for species-specific applications, such as ESPs and indices of abundance. ESRs can also be used to identify anomalous conditions. Fortunately, most FMCs have some access to regular ecosystem reporting (Link and Marshak, 2021). For those FMCs, first steps should focus on identifying tools that will best meet management needs and mapping places where climate information could be brought into decisions. Increasing dialogue on climate information could be initiated by establishing mechanisms to regularly discuss climate items, for example by having a regular ecosystem agenda item at FMC meetings (see section 4.1).

Management on-ramp mapping could begin with an FMC tasking a relevant advisory body or technical committee or establishing a new task force to do the work. For example, the Pacific FMC started an Ecosystem and Climate Information Initiative, which is intended to review the incorporation of climate and ecosystem information into the FMC's harvest-setting and management processes, identify if there is a need for fishery management plan specific climate and ecosystem information, and map pathways for its use in management processes and actions (Pacific Fishery Management Council, 2022). An existing advisory body at the PFMC, the Ecosystem Workgroup, has been tasked with moving the initiative forward. The North Pacific FMC created a new Climate Change Task Force under its Bering Sea Fishery Ecosystem Plan that undertook a process to identify management on-ramps for climate and ecosystem information as part of a broader climate readiness synthesis (North Pacific Fishery Management Council, 2021). A task force or other working group should include FMC members and should include engaging stakeholders as part of its process.

3.3.2 Implement robust harvest control rules

Implementing robust harvest control rules included five short-term actions that propose the use of HCRs at different steps of the management process. The actions generally fall into two buckets: increasing the robustness of classic control rules (Da-Rocha et al., 2024) and creating environmentally linked dynamic control rules that account for climate or environmental conditions. Given the different approaches to implementing robust HCRs ("static and robust" or "dynamic and adaptive") there are a number of possible pathways for FMCs to consider. As a generalized first step, FMCs can review control rules to determine if any existing control rules do not align with existing best practice approaches (such as threshold and ramped fishing mortality type rules as opposed to constant *F* rules) (Free et al., 2023b), and where the application of these existing approaches could benefit stock resilience. Beyond that, FMCs should consider environmentally informed reference points or assessments, which should be weighed against existing robust HCR methods. For example, an FMC could undertake a review of its control rules to 1) determine where threshold rules could be effectively applied, and 2) assess whether there are appropriate uncertainty buffers and biomass limits in place, and, if not, how those could be implemented.

Recommended actions that increase the robustness of classic control rules include: reviewing and tuning-up existing control rules (Free et al., 2023b), phasing in increases to catch (Link et al., 2021), modifying *F* or Spawning Potential Ratio (SPR) reference points to ensure alignment with productivity and variability over time (Orio et al., 2022), and preserving status quo or precautionary biomass and fishing mortality reference points to avoid maladaptation (Szuwalski et al., 2023; Punt et al., 2024). In response to either changes in productivity and/or shifts in species distribution, FMCs could consider the best way to phase in, or even pause, increases in catch (Link et al., 2021). In response to changes in production because of shifting stock distributions, an FMC could also consider developing an omnibus amendment for emerging stocks to establish default protections from increasing fishing pressure until there has been sufficient time to collect data and examine information on the stock, ecosystem, and socioeconomic impacts of fishing.

Some actions in this category directly used environmental forcing mechanisms to dynamically adjust catch or fishing pressure in response to current environmental conditions. Two papers (Karp et al., 2019; Link et al., 2021) include actions to develop harvest control rules that are responsive to, and account for, changing conditions. For example, in Pacific sardine (*Sardinops sagax*), an environmentally informed HCR adjusted the exploitation rate based on sea surface temperature (Karp et al., 2019); however, the rule is under review (National Oceanic and Atmospheric Administration, 2024) as the mechanistic link between sardine recruitment and temperature has not held up over time (Muhling et al., 2020; Wildermuth et al., 2023). As a first step towards environmentally informed HCRs, FMCs could assess which stocks could benefit from an environmentally linked HCR and inventory what strong environmental covariate relationships exist for those stocks.

When relevant environmental data can directly inform the stock assessment, new reference point and uncertainty estimates can be estimated from the stock assessment directly. When considering adapting reference points to reflect current conditions, the FMCs should maintain status quo reference points for *F* and *B* until a weight-of-evidence approach suggests a change (e.g., by developing and using criteria to indicate whether a regime shift has occurred). Another step is to assess the feasibility of using updated reference points directly from stock assessments given risk of type I (assuming there is a change when there is not) and type II (failing to detect a change) errors. In particular, a type I error is concerning because of the associated risk of lowering reference points and effectively increasing pressure on a stock that is declining or depleted (Link et al., 2021).

3.3.3 Detect and address short- and long-term ecosystem change

The category to detect and address short- and long-term ecosystem change included six unique actions. The first was to implement or review existing ecosystem removal caps to consider broader ecosystem production and function (Holsman et al., 2020; Peterson Williams et al., 2022; Stram et al., 2022; Free et al., 2023b). In the Bering Sea, the 2 million metric ton cap on groundfish has been largely successful in preventing overfishing while sustaining high yields despite being based upon outdated (1968-1977) productivity and catch data (Holsman et al., 2020). No other region in the US currently utilizes an ecosystem cap approach (Morrison et al., 2024), although many species are managed in some manner at the species complex level. As a first step, FMCs in many regions could simply request that their scientific committees or NOAA Fisheries Science Center provide a time series of *total* landings across the entire ecosystem and across other management units, such as Fishery Management Plans or stock complexes. This, along with a request for other metrics of system production can be used to inform discussion about the tradeoffs and structure of a potential cap.

Karp et al. (2019) recommended an action to add an ecosystem considerations component in the TOR for conducting and reviewing stock assessments, in alignment with broader NOAA Fisheries policies and plans [e.g., as in Lynch et al. (2018)]. These considerations could include environmental or climate interactions if they are available, though these are included in only a minority of stock assessments (Marshall et al., 2019). If those interactions are not available, the increased reporting of qualitative ecosystem considerations during stock assessment may provide a starting point for detecting ecosystem change.

Additional actions included collecting, reporting, and investigating enhanced information for drivers and responses of climate change, such as population vital rates (Link et al., 2021); addressing shifts in stock availability to surveys (Bell et al., 2020; Link et al., 2021); and using modeling methods to investigate time-varying parameters to detect changes in productivity (Collie et al., 2021). These time-varying parameters may be distinguished from other methods of regime shift detection in that, once implemented, they may automatically capture ongoing short-term and historical variability in stock productivity parameters, as opposed to a single decision point, such as the assumed future recruitment levels (see section 3.2.3). To determine whether a shift in productivity is occurring, FMCs can ask stock assessors to compare historical trends in time-varying productivity.

To understand and act upon other fish stock responses to climate change, FMCs can initiate asks for basic data that track population-level changes and vital rates, as well as analyze changes to survey catchability, with a priority on receiving information with species identified with very high and high vulnerability to climate change. This information can be delivered annually as part of regular reporting (e.g., in SAFE reports, stock assessment reports, or through Ecosystem and Socioeconomic Profiles, see Shotwell et al (Shotwell et al., 2023). A final action was to develop ecosystem factors or indicators to be considered under an F-eco framework, which modifies fishing mortality targets to account for ecosystem changes in productivity (Orio et al., 2022). With F-eco, stock-specific ecosystem indicators or ecosystem models are used to set an ecosystem-based fishing mortality reference point (F-eco), which can be used to select the most plausible fishing mortality target from a range of scenarios informed by the ecosystem conditions for the stock (Bentley et al., 2021). As a first step, an FMC could request the relevant NOAA IEA program or NOAA Fisheries Science Center identify environmental factors impacting individual fish stocks, including indicators from ecosystem models. These could then be brought back to the FMC to consider under F-eco. Key sources for these environmental factors include indicators from ecosystem reporting climate vulnerability assessments, which FMCs may already be familiar with.

A complete list of actions considered, including short-, medium- and long-term actions, and their associated characterizations, can be found in the Supplementary Materials.

4 Discussion

The U.S. federal fishery management system is generally considered robust and successful at meeting conservation objectives (Gourlie, 2017; Melnychuk et al., 2017; Battista et al., 2018). It has also demonstrated a relatively high potential adaptive capacity (Bryndum-Buchholz et al., 2021). However, with ongoing climate change, even robust existing management regimes are unlikely to be sufficient to continue to attain management objectives (Holsman et al., 2020). There is a need to implement new approaches that can improve short-term responsiveness of management while supporting long-term resilience of fisheries and avoiding unintended harm to stocks in a highly uncertain context. Ultimately, the development of climate-ready management approaches must address the challenges climate change poses to status quo assumptions of stock biology, management process, and risk (Karp et al., 2019).

Addressing climate change also requires fishery managers to consider the impacts of management actions on communities and the nation as a whole, adhering to principles of fairness and equity found in federal and state law (for example, see National Standards 4 and 8 of the Magnuson-Stevens Fishery Conservation and Management Act and Title VI of the Civil Rights Act of 1964). Food security, livelihood, and culture are all critical axes to consider, especially when decisions impact subsistence fishers, Tribal fisheries, fishery-dependent economies, or groups of people historically denied access to fisheries decision-making. Equitable adaptation strategies are not optional, but are instead required to ensure that long-term adaptation and sustainability is achieved (Agyeman et al., 2016).

There are many proposed solutions to address the various challenges climate poses for fisheries, but the current management system has considerable inertia. In this context, fishery management bodies, including the FMCs, have found it difficult to begin the process of implementing changes (Bell et al., 2020; Lomonico et al., 2021). The gap between the production of scientific knowledge and its use in management has been a key obstacle (Holsman et al., 2019; Vogel et al., 2024). In our experience, another challenge is the perceived tradeoff between waiting for future advancements in knowledge and acting more immediately and with imperfect information.

The near-term actions presented in this paper represent a set of options for fishery management systems to overcome the key hurdle of where to begin. We view this set of actions as a menu rather than a prescriptive list. Any of the individual actions presented here represents a tangible step managers can take in the next few years to increase climate resilience and the adaptive capacity of a fishery. These individual actions do not supplant the need for a comprehensive approach to tackle climate risks, but these actions can act as a stopgap while more systematic changes are made over time and new models and tools become available.

45% of the 60 distinct actions we identified can be accomplished in the short term, many years ahead of the anticipated wide availability of highly skilled forecasting systems. Additionally, we were able to identify a first step for every single action identified, suggesting these actions can be implemented into existing fishery management frameworks and that these ideas do not pose a regulatory barrier. Our analysis demonstrates managers have extensive options available for immediate action that will increase fishery resilience while more complex forecasting is developed.

There are a number of climate-specific actions that can be implemented in the near-term, but minor improvements to existing processes can also have benefits for climate preparedness by supporting resilience. These established actions to improve management do not require new forecasting systems to be built or tools to become available. Actions like expanding the types of information presented to managers, assessing ecosystem status on a more frequent basis, and applying robust control rules are not new (Levin et al., 2018), and are reflected in ongoing efforts at various FMCs, such as increasing the reporting ecosystem information and right-sizing stock assessments to increase throughput. These generalized (rather than climate-specific) actions can provide essential tools for managers to adapt to changing conditions and should not be overlooked in the development of climate-ready strategies.

4.1 Development of ecosystem indicators and information

The development and delivery of ecosystem indicators and other types of information played an outsized role in the actions that were identified as climate specific (Section 3.2). The use of climate and ecosystem information was extremely broad, was mentioned directly in 20 of the actions, and ranged from communicative (such as providing ecosystem status reports and ecosystem and socioeconomic profiles (Shotwell et al., 2023) (Section 3.2.2); to strategic advice, such as prioritization of climate-vulnerable stocks for action (Section 3.3.2); to tactically focused quantitative indictors to be incorporated into stock assessment (Section 3.3.2). The widespread use of indicators made them particularly difficult to categorize into our high-level groupings, and as such they appear throughout most of the recommendations rather than as a stand-alone action.

Developing this type of information is a necessary first step of any kind of ecosystem and climate informed decision-making, as is communicating this new information on an ongoing basis to FMCs. While indicators may be applied differently depending on management objectives, they all represent factors that will track or impact fisheries in one way or another. The development of ESRs and single-species ESPs for communicate can provide a tangible jumping off to point to identify relevant and import environmental, ecological, and social factors to begin tracking over time and to then build the data and reporting infrastructure required. Each of these processes will require the co-development of a set of practical indictors, which can evolve over time to suit the specialized needs of Councils in the long term. Examples of the evolution of indicators from scoping, communication, and tactical applications have been led in at least four regions of the U.S. through engagement of NOAA's IEA program scientists (Figure 4).

4.2 Avoiding maladaptation

Near-term actions are needed, but the rush to implement technical scientific solutions could increase the risk for maladaptation given the inherent complexity and uncertainty in most fisheries (Schipper, 2020; Szuwalski et al., 2023). With maladaptation, actions increase climate vulnerability or risk, often inadvertently, rather than reducing these factors. Concerns about maladaptation could cause managers to delay or defer taking necessary initial adaptive actions, which is a challenge for climate-ready implementation.

Each of the categories for climate-ready actions has the potential to yield maladaptive outcomes if they are approached without a full understanding of risks. Potential maladaptive examples include: incorporating only a subset of environmentally driven factors (e.g., incorporating recruitment but not growth), which may lead to incomplete and misinformed scientific advice (Szuwalski and Hollowed, 2016; Punt et al., 2024); revising fishery management targets to solely reflect prevailing ecological conditions, which can expedite population declines or limit the potential for future population recovery (Perälä et al., 2020; Szuwalski et al., 2023); and making socioeconomic management decisions with unintended impacts to fishing communities (Hilborn et al., 2004; Punt et al., 2014; Holland and Kasperski, 2016; Maltby et al., 2017; Pendleton et al., 2018).

Robust control rules will remain an important feature of any actively managed fishery and are typically applied to fishing mortality and biomass reference points. In this context, we have included actions for both static and dynamic control rules (which can also encompass dynamic reference points). Dynamic reference points have been simulation tested, but they remain largely untested in a management context (Punt et al., 2014; Bessell-Browne et al., 2024; Peterson et al., 2024). Given the uncertainties that persist in stock assessments, broad application of dynamic reference points could pose the greatest risk for maladaptation without robust knowledge of environmental drivers of change for a given stock (Punt et al., 2014; Szuwalski et al., 2023). If scientists and managers do proceed with dynamic rules or reference points, careful consideration and transparency need to be applied to that process (Klaer et al., 2015), and long-term reference points should be tracked as a baseline to ensure some baseline metric of potential productivity. It is also important to acknowledge these types of high-skill and environmentally driven fishery forecasts will not be ready in the 1-2-year timeframe that we focus on here and will likely never be available for most managed species. Conversely, static (but robust) control rules are proven tools for conferring resilience. A review of control rules in U.S. federal fisheries FMCs (Free et al., 2023b) suggests there is much room for improvement for upgrading existing static control rules, which can be accomplished on a much faster timeframe than implementing dynamic ones.

Rather than leading to inaction, the risk of maladaptation can be addressed through the selection of strategies that are "no-regret" or "low-regret" as well as those that are "win-win" and provide benefits in both near and long term (Poulain et al., 2018). These strategies will be case-specific. However, no and low-regret strategies are often those that have anticipated benefits irrespective of climate change impacts or strategies that lay groundwork for later actions, such as establishing monitoring systems (Poulain et al., 2018). Win-win strategies offer immediate and long-term benefits. For example, for small-scale fisheries in the Pacific Islands, habitat restoration and other actions that support increased fish production were identified as win-win; a strategy to shift fishing effort away from demersal fisheries to nearshore pelagic fish was also a win-win because it increased access to fish in the near-term while preparing the fishery to adapt to growing losses to demersal fisheries due to climate change impacts like coral bleaching and ocean acidification (Bell et al., 2018). Low-risk strategies are intended to build the resilience and adaptive capacity of the fishery management system in the immediate future. Over time, individual actions can be incorporated into an intentional policy to mitigate climate risks across the entire management system, including for data-rich and data-poor stocks. As an example, annual updates of recruitment indicators or simple stock assessments could counter the need for precise 3–5-year look-ahead predictions of recruitment. Likewise, precautionary catch buffers for climate-vulnerable stocks may not be required for those stocks where environmental drivers have been included in the stock assessment with high skill.

5 Policy implications

As is often the case with fishery management, there is no single solution to adapt to climate change given the social and ecological diversity of fisheries and the complexity of climate impacts. This review offers a structured perspective on priority actions that can be taken in the next 1-2 years to increase the resilience and adaptability of fish stocks and communities that rely on them. From this review, we can infer three important findings. First, nearly half of the climate-ready fisheries actions can be implemented in this short timeframe. Second, nearly all actions identified can be implemented in the current fishery and regulatory framework. Third, while new approaches are needed, managers should proceed with caution to avoid maladaptation and choose no- or low- maladaptation risk approaches wherever possible.

Managers will need to be prepared to anticipate and respond to both gradual and short-run shocks to fishery systems. Climate-ready fisheries can improve the adaptive capacity of a fishery, inclusive of both the social and ecological components, through proactive yet precautionary fishery decision making that is better suited to an increasingly uncertain reality. While the political context of fishery management can be controversial at times given the challenge of meeting many different objectives, we think that near-term climate-resilient fishery management approaches could be a unifying force in the context of climate challenges. Tools and approaches already in hand, paired with effective science communication, and increased transparency in management, could be an important element of building unity around the goal of climate resilience in fisheries and developing a set of short- and long-term adaptive actions. While the needs and solutions for each fishery may be different, we hope this review and the identified near-term actions can contribute to overcoming the barriers to starting greater adaptive action.

Author contributions

MD: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. EC-C: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. MP: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. MM: Conceptualization, Investigation, Writing – review & editing. CR: Conceptualization, Investigation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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