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Embracing social-ecological system complexity to promote climate-ready fisheries

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Abstract Climate variability and change are having dramatic effects on marine species, fisheries, and fishing communities. Climate perturbations elicit fishery management responses intended to mitigate negative effects, but the responses often do not account for the complexity of fisheries systems, leading to unintended consequences. However, including more diverse forms of ecological, economic, and social information reveals elements of system structure that could lead to more climate-adaptive management approaches and better outcomes. Here, we examine four U.S. case studies that span a range of climate-fisheries interactions: target species distribution shifts; bycatch of juvenile fish; harmful algal blooms that delay fishery openings; and offshore wind energy development on fishing grounds. In each example, as management actions or plans were undertaken to mitigate climate impacts, subsequent quantitative and qualitative indicators and knowledge revealed potential system feedbacks, fishery participant responses, and/or undesirable fishery outcomes. These case

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studies highlight the complex and iterative nature of developing climate-adaptive strategies for fisheries management. They also illustrate that how we define "fishing community" is a key determinant of both the outcomes of climate-driven management actions and how those outcomes are perceived. Finally, they underscore the value of engagement and knowledge exchange among participants, scientists and managers, and provide insight as to how to more rigorously apply "best available science" to climate-ready fisheries management, in accordance with fishery policies and laws that emphasize both biological and social outcomes.

Keywords Climate change · Ecosystem-based fisheries management · Fishery policy · Fishing communities · Knowledge · Social-ecological systems

Introduction

Climate change and extreme events are having drastic impacts on marine fisheries worldwide. Species, habitats, and food webs are experiencing changes in temperature, circulation, oxygenation, and acidification (Brierley and Kingsford 2009; Bahri et al. 2018; Gaines et al. 2019; Clay et al. 2020) that profoundly affect demographics, productivity, distributions, and ecology (Doney et al. 2012; Cheung et al. 2013; Hollowed et al. 2013; Free et al. 2019; Pinsky et al. 2020). Fishing practices and infrastructure are jeopardized by rising sea levels, increases in storm frequency and intensity, and lost opportunities as coastal habitats are degraded or dedicated to other sectors like renewable energy (Colburn et al. 2016; He and Silliman 2019; Schupp et al. 2021). These changes affect the very nature of fishing: what and how much is caught; where and when it can be caught, landed, and processed safely and profitably; and what types of vessels, gear, infrastructure, and other capital are needed to adaptively fish and process what is available (Cheung et al. 2010; Papaioannou et al. 2021; Samhouri et al. 2024; Selden et al. 2024). Potential consequences on economies, livelihoods, and food security are profound (Allison et al. 2009; Barange et al. 2018; Free et al. 2019; Singh et al. 2019; Mendenhall et al. 2020; Galappaththi et al. 2022; Cooley et al. 2022; Mills et al. 2023), and may force us to reconsider long-held notions of managing fisheries "sustainably."

Preventing, mitigating, or adapting to climate impacts is an urgent challenge for fisheries participants, managers, and policymakers (Free et al. 2020; Bryndum-Buchholz et al. 2021). Part of meeting that challenge is developing, sharing, and integrating knowledge of how climate drivers affect the components and connections in fishery systems (Colburn et al. 2016; Levin et al. 2016; Clay et al. 2020; Galappaththi et al. 2022). Such knowledge is essential for developing climate readiness strategies and assessing actions meant to support climate resilience (Anderson et al. 2015; DePiper et al. 2017; Whitney et al. 2017; Haugen et al. 2021). The types of knowledge prioritized for use in fisheries management are often referred to as "best available science." In the U.S. for example, the Magnuson-Stevens Fishery Conservation and Management Act (MSA) is guided by ten National Standards. One of these, National Standard 2, requires using "the best

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scientific information available" in decision-making, including "high quality and timely biological, ecological, environmental, economic, and sociological scientific information" (50 CFR 600.315). "Best scientific information available" largely has been associated with quantitative data, models, and reference points for biological attributes associated with optimal fisheries yield and avoiding overfishing (e.g., abundance, recruitment, mortality, age structure, maximum sustainable yield); or with economic attributes (e.g., revenue, operating costs, maximum economic yield). As a result, U.S. fisheries management typically has better-defined goals and reference points for biological and economic outcomes than for social and cultural outcomes (Hall-Arber et al. 2009; Charnley et al. 2017).

The 1996 amendment to the MSA introduced National Standard 8, which states that fishery management actions must "take into account the importance of fishery resources to fishing communities by utilizing economic and social data" in order to "provide for sustained participation" in fisheries and "to the extent practicable, minimize adverse economic impacts" (16 U.S.C. § 1851(a)(8)). Since the advent of National Standard 8, greater effort has gone into quantifying social and economic conditions in fisheries and fishing communities (Smith and Clay 2010; Colburn and Jepson 2012; Jepson and Colburn 2013; Anderson et al. 2015; Himes-Cornell and Kasperski 2015, 2016; Breslow et al. 2016; Seara et al. 2022). Further effort has gone toward including qualitative information, such as the knowledge and values of fishery participants (Charnley et al. 2017; Farr et al. 2018; Murphy et al. 2021; Reid et al. 2021; Frid et al. 2023). Definitions of "best available science" for U.S. agencies have expanded to include Indigenous Knowledge (OSTP-CEQ 2022), and some U.S. fishery management councils are exploring inclusion of Indigenous Knowledge in fisheries management (e.g., NPFMC 2023).

Although fisheries management often emphasizes quantitative indicators (e.g., Rice and Rochet 2005; Fulton et al. 2005; Rochet and Trenkel 2014), qualitative approaches to understanding and characterizing economic, and, especially, social and cultural impacts of management decisions can add rich context to quantitative analyses. Qualitative data provide valuable contextual information and offer insights into mechanisms of change in social-ecological systems (Johnson et al. 2014; Barclay et al. 2017; Selden et al. 2024), particularly when participants are empowered to explain and interpret their own priorities, experiences and interests (Fontana and Frey 2005; Colburn and Clay 2012; Bernard 2017). Additionally, mixed methods approaches that bring together quantitative and qualitative data can provide a more holistic understanding of fisheries dynamics (Lorance et al. 2011; Young et al. 2019; Gordon et al. 2022). A more balanced consideration of biophysical and social information can help to explain and anticipate human connections, responses and perspectives within complex systems (Smith et al. 2013; Young et al. 2018; Murphy et al. 2021).

The threats that climate change and extreme events pose to fishing communities necessitate greater incorporation of social and economic data into assessments of fisheries management performance (e.g., Melnychuk et al. 2023), and inclusion of more diverse bodies of knowledge into management (Beaudreau and Levin 2014; Cooke et al. 2021). Here, we present four case studies from the U.S. that span a range of climate-fisheries interactions, response pathways, and opportunities for inclusion of participant knowledge and perspectives. We find that: (a) management interventions spurred by climate variability and change may not fully address fishery system complexity, leading to undesirable feedbacks and outcomes; (b) exchange of knowledge among fishery participants, managers and researchers can reveal important pathways and loops of system complexity; and (c) incorporating qualitative and quantitative information from the ecological and human domains better reflects system complexity and can improve climate adaptation and readiness. A case study approach highlights examples in which a social-ecological systems perspective can guide forward-looking strategies to increase climate change resilience and adaptive capacity in fisheries (Mason et al. 2022).

Pathways of climate effects, management actions, and outcomes

Amidst growing interest in ecosystem-based fisheries management, many management systems are considering ways to incorporate ecosystem information, such as climate forcing, species interactions, or human well-being (e.g., Link et al. 2021). However, bringing ecosystem and social-ecological considerations into existing management structures has proven challenging. This challenge stems from having diverse and competing societal goals and values; incomplete understanding of social-ecological system processes and transdisciplinary problems; and gaps between gathering knowledge and acting upon it (Rice 2005; Bednarek et al. 2018; Ojaveer et al. 2018; Bryndum-Buchholz et al. 2021; Karcher et al. 2022). The pace of ecosystem change threatens to outstrip the ability of research and management systems to adapt (Fulton 2021; Golden et al. 2024). Moreover, fisheries governance systems are often complex, with interacting jurisdictions and both formal and informal processes (Dutra et al. 2019). Complex governance systems that include multiple centers of decision-making across different scales can allow for innovation in response to climate change (Ostrom 2010). But, outcomes for communities can depend on the extent to which their authority and knowledge is recognized by formal institutions (Dutra et al. 2019), and on how effectively governance processes reflect cultural values, or broaden institutional perspectives to consider specific social-cultural contexts (Torre-Castro and Lindström 2010; Kelly et al. 2018). Including local and regional customary governance institutions and actors can strengthen resource management and planning (Acheson 2006; Kittinger et al. 2015).

As the effects of climate variability and change grow more apparent, they are ever more likely to induce fishery management responses and adaptive behaviors. Implementing fisheries policy is typically a cyclical process of collecting information, evaluating it relative to fisheries management objectives and reference points, and making decisions on how participants may exercise fishing rights (Ojaveer et al. 2018; Karp et al. 2019; Link et al. 2021). However, as the case studies below illustrate, management cycles for climate mitigation actions are unlikely to follow simple pathways, e.g., from perturbation → action → preferred outcome (Fig. 1a). At a minimum, we should anticipate that outcomes of the action have effects and feedbacks on other actors in the system (Fig. 1b). More likely, the climate perturbation, the management action, or the interacting effects of both will affect multiple ecological, economic, and social components, leading to even more complex feedbacks (Fig. 1c; see also Roux and Pedreschi 2024). Direct and indirect effects and feedbacks may extend further to include fishery-related markets and trade networks. The best available science required to understand this level of system complexity likely includes both quantitative and qualitative information about system structure and dynamics.

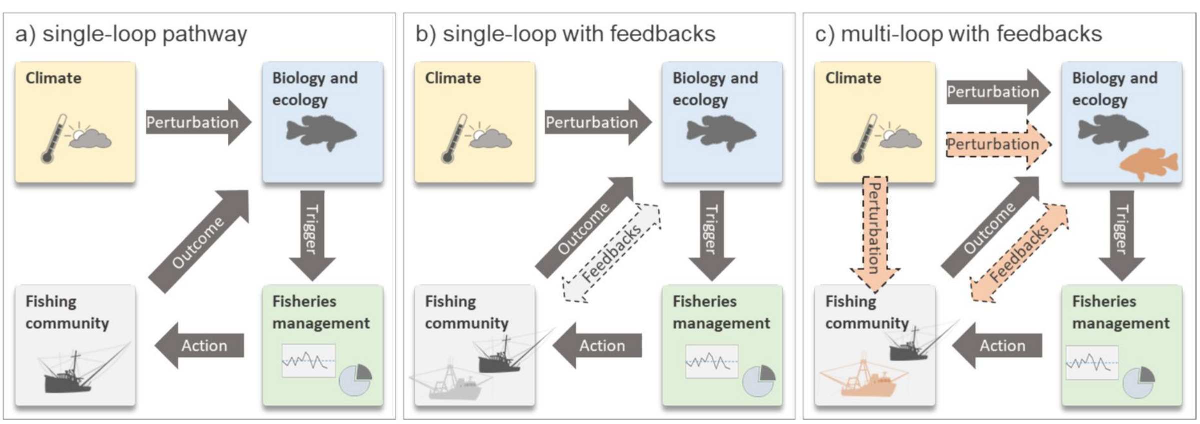

Fig. 1 Pathways of impacts, actions and outcomes in climate-perturbed fishery systems. **a** A single-loop pathway, where climate impacts on ecological variables of interest trigger a management response that alters fishing practices and leads to a biological outcome. **b** A more complex pathway, where the climate-triggered management response directed at one fishery (dark vessel at lower left) has an indirect feedback on a different fishery (light vessel at lower left). **c** A multi-loop pathway, where the climate driver has direct effects on multiple species and on fisheries, leading to even more complex indirect feedbacks. Climate drivers, management responses, and feedbacks potentially affect both the fisheries and their associated communities of place or practice

Case studies

We identified four case studies of U.S. fisheries systems in which actual or anticipated climate variability or change induced a mitigation plan or action, and complex social-ecological system pathways led to social outcomes that warranted further actions. The climate effects include species distribution shifts, episodic bycatch events, fishery closures due to climate-exacerbated harmful algal blooms, and planning for development of renewable energy infrastructure on traditional fishing grounds. For each case study, we highlight qualitative data or context that augmented decision support, and illustrate the pathways of system feedbacks and information flow with schematics adapted from Fig. 1.

Distribution shifts, port linkages, and community resilience in a Northwest Atlantic groundfish fishery

The distribution of fluke (or summer flounder, *Paralichthys dentatus*) on the Northeastern U.S. Continental Shelf has shifted north over the last five decades, likely due to a combination of factors (Bell et al. 2015; Dubik et al. 2019; Perretti and Thorson 2019). Warming temperatures since the late 1960s have expanded the seasonal availability of thermally suitable fluke habitat, and this trend is projected to continue (Kleisner et al. 2017; Alexander et al. 2020). Also, reduced fishing pressure on fluke has promoted recovery of older age classes, which tend to inhabit more northerly waters (Bell et al. 2015). Fluke is managed cooperatively by the Mid-Atlantic Fishery Management Council (MAFMC) and the Atlantic States Marine Fisheries Commission (ASMFC). The northward shift of fluke complicates the commercial quota allocation system, which is awarded on a state-by-state basis across eleven states based on the distribution of commercial fluke landings from the 1980s (Table S.1; see also MAFMC 1993; Palacios-Abrantes et al. 2023). Fluke landed in a given state counts toward that state's allocation, regardless of whether vessels landing the catch are from in-state or out-of-state.

Conflict is emerging between northern and southern states over potential policy changes, which may include a new quota allocation scheme that reflects the current distribution of fluke (Dubik et al. 2019). In response to stakeholder concerns, the MAFMC and ASMFC considered a range of allocation options (MAFMC 2020). An environmental impact statement (EIS) for the options incorporated extensive analysis of how allocation changes would affect fishery revenues in each state, and concluded that southern states have the most to lose from a change in the status quo (MAFMC 2020). However, examining impacts on specific fishing communities can reveal differential impacts within northern and southern states, and also reveal key linkages between ports that would otherwise be obscured by a focus on where fish are landed. The EIS selected ports where fluke represented > 1% of revenue, examined the proportion of total fluke volume and value landed in each port, and coupled this with general community profiles of those ports (Appendix C of MAFMC 2020). An alternative approach would be to focus on relative reliance on fluke in those ports. For example, while Beaufort, North Carolina and Chincoteague, Virginia rank fifth and seventh by volume of fluke landed, the groundfish trawl fleets in those ports derive ~ 50–75% of their total landings from fluke (Fig. S.1). In contrast, Point Judith, Rhode Island ranks first for fluke landings by volume and value, but fluke represents < 10% of Port Judith's groundfish trawl landings (Fig. S.1). The reliance of southern fleets on fluke was expressed to the MAFMC in a public comment period (Appendix D of MAFMC 2020).

A shift to quantifying the relative reliance of different ports on fluke would constitute a relatively minor change in the ways that the MAFMC has evaluated the impacts of re-allocation decisions in past decision-making. In contrast, an examination of which permit holders are landing fluke in southern ports could fundamentally change who is considered a stakeholder for the quota allocation to southern states. For instance, the degree to which permit holders living in one port are landing regularly in another port, and how that has changed over time, varies across ports in the southerly states of North Carolina and Virginia (Fig. 2). In Beaufort, North Carolina, landings of fluke made by out-of-state vessels have increased dramatically since 2013 and now represent more than 80% of all fluke landed since 2017. In Wanchese, North Carolina, out-of-state vessels have more consistently represented 30–50% of landings throughout the time series. In Virginia, out-of-state vessels have consistently represented 70–75% of the total fluke landed

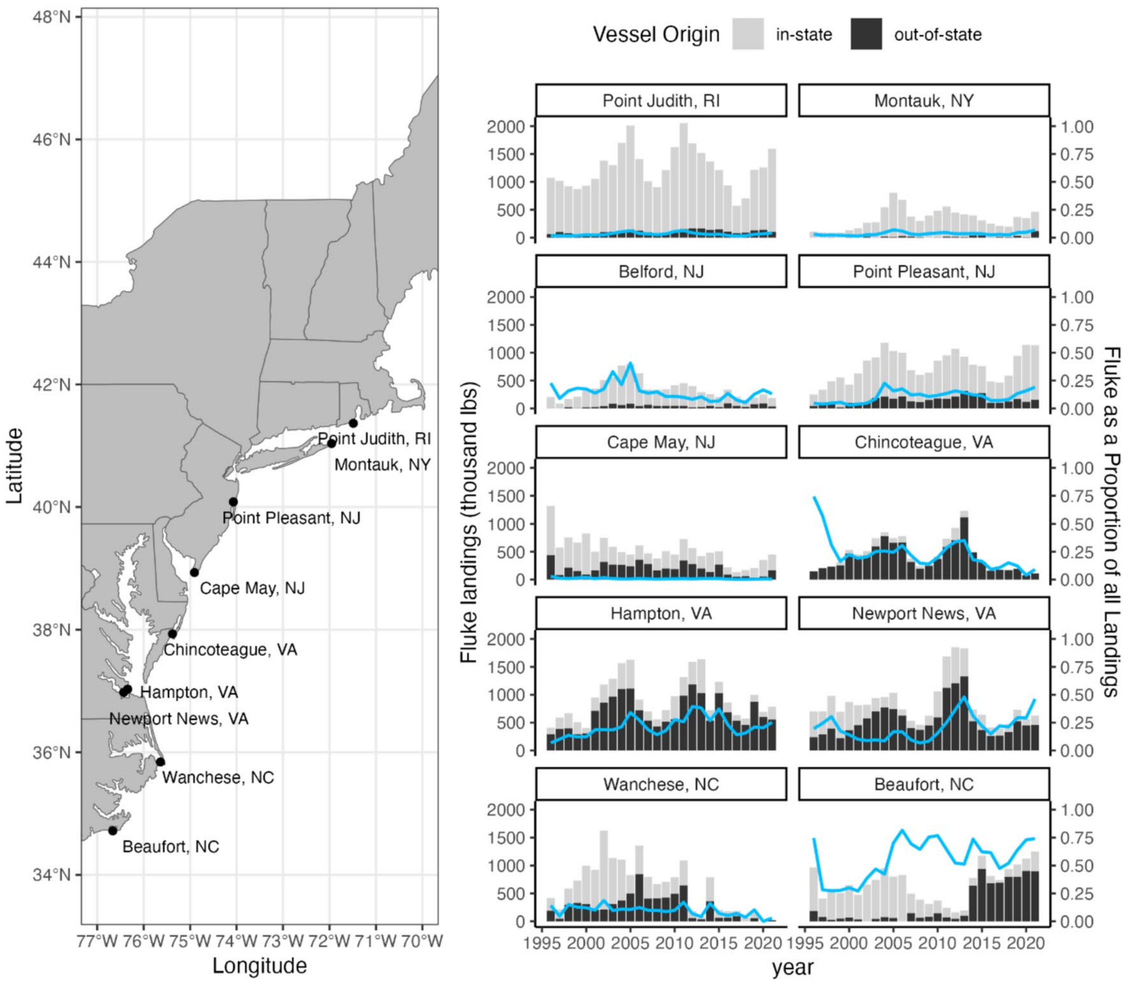

Fig. 2 Total and proportional landings of fluke (*Paralichthys dentatus*) along the U.S. East Coast, 1996–2021, in ten ports representing the greatest fluke landings in recent decades. Left y-axis / bars: total landings of fluke, categorized by vessels declaring a home port in the same state (gray) vs. declaring a home port in a different state (black). Right y-axis / blue line: fluke as a proportion of total commercial landings to the port. Ports are in the states of Rhode Island (RI), New York (NY), New Jersey (NJ), Virginia (VA), or North Carolina (NC)

in the ports of Newport News and Hampton since 2000, and 90% of fluke landed in Chincoteague (Fig. 2). As a result, many fish processors, dealers, markets, and other shoreside activities are dependent on fluke landings by out-of-state vessels that would be lost if more quota was allocated to northern states. Changes in fluke allocation may reduce overall fishing activity within those states in unanticipated ways that impact the economies of entire communities. Explicitly accounting for out-of-state contributions to total fluke landings may better inform the community-level economic risks of different reallocation policies.

Participant interviews also revealed the importance of “port flipping” as an adaptation strategy for dealing with poleward distribution shifts in fluke (Papaioannou et al. 2021). The interviews indicated that many fishers from northern states have purchased permits to land fluke in southern states, where quota is relatively high (Table S.1) and processor capacity exists. This was corroborated in media interviews with a New Bedford, Massachusetts trawl fisherman who had invested in the status quo allocation system by purchasing landing permits for southern states (Tamman 2018). The EIS noted that out-of-state vessels made up a large proportion of vessels landing fluke in

North Carolina (Table 46 in MAFMC 2020), but did not analyze this further. The proportion of fluke that vessels from individual northern states land in Virginia or North Carolina varies, with some states (e.g., Massachusetts, New Jersey) leveraging this strategy heavily since 2010 and others (e.g., New York, Rhode Island) using it less (Fig. S.2). Out-of-state fishers can only land fluke in North Carolina or Virginia by purchasing a landing permit from a fisher who was operating there in 1993–1995. These permits can cost tens of thousands of USD (MAFMC 2020, Appendix D). Changing the allocation scheme toward northern states would reduce the value of those investments substantially. Tracking the connections and potential tipping points between where fishers are based and where they land would significantly extend the consideration of what communities are affected by state-level quota reallocation.

Ultimately, the MAFMC implemented a new rule in 2020 that retains the historical state-level allocation up to a baseline total harvest level, but equally divides quota above that baseline among the primary fluke-fishing states (Table S.1, Option 2C). This option was a compromise in response to robust stakeholder and MAFMC support for both the status quo (Table S.1, Option 2A) and a full reallocation of quota (Table S.1, Option 2B). The high reliance on fluke for southern trawl fleets, the dependence of southern ports on fluke landings from outside vessels, and southern permit-holders from northern states give some context for broader support for the status quo than might be expected. Fishing communities in New York were the most opposed to the status quo and have argued for a greater percentage of quota, beyond even that considered under Option 2B (US Court of Appeals 2022). Their opposition may reflect the relative lack of New York fishing vessels that land in southern states, which gives them the most to gain from redistributing quota to northern states.

This case study highlights the importance of including a broader social and community context in decisions about changes in fish distribution and harvest allocation policy (Fig. 3). It illustrates that community-level reliance on a species can provide different information from overall landings totals for a state. Also, where out-of-state vessels provide a large proportion of overall fishing activity (Fig. 2), social indicators based only on the total number of permits for that species held by fishers based in that community (analogous to what was used in the EIS) will underestimate the dependence of that community on the species. Further, links between ports, created by vessels landing in ports outside their home states and investments made in out-of-state landing permits, dramatically expand the set of stakeholders negatively impacted by a reduction in the allocation of quota to southern states. A community-based perspective highlights the need for species-specific reliance metrics for fishing communities, indicators that reflect the overall dependence of community well-being on revenue generated by a specific species, and a consideration of the spatial links between ports that may change who has the most to gain or lose from reallocation decisions.

The outcomes of this case study are relevant to allocation challenges for stocks that are co-managed by multiple jurisdictions, or that are shifting from one jurisdiction into another due to climate change (see Golden et al. 2024). Federal fishery resources along the U.S. East Coast are managed by three separate councils (the New England, Mid-Atlantic, and South Atlantic fishery management councils), with some stocks cooperatively managed by multiple councils and/or with the ASMFC and individual states. Fishery management bodies must develop adaptive strategies for harvest allocation that reflect state or federal regulations, target stock biology, seasonal and long-term distribution shifts, and social and economic considerations for both historic and emerging fishing communities for a given stock or complex. The assumptions that go into allocation strategies can produce dramatically different outcomes for states and ports (Palacios-Abrantes et al. 2023). This calls for careful consideration of fishing community definitions and indicators of community-level impact of allocation policies.

Bycatch of juvenile sablefish in U.S. West Coast fisheries

Sablefish (*Anoplopoma fimbria*) support valuable pot, longline and bottom trawl fisheries along the U.S. West Coast (ex-vessel revenue \$22 M in 2022; Pacific Fisheries Information Network, https://pacfin.psmfc.org). The West Coast sablefish stock is managed by the Pacific Fishery Management Council (PFMC), and had its most recent benchmark stock assessment in 2019 (Haltuch et al. 2019). Sablefish have episodic

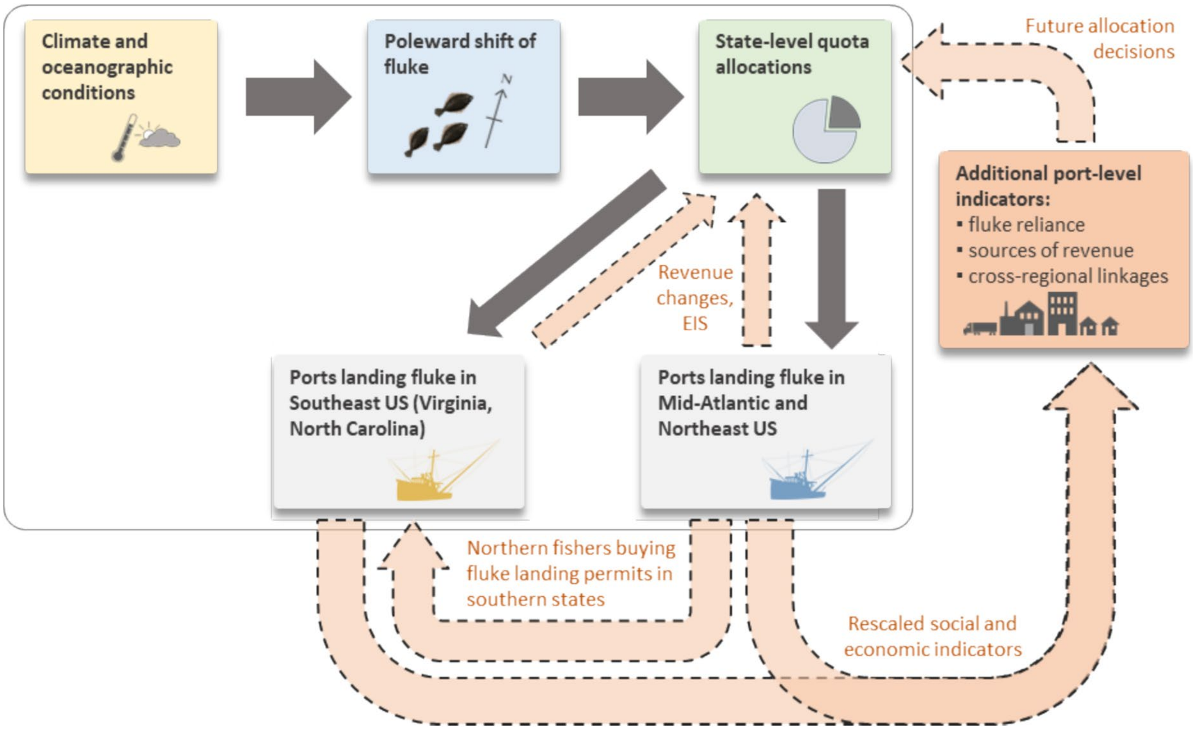

Fig. 3 Conceptual model of the fluke (*Paralichthys dentatus*) case study. Dark arrows map a relatively simple pathway of climate and oceanographic conditions driving a northward shift in fluke distribution, which triggers a spatial reallocation of state-level fluke quotas. Orange arrows, box and text represent social and economic considerations and indicators that are more representative of system complexity and help to inform future allocation decisions

strong year classes that have been linked to oceanographic conditions for pre-spawning adult females and larvae (Tolimieri and Haltuch 2018), and juvenile densities that vary considerably by year and latitude (Tolimieri et al. 2019). Sablefish typically enter fisheries at age 4, although smaller sablefish are caught incidentally throughout the water column, notably in midwater trawling for Pacific whiting (*Merluccius productus*), the largest fishery by volume on the U.S. West Coast. Sectors of the whiting fishery that process their catch at sea have an annual set-aside of sablefish bycatch; in years when the set-aside is at risk of being exceeded, these sectors may voluntarily avoid areas with large densities of sablefish. Whiting vessels that land their catch (the "shoreside" sector) must purchase sablefish quota if their catch exceeds their allocation, which increases operational costs and may restrict targeted fishing for whiting.

Between 2022 and 2023, several sources of information suggested that very large numbers of juvenile sablefish were present along the U.S. West Coast. All sectors of the whiting fleet reported encountering large concentrations of juvenile sablefish in 2022 (US-Canada Joint Technical Committee 2023). Salmon fishers reported catching juvenile sablefish in 2022 at depths where they had not seen them previously (D. Ogg, F/V *Karen Jeanne*, pers comm.). Harvey et al. (2023) reported to the PFMC that in 2021, age-0 sablefish catch-per-unit-effort in a fishery-independent bottom trawl survey was the greatest of the last 20 years, and coincided with an environmental indicator (anomalously low sea surface height) of strong sablefish recruitment (Fig. S.3; Tolimieri and Haltuch 2023). Harvey et al. (2023) noted that these results might be leading indicators of a large cohort that will enter the sablefish fishery in a few years.

While indicators of sharp, climate-driven increases in abundance or year-class strength of a species can inform present or future fishing conditions for that species, a second pathway for climate adaptation exists for other fisheries for which the first species is bycatch (Fig. 4). Here, the risk of sablefish bycatch

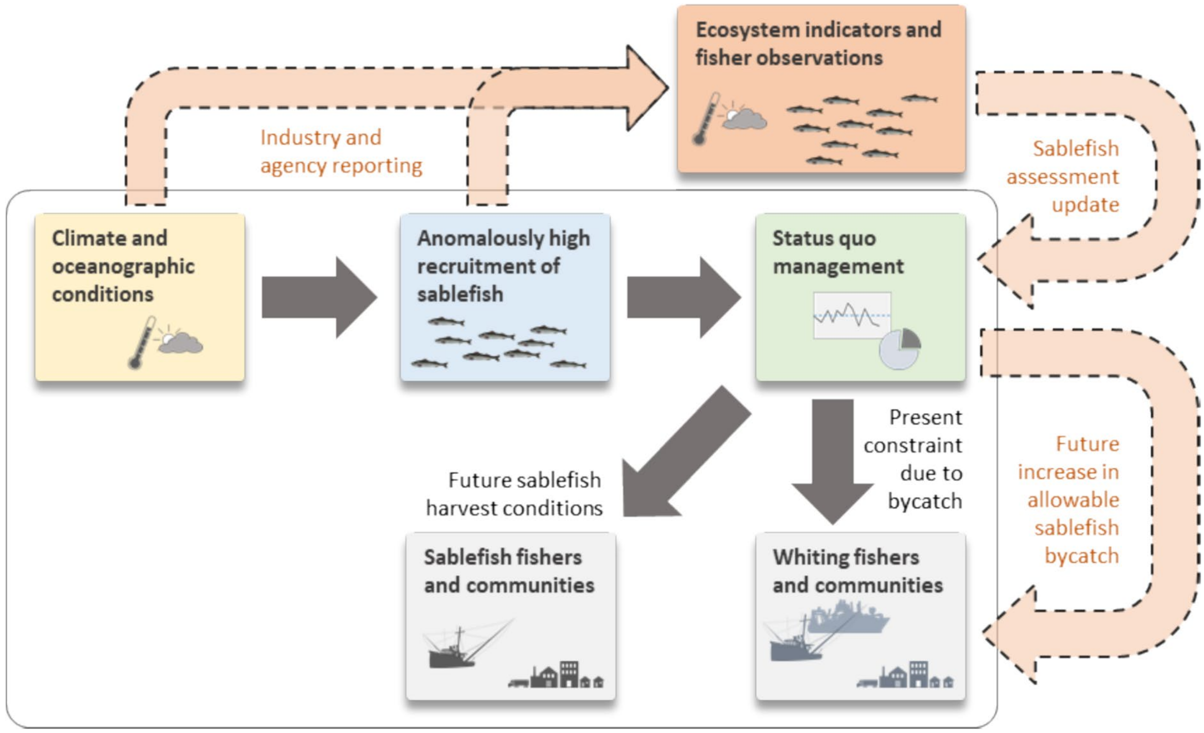

Fig. 4 Conceptual model of the sablefish (*Anoplopoma fimbria*) case study. Dark arrows map a relatively simple pathway of climate and oceanographic conditions promoting a large year class of juvenile sablefish, which is relevant both to management of future sablefish harvest and present-day sablefish bycatch mitigation in the Pacific whiting (*Merluccius productus*) fishery. Orange arrows, box and text represent inclusion of ecosystem indicators and fisher observations that triggered more rapid and climate-adaptive management actions

constrained opportunity in the whiting fleet: many whiting vessels moved away from productive fishing grounds to avoid sablefish (US-Canada Joint Technical Committee 2023). However, the influx of juvenile sablefish may have meant that the sablefish allocations to the whiting sectors no longer reflected the rate of sablefish encounters when fishing for whiting. The findings of Harvey et al. (2023) and concurrent accounts of widespread and abundant juvenile sablefish from fishery participants prompted a reanalysis of data that go into the process of prioritizing which stocks should be assessed; the reanalysis confirmed that this new year class of sablefish was exceptionally large. This led to a concrete management action by the PFMC: sablefish, which had not previously been scheduled for a new assessment, received an assessment update in 2023 (Johnson et al. 2023). Collectively, the information on new juvenile sablefish suggests that the set-aside for the whiting fishery could be increased up to fourfold (PFMC 2022a, 2023).

While this adaptive outcome can be considered a success story, there are caveats. First, the allowable bycatch update for the whiting fishery is still being evaluated, several years after the initial bycatch occurrence (though earlier than it may have if the sablefish assessment update not occurred). Second, the convergence of information that led to the sablefish assessment update began in part through informal conversations between observant attendees at a PFMC meeting, and similar events may not generate adaptive responses if the informal connections do not occur. Alternatively, the convergence of information may happen, but a lack of capacity (e.g., insufficient resources for an unscheduled stock assessment) may inhibit action. With these caveats in mind, we conducted a subsequent analysis (methods in Supplement 2) to assess which ports are most exposed to disruption in the shoreside whiting fishery as a result of high juvenile sablefish bycatch, and which communities could benefit most from increasing the sablefish allocation for shoreside whiting. Briefly, we used fishery participation networks (FPNs) to estimate the social-ecological risk of excessive sablefish bycatch in whiting-dependent ports (Fig. 5a). FPNs are network models that describe participation within and across different fisheries in a given area (Fuller et al. 2017; Fisher et al. 2021; Samhouri et al. 2024). We used network metrics derived from FPNs and indicators of port-level participation in the whiting fishery to assess the potential impacts in each port group. We evaluated these indicators relative to the abundance of juvenile sablefish near each port, and to a port-level index of social vulnerability, based on factors like poverty, labor, housing, education, and public health.

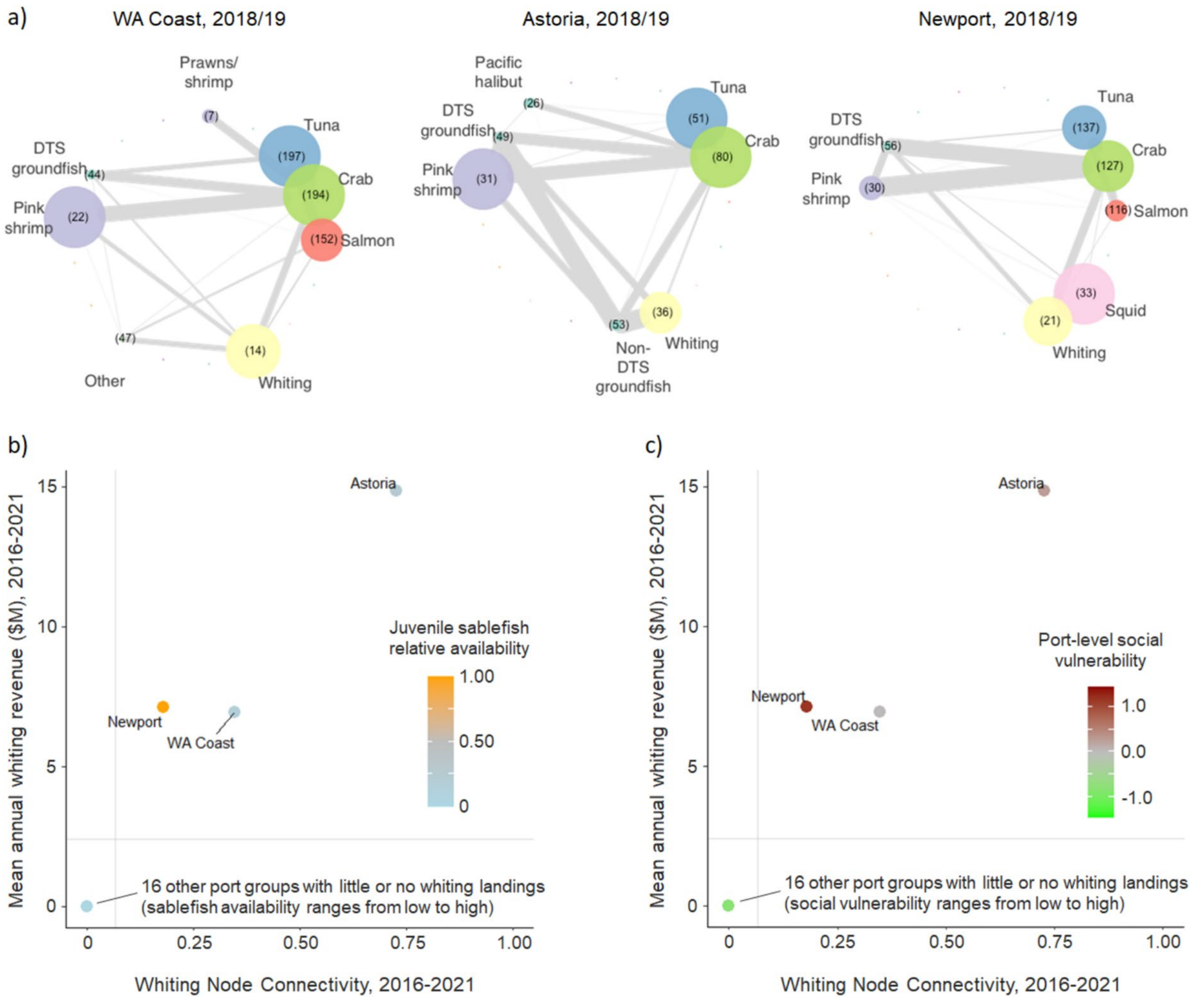

Fig. 5 **a** Fishery participation networks (FPNs) for three U.S. West Coast port groups with significant landings of Pacific whiting (*Merluccius productus*) from a representative year prior to the high occurrence of juvenile sablefish (*Anoplopoma fimbria*). Circles are proportional to the contribution of the fishery to vessel-level revenue; values in parentheses are the number of vessels in a fishery; thickness of gray lines is proportional to the number of vessels participating in both fisheries, and evenness of revenue from each fishery in the pair. **b** Relationship between mean annual port group-level economic dependence on shoreside whiting, mean annual connectivity of the shoreside whiting node to other fisheries in the port FPN, and risk of juvenile sablefish bycatch. The bycatch risk estimate is a normalized, fishery-independent measure of juvenile sablefish catch per unit effort in 2022 within a 232-km radius of the main port of each port group. **c** Relationship between port-level economic dependence on shoreside whiting, connectivity of the shoreside whiting node in the FPN, and a port group-level social vulnerability index

Only three West Coast port groups had substantial shoreside whiting landings in 2016–2021: Astoria, Oregon; Newport, Oregon; and the Washington Coast port group. Of these port groups, Newport's FPN had the lowest inherent resilience to a shock in the whiting fishery (Fig. 5b, c, x-axis). Newport also had the highest relative availability of juvenile sablefish (Fig. 5b, left), and thus the highest exposure to sablefish bycatch risk. Further, Newport had the highest social vulnerability among these port groups (Fig. 5c), suggesting that the Newport port group will benefit the most from increased flexibility in the whiting fishery as a result of the updated assessment. Importantly, the social vulnerability indices were calculated at the county level and then aggregated by port group; census-designated places within a port group can range from relatively low to relatively high social vulnerability (data available from NOAA Fisheries' social indicators tool, https://www.st.nmfs.noaa.gov/data-and-tools/social-indicators/).

Rapid and surprising changes in the abundance of bycatch species due to environmental change are common to fisheries worldwide (Pons et al. 2022), yet clear traces of the social consequences of status quo management responses compared to more dynamic responses are less common. This case study reveals the importance of quantitative and qualitative information entering a management process through unconventional routes, enhancing flexibility to respond to environmental change. Typically, stock assessments provide retrospective descriptions of younger cohorts and their influence on current and future population status. Assessments often serve as the nearly singular scientific advice for decisions about sustainable harvest. However, as shown here, insights from fishers with on-the-water experience, in combination with ecosystem indicators, can accelerate the analysis of changing population and bycatch dynamics provoked by a climate event, and lead to a positive management outcome. This may be a useful counterpoint to cases in U.S. fishery management where participatory processes have constrained flexibility and slowed decision-making (Golden et al. 2024). In addition, complementary analyses may help to ameliorate socioeconomic impacts. For example, as part of an EIS process, specific impacts of ecological variability on different communities could be identified; fishery management bodies in the region could then amend proposed rules in management plans to lessen expected impacts on those communities through mechanisms such as community quota allocations, regional delivery requirements, quota ownership and use caps, or quota transfer rules.

Dungeness crab fisheries and climate-related harmful algal blooms

Under certain environmental conditions in the California Current ecosystem, species of the diatom *Pseudo-nitzschia* experience significant blooms and produce the toxin domoic acid, which may cause amnesic shellfish poisoning in people who eat contaminated seafood (Todd 1993). The largest, most toxic HAB of *Pseudo-nitzschia* ever recorded on the U.S. West Coast occurred in the spring of 2015, exacerbated by a major marine heatwave (McCabe et al. 2016). Among the species affected was Dungeness crab (*Metacarcinus magister*), which supports commercial fisheries with average ex-vessel revenues of > \$200 million yr^{-1} (Holland and Leonard 2020). Domoic acid levels in Dungeness crab remained above the threshold for human consumption into the fall and delayed the 2015/16 fall/winter fishing season by one month in Washington and Oregon, and up to six months in California (Jardine et al. 2020). During the delays, some commercial fishers shifted to alternative fisheries or fished other areas, but most did not fish at all (S. Moore et al. 2020a, b; Fisher et al. 2021; Liu et al. 2023). Landings for 2015/16 in California reached only 52% of the average of the previous five seasons, resulting in a fishery disaster declaration and eventual allocation of > \$26 million in federal relief funds (Holland and Leonard 2020; S. Moore et al. 2020a, b; Bellquist et al. 2021). Semi-structured interviews revealed how the economic shock extended to schools, grocery stores, gas stations, restaurants, and other private and public sectors (Ritzman et al. 2018). Newspapers reported surges in food bank usage (Magee 2017). Almost every aspect of human well-being was affected, including emotional well-being, social relationships, culture, and identity (Ritzman et al. 2018; K. Moore et al. 2020a, b; S. Moore et al. 2020a, b; Moore et al. 2024). Impacts were especially acute in communities dependent on shellfish for cultural practices and economic needs (Kourantidou et al. 2022).

The 2015 event revealed a number of weaknesses in the monitoring and management of domoic acid in the Dungeness crab fishery that eroded trust in governance systems and produced undesirable outcomes for fishers and fishing communities (Ritzman et al. 2018; Ekstrom et al. 2020; Free et al. 2022). Management has evolved in three main ways to address subsequent HAB events: (1) changes in the scales of HAB monitoring and management responses; (2) changes in protections for different fishing vessel size classes; and (3) the introduction of new processing techniques to get affected crab to market (Fig. 6). Each adaptation involves quantitative and qualitative information, fishery participant input, and, crucially, iterative or place-based adjustments. Below, we step through each management change and describe the diverse socioeconomic information that informed and supported their implementation.

Increased resolution of management and monitoring: In northern California, the 2015/16 commercial Dungeness crab season was delayed six months. Immediately to the north in Oregon, the fishery was delayed by only one month. Semi-structured interviews revealed frustration among northern California fishers that their region remained closed, with some concluding that agencies were using "arbitrary threshold[s]" to close the fishery based on political boundaries (Ritzman et al. 2018). Citing poor transparency and inconsistent information, community members grew to distrust the process used to determine if seafood was safe and how test results were informing management decisions, particularly decisions about closure boundaries (Ritzman et al. 2018; Ekstrom et al. 2020). To provide clarity, the California Ocean Science Trust (2016) published a FAQ document with information on the HAB event, state monitoring programs, seafood safety, and the management framework. Nevertheless, in a survey of 16 communities, 78% of California fishers felt that the fishery closures were not managed effectively, compared to just over half of fishers in Washington and Oregon (Ekstrom et al. 2020). States responded by increasing the frequency of biotoxin monitoring in crab and delineating clear, finer-scale biotoxin management zones (Fig. 7). This has increased the consistency, predictability, and transparency of

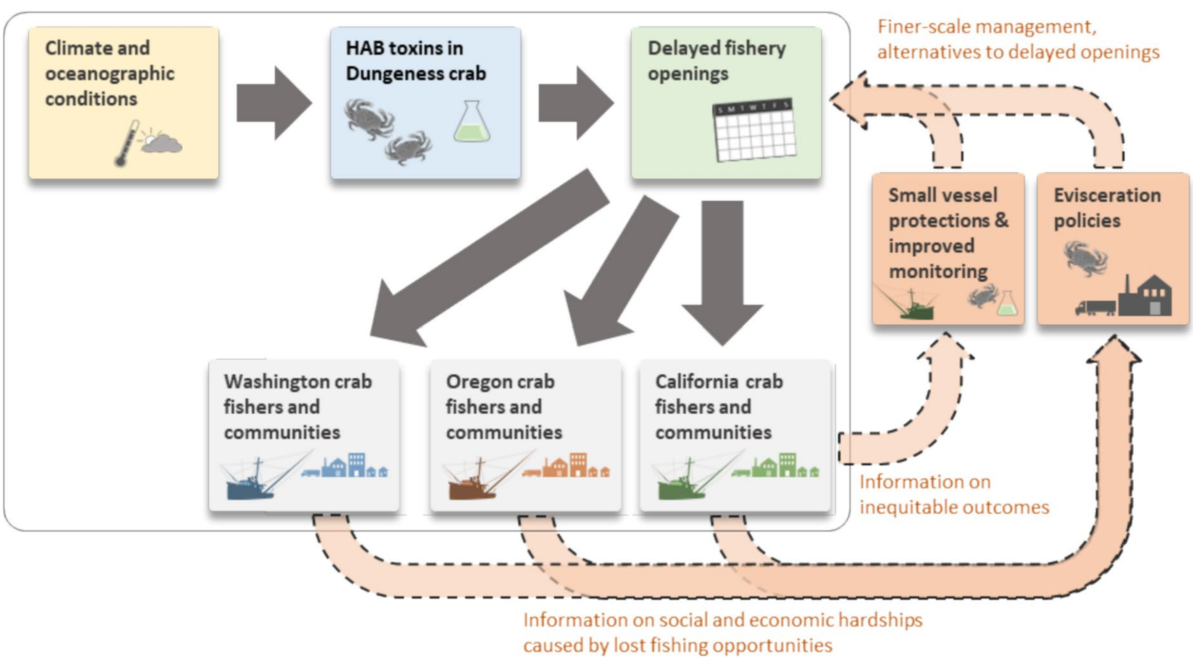

Fig. 6 Conceptual model of the harmful algal bloom (HAB) case study. Dark arrows map a relatively simple pathway of climate and ocean conditions promoting a HAB that triggers delayed openings fisheries for Dungeness crab (*Metacarcinus magister*) in three U.S. states. Orange arrows, boxes and text represent social and economic information on fisher responses and community effects of the HABs and fishing delays, and how that information is used to inform state-level adaptations and management outcomes

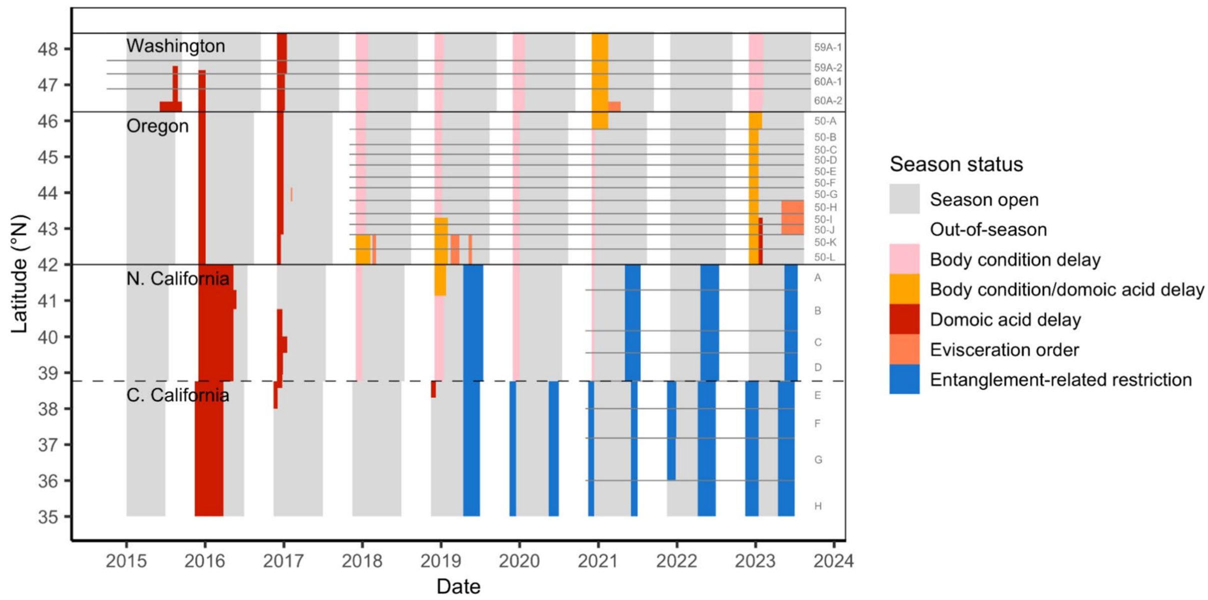

Fig. 7 Spatiotemporal management restrictions in the U.S. Dungeness crab (*Metacarcinus magister*) fishery from 2015 to 2023, related to harmful algal blooms (domoic acid delays, evisceration orders) and other factors (crab body condition, risk of whale entanglement in crab gear). Solid black lines indicate state borders; the dashed line demarcates the Northern and Central California management zones. Gray lines demarcate biotoxin management zones in Washington (established decades ago), Oregon (established before the 2017/18 season), and California (established before the 2020/21 season). Colored shading indicates the season status and type of management restriction enacted by the California, Oregon, and Washington Departments of Fish and Wildlife. Adapted from Free et al. (2022)

management for fishers, and has allowed managers to implement more precisely targeted closures when and where domoic acid levels are elevated (Free et al. 2022).

Protections for small vessels: In the delayed 2015/16 commercial Dungeness crab fishery, California staggered its fishery openings in three stages (Fig. 7) as crab began to test clean in different areas. California used the same strategy in 2016/17 when domoic acid caused another, shorter delay. This provided some flexibility by allowing access to crab once it was safe for consumers. However, local media reported that small operations were at a competitive disadvantage because large, mobile vessels converged on newly opened areas to take advantage of high early-season catch rates (Callahan 2017). In contrast, small vessels that are less mobile and more restricted by water and weather conditions were more limited in their ability to access the resource. Quantitative studies concurred: revenue for small vessels declined by 30% during the 2015/16 season (Jardine et al. 2020), while large, roving vessels were able to profit from their greater mobility (Liu et al. 2023). In 2018, management adapted by amending the "Fair Start" regulations (California Fish and Game Code FGC § 8279.1) to protect local operations and more equitably manage how and when different vessels can participate in staggered regional openings.

Evisceration orders: The disastrous 2015/16 fishing season and the increasing threat of HABs exacerbated by climate change (Trainer et al. 2020) signaled a need to bolster resilience to future HABs. One adaptation developed collaboratively by industry representatives and fishery managers is an option to open HAB-affected areas under "evisceration orders". In Dungeness crab, domoic acid mostly accumulates in viscera, with low levels distributed to meat and other tissues (Schultz et al. 2013). Removal of viscera by a licensed and approved processor can allow for the capture and sale of crab when domoic acid in the viscera tests above the regulatory limit for human consumption, but the meat is safe. At first, fishers had reservations about whether evisceration orders could work, but confidence grew as discussions with processors and managers identified existing practices and rules that could support its implementation

(Chambers 2016). Laws enabling evisceration orders passed in Oregon in 2017 and in California in 2021 (Free et al. 2022). Washington adopted a temporary rule in 2022, and is considering long-term legislation to enable evisceration.

Evisceration practices are a potentially transformative change because they enable fishers and processors to continue working with local catch as an alternative to a closure or delay. However, social and economic effects of this adaptation will need to be monitored to determine if the orders create beneficial outcomes, or if refinements are needed to contend with negative consequences such as declines in market price or consumer perception (e.g., Kourantidou et al. 2022) or the potential to overwhelm processor capacity given the increased processing requirements. Some areas lack approved processors, rendering the benefits inaccessible to those communities (C. Pomeroy, University of California-Santa Cruz, pers. comm.).

The Dungeness crab case study is an example of how iterative adjustments may be required before an adaptive approach emerges that sufficiently addresses system complexity and social-ecological tradeoffs at different scales. Input from participant groups is essential to understanding why some interventions are more or less likely to produce acceptable outcomes, which is a key to successful management implementation. When collecting this information, we can expect participants' perspectives to vary spatially due to heterogeneity in fishing conditions, port conditions, social vulnerability, cultural factors, regulatory frameworks, markets, and other factors. Perspectives will also vary over time with changes in fishing conditions, socioeconomic conditions, and regulatory changes.

Offshore wind energy siting and tradeoffs with fishing activities

Climate change is driving development of offshore wind energy (OWE), which generates cost-effective, high-yield renewable electricity in many parts of the world (Akbari et al. 2020). While the ecological effects of OWE are in early stages of study (Daewel et al. 2022; Galparsoro et al. 2022; Raghukumar et al. 2023), a clear social-ecological consequence is that OWE will disrupt or displace many types of fishing (Gill et al. 2020). In the U.S., OWE development is underway off the East and West coasts and in the Gulf of Mexico. Here we focus on the identification of leasing areas within two "Call Areas" for OWE off the West Coast. The Oregon Call Areas (OCAs; BOEM 2022) overlap with grounds for many commercial and recreational fisheries. From 2011 to 2020, annual ex-vessel revenue from commercial landings harvested within the OCAs averaged ~ $12 million and came from > 500 unique fishing vessels. In the same period, 15% of the ex-vessel revenue for U.S. at-sea whiting sectors came from the OCAs. Fishing is a major contributor to Oregon's coastal economy and labor force (Leonard and Watson 2011; Kaplan and Leonard 2012; The Research Group 2021). Disruptions to this industry could have significant impact in coastal communities of Oregon (Norman et al. 2007).

The U.S. Bureau of Ocean Energy Management (BOEM) is entrusted with planning and leasing areas for OWE development in U.S. federal waters. BOEM's planning process for new OWE projects includes several phases of data gathering, spatial analysis, and opportunities for public comment (Fig. 8; BOEM 2016). The goal of the process is to assess the suitability of an area for OWE, and the potential environmental impacts and tradeoffs with other sectors like fishing. Key steps in the Oregon process were: establishment of a state-federal task force in 2010; a data gathering and engagement plan in 2019 (BOEM 2020); and development of a mapping and visualization tool for spatial data on relevant social-ecological system components (e.g., wind variability, protected species occurrence, essential fish habitat, commercial fisheries occurrence, marine transportation, and military activities). This tool (OROWindMap, https://offshorewind.westcoastoceans.org/visualize/) was used to broadly identify areas where conflict between environmental resources, current ocean users and OWE development might be high, and informed the initial selection of the OCAs (Fig. 9).

During public comment on the OCAs, many individuals, municipalities, managers and organizations recommended increased transparency in the area identification process (BOEM 2022). This prompted BOEM to employ a spatial planning analysis using a suitability model developed by NOAA's National Centers for Coastal Ocean Science (NCCOS; Farmer et al. 2022). In addition, comments from multiple fishing industry stakeholders and the PFMC argued that the spatial data used to represent fisheries in

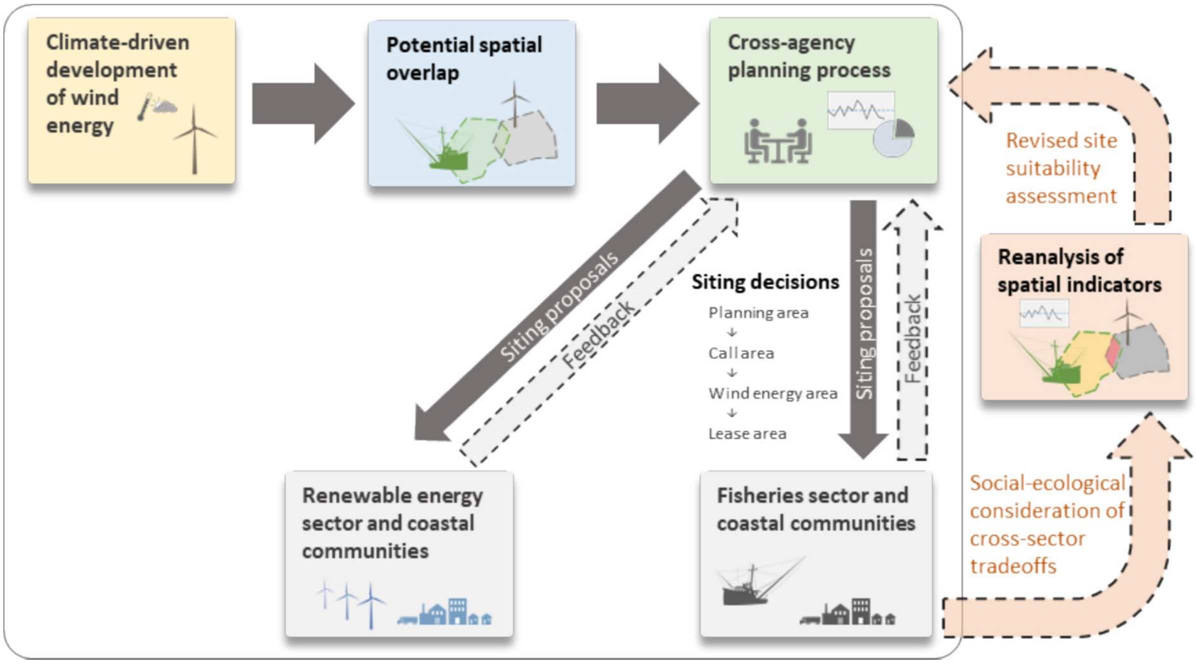

Fig. 8 Conceptual model of the offshore wind energy (OWE) case study. Dark arrows map the multi-phase pathway of the OWE planning process, from the proposal phase to the leasing phase for an ocean area; gray arrows represent opportunities for data gathering, analysis, and public comment in each phase. Orange arrows, box and text represent expert-based consideration and analysis of social and ecological factors that reflect the importance of different areas to fishing, leading to more informed identification of cross-sector tradeoffs

OROWindMap did not adequately represent overall fishing activity in and around the OCAs (PFMC 2022b). In response, BOEM engaged with NOAA Fisheries and the Oregon Department of Fish and Wildlife (ODFW) to improve representation of the spatial distribution of commercial and recreational fishing within the OCAs. This brought fisheries experts into the process, which helped to address many public comments related to the complexity of fisheries data analysis and interpretation (Fig. 8). For example, the availability of fishing location data differs across fisheries in the region, and even across vessels within some fisheries, depending on vessel size. Different data sources (e.g., vessel logbooks, electronic monitoring, vessel monitoring systems, shoreside interviews) also vary in temporal coverage and spatial resolution, depending on state and federal regulations. Understanding and accounting for these differences required deep familiarity with fishing activity data.

NOAA Fisheries and ODFW staff gathered information on regional fisheries and narrowed the list to one recreational and eight commercial fisheries that could be adequately represented spatially in the suitability model within OCA boundaries (Carlton et al. 2024, Appendix E). Many quantitative indicators can reflect the importance of specific areas to fishers, including the number of fishing events, duration of time spent fishing, amount of seafood caught, and amount of revenue derived from a specific area. NOAA Fisheries and ODFW thus determined that the best approach to capture overall fishing activity and variability was to develop a multivariate index that accounts for spatial variation in fishing effort, fisheries landings and ex-vessel revenue, and integrates data from all data sources. Without this intimate consideration by disciplinary experts, Oregon fisheries likely would have been represented by a single indicator of fishing effort, and areas important for other reasons (e.g., revenue) would have been deemphasized.

The analysis further illustrated how statistical assumptions can mask the relative importance of some areas during spatial planning analyses. Dialogue between data-providing agencies, analysts,

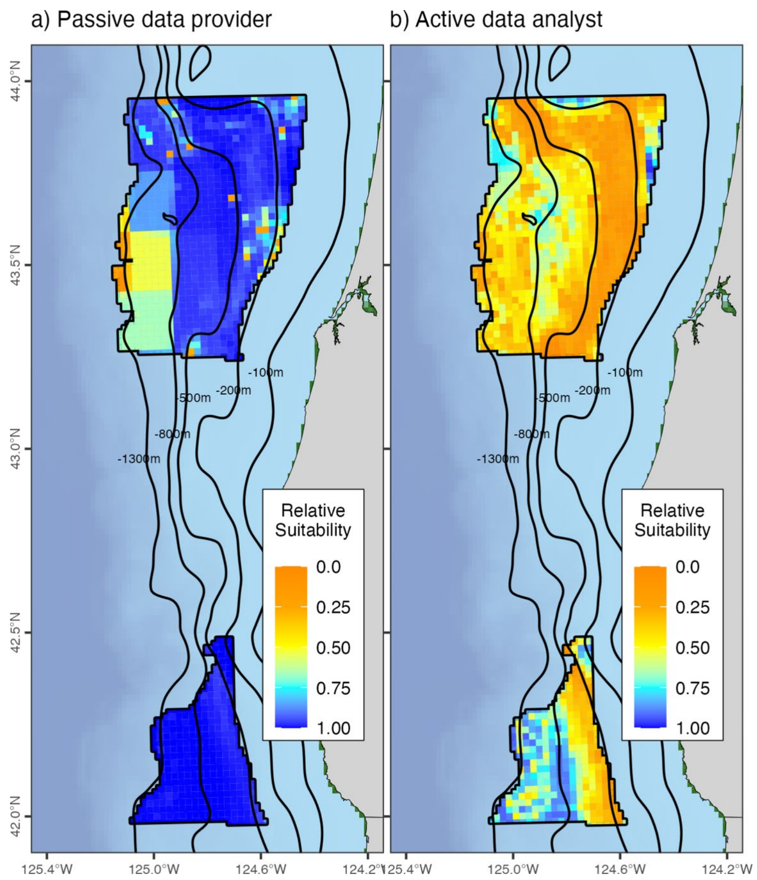

Fig. 9 Relative Offshore Wind Energy (OWE) suitability scores of 2×2-km grid cells in the two call areas off the coast of southern Oregon on the U.S. West Coast. OWE suitabilities were calculated from the same fisheries-dependent data, but under two different agency participation scenarios: **a** passively providing raw fishery data; and **b** active engagement by fisheries experts in the analysis and interpretation of fishery data. Warm colors (lower suitability scores) represent areas that are relatively important to nine fisheries that operate in the region, and are thus areas of greatest potential OWE/fishery tradeoffs

and the fisheries sector is necessary to limit or prevent this masking. Specifically, preliminary analyses using raw activity data and the multivariate indicator showed that the results were skewed by a small number of spatial grid cells where activity was the most intense (Fig. S.4, columns 1–3). The initial suitability estimates for OWE areas were also highly skewed by these rare hotspots of fishing importance (Fig. S.4, column 4). In particular, commercial albacore (*Thunnus alalunga*) data, which has much coarser spatial resolution than the other eight fisheries, appeared to drive identification of areas of greatest importance to fisheries within the OCAs (Fig. 9a). That bias deemphasized the broader areas of operation known for the nine fisheries in total (Somers et al. 2023; Shirk et al. 2022; Derville et al. 2023; Howard et al. 2023; Sabal et al. 2023; Samhouri et al. 2024). Given the severe right skewness of the data, NOAA Fisheries and ODFW analysts rank-transformed the raw fishing effort and revenue data and recalculated the multivariate indicator and suitability scores (Fig. 9b; details in Appendix E of Carlton et al. 2024). The composite result more closely represented the spatial distribution of operations across the nine fisheries. These data were used in BOEM's final suitability analysis, which subsequently identified wind energy lease areas that avoided most areas highly used across the nine fisheries (Carlton et al. 2024). Similar efforts on the U.S. East Coast have shown how the scale of resolution of fisheries data can over- or underestimate the exposure of fisheries activities to OWE development (Allen-Jacobson et al. 2023).

Active engagement by fishery participants through the public commenting process and by subject-matter experts in planning processes is critical to meet the ultimate goal of developing OWE in a manner that minimizes impacts on natural resources and promotes ocean co-use with existing ocean-user groups. Importantly, that engagement must be sustained over time because the suitability of parcels of habitat for different fisheries will vary into the future as climate change forces productivity and distribution shifts of fished stocks (Karp et al. 2019; Pinsky et al. 2020; Liu et al. 2023; Samhouri et al. 2024). Future projections of target species distributions have not been considered in OWE spatial planning efforts to date. However, lease agreements for five areas of development in offshore waters of California include language that identifies climate change as an important consideration in the development of mitigation measures to minimize conflict with commercial fisheries (e.g., BOEM 2023). More broadly, this case study serves as a cautionary tale about how responses to climate variability and climate change within and beyond the fishery sector can have unintended consequences that can be averted through transdisciplinary, iterative, systems approaches.

Discussion

Building adaptive capacity to climate variability and change will require fishery management systems to innovatively balance among diverse legal requirements, social complexities, and capabilities (Roscher et al. 2018; Mason et al. 2022; Golden et al. 2024). Our case studies demonstrate that the "best available science" that can support climate-adaptive fisheries management will involve careful and intentional inclusion of qualitative data and knowledge alongside the well-established quantitative data streams we have long relied upon. Below we discuss key themes from the case studies and their implications for fisheries management in an age of climate change.

Key themes from case studies

The effects of climate variability and change move through fisheries systems in complex pathways to affect a wide range of outcomes for ecosystems and fishing communities. The four case studies here show the importance of broad systems thinking and social science integration in fisheries management. Continued progress will be needed to identify and include forms of knowledge that more fully comprise best available science in support of climate-ready fisheries management, particularly in understanding tradeoffs among diverse objectives like optimal yields, viable fisheries, and coastal community well-being. Social science research can help to explain how and why fishers respond in particular ways to environmental variability (e.g., fluke fishers investing in fishing and landing opportunities far from their home ports; Papaioannou et al. 2021; Selden et al. 2024) or to management actions (e.g., crab fishery participants choosing not to switch to alternative target species during HAB-driven crab season delays; Ritzmann et al. 2018). Social science and participant feedback can reveal how climate effects or management outcomes can be distributed unevenly across ports, sectors, and vessel size classes (e.g., fluke reallocation options; port-level sablefish bycatch effects; Dungeness crab "Fair Start" regulations). Similarly, participant knowledge shared through technical reports or public discussions adds to our understanding of system dynamics (e.g., fisher reports of avoiding certain fishing grounds to reduce bycatch; US-Canada Joint Technical Committee 2023). This information can be instrumental in identifying the various pathways and feedback loops that influence system behavior, which expands our focus on how impact and risk are propagated and how system interdependencies influence the achievability of both environmental and social objectives (Roux and Pedreschi 2024). This information is distinct from (but complementary to) quantitative time series of biophysical and economic data that have been the historical focus of marine fisheries assessment. The call for greater inclusion of social science research, Indigenous Knowledge, and fishers' knowledge in management is not new (Johannes 1981; Neis et al. 1999; Johannes et al. 2000; Haggan et al. 2007; Hind 2015; Charnley et al. 2017; Raymond-Yakoubian et al. 2017), but has taken on increasing urgency in light of climate change.

The feedback loops in the case studies illustrate that implementing climate-ready fisheries management strategies will be an adaptive process. In none of our case studies was a lasting and complete solution identified during the initial phase of understanding and evaluating the problem. Rather, climate risks or impacts were addressed across a series of iterative steps. With each iteration, varying degrees of learning, reacting, and/or adapting occurred for all actors involved, and lags often occurred before outcomes were realized. Ongoing climate change and increasing climate variability will continue to introduce stresses that force fishery systems to adapt. For example, Dungeness crab fishers are affected not only by periodic HABs, but also by climate-driven shifts in baleen whale distributions onto fishing grounds, which can cause fishery closures to reduce entanglement risk (Fig. 7; see Santora et al. 2020; Samhouri et al. 2021; Free et al. 2023a,b). At longer time horizons, climate-induced shifts in species distributions may paint a different picture of the suitability of a location due to changes in spatial overlap and subsequent tradeoffs between fisheries and other newly located ocean-use sectors. All of these interacting factors influence the efficacy of prior actions and inform development of future actions. In the fluke example, past adaptations by fishers to own permits in multiple states weigh heavily on present and future considerations for climate-adaptive fluke allocation. In the Dungeness crab fishery, several iterative local- and state-level actions and policy adjustments were employed to mitigate the effects of HABs, and each has presented new decision points, such as the various tradeoffs that fishers and processors face related to evisceration orders. In the sablefish case study, whiting fleets that shifted fishing grounds in 2022 to avoid juvenile sablefish experienced high bycatch of shortspine thornyhead (*Sebastolobus alascanus*), another quota-limited groundfish (Zahner et al. 2023). In the past, the whiting fleet incurred anomalously high bycatch of shortbelly rockfish (*Sebastes jordani*), which surged in abundance following the 2014–2016 marine heatwave. This forced the PFMC to rapidly evaluate updated recruitment data for the species and raise the previously established shortbelly rockfish catch limit in order to prevent an early whiting fishery closure (Free et al. 2023a).

Due to the complexity of a given fishery system, indicators of climate-driven impacts will need to be tailored to local or regional goals and objectives (Kershner et al. 2011; Breslow et al. 2016). Participant knowledge and consideration of human well-being can promote the development or refinement of indicators that will aid in monitoring system behavior and management performance in response to climate-driven impacts or risks. The offshore wind case study shows how subject matter expertise and thoughtful data analysis can reframe an indicator to affect the inputs that go into a decision-making process. That analysis of fishing activity indicators essentially altered the focal question from "how much fishing effort or revenue is associated with a specific location?" to "what are the next-best places to fish and earn income if good fishing locations become operationally off limits?" The ranking of spatial grid cells helped to limit the influence of a small number of outlier hotspots, and better reflected the broad importance of fishing grounds to regional fisheries, consistent with MSA National Standard 8's focus on sustained participation.

Identifying, scaling, and tailoring indicators to track climate and management effects in a fishery depends in large part on how a "fishing community" is defined (Clay and Olson 2007, 2008; Martin and Hall-Arber 2008; Martin and Olson 2017). Effects of climate-driven system change and management response can vary across place-based communities, as with the distinctive challenges that fluke quota allocations posed to northern and southern groundfish fishers along the Atlantic coast, or the different levels of vulnerability and exposure of Pacific coast ports to bycatch. In such cases, indicators estimated at local or regional scales (e.g., port- or state-level) are likely more relevant and informative than fishery-wide aggregated indicators (see Heim et al. 2021). Other risks varied according to communities of practice. In the fluke case study, alternative strategies for quota allocation posed different types of risk to fishers, who can shift fishing locations (Papaioannou et al. 2021), than to processors and other shoreside support industries that are fixed in place and more dependent upon what is landed into their port. Indicators related to the objectives of each group can be framed and scaled accordingly. Similarly, in the Dungeness crab fishery, HAB mitigation measures initially had different levels of benefit for large versus small vessels (Jardine et al. 2020), thus vessel size groupings of indicators provide distinct information from port-level groupings. Conversely in the OWE example, aggregating the fishing activity index across multiple fisheries was appropriate for estimation of potential cross-sector spatial tradeoffs. In the U.S., "fishing community" as used in the MSA has historically been understood to be place-based and located on land, based on the official guidelines (e.g., "A fishing community is a social or economic group *whose members reside in a specific location* and share a common dependency on commercial, recreational, or subsistence fishing or on directly related fisheries-dependent services and industries"; 50 C.F.R. § 600.345(b)(3), emphasis added). Our case studies suggest that management systems generally may benefit from tracking climate impacts and management responses across multiple conceptions of "fishing community."

Implications for fisheries management

Despite wide acknowledgment that fisheries are social-ecological systems (Ostrom 2009; Levin et al. 2016; Roux and Pedreschi 2024), many management policies, interpretations of legal mandates, and research programs retain primary focus on biophysical and economic components and traditional fisheries metrics, and put less emphasis on social components and objectives. This reinforces systemic prioritization of simplified responses to climate variability and change (e.g., Fig. 1a or 1b), when in fact fisheries systems are more likely to have multiple feedback loops (e.g., Fig. 1c) and require greater consideration of social-ecological interdependencies (Ojaveer et al. 2018; Roux and Pedreschi 2024). Intentional participatory processes that engage local knowledge and experience are essential to ensure that additional pathways and feedback loops are identified and included in tradeoff analyses that span biological, economic, and social goals, objectives and outcomes. These processes can bolster community-level adaptive capacity (Green et al. 2021), which will grow more important as climate change and emerging ocean uses impose additional pressures on marine species, habitats, fishing practices, and other ocean-use sectors.

The participatory processes that are needed go beyond simply accumulating information; they require effective knowledge exchange among scientists, policy makers, managers, fishery participants, and others at the science-policy interface (Karcher et al. 2022). Including rights holders and stakeholders on decision-making bodies or advisory committees, and soliciting public comment on management actions, are steps toward more representative knowledge exchange, and are already practiced in many management systems, including in U.S. fishery management councils (e.g., deReynier 2014; Muffley et al. 2021). Formal co-management arrangements that engage in social learning can also foster greater responsiveness to community concerns and changing ecosystems (e.g., Cadman et al. 2022). Next steps include expanding access to individuals and communities impacted by fisheries management decisions but underrepresented in the decision-making process. This is evident, for example, in the context of federal fishery disasters, which reflect disproportionate climate impacts on salmon fisheries and Indigenous communities in the northwestern U.S. (Bellquist et al. 2021). Many studies also emphasize the tremendous and often overlooked value of knowledge brokers and boundary-spanning organizations in elevating balanced knowledge exchange in complex fisheries systems (e.g., Cvitanovic et al. 2015; Bednarek et al. 2018; Fulton 2021; Karcher et al. 2022; Cooke et al. 2024). Other participatory processes such as conceptual model development (DePiper et al. 2021; Rosellon-Druker et al. 2021), scenario planning (Maury et al. 2017; Nash et al. 2022; deReynier et al. 2023), and scenario analysis (Arkema et al. 2015) have helped to identify and prioritize broader ranges of objectives, perspectives, risks, and related indicators in some fisheries systems.

Fulton (2021) cautions that iterative adaptation is challenging, that the outcomes of individual iterations are difficult to predict, that windows of opportunity to act may be limited, and that science and management processes typically operate at different timescales. Mismatches in science and management timescales can severely impede progress in some cases (Rice 2005). This highlights the value of timely and effective knowledge exchange, and of analytical tools like FPNs (Fuller et al. 2017; Fig. 5) that can help to identify communities that are most vulnerable to climate pressures and/or most in need of adaptive capacity development. Formal analysis of governance structures and knowledge-action gaps can help to identify and reduce potential barriers to timely climate-responsive management (Dutra et al. 2019; Cooke et al. 2024). An openness to a range of approaches at each step of an iterative process may further improve decision-making and outcomes (e.g., Deroba et al. 2019; Fulton 2021), particularly as more communities and perspectives are included in participatory processes, and as climate change pushes system behavior outside of historic conditions.

Conclusion

Complex system responses driven by climate and ocean change will continue to elicit fisheries management actions, tradeoffs, and surprises (e.g., Brown et al. 2012; Barbeaux et al. 2020; Szuwalski et al. 2023). We would be wise to broaden what we consider “best available science” to plan for them, learn from and adapt to them, and strive to better foresee them. Many regions have invested heavily, and fruitfully, in developing quantitative indicators to help describe ecosystem state and the pace of change, particularly in biophysical and economic domains. Additional social indicators and qualitative information can play a critical role of more fully revealing system complexity (Murphy et al. 2021). This underscores the value of continuous and meaningful engagement among fishery managers, participants, and scientists, including social scientists. Our case studies reflect this, though they reveal generous amounts of trial-and-error, slow progress, difficult tradeoffs, and occasional serendipity. Including knowledge brokers, boundary-spanning organizations, and analysis of social networks within fisheries management systems may accelerate progress and efficiency (Cvitanovic et al. 2015; Fulton 2021; Karcher et al. 2022). Acknowledging system complexity and improving knowledge exchange may promote greater communication, flexibility, and adaptability that will enhance the effectiveness of climate-ready fisheries management.

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Author contributions CJH, PMC, RS, YLD, ORL, KCN, JFS and ICK conceived of the study. CJH, RS, SKM, KSA, JFS, CLS, NT and JLW compiled data, conducted analyses, and produced figures and tables. CJH, RS, SKM and KSA developed and wrote case study narratives. All authors contributed to the writing, review and finalization of the manuscript.

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Data availability All non-confidential data and code used in this study are available from the authors upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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