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Fisheries in flux: Bridging science and policy for climate-resilient management of US fisheries under distributional change

Jacqueline M. Vogel [a,b,*], Arielle Levine [a], Catherine Longo [c], Rod Fujita [d], Catherine L. Alves [e], Gemma Carroll [d], J. Kevin Craig [f], Kiley Dancy [g], Melissa Errend [h], Timothy E. Essington [i], Nima Farchadi [j], Sarah Glaser [k], Abigail S. Golden [i], Olaf P. Jensen [l], Monica LeFlore [m], Julia G. Mason [d], Katherine E. Mills [n], Juliano Palacios-Abrantes [o], Anthony Rogers [m], Jameal F. Samhouri [p], Matthew Seeley [d], Elizabeth R. Selig [q], Ashley Trudeau [l], Colette C.C. Wabnitz [o,q]

[a] Department of Geography, San Diego State University, San Diego, CA 92182, USA
[b] Department of Geography, University of California Santa Barbara, Santa Barbara, CA 93106, USA
[c] Marine Stewardship Council, London EC1A 2DH, UK
[d] Environmental Defense Fund, San Francisco, CA 94105, USA
[e] Save The Bay - Narragansett Bay, Providence, RI 02905, USA
[f] National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort, NC 28516, USA
[g] Mid-Atlantic Fishery Management Council, Dover, DE 19901, USA
[h] Northern Economics, Anchorage, AK 99511, USA
[i] School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA 98195, USA
[j] Department of Biology, San Diego State University, San Diego, CA 92182, USA
[k] World Wildlife Fund, Washington, DC 20037, USA
[l] Center for Limnology, University of Wisconsin Madison, WI 53706, USA
[m] California Ocean Science Trust, Sacramento, CA 95814, USA
[n] Gulf of Maine Research Institute, Portland, ME 04101, USA
[o] Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
[p] Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA 98112, USA
[q] Stanford Center for Ocean Solutions, Stanford University, Stanford, CA 94305, USA

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ABSTRACT

As climate change reshapes marine ecosystems, the dynamics of fish stocks are undergoing rapid transformation. Understanding these shifts and their multifaceted impacts demands more than just scientific inquiry; it necessitates a fusion of knowledge, collaboration, and action. However, the translation of cutting-edge research on the changing distributions and abundance of fish stocks into actionable strategies remains a daunting challenge. Climate change considerations are a relatively new area for fisheries management in the US, and there is often a gap between the scientific research being produced and the management processes through which it can be applied in practice. To address this gap, this research utilizes a co-productive workshop approach to elucidate and assess the current trajectory from scientific inquiry to management practice in the context of climate-impacted US fisheries. The workshop and subsequent analyses yielded 27 actionable recommendations and two strategic pathways. These pathways were designed to concentrate efforts on two critical fronts: 1) enhancing venues for collaboration between scientists and managers; and 2) establishing a cooperative framework for defining and prioritizing goals for climate-resilient management. Post-hoc analyses grounded these pathways within established frameworks and literature related to implementation science and science-policy connectivity. Tangible examples further exemplify the recommended actions and demonstrate the practical significance of this work for enhancing resilient management of fisheries in the face of climate uncertainty.

* Corresponding author at: Department of Geography, San Diego State University, San Diego, CA 92182, USA.
E-mail address: jvogel9051@sdsu.edu (J.M. Vogel).

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1. Introduction

Anthropogenic climate change is causing dramatic shifts in the abundance and distribution of marine species [55]. These changes are exacerbating a variety of challenges in fishery management, such as inter-jurisdictional disputes over catch allocations, difficulties in monitoring both stock abundances and catches, conflict between fishing nations, and heightened livelihood insecurity [47,71,75]. Changing distributions of transboundary stocks (i.e., those spanning two or more national jurisdictions) are a growing challenge that requires enhanced cooperation and coordination between governments and management entities [13,54,8]. However, intra-national stock distribution changes (i.e., geographic shifts between state boundaries or fisheries management areas) can be similarly difficult to manage [21,66].

In the United States (US), management and governance systems must adapt to deal with increasingly uncertain, dynamic, and cross-boundary fishing opportunities to preserve the many benefits that resilient and healthy fisheries provide [26,46,48]. Much ongoing research is dedicated to observing and projecting the impacts of climate change on the spatial distribution of fish stocks [12,49,55]. Additional research has specifically explored climate-ready management tactics for species redistribution, including strategies for the detection, evaluation, and management of shifting stocks [36,41]. Despite these targeted efforts, there is still no clear and commonly accepted framework to guide how scientific research in this area can be consistently and effectively integrated into decision-making [45,48,58,73]. Here, strategies for applying science to support US fisheries managers in solving practical problems are referred to as 'science-to-action pathways.'

These science-to-action pathways are highly relevant for climate-impacted and dynamic fisheries, where rapid translation of research into management is vital for effective adaptation. Fisheries managers make time-sensitive decisions with multiple tradeoffs under conditions of high uncertainty [60,61]. Regulatory changes can have enormous social, economic, or ecological consequences, which can incentivize inaction by managers and policymakers [20]. These challenges are further compounded by the differing monitoring and reporting requirements that exist across management jurisdictions in the US, necessitating a high level of coordination [42,7]. Challenges faced by fisheries governance also tend to be "wicked problems," where neither conclusive definitions of the problem nor optimal solutions exist [31,37,64].

1.1. Theoretical grounding

The lack of formal and approachable pathways between science and policy is a common and long-standing challenge across fields, especially those relating to sustainability and human welfare. Commonly cited barriers include the temporal mismatch between the frequency of scientific publication and the uptake of science into policy processes, as well as the lag between policy enactment and tangible implementation [18,39]. Only recently have funders in the medical field investigated the 17-year average lag time between production of new scientific knowledge and its implementation in healthcare or public health policy [33,5]. This new field of implementation science emphasizes the dual stages of science, including: 1) the production of novel information relevant for a particular population or region, and 2) the dissemination, implementation, and communication of that actionable information to the target audience [30,62]. These two stages are highly relevant to the management of fisheries. However, for the case of climate-impacted fisheries distributions and nonstationary management, a newer model that is adaptive, flexible, and able to be downscaled would better suit the complexity and uncertainty injected into the system by climate change.

Knowledge sharing and co-production approaches can help address some of this complexity by drawing on diverse experiences and information to define the scope, goals, and protocols for US fisheries management [15]. Cvitanovic et al. [17] found that when knowledge brokers and boundary-spanning organizations (i.e., entities that operate at the intersection of different sectors, disciplines, or groups) were involved as facilitators of organizational change, knowledge exchange among scientific researchers and natural resource decision-making organizations was improved [17]. Boundary spanners are particularly relevant in the context of climate-adaptive fisheries. These actors play a crucial role in bridging gaps not only between diverse stakeholders such as academia, industry, and governmental agencies, but also between jurisdictions for the management of transboundary or co-managed stocks [67].

Multiple frameworks have been developed over time to address the gap between science and action in fisheries management and governance. Adaptive management approaches, for example, embrace uncertainty in ecological, social, and economic dimensions and require collaboration to iteratively assess the fishery system, implement management strategies, and monitor outcomes in a systematic trial-and-error process [35,65]. Ecosystem-based fisheries management (EBFM) similarly involves well-defined management objectives that can be informed through research, early and iterative communication between scientists and policymakers, and a tailored review process to facilitate uptake by management bodies [16,25,40,72]. The developing field of 'science of actionable knowledge' further emphasizes the importance of boundary-spanning individuals and organizations [29] and the role of funders in incentivizing and supporting knowledge exchange between researchers and decision-makers [3,63].

Building on these established principles and frameworks, this study examines the hurdles and opportunities for translating scientific knowledge into policy action regarding changing fish distributions under climate change in the US. The intended audience is scientists involved in fisheries research, aiming to offer insights for making their scientific work more applicable to management practices. Additionally, the findings have implications for boundary organizations, fishery management agencies, and governmental bodies seeking to enhance the incorporation of new scientific discoveries into management procedures.

2. Methods

The findings presented here were co-developed by an interdisciplinary group of experts at an in-person workshop held in Seattle, WA, USA from September 6–8, 2023. The goals of this workshop were to: 1) form a collective understanding of the research landscape regarding climate-impacted fish stocks in US waters, 2) explore current applications of science in the management of these stocks, and 3) co-develop science-to-action pathways to provide practical guidance for scientists and managers to promote translation and uptake of emerging research into fishery management.

Thirty-one participants attended the workshop, selected based on their broad knowledge of or experience working with transboundary fisheries, changing fish distributions, and/or climate-resilient fisheries management. Initial outreach efforts targeted a roughly equal number of managers and scientists with the goal of diverse geographic and institutional representation in the US context. Participants were identified through the scientific networks of workshop organizers and expanded using the snowball sampling method [28]. A list of Lenfest Ocean Program-funded projects focused on supporting fisheries management solutions under climate change was used to identify potential participants and specific projects for inclusion [43].

Fifteen distinct projects were presented at the workshop. These projects were chosen via a deliberative selection process, building upon existing knowledge and networks of workshop organizers and bolstered by extensive review of relevant literature and initiatives [56]. The presented projects were not intended to be representative of the field but instead were solely intended as a starting point for workshop discussion. In-person workshop attendance was encouraged to enable discussion, with representatives from two research projects involved virtually. The reliance on individual availability and visibility of relevant work clearly skews the geographic and topical scope of work represented. Therefore, the themes and recommendations presented here should be perceived as such.

The geographic distribution of workshop participants encompassed all eight US Fishery Management Council (FMC) regions (Fig. 1) [14]. Participants were also classified by institutional affiliation due to the vast differences in knowledge of and proximity to the management process depending on one's role. Three general affiliation categories were used for the purpose of the workshop: management or government institutions (n=8), academic or research institutions (n=15), and NGOs (n=8). Individuals affiliated with management or government institutions include those actively working in a decision-making or decision-support capacity at a fisheries management agency such as the National Oceanographic and Atmospheric Administration (NOAA) or a regional FMC (fisherycouncils.org). These delineations are not mutually exclusive (e.g., NGO representatives are also often involved in research, as are NOAA scientists) and are solely intended to demonstrate the range of institutional affiliations represented at the workshop.

2.1. Workshop day one

The first day of the workshop was focused on collective learning and establishing a shared understanding of science and management relating to climate-impacted fisheries distributions within the US. Fifteen project groups gave presentations (see Supplemental Materials, S1) to provide an overview of research priorities, management efforts, and ongoing challenges. Presentations by managers, funders, and researchers allowed for a broad range of research priorities and perspectives to be considered.

Following project presentations, participants were asked to identify the challenges and solutions covered by each project and to synthesize these into thematic **project statements** (n=414). Each project was represented on a poster, and participants physically recorded and placed project statements on posters around the room. These statements were then synthesized and collated by the group into general **concepts** (n=14) relevant to climate-adaptive fisheries management (Fig. 2). Participants were asked to focus on the 15 projects presented during the workshop to make the activity more tangible and manageable, which likely narrowed the scope of responses. Raw data is confidential as it is composed of personal statements, but an aggregated matrix of project-concept connections and concept definitions are included in Supplemental Materials (S2, S3).

The 14 concepts are bucketed into four overarching **themes**: 1) **prediction and risk assessment** for characterizing shifting stocks; 2) **allocation and policy concerns** arising from changes in stock distributions and resource access; 3) **adaptive capacity** of the fishery management system for conferring climate resilience; and 4) **cooperative governance processes** focused on building resilience to shifting stocks. The primary purpose of the themes was to split workshop participants into smaller groups of 5–8 to facilitate deeper discussion. Fig. 2 situates the 14 concepts within the four themes, with the 414 project statements tallied to visualize relative thematic frequencies.

2.2. Workshop day two

The second day of the workshop focused on the co-creation of science-to-action pathways through which research relevant to the 14 research concepts could be translated into policy. Participants assigned themselves to groups based on their interest and expertise, and organizers facilitated guided discussions (Box 1) to identify specific actions and associated pathways for each theme. The term *science-to-action pathway* was intentionally left undefined to avoid restricting the types of "action" the groups might consider. The questions in Box 1 were intended to guide discussion towards tangible research-action

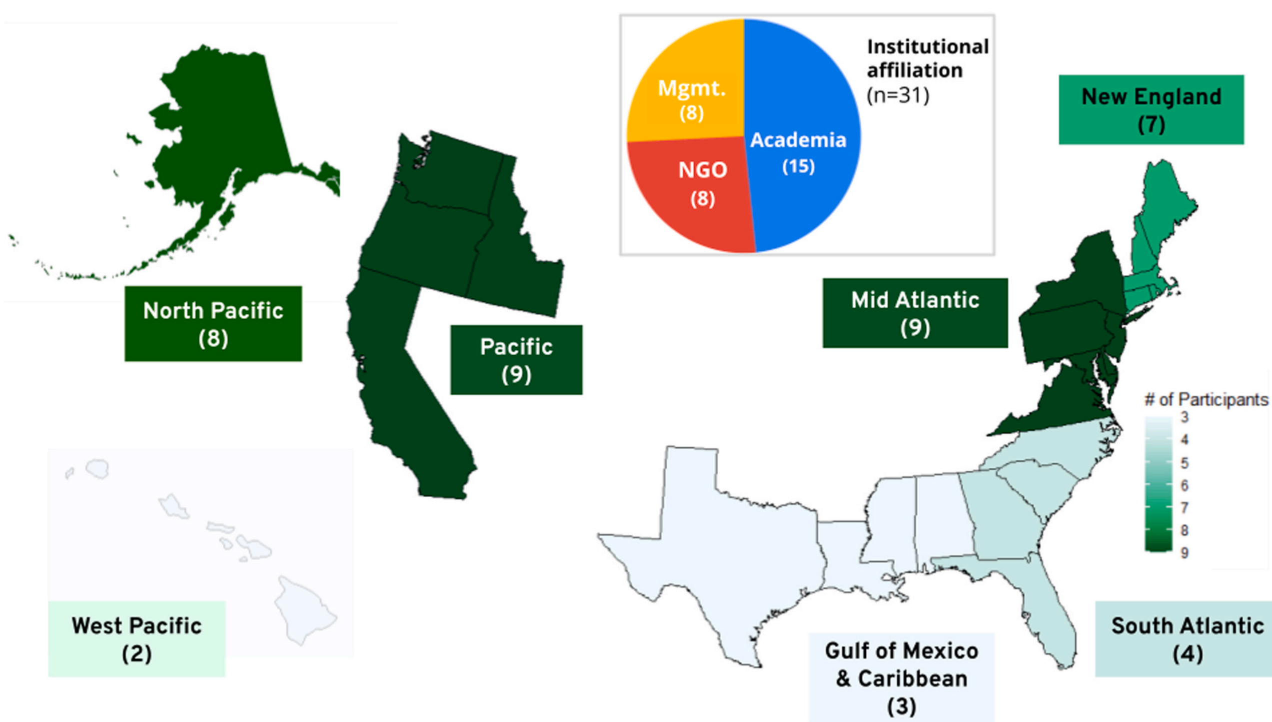

Fig. 1. Relative geographic representation of workshop participants (n=31) based on the eight US regional FMCs. Choropleth shading indicates the number of participants that regularly work in each region. The pie chart displays the affiliation breakdown, with management or government institutions (Mgmt.) (n=8), academic or research institutions (Academia) (n=15), and non-governmental organizations (NGO) (n=8). The Gulf of Mexico and Caribbean are visualized together due to the dual involvement of workshop participants in both Council regions. Only one institutional affiliation was assigned to each participant, but participants who work in multiple regions are represented by multiple data points in the figure. Total virtual and in-person participants n=31, and total region-affiliation combinations n=63.

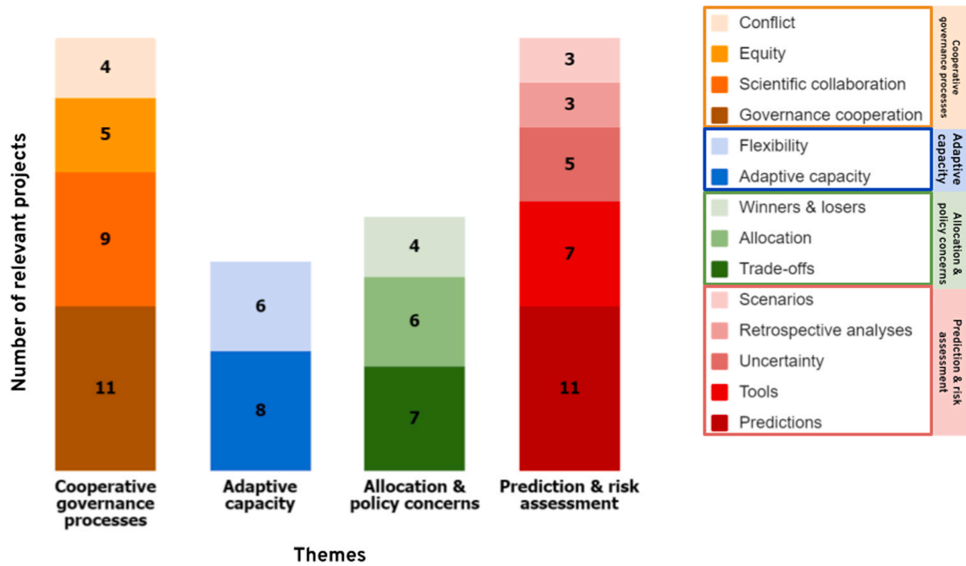

Fig. 2. Grouped histogram of concepts (n=14) categorized into the four broader themes (see color-coded legend on right side of figure). Histogram bar heights represent the number of projects that were linked to each concept. Concepts with higher frequency of mention were more widely relevant across projects (i.e., a concept that is relevant to each project would have n=15). Frequencies were extracted from project statements (n=414). This data reflects the projects presented during the workshop and is not representative of fisheries science as a whole.

Box 1
Guiding questions for thematic breakout groups on day two. These questions led to the formation of the 27 actions in Table 1.

1. How are research projects relating to this theme interacting with policy or other tangible action?
2. How could this research better align with policy-making timelines? What would need to change (on either the science side or the policy side) to make the time scales match up?
3. What are the barriers or potential opportunities for implementation?
4. Where are the general bottlenecks in the science-to-action pipeline?
5. What processes should be in place for engagement, buy-in, and collaboration?
6. Who are the appropriate groups or stakeholders to engage when considering this theme?

translation and the specific operational challenges involved in doing so.

2.3. *Workshop day three*

The list of actions produced on Day Two (Table 1, Results) was further explored in Day Three via a participant ranking exercise [1,79,11]. This exercise involved collaborative identification of actions deemed: 1) feasible to implement, 2) useful for managers, 3) useful for scientists, and 4) applicable across scales and management boundaries. Each of these characteristics was assigned a color and participants placed colored sticky dots adjacent to relevant actions. Actions that received the largest quantity and color diversity of dots were extracted and synthesized into pathways via an interactive group activity, producing two science-action pathways relating to: 1) communication venues, and 2) collaborative goal definition and prioritization. After the workshop, an iterative review and synthesis process refined the two pathways to further support this analysis. Concrete examples of each pathway were provided by co-authors with deep regional knowledge and expertise. Fig. 3 provides a visual overview of the workshop methodology along with the process of pathway formation.

3. Results

The co-production workshop methodology resulted in the identification of 27 actions (Table 1) and two discrete science-to-action pathways (Figs. 4 & 5) to advance the continuous and effective transmission of relevant science into US fisheries decision-making processes. The 27 actions are classified into three categories: 1) conducting actionable research (**Research**); 2) fostering collaboration and communication (**Communication**); and 3) building adaptive governance and management structures (**Governance)**. All actions in the Communication and Governance categories mapped directly to the two pathways, given their process-oriented nature. Only three of the nine Research actions mapped directly to the pathways, but the pathways themselves provide a process for better integrating the outcomes of these research actions into policy.

The categories were developed after the workshop to aid in visualization and to delineate the likely source or initiating organization for each category. For example, Action 6 (*Advance research into the US permitting system and performance of the current structure under change*) and Action 21 (*Explore and test innovative changes to the fisheries permitting system that integrate climate projections (e.g., blanket permits)*) both discuss the US fisheries permitting system and the need for more innovative integration of climate risks. The key difference lies in where these actions would need to originate: Action 6 would likely start with a research group initiating a permit-focused research project, while Action 21 would need to come from a management body or adjacent group that could actually test or implement this change. In this way, the action categories are not mutually exclusive, and some actions cannot be undertaken successfully without the complementary actions in another. A description of each pathway is provided followed by visualizations linking the pathways to the actions (Figs. 4 & 5) and several demonstrative examples.

Table 1
Twenty-seven tangible actions identified by workshop participants to enhance science-to-action pathways for adaptive management of new species distributions. The order of actions within each category is arbitrary.

Research (n=9)	Communication (n=10)	Governance (n=8)
1. Improve fisheries distribution models for 3–5 year timescales (focusing on oceanographic modeling advancement)	**10.** Formalize integration of forward-looking stock projection in present-day management decisions	**20.** Adapt disaster relief funds to address long-term disturbances. Consider application of land-based food system disaster avoidance mechanisms for fisheries
2. Utilize science from previous short-term disturbances to inform planning for longer-term disturbances. Develop bi-level indicators to automatically detect and adapt management in response to both types	**11.** Identify long-term adaptive targets and work incrementally toward change	**21.** Explore and test innovative changes to the fisheries permitting system that integrate climate projections (e.g., blanket permits)
3. Improve models for evaluating effects of conventional and dynamic allocation policies on distribution of landings, revenues, and fuel use under different climate change scenarios	**12.** Identify new industry leaders to participate in Council processes and to advocate for initiatives to advance adaptive capacity in their fisheries	**22.** Evaluate trade-offs of flexibility and rigidity in fisheries management
4. Incorporate projections of weather impacts on fisheries, including shifts between different weather regimes and impacts of bad weather days on catch effort and landings distributions	**13.** Promote cross-regional learning supported strategically by existing NGOs and networks of fisheries with diverse experiences with adaptive management	**23.** Utilize federal guidelines and approval processes for fishery management plans as an opportunity window
5. Advance socioeconomic research into the impacts of rigid structures on responses to rapid and unexpected change	**14.** Create and fund new boundary-spanning institutions to support action-oriented research on resilient fisheries, emphasizing scalability, accessibility, and targeted action	**24.** Work with NGOs to arrange briefings on climate resilience science for legislative committees
6. Advance research into the US permitting system and performance of the current structure under change	**15.** Extract learnings from successful Council adaptive evaluation processes and communicate to other regions	**25.** Establish regular engagement with Congressional Research Service
7. Identify opportunities or practices for enhancing equity within fisheries management	**16.** Hire or designate staff for each Science Center, Council, and regional NOAA office to be cross-region data coordinators	**26.** Increase transparency and researcher involvement in processes of jurisdictional transfers related to changes in stock distribution
8. Explore the US distant water fleet as a testing ground of the scalability of climate-resilience measures	**17.** Improve communication of conflict risk and societal threats associated with species distribution changes	**27.** Prioritize management goals to align with a shared vision for the future of US fisheries
9. Conduct a policy landscape analysis of the climate-fisheries field	**18.** Implement requirements for funding requests for proposals to explicitly require communication and policy implementation plans	
	19. Develop methods and interactive tools for allocating biomass spatially when boundaries are unclear (e.g., fishing ports, state waters, seasonal fishing grounds)	

3.1. Pathway #1 - enhance venues for information sharing and coordination

Decision-makers and fishery participants need access to information on stock redistribution to inform operational decisions on quota allocation, strengthen governance institutions, enhance cooperation between management bodies, and anticipate risks to fisher livelihoods. Pathway #1 (Fig. 4) urges support for continuous science-to-action translation via funding, engagement, establishment of communication venues, and specific products. This pathway prioritizes information sharing among governing bodies, managers, marine resource users, and researchers (*Actions 13, 14, 17, 24, 25, 26, 27*). While frameworks do exist in some Council regions to facilitate information exchange between these groups via collaborative research and monitoring activities (e.g., citizen science programs, survey monitoring coordination, etc.), these frameworks are not typically situated or resourced at the scale needed to address long-term species distribution changes over multiple jurisdictions [73]. As an illustration of this concept, Golden et al. [26] found that managers within the US fishery management system cited a lack of information about concrete adaptive strategies as a major barrier to their own ability to address adaptive capacity within their region [26].

Specific enabling conditions to promote knowledge exchange come from Cvitanovic et al. [17]. These include allocating resources for stakeholder engagement and knowledge co-production as well as creating venues for bi-directional communication and learning between decision-makers and researchers, between researchers and stakeholders (*Actions 12, 13, 14, 24, 25, 26, 27*), and between management regions (*Actions 15, 16, 29)*. Funder prioritization of collaborative science approaches has been associated with improved actionability of climate adaptation research [3]. Disaster relief programs may provide opportunities to fund actionable research on adaptation to shifting stocks in the short term as longer-term funding streams are developed (*Actions 18, 20*). Communication between decision-makers and researchers can additionally be facilitated through tools such as collaborative mapping of existing initiatives and identification of cross-cutting research objectives (*Actions 13, 14*).

Review articles aimed at scientists can communicate research needs and policy development timelines to facilitate future collaboration. Connecting researchers and managers with policymakers at the state or federal level would likely require the assistance of boundary-spanning individuals or organizations who can communicate the different information needs and timelines of research and governance organizations (*Actions 12, 14, 16, 23, 24, 25*) [29]. Novel organizational structures such as the Gulf of Maine Research Institute provide a region-specific model, along with initiatives such as the Distribution Mapping and Analysis Portal (DisMap) which attempts to make species distribution models developed by the research community more available and accessible.

In general, the need for enhanced two-way communication between those who produce vital information on changing fish distributions (researchers) and those who utilize that information to create tangible policies (managers) is a vital step in designing systems equipped to deal with increased scientific and political uncertainty and change. The following cases exemplify these recommendations and offer insight into how these concepts may play out on the water.

3.1.1. Example 1: parallel science-management processes for quota allocation

In a recent example from the Mid-Atlantic, expansion of the black sea bass stock into areas with historically minimal fishing effort created significant management challenges. Commercial fishery stakeholders raised concerns over disparities between state commercial quota allocations – which were loosely based on historical landings – and demonstrated changes in distribution and abundance of the stock [6]. In 2019, managers initiated a process for revising the commercial state allocations through a fishery management plan amendment [50].

While this management process was underway, a group of scientists and managers initiated a parallel process to test various geographic quota allocation mechanisms to ascertain their performance under continued distribution shifts. The resulting project sought to replace one-off renegotiations of catch allocation with ‘dynamic allocation,’ or an automated process for quota allocation that proportionally accounts for both current observed distributions and historical catches. Scientists and managers agreed that a lack of understanding of the economic and social impacts of dynamic allocation may be one of the obstacles to its general uptake in regions faced with new species distributions. To

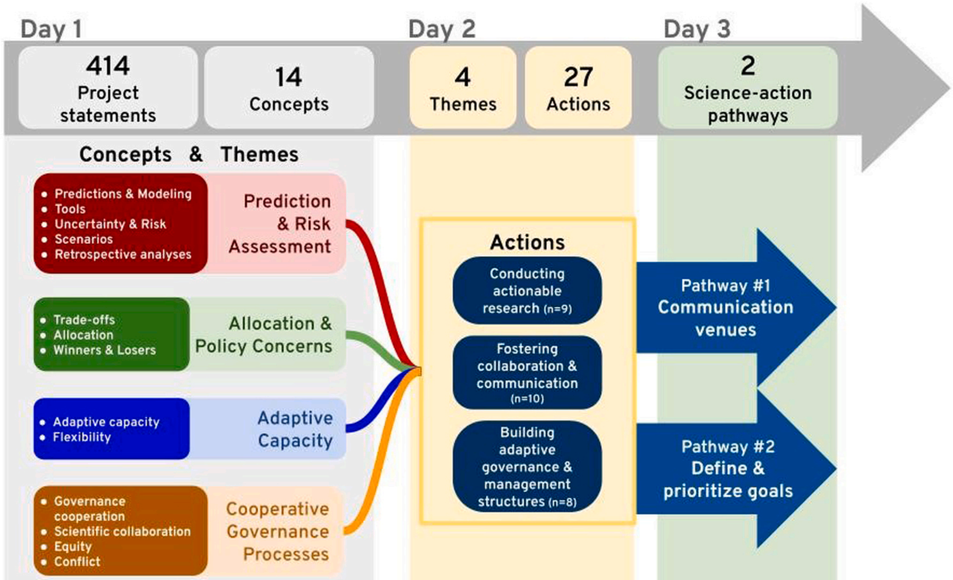

Fig. 3. Schematic of workshop process and interim results. Projects themselves are not represented in the schematic but were the initial input for the development of the 414 project statements and 14 concepts on the left side of the figure.

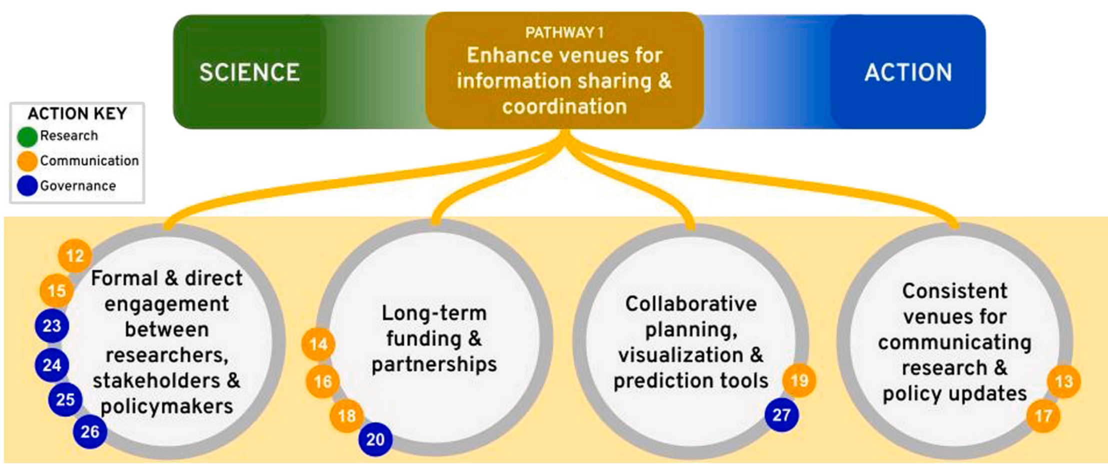

Fig. 4. Visualization of Pathway #1, focusing on enhancing support for continuous science-to-policy translation via funding, engagement, establishment of venues, and specific products. Gray circles denote broad categories of action and smaller numbered circles show the relevant actions from Table 1.

address this uncertainty, this project aimed to quantify and compare the economic impacts that might have arisen if various dynamic allocation policies had been implemented over the history of the fishery. Model parameters were vetted with stakeholders, and different weighting scenarios of historical catch and actual stock distribution were applied.

The researchers were able to share preliminary findings with a subset of the Mid Atlantic Fishery Management Council (MAFMC). However, they were unable to fully engage the relevant Council Advisory Panel in co-designing and vetting the scenarios due to new policies and an incompatible decision-making timeline. Although the project was designed in close coordination with management staff, this example shows that sometimes this is not enough to avoid a mismatch in the timeline of information production and policy window of opportunity [57]. This is where the support of boundary organizations might allow research products to be retrieved and shared at a later, more opportune time – something that may be difficult for the researchers themselves, as their engagement is constrained by project and funding commitments that are often on a shorter time frame.

3.1.2. *Example 2: direct engagement through research set-aside program*

Another strategy for aligning the timelines of research outputs with policy processes is for fishery management bodies to implement research funding programs. The research set-aside (RSA) program is a competitive grant program established by two regional FMCs (New England Fishery Management Council (NEFMC) and MAFMC) in collaboration with federal managers (National Marine Fisheries Service (NMFS)) to support management-relevant fisheries research. Both Councils develop requests for proposals that align with their respective management priorities, thus streamlining the science-to-policy pathway. For participating fishery management plans, a portion of the allowable catch or days-at-sea are made available to grant recipients for research purposes, such as for understanding the distributions of certain target stocks and monitoring any changes over time. Grant recipients must then partner with fishermen to harvest their research quota, in a process referred to as compensation fishing.

This direct partnership between researchers and fishermen encourages on-the-water collaboration while directly addressing research needs defined by managers, stakeholders, and stock assessors. Often, the RSA findings are reviewed by the Councils and used to inform management measures in upcoming fishing years. While the RSA model works very well for valuable fisheries such as scallops and monkfish in New England, the administrative costs of the program combined with enforcement issues, improper reporting, and lower-valued fisheries in the Mid-Atlantic led to its suspension there in 2014 [51]. Ultimately, this example illustrates the importance of formalized processes for early communication and priority alignment to ensure specific management needs are being met. Additionally, the variable success of this program across management regions highlights how research and management needs may vary substantially region-by-region and thus alter the strategies needed for adaptive management now and under future change.

3.1.3. Example 3: synthesis via Ecosystem Status Reports

The production and delivery of Ecosystem Status Reports to regional FMCs in the US provides another concrete example of how researchers can synthesize climate and ecosystem information to facilitate communication and learning with decision-makers. Ecosystem Status Reports capture information that spans multiple fisheries and examines these changes based on climate, ecological, and social drivers. These reports can fill gaps in the mechanistic understanding of species distributions and ecological interactions that are left unanswered by single-species stock assessment models.

These reports are delivered in writing and also through oral presentations to Advisory Bodies during public meetings and on Council floors, allowing for dialogue between the researchers that produce them, fisheries managers, fishers, and members of the public. Such dialogue allows decision-makers to integrate quantitative data provided in Ecosystem Status Reports with qualitative information expressed during discussions and public comment to inform their actions. A concrete example of this knowledge exchange emerged in the Pacific FMC in 2023, when the Ecosystem Status Report revealed a surge in the abundance of juvenile sablefish at the same meeting in which fishers reported an increase in bycatch of juvenile sablefish and concerns about exceeding their quota, particularly in northern ports. Through a rapid series of formal and informal discussions, this situation led to the development of an unscheduled, updated stock assessment for sablefish to provide a more current basis of information for setting harvest policy. This example highlights a case where formal communication venues involving management and stakeholders allowed for timely decision-making and responsive management of a fishery.

3.1.4. Pathway 1 recommendations

Synthesized recommendations for enhancing venues and information sharing for coordinated shifting stock management are listed in Box 2. The recommendations are neither ranked nor listed in order of importance – prioritization is a highly contextual and region-dependent exercise, so any ranking is at the discretion of practitioners and local managers. Additionally, some of these recommendations have been proposed or implemented to variable success in the past. To address this variable feasibility, an expanded table in Supplemental Materials (S4) addresses examples, barriers, and barrier removal tactics for each recommendation.

3.2. Pathway #2 - define and prioritize goals for climate-resilient management

The proactive harmonization of scientific and management priorities can help ensure that research on shifting stocks is conducted and communicated in a way that aligns with relevant management goals (*Actions 23, 24, 25, 26*). Policy-relevant science can be driven by the need to fill known knowledge gaps that impede the achievement of existing policy and management goals, and also by the need to elucidate new concerns and solutions that were not understood at the time that management systems were developed. Pathway #2 (Fig. 5) urges cooperative and adaptive management involving researchers, managers, and stakeholders by prioritizing opportunities for organizational change and collaborative goal-setting.

A vital requirement for this cooperative process is that research is conducted and communicated to fishery managers and stakeholders in clear, understandable, and actionable terms (see Pathway #1). Although it may seem obvious, there is no widespread consensus on the most effective ways to do this – whether via simplified and easily digestible approaches, such as ‘traffic light’ vulnerability assessments [25,32], or more fine-scale but complicated approaches, such as spatial climate risk indices [10]. To address this uncertainty and promote usable research outputs, the goals and format of research initiatives involving fish distributions and climate-impacted fisheries must be informed by managers and stakeholders before relevant research activities take place (*Action 23*). Ideally, this would result from a cooperative planning process during which current needs and knowledge gaps are articulated and future needs are identified (*Actions 13, 14, 18, 26, 27*).

However, in practice, the processes through which researchers identify projects and goals, and through which management groups identify their research needs and priorities, vary considerably. Thus, the degree to which research outputs are slotted into regulatory processes also varies. A critical aspect of this pathway is its focus on dynamic fisheries distributions and increased management uncertainty, so the process of co-designing and prioritizing goals should focus on long-term goals and the role that research outputs can play in an incremental process of moving towards these shared goals over time (*Action 11, 22, 26*). The communication discussed in Pathway #1 is a vital conduit through which this process can occur. Prioritizing learning from past disturbances combined with projections of future threats can benefit the collaborative goal-setting process, and allow both managers and researchers to vocalize priorities, information needs, and ideal socioeconomic outcomes under expected ecological change (*Actions 2, 10*).

Box 2
Recommendations to support Pathway #1: enhance venues for information sharing and coordination.

- Create **venues** for formal sharing of fisheries distribution information with relevant management bodies to support knowledge sharing, not just knowledge creation [41,74]
- Tap into **existing funding** and response sources to create opportunities for collaborating with fisheries actors and communities to enhance their participation and resilience
- Engage directly with **policy-makers** to build relationships and influence decision-making
- Foster a deeper understanding by scientists of the **timeline of Council processes** and specific opportunities (or on-ramps) for science integration into decision-making processes [48,70]
- Facilitate **consistent interactions** between scientists and Council staff as a way to more effectively link management priorities and timelines with research activities
- Encourage **participatory workshops** and **stakeholder-driven conceptual modeling** to promote integration of LEK into Council processes and decision-making [9]

Fig. 5. Visualization of Pathway #2, focusing on collaborative processes for defining and prioritizing goals. Gray boxes denote broad categories of action and smaller numbered circles show the relevant actions from Table 1. The overall figure structure was created during the workshop, and related actions from Table 1 were added in subsequent analyses.

Innovative approaches can also be explored to integrate these collaborative goals into existing or novel management processes (*Actions 6, 8, 20, 21)*. The following examples expand upon these recommended actions and offer insight into how these concepts may play out on the water.

3.2.1. *Example 1: co-creating principles for equitable allocation*

Collaborative goal-setting exercises can be conducted both inside and outside of management institutions. Recently, the Environmental Defense Fund (EDF) worked to convene a group of fishery stakeholders from across the US to develop shared principles for allocating fisheries under climate change. The changing abundance, distribution, and productivity of fish stocks creates a mismatch in the demand for quota between various geographies and existing allocations, which are predominantly based on historical participation. The reallocation of these quotas tends to be one of the most contentious fishery management actions, in part due to the challenge of determining what is fair and equitable to all involved parties, with climate change further exacerbating this challenge in some regions.

The goal of EDF's project was to address the challenges of climate change by developing a nationally relevant vision for a climate-resilient fishery allocation system. In March 2022, a convening was held with fisheries stakeholders and researchers from commercial, recreational, and tribal sectors across the US to discuss key considerations for setting or revising allocations in the face of climate change. As a result, eight principles were proposed by 14 signatories, emphasizing the need for more flexible regulatory systems and dynamic, bottom-up quota control, while still maintaining other priorities like stock sustainability [52]. This initiative demonstrates collaborative priority-setting and heightened awareness of the trade-offs involved in managing fisheries amid increasing uncertainty and change. However, its impact on the allocation system is still to be determined.

3.2.2. *Example 2: participatory climate change scenario planning*

Participatory scenario planning has been used to bring together diverse stakeholders to address uncertainty by envisioning possible futures and collaboratively developing interventions and strategies to prepare for them [24]. The Pacific FMC conducted a scenario planning process as part of its Fishery Ecosystem Plan Climate and Communities Initiative [19]. The East Coast Scenario Planning Process was a joint initiative among the three East Coast FMCs, the Atlantic States Marine Fisheries Commission, and NMFS [50]. Both initiatives used iterative processes to bring together managers, scientists, fishers, and other stakeholders to develop and validate plausible scenarios for how shifting fish distribution could impact fisheries. From these and subsequent discussions, initiative leaders compiled management recommendations and actions to be shared via a combination of webinars, in-person workshops, and interim communications to facilitate broad and sustained participation.

On the west coast, the scenario planning process led to new initiatives for increased communication of climate information between scientists and the FMC via Fishery Management Plans and other Council processes [48]. While these initiatives were not explicitly about setting collective goals for future fisheries, they provided a platform for diverse stakeholders to voice concerns and aspirations relating to current and envisioned future impacts of distribution shifts. These initiatives were also pivotal in raising climate change and species distribution shifts as priority management issues for participating FMCs.

3.2.3. *Pathway 2 recommendations*

Synthesized recommendations for defining and prioritizing goals for climate-resilient management are listed in Box 3. An expanded version of this table is included in Supplemental Materials (S5).

4. Discussion

There is broad recognition among US fishery managers and scientists that climate adaptation is necessary and potentially transformative for fishery management [26]. However, there remains a considerable mismatch between emerging science describing stock redistribution, the adaptive traits of fisheries systems, and the priorities and needs of on-the-ground managers [27]. This paper outlines two pathways for alleviating this mismatch by improving collaboration, communication, and shared goal-setting across the science-policy spectrum.

The primary challenge this work attempts to address is the complex process through which science is incorporated into policy. Another goal was to understand how researchers and managers may be willing or able to adapt their current research and decision-making processes to utilize these pathways while acknowledging that science-to-action looks very different depending on the positionality (e.g., geographic location, personal networks, place of employment) of each individual or organization. Furthermore, this work has a narrow focus on fisheries and their management under climate change. Fisheries are one of many activities that utilize marine space, and climate-driven distributional shifts are likely to incite conflict not only between shifting fisheries, but also between fisheries and these other maritime user groups [59,69].

The concepts and theoretical frameworks surrounding adaptive management and ecosystem-based management are not new, and this work reiterates some of the management recommendations that have been proposed in other contexts [34,41,44,77]. The added value of this

Box 3
Recommendations to support Pathway #2: define and prioritize goals for climate-resilient management.

- Co-determine long-term shared **societal fisheries goals** that are desirable to scientists, fishing communities, and managers [23,4]. Define goals in such a way that they are measurable by scientists and managers [22,78]. In some cases, climate change may completely alter long-standing management priorities, so redefining what is feasible and desirable under increased uncertainty is a vital first step [76]
- Create a **shared understanding** between scientists and managers of key uncertainties and risks for management under future change. Co-determine these risks and uncertainties via broad stakeholder participation among scientists, other knowledge holders, and managers to ensure that we're tackling the most vital climate challenges [15,53]
- Ensure **consistent definitions** and understanding of vital concepts across regions and sectors (i.e., adaptive capacity) [26]
- Identify and consider **tradeoffs**. All management goals can rarely be achieved simultaneously, especially under uncertainty and changing ecosystem dynamics over time [26,2].
- Identify ambitious **long-term adaptive targets** and formalize consideration of forward-looking models in decision-making
- Apply research on management and **permitting** to explore if and where strategic flexibility has potential to increase adaptability without compromising priority goals, such as sustainability

Create **risk profiles** for potential conflicts between any marine resource users (not just fishers) over ownership, access, or management of ocean space [75]. Create formal pathways for conflict de-escalation and avoidance at Council, Federal, and State levels (including coordination across scales)

research therefore lies in the explicit focus on managing for geographic and jurisdictional uncertainty under increasing climate change, with additional complexity added by the region-specific initiatives explored during the workshop process. The specific actions, pathways, examples, and recommendations presented here complement the best practices developed by Mason et al. [48], which distilled successes from ongoing efforts to incorporate climate-related information into US fisheries management. Mapping out relevant management processes was similarly emphasized as an enabling step, and the additional best practices – such as framing climate initiatives within existing management mandates – could be thought of as specific strategies to employ while carrying out the pathways and recommendations articulated here.

It is also important to examine how we define 'science' and 'knowledge' in this context, and to identify who is considered a producer of the knowledge essential to the pathways discussed. This research intentionally focuses on the translation of science that is produced in academic or formal research settings into regional US fishery management. While our recommendations and examples do highlight opportunities to incorporate diverse knowledge sources through direct engagement with fishers in the research process, we acknowledge the need for greater engagement with multiple forms of knowledge production, including Indigenous knowledge and fisher local ecological knowledge [9,68]. Further studies could analyze the US fishery management system with a more comprehensive definition of knowledge that encompasses academically produced science, Indigenous knowledge, the experience and observations of fishermen, and local community perspectives [38]. Social science studies on this topic should additionally be prioritized to highlight stories or examples of where diverse knowledge integration is occurring or could occur in the future.

Local and Indigenous knowledge is best represented by the knowledge holders themselves. However, in cases where these individuals may be overburdened or unable to directly engage, scientists should attempt to accurately and respectfully communicate this knowledge in relevant decision-making fora. In these cases, it is vital that scientists present this experiential knowledge as having equal value to other forms of scientific knowledge.

Finally, this paper specifically focuses on policy-relevant research and its application to real-world situations. However, this particular focus does not negate the importance of fundamental or innovative scientific research that may not have an obvious application to contemporary societal challenges. For example, research may illuminate new areas of concern that have no existing management structures, or findings may become policy-relevant even if this was not a goal of the initial research design. These other types of research are largely omitted here due to our focus on intentional science-to-action pathways, but it is vital to recognize their significance.

5. Conclusion

In the domain of climate-affected fisheries management, identifying and addressing bottlenecks and gaps along the science-to-policy continuum is an essential task. This paper offers recommendations, derived from expert elicitation and collaborative ideation, aimed at fostering dynamic and climate-resilient management of fisheries in the US. Two principal pathways are delineated to better integrate scientific insights into management practices: first, by fostering enhanced collaboration between scientists and managers; and second, by promoting collaborative goal-setting to synchronize research and management priorities amidst changing fish stocks. The 27 proposed actions outlined herein, detailed in Table 1 and illustrated in Figs. 4 and 5, serve as tangible steps towards these pathways.

The actions are categorized based on the component of the management or research system they are intended to address. In many cases, these actions require the transcendence of geographic and institutional boundaries to sufficiently address the uncertain and non-stationary nature of climate-impacted fisheries. While tailored to the management of fisheries facing increasing change and uncertainty, these recommendations hold relevance for fisheries grappling with stressors beyond climate, such as overfishing and stock depletion. Interdisciplinary endeavors such as this represent a key step in fostering solution-oriented initiatives and promoting the consideration of diverse priorities and perspectives across sectors. Recognizing the intricate and evolving landscape of US fisheries management, these recommendations necessitate ongoing refinement and adaptation to align with ever-changing climatic and management contexts.

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CRediT authorship contribution statement

Jacqueline Marie Vogel: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Arielle Levine:**

Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Catherine Longo:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Rod Fujita:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Catherine L Alves:** Writing – review & editing, Investigation. **Gemma Carroll:** Writing – review & editing. **J Kevin Craig:** Writing – review & editing, Investigation. **Kiley Dancy:** Writing – review & editing, Investigation. **Melissa Errend:** Writing – review & editing, Investigation. **Timothy E Essington:** Writing – review & editing, Investigation. **Nima Farchadi:** Writing – review & editing, Investigation. **Sarah Glaser:** Writing – review & editing, Investigation. **Abigail S Golden:** Writing – review & editing, Investigation. **Olaf P Jensen:** Writing – review & editing, Investigation. **Monica LeFlore:** Writing – review & editing, Methodology, Investigation. **Julia G Mason:** Writing – review & editing. **Katherine E Mills:** Writing – review & editing. **Juliano Palacios-Abrantes:** Writing – review & editing, Investigation. **Anthony Rogers:** Writing – review & editing, Investigation. **Jameal F Samhouri:** Writing – review & editing, Investigation. **Matthew Seeley:** Writing – review & editing, Investigation. **Elizabeth R Selig:** Writing – review & editing, Investigation. **Ashley Trudeau:** Writing – review & editing, Investigation. **Colette C.C. Wabnitz:** Writing – review & editing, Investigation.

Data availability

The data that has been used is confidential.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106385.

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