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Diverse pathways for climate resilience in marine fishery systems

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Abstract

Both the ecological and social dimensions of fisheries are being affected by climate change. As a result, policymakers, managers, scientists and fishing communities are seeking guidance on how to holistically build resilience to climate change. Numerous studies have highlighted key attributes of resilience in fisheries, yet concrete examples that explicitly link these attributes to social-ecological outcomes are lacking. To better understand climate resilience, we assembled 18 case studies spanning ecological, socio-economic, governance and geographic contexts. Using a novel framework for evaluating 38 resilience attributes, the case studies were systematically assessed to understand how attributes enable or inhibit resilience to a given climate stressor. We found population abundance, learning capacity, and responsive governance were the most important attributes for conferring resilience, with ecosystem connectivity, place attachment, and accountable governance scoring the strongest across the climate-resilient fisheries. We used these responses to develop an attribute typology that describes robust sources of resilience, actionable priority attributes and attributes that are case specific or require research. We identified five fishery archetypes to guide stakeholders as they set long-term goals and prioritize actions to improve resilience. Lastly, we found evidence for two pathways to resilience: (1) building ecological assets and strengthening communities, which we observed in rural and small-scale fisheries, and (2) building economic assets and improving effective governance, which was demonstrated in urban and wealthy fisheries. Our synthesis presents a

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novel framework that can be directly applied to identify approaches, pathways and actionable levers for improving climate resilience in fishery systems.

KEYWORDS
adaptive capacity, climate change, coastal communities, fisheries management, global change, social-ecological systems

1 | INTRODUCTION

In fisheries systems, resilience is the ability to prepare for, resist, cope with, recover from or adapt to a given stressor to ensure the sustainability of marine ecosystems, fishery resources and human benefits. Identifying and understanding inherent resilience, including the maintenance of the coupled natural and human system's essential function, identity and structure (IPCC, 2018), and the scale of the impacts projected are important for evaluating the response needed and the feasibility of interventions. Resilience in social-ecological systems relies not only on the availability of assets but also on the capability to mobilize those assets to enable adaptive behaviour (Cinner & Barnes, 2019; Holsman et al., 2019). Thus, the ability to build resilience is an important feature of planning and preparedness in the face of climate change (Plagányi et al., 2014). While the urgency in planning for resilience in the face of climate change is clear, practitioners lack context-specific pathways and tools to enhance resilience (Cinner et al., 2018; Karp et al., 2019; Mason et al., 2022). Here, we present (1) a framework for identifying and evaluating resilience in a system, specifically the 'attributes' or characteristics that enable or inhibit resilience, and (2) guidance on actions or approaches that can build or bolster resilience.

Fisheries are complex social-ecological systems and climate change is affecting the natural and human drivers of these systems. In particular, climate change has impacted the metabolism, growth and life history functions of marine species, which in turn have impacted the fisheries and communities that depend on these resources (Free et al., 2019; Mellin et al., 2022). Fishing communities are also vulnerable to the biophysical effects of climate change, including sea level rise and increased coastal erosion, resulting in disruptions to local marine economies (Colburn et al., 2016; Himes-Cornell et al., 2016). These effects are projected to continue and intensify, potentially resulting in major shifts in stock distributions and habitats, population productivity, disease prevalence and storm frequency and severity—all of which could affect species directly, damage important marine infrastructure or create barriers to fishing (Barange et al., 2014; Cheung et al., 2021; Weatherdon et al., 2016). These impacts reduce the production and revenues from fisheries, threatening livelihoods and food security in fishing communities (Cinner et al., 2022; Golden et al., 2021; Tigchelaar et al., 2021). Fishery practitioners will be challenged to balance these community needs with other goals as they attempt to promote sustainable harvests, protect stock dynamics and conserve key habitats (Madin et al., 2012; Malhi et al., 2020).

Fishery practitioners and fishing communities are seeking guidance on how best to build climate-resilient fisheries (ICES, 2023; NOAA, 2022; UN General Assembly, 2015). Identifying attributes of resilience present in a system and describing how these attributes function may provide the basis for generating such guidance. Some attributes of resilience have been described in the fisheries literature, although they may not have been identified as such. For example, research has highlighted how climate-adaptive fisheries science and management approaches can reduce negative consequences of climate change (Bell et al., 2020; Burden & Fujita, 2019; Gaines et al., 2018; Holsman et al., 2019), but defined attributes of resilience specific to fisheries management are not clearly identified. Additionally, participatory approaches are being promoted to boost social resilience by integrating multiple perspectives and goals that extend from community to international scales (Carroll et al., 2023; Heenan et al., 2015; Mills et al., 2023). While these approaches provide options, there is a lack of clarity and synergy on how to holistically build and operationalize resilience across the natural and social dimensions of a system. The challenge inherent in operationalizing resilience is exacerbated because resilience attributes are difficult to apply in fisheries contexts (McClanahan & Cinner, 2011), and case studies with empirical examples remain rare (but see Duplisea et al., 2021; Kleisner et al., 2022; Roux et al., 2022).

To address this challenge, Mason et al. (2022) paired the understanding of social-ecological system resilience with fishery-specific parameters by synthesizing attributes of climate-resilient fisheries from the literature and from expert knowledge across three dimensions: (1) ecological, (2) socio-economic and (3) governance. We adopt a broad and inclusive lens for governance that encompasses the diverse formal and informal non-governmental structures that operate from local to national to international scales throughout global fisheries. The aggregations of attributes are intended to be useful for fisheries practitioners who are attempting to identify pathways for building resilience in their fishery (see McClanahan et al., 2009). Thus, we expect that combinations of these attributes would enable more resilient system states by mediating social and ecological feedbacks or resilience pathways. Although Mason et al. (2022) identified and classified many of the attributes in the fisheries literature and articulated logical hypothetical mechanisms, concrete examples that explicitly link attributes to resilience outcomes are lacking for fishery systems. Here, we present a companion piece, in which we describe how these attributes are operationalized in case studies; which attributes and combinations thereof are relevant for different fishery contexts and stressors; and how attributes interact. Advancing from theory to practice by assessing empirical examples via comparative case studies will help fill a critical knowledge gap for building actionable pathways to resilience (Bahadur et al., 2013; Whitney et al., 2017).

We assembled 18 case studies spanning broad ecological, socio-economic, governance and geographic contexts. Using a novel framework for evaluating attributes, the case studies were assessed by experts familiar with each fishery to understand external stressors affecting the fishery and attributes present in each fishery that enabled or inhibited resilience to the stressors. We used these responses to (1) derive insights on the importance and strength of these attributes, presented as a 'score', for current or future resilience; and (2) examine interactions among attributes. From this, we created a typology of resilience attributes based on the variability between attribute importance and scores, identified fishery archetypes for analysing resilience and evaluated how attributes of resilience enable or inhibit one another within case studies to identify two contrasting examples of pathways to resilience.

2 | METHODS

From 2020 to 2022, a group of international fisheries experts convened for the Science for Nature and People Partnership (SNAPP) Climate Resilient Fisheries Working Group (hereafter 'working group') facilitated by the National Center for Ecological Analysis and Synthesis (NCEAS) (see Appendix 1, Table S1, for working group leaders, members, advisors and other consulted external experts). The goal of the working group was to synthesize the processes and attributes that enable or inhibit the resilience of marine fisheries to climate change. Working group members identified and developed case studies based on their areas of expertise, sometimes in collaboration with other working group members or with colleagues outside the working group. In several cases, working group members engaged knowledgeable reviewers to validate their case study rubric responses (see Section 2.1 below). The group developed 18 case studies representing a diverse array of geographies, target species, fishery scales and management contexts (Figure 1; Table 1). The case studies spanned three ocean basins (Pacific = 11; Atlantic = 6 and Indian = 1) and extend from the tropics to the poles. They included single-species (n = 7) and multispecies (n = 11) fisheries targeting marine finfish (n = 11) and invertebrates (n = 7). They spanned both large-scale (n = 6) and small-scale (n = 12) fisheries operating in social-ecological systems with varying levels of data availability and management capacity. Case studies considered the historical and projected impacts of climate change, including ocean warming (n = 6), marine heatwaves (n = 7), changing currents or upwelling (n = 3), ocean acidification (n = 4), increased frequency and/or intensity of storms and El Nino-Southern Oscillation events (n = 4), sea level rise (n = 3), loss of sea ice (n = 1) and other stressors (n = 8) (see Appendix 1, Table S2, for summary of case study characteristics).

2.1 | Case study framework

To collect standardized information on each case study, we designed a mixed-methods rubric for case study contributors to complete based on their knowledge of the specific system and associated literature. The rubric collected: (1) definitions of the scope and scale of the case study (e.g. spatial, temporal, taxonomic and fishery scales); (2) contextual information on the case

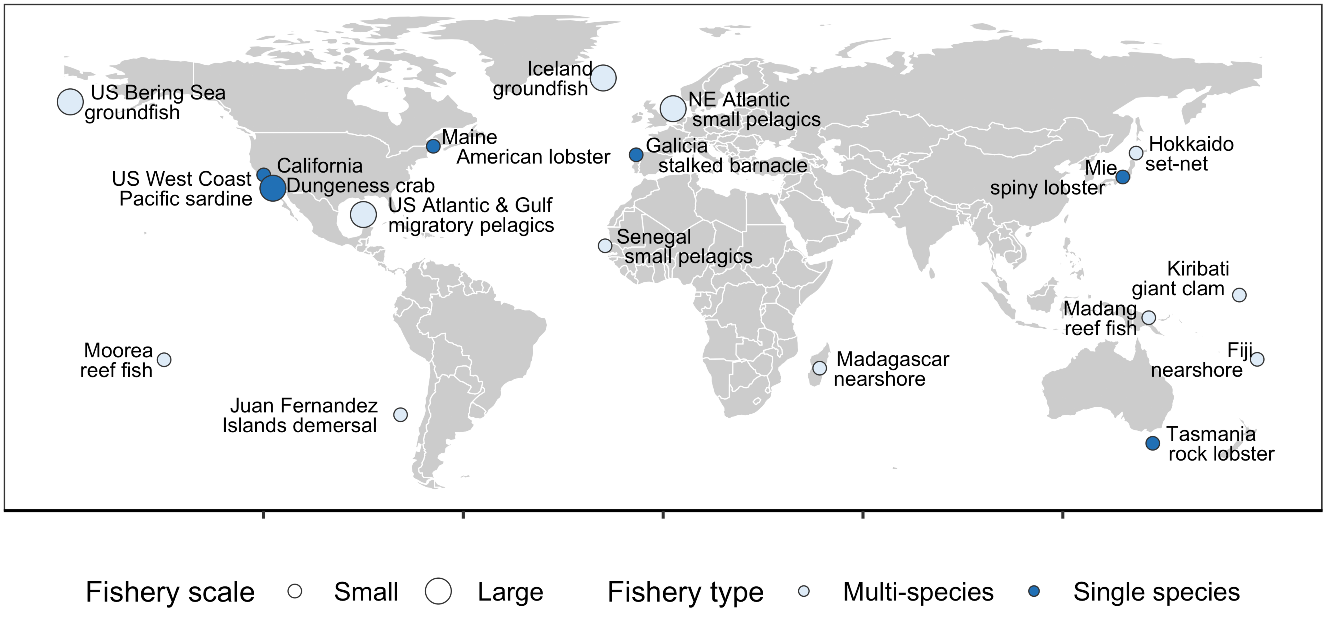


FIGURE 1 Map of the location of 18 evaluated case studies spanning diverse geographies, target species, fishery scales and management contexts.

study fishery (e.g. biogeography, social-political conditions, management context and climate stressors); (3) existing resilience actions and their history; (4) opportunities to expand resilience within the fishery; and (5) information on the importance, score and data quality of the 38 resilience attributes (hereafter referred to as 'attributes'; attribute names *italicized* throughout) identified by Mason et al. (2022) (defined in Table 2). The last category is the main source of quantitative data for this paper. See Appendix 2 for the full case study rubric and Appendix 3 for detailed case study narratives based on the qualitative responses. We focused this analysis on climate resilience, where climate change represents a potential stressor for each case even if past climate impacts and responses have not yet been documented. In several cases, climate stressors are presented in conjunction with other environmental stressors, management changes or economic events. In cases where the predominant past stressors are not directly attributable to climate change, we use responses to these stressors to indicate the general resilience of these systems.

2.2 | Attribute importance, score, data quality and typology

To examine the attributes in each case study, each contributor: (1) assessed how important each of the 38 attributes is or could be for current or future resilience to the climate stressors considered within the focal system; (2) scored the strength of the 38 attributes, hereafter referred to as 'score', as they actively occur in the focal system, relative to other similar and well-understood systems; and (3) recorded the quality of the information used to determine these ratings. Attribute importance was recorded with a three-option rating (Likert) scale (low: 1, medium: 2 or high: 3). Attribute scores were recorded using a four-option rating scale (very low: 1, low: 2, moderate: 3 or high: 4). Data quality was recorded with a five-option rating scale: no data (0), unconfident expert judgment (low: 1), fairly confident expert judgment (fair: 2), expert judgment and limited data (good: 3) and adequate/reliable data (excellent: 4).

To improve reliability (i.e. ensuring that our indicators are consistently applied across cases; Adcock & Collier, 2001), an internal peer-review process was conducted to compare and contrast studies, enhance cross-case consistency of attribute importance ratings and scores, discuss whether and how the attributes occurred in each case study and outline high-level findings. We engaged in small group and plenary exercises designed to draw out diverse perspectives and maximize the potential for group knowledge to reduce common pitfalls such as tendencies towards uniformly moderate scoring (Gregory et al., 2012; Himes-Cornell et al., 2016). To confirm that attribute importance and score were distinct, we tested for monotonic correlations by calculating Spearman's rank correlation coefficients. We found a weak correlation between importance and score ($\rho = 0.31$) and thus considered the variables independent in our analysis (see Appendix 1, Figure S1).

We examined the distribution of mean attribute scores and mean attribute importance across case studies to classify and prioritize attributes. We categorized high-scoring attributes with consistently high importance as 'robust sources of resilience.' Attributes identified as important but with generally lower scores were termed 'priority areas' with the assumption that these attributes might provide foci for interventions to build resilience if their strength in the fishery system was enhanced. We categorized attributes with low importance but highly variable scores as 'case-dependent contributors.'

TABLE 1 Summary of case studies grouped according to the fishery archetypes identified through the hierarchical cluster analysis.

Case study	Target species	Resilience of what to what	Description of fishery and major factors contributing to or limiting resilience
Group 1: Ecologically strong, governance constrained			
Senegal small pelagics fishery	Multispecies; Round sardinella (*Sardinella aurita*, Clupeidae), Madeiran sardinella (*Sardinella maderensis*, Clupeidae) and Bonga shad (*Ethmalosa fimbriata*, Clupeidae)	Resilience of the fishery system to environmental, social, economic and institutional change	Climate change is affecting the migratory pattern as well as the productivity of the target species (*Sardinella aurita* and *Sardinella mderensis*). In addition, overexploitation by both small-scale and large-scale fisheries exerts extra pressure on the resource. The high mobility of the adult stock as well as habitat diversity and ecosystem connectivity support ecological resilience. Overexploitation and social and economic changes challenge the fishing communities, but they show resilience through high social diversity, mobility and social capital
Moorea reef fish fishery (French Polynesia)	Multispecies (>40 genera fished); most frequently fished groups include soldierfish (*Myripristis* spp., Holocentridae), parrotfish (*Chlorurus* and *Scarus* spp., Scaridae), unicornfish (*Naso* spp., Acanthuridae) and others	Resilience of the fishery system to increased intensity of cyclones, increased frequency and intensity of marine heatwaves, ocean acidification and sea level rise in the context of increasing development	Growing tourism and coastal development have led to increasing tension over management of lagoon space in relation to fishing access. Moorea's ecological connectivity creates high population abundance, which buffers the lower governance attributes. Perceptions of limited equitable and inclusive governance impacted protected area compliance but built social capital needed for collective action towards management reform
U.S. Atlantic and Gulf of Mexico highly migratory pelagic longline fishery	Multispecies; Swordfish (*Xiphias gladius*, Xiphiidae), Bigeye tuna (*Thunnus obesus*, Scombridae), Albacore tuna (*Thunnus alalunga*, Scombridae), Yellowfin tuna (*Thunnus albacares*, Scombridae), Dolphinfish (*Coryphaena hippurus*, Coryphaenidae), Wahoo (*Acanthocybium solandri*, Scombridae) and some pelagic shark species	Resilience of the fishery system to climate change impacts	The fishery, which is managed both domestically and internationally, is currently not performing optimally, hindering the fisheries resilience to climate change. Resilience is mainly provided by high spatial and behavioural flexibility, coupled with a domestic system that favours accountability, adaptation and learning. Conversely, resilience is hindered by overfishing, combined with an international governance structure often lacking effective compliance and responsive management strategies and a top-down domestic decision-making process that tends to be less transparent and participatory than those of other U.S. fisheries
Group 2: Strong ecological and social processes, despite lower wealth and infrastructure			
Kiribati giant clam fishery	Multispecies; Giant clam (*Tridacna gigas*, Cardiidae), small giant clam (*Tridacna maxima*, Cardiidae), fluted clam (*Tridacna squamosa*, Cardiidae) and strawberry clam (*Hippopus hippopus*, Cardiidae)	Resilience of the fishery system to marine heatwaves and ocean acidification	The Kiribati giant clam multispecies subsistence fishery in the Gilbert Islands shows resilience in the ecological and socio-economic dimensions to marine heatwaves and ocean acidification where adaptive customary management has been successfully implemented (Eurich et al., 2023). Local actors influence the island's traditional government by fostering place attachment, agency and a resilience mindset. The resulting accountability and adaptiveness of the local government, coupled with inherent ecological resilience of the species, helps support management initiatives and a sustainable fishery
Madagascar nearshore fisheries	Multispecies; over 100 species of fish and invertebrates	Resilience of the fishery system to changes in access to coral reef fisheries	Species in the coral reef and nearshore fisheries are very sensitive to climate-induced cyclonic activity in the Bay of Antongil, leading to reductions in catch. This particularly affects certain villages as the reef and mangrove system is highly modularized and most villages tend to fish in their own immediate surroundings. Nevertheless, the overall nutritional resilience of the local Malagasy population is strong, with flexibility in food choices, socio-economic diversity and multiple livelihood strategies and shifts in fishing behaviour to enhance catch success

TABLE 1 (Continued)

Case study	Target species	Resilience of what to what	Description of fishery and major factors contributing to or limiting resilience
Fiji nearshore fisheries	Multispecies; over 300 species of fish invertebrates and marine algae	Resilience of the fishery system to current and projected impacts of climate change, including increased intensity of cyclones, increased frequency and intensity of marine heatwaves and sea level rise	Fijian nearshore fisheries have shown resilience to tropical cyclones and marine heatwaves due to strong ecological and social assets. Reefs have high biodiversity, biomass and connectivity; contributing to ecological recovery and resilience. Indigenous Fijians maintain rights to traditional fishing grounds; and communities have strong place attachment, social capital, knowledge and agency. In response to tropical cyclones, communities work together to rebuild, despite limited financial capital, and resource sharing is common. Finally, differences among fishing groups acts as a nutritional buffer; with female fishers targeting a wider range of species and habitats
Madang reef fish fishery (Papua New Guinea)	Multispecies; snappers (*Lutjanus* spp., Lutjanidae), emperors (*Lethrinus* spp., Lethrinidae), surgeonfish (*Ctenochaetus* spp., Acanthuridae), parrotfish (*Chlorurus* and *Scarus* spp., Scaridae), unicornfish (*Naso* spp., Acanthuridae) and others	Resilience of the fishery system to climate shocks and declining biomass	The small-scale reef fishery on Karkar Island in Madang Province demonstrates how adaptive customary management confers some resilience of key habitats, stock and social benefits in the face of fishing pressure and climatic shocks, by enabling adaptive learning, agency and flexibility. The fishery is governed at a local level, enabling quick adaptive decisions. Strong leadership through clan leaders (who have an interest in continuing the tradition of rotational closures) helps ensure a balance of ecological and social resilience. However, previously successful adaptive management alone may not confer long-term resilience.
Group 3: Economically wealthy and well governed			
Tasmania rock lobster fishery (Australia)	Southern rock lobster (*Jasus edwardsii*, Palinuridae)	Resilience of the fishery system to ocean warming, marine heatwaves and ecosystem changes caused by warming	The fishery occurs within one of the fastest-warming regions in the southern hemisphere. The climate-driven intrusion of the sea urchin (*Centrostephanus rodgersii*) has decimated key lobster habitat as urchins overgraze the kelp forests leaving 'urchin barrens.' However, royalties from abalone (*Haliotis* spp.) fishery subsidize dedicated commercial fishing of *C. rodgersii*, which has helped control the urchin population. Community support and alternative markets also helped the lobster fishery respond to supply chain disruptions associated with the COVID-19 pandemic, but cumulative impacts of climate change, overfishing and a lack of leadership continue to threaten resilience.
U.S. West Coast Pacific sardine fishery	Pacific sardine (*Sardinops sagax*, Clupeidae)	Resilience of the fishery system to marine heatwaves, oceanic decadal oscillations and overfishing	The Pacific sardine fishery has historically been a productive and lucrative industry along the West Coast of North America, but climate change (i.e. marine heatwaves) and increased fishing pressure caused the fishery to collapse in 2015. Although the species regularly experience boom and bust cycles, recent cyclic population booms have been far less productive and busts more devastating. The fishing community has been able to remain profitable by adaptively targeting different species and maintaining high levels of fishing skills within the community
Iceland groundfish fisheries	Multispecies; Atlantic cod (*Gadus morhua*, Gadidae), capelin (*Mallotus villosus*, Osmeridae), haddock (*Melanogrammus aeglefinus*, Gadidae) and others	Resilience of the fishery system to species composition and distribution changes related to ocean warming	Iceland's individual transferable quota (ITQ) fisheries demonstrate how flexible and responsive management, centralized organization that promotes learning, ample assets and resilience mindsets interact to confer resilience of sustainable and profitable stock management to climate-driven changes in species abundance and distribution. However, the strong reinforcing feedback among attributes that stabilize the system may entrench economic inequalities and preclude adaptation to broader change

(Continues)

TABLE 1 (Continued)

Case study	Target species	Resilience of what to what	Description of fishery and major factors contributing to or limiting resilience
North-East Atlantic small pelagics fishery	Multispecies; Atlantic herring (*Clupea harengus*, Clupeidae), mackerel (*Scomber scombrus*, Scombridae), Blue whiting (*Micromesistius poutassou*, Gadidae) and others	Resilience of the fishery system to the perturbations caused by climate change	Resilience is provided by the portfolio fishing method (seasonal sequential mixed fishery), flexibility attributes of mobility and responsiveness, together with the socio-economic assets of wealth, reserves, capital and learning and agency. The major risk is the inflexibility in the governance dimension, with entrenched actors protective of their influence and opportunities. A failure to adapt the organization of the fisheries management is the greatest risk posed by climate change
Group 4: Variable stocks, reliable social processes and governance			
Hokkaido set-net fishery (Japan)	Multispecies; over 100 genera, keynote species include Japanese common squid (*Todarodes pacificus*, Ommastrephidae) and Yellowtail (*Seriola quinqueradiata*, Carangidae)	Resilience of the fishery system to changes in the species composition of landings due to marine environmental changes	The large-scale set-net fishery is immobile as it stays within designated fishing grounds and catches migratory fish species, which are affected by changes in sea surface temperatures and heatwaves. As a result, the composition of landings is volatile. However, vertical integration of the seafood supply chain is created by the local seafood industry, which can adapt to changes in species composition by quickly expanding markets. As a result, the resilience of the fishery is induced by the vertical integration of the seafood supply chain
Mie spiny lobster fishery (Japan)	Japanese spiny lobster (*Panulirus japonicus*, Palinuridae)	Resilience of the fishery system in Japan (i.e. exhibiting a high level of cooperation among harvesters) to ocean warming	High social capital, agency and participatory governance contribute to achieving adaptive governance, which contributes to resilience. While high learning capacity, resilience mindset and highly responsive governance, in conjunction with the attributes listed above, contribute to harvesters responding to the changes they observe and experience themselves effectively, lack of scientific information (i.e. limited access to knowledge) such as stock forecasts limit their ability to plan and take proactive adaptation actions
Juan Fernandez Islands demersal fisheries (Chile)	Multispecies; Lowfin moray (*Gymnothorax porphyreus*, Muraenidae), Breca de Juan Fernández (*Nemadactylus gayi*, Cheilodactylidae), Juan Fernandez trevally (*Pseudocaranx chilensis*, Carangidae), Yellowtail amberjack (*Seriola lalandi*, Carangidae), Pulpo de Juan Fernández (*Octopus crusoe*, Octopodidae) and Juan fernandez rock lobster (*Jasus frontalis*, Palinuridae)	Resilience of the fishery system to climate change and other stressors (invasives, contamination) as well as shocks to the system (tsunami, COVID-19)	The Juan Fernandez Islands demersal fisheries are resilient to climate change and other stressors, as well as shocks to the system from tsunamis and the pandemic due to strong ecological assets in combination with strong socio-economic attributes. Locals have a resilient mindset, a strong sense of place attachment, high learning capacity, relatively high agency to make decisions and a good deal of social capital. While there is limited infrastructure on the island and not a lot of technology transfer, governance tends to be participatory, equitable and inclusive and enables strong local leadership and initiative of locals
Group 5: Enabled by all dimensions			
U.S. Bering Sea groundfish fisheries	Multispecies; Alaska pollock (*Gadus chalcogrammus*, Gadidae), Pacific cod (*Gadus macrocephalus*, Gadidae), Yellowfin sole (*Limanda aspera*, Pleuronectidae), Flathead sole (*Hippoglossoides elassodon*, Pleuronectidae) and Pacific Ocean perch (*Sebastes alutus*, Scorpaenidae)	Resilience of the fishery system to environmentally driven changes in productivity	The Bering Sea groundfish fisheries have been resilient to interannual environmental shocks and have been prosecuted sustainably for the past 40 years. However, marine heatwaves and the loss of sea ice have affected the distribution of some target species. Limited access privilege programmes and gear-area closures have created management rigidities, which may become more problematic as marine heatwaves intensify. However, an open and transparent management process through which the public is given ample avenues for comment has increased resilience. The management system is inclusive and equitable, precautionary, accounts for risks and considers ecosystem indicators prior to setting harvest limits

TABLE 1 (Continued)

Case study	Target species	Resilience of what to what	Description of fishery and major factors contributing to or limiting resilience
Maine American lobster fishery (U.S.)	American lobster (*Homarus americanus*, Nephropidae)	Resilience of the fishery system to ocean warming and marine heatwaves	The resilience of the Maine lobster fishery has been supported by conservation measures that enabled stock abundance to increase as waters warmed. This ecological resilience was enhanced by socio-economic and governance attributes, including wealth and reserves, knowledge and learning and high levels of agency and participation in a polycentric governance system. These features enabled the fishery to weather shocks from marine heatwaves, but long-term climate resilience planning has been constrained by limited economic opportunities, strong place attachment and a sense of confidence in the current population status and experiences weathering past fishery fluctuations
California Dungeness crab fishery (U.S.)	Dungeness crab (*Metacarcinus magister*, Cancridae)	Resilience of the fishery system to heatwave-induced harmful algal blooms and marine life entanglements	The Dungeness crab fishery is the most lucrative fishery in California and plays a central role in the portfolio of species targeted by fishers. Recently, the fishery has experienced closures and unpredictability due to heatwave-induced harmful algal blooms and increased entanglements of marine life in fishing gear. The critical importance of the fishery has catalysed high government and stakeholder involvement in adapting management to meet these challenges. The high productivity of the stock also contributes to resilience. Improved monitoring and quantitative tools are needed to enable more nimble management and design effective strategies for preventing marine life entanglements
Galicia stalked barnacle fishery (Spain)	Stalked barnacle (*Pollicipes pollicipes*, Pollicipedidae)	Resilience of the fishery system to climate change (warming, changes in upwelling) and other stressors (overfishing, oil spill, conflict with mussel seed harvesters)	Resilience is provided by the establishment of well-defined boundaries and the use of adaptive spatial management with nested scales at a regional, local (TURFs) and patch/rock level. This detailed spatial scale is only possible through collaboration between fishers' associations and managers. Ecologically, the stock demonstrates resilience due to its high plasticity, genetic diversity and connectivity. The learning capacity of the TURFs and the consideration of ongoing change in management are key aspects of resilience, although the capacity of the fishery to respond to change could be improved by a higher level of cooperation and information exchange between TURFs

Note: The country is noted in parentheses if the fishery or fisheries are specific to a province, autonomous community, state, prefecture, island or island chain.

Attributes with consistently low scores and low importance could be deprioritized for further applications of this framework and management interventions. However, these scores could also reflect insufficient data or awareness of these topics; we thus categorized these attributes as topics that 'require research'.

2.3 | Archetypes of fishery resilience

We used agglomerative hierarchical clustering analysis to evaluate similarities and differences in attribute scores among case studies ('hclust', method = ward.D2 and distance = Euclidean) to derive archetypes of fishery resilience related to case study characteristics. Scores were standardized across attributes prior to clustering, allowing us to compare the resulting clusters of cases to one another relative to the observed distribution of scores within each attribute. We differentiated groups based on tertiary splits in the dendrogram to create groups with three or more contributing case studies, which we judged to offer sufficient generalizability. All data analysis and visualization were done in R (v. 4.1.2; R Core Team, 2022). All data and code are available on GitHub at https://github.com/Science-for-Nature-and-People/climate-resilient-fisheries.

2.4 | Pathways of resilience

We used the case study attribute ratings and narratives (see Appendix 3) to assess common linkages within and across fishery archetypes. For each case study, we asked the author(s) to select the three most important attribute linkages, which could represent indirect or direct connections between attributes that were likely to enable or inhibit resilience in the fishery. In small group and plenary exercises, the working group used the patterns in linkages

TABLE 2 Attributes that confer resilience to climate change in fisheries.

Dimension	Attribute	Definition
Ecological	*Population abundance*	The abundance or biomass of a species present in a defined geographic range
	Age structure	The age distribution of individuals within a population
	Genetic diversity	The diversity or variability of genetic traits within a population
	Species diversity	The diversity of species within a community
	Adult mobility	The mobility of a population's mature adults
	Larval dispersal	The degree to which eggs or larvae spread from a spawning site to a settlement location or until yolk sac re-adsorption
	Environmental niche breadth	The degree and extent to which a species can tolerate or acclimate to changes in environmental conditions
	Dietary flexibility	The range of prey items that a population can exploit or the diversity of feeding strategies available
	Habitat diversity	The range of suitable, adjacent and available habitats that a population can exploit
	Plasticity	The capacity for one genotype to yield more than one phenotype in response to environmental cues
	Evolutionary potential	The capacity of a population to evolve in response to environmental change
	Ecosystem connectivity	The degree to which an ecosystem facilitates the structural and physical connection among suitable, adjacent and/or available ecosystem functions and components
	Population modularity	Modularity, the opposite of connectivity, refers to the compartmentalization of populations in space and time
Socio-economic	*Wealth and reserves*	The aggregate value of assets available to individuals, organizations and communities that contribute to human well-being
	Economic diversity	The variety of income-earning activities that an individual, household or community can partake in
	Social diversity	The variety of social characteristics that shape the preferences, attitudes, values and norms in a particular population
	Flexible and agile infrastructure	The ability of built structures and facilities to provide needed services under a wide range of conditions and to quickly respond to predictable and unpredictable changes
	Mobility	An individual's and/or community's ability to move freely and easily, either temporarily or permanently
	Economic opportunity	Physical and non-physical means and processes that enable individuals and communities to benefit from new or alternative income-earning or subsistence activities
	Resilience mindset	The degree to which individuals accept 'resilience thinking' from a perspective that recognizes characteristics of complexity, uncertainty, nonlinearity, thresholds, feedbacks, irreversibility and multi-scale and multi-level interactions in a changing world
	Place attachment	The extent to which individuals and communities feel tied to the geographical location in which they live and operate, affecting their response to risk, including willingness to move homes, fishing grounds or processing location in the face of adverse conditions
	Social capital	The strength of networks of relationships among people and organizations who live and work in a particular community
	Technology transfer	The level and capacity of individuals and communities to develop and acquire new technologies and methods as well as the ease with which these technologies and methods are transferred between and among actors in the system
	Modular infrastructure	The degree of compartmentalization within and across built structures and facilities and the ease with which diffusion can proceed
	Knowledge diversity	The variety of types and origins of knowledge that are available to individuals and members of the community
	Knowledge access	The ability of individuals and communities to obtain and derive benefit from existing knowledge about the system
	Learning capacity	The degree to which individuals and communities are able to perceive risk, learn from experience, synthesize information and grow their own knowledge
	Agency	The capacity of individuals and communities to negotiate, make decisions and act on their own free will

TABLE 2 (Continued)

Dimension	Attribute	Definition
Governance	*Responsive*	The sensitivity, readiness, speed and accuracy with which a governance system handles, resolves and follows up on a management-relevant change to meet stakeholders' needs
	Participatory	The degree to which an institution empowers participants to influence and share control in processes of public decision-making, ranging from intermittent consultation opportunities to ongoing self-mobilization
	Equitable and inclusive	The degree to which the governance system is fair in the distribution of benefits and burdens, participatory in rule and decision-making for relevant actors and engaged and inclusive of marginalized and disadvantaged groups
	Accountable	The degree to which decisions and decision makers can be held culpable to both the individuals and communities that they govern as well as to higher-level mandates, commitments, goals and objectives they serve
	Transparent	The openness and accessibility of timely information, decision-making rules and procedures and outcomes to members of the public or stakeholders affected by management actions
	Efficient and effective	The degree to which the governance system produces outcomes that achieve societal and/or fishery objectives while efficiently using available resources
	Polycentric	The degree to which multiple bodies at different levels of the governance system overlap and interact to make and enforce rules within a specific policy arena or location
	Cross-scale integration	The degree to which actors and/or organizations acknowledge, work with and attempt to understand the relevance and transition of scale and the interlinkages between various other organizations, institutions and management structures
	Adaptive	The capacity to implement a structured, iterative process of continual innovation, testing, learning and adjustment that facilitates robust, flexible decision-making and action in the face of uncertainty and complexity
	Leadership and initiative	A system that legitimizes and supports the development of leaders who are guided by collective interests, who mobilize and direct responses to disruptions and who take responsibility and act when necessary

Note: See Mason et al. (2022) for full attribute names, definitions, proposed mechanisms and references. Table is reproduced with permission from Mason et al. (2022).

to identify common pathways of resilience, including positive and negative feedback loops, based on the individual attribute links. We explore two pathways of resilience derived from the exercise in the discussion.

3 | RESULTS

3.1 | Attribute importance

The 38 resilience attributes we operationalized (Table 2) varied in their importance to confer resilience to current or future climate impacts examined in the case studies (Figure 2a). Within the ecological dimension, the *population abundance*, *environmental niche breadth* and *ecosystem connectivity* attributes were highest ranked and most frequently identified by experts as important to conferring resilience (Figure 2a). In contrast, the *genetic diversity*, *plasticity* and *dietary flexibility* attributes were the least frequently identified as important to conferring resilience. Within the governance dimension, the *responsive*, *participatory* and *adaptive* attributes were most frequently identified as being important to conferring resilience, whereas the *polycentric*, *accountable* and *transparent* governance attributes were identified as less important. Within the socio-economic dimension, the *learning capacity*, *economic diversity* and *resilience mindset* attributes were most frequently identified as being important to conferring resilience, whereas the *modular infrastructure*, *social diversity* and *technology transfer* attributes were the least frequently identified as important.

3.2 | Attribute scores

The magnitude of attribute scores, or the degree to which attributes were manifested, varied within and between case studies (Figure 2b). While case studies for the Maine American lobster (*Homarus americanus*, Nephropidae), U.S. Bering Sea groundfish, Iceland groundfish and North-East Atlantic small pelagic fisheries recorded generally high scores across attributes, case studies for Madagascar nearshore, Madang reef fish (Papua New Guinea), Senegal small pelagics and Fiji nearshore fisheries scored lower on average. No case study exhibited a ‘perfect’ score; thus, all of the evaluated fisheries may have opportunities for improving their resilience to climate change. In general, *place attachment*, *social capital* and *learning capacity*—three socio-economic attributes—were the strongest attributes across the fishery case studies (Figures 2b and 3). Specifically, *place attachment* and *social capital* were scored

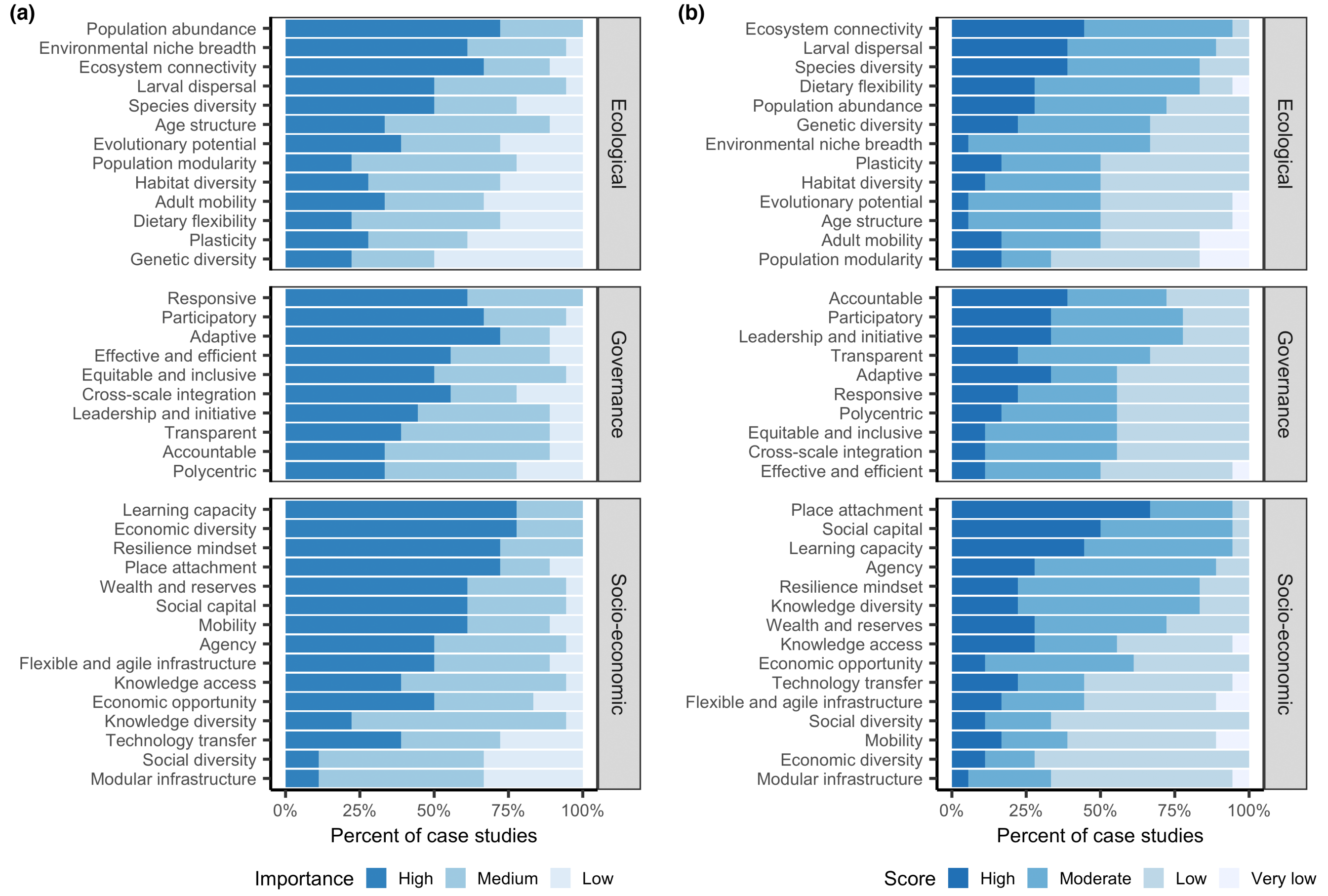


FIGURE 2 The (a) importance of the attributes for current or future resilience to the climate stressors considered within the 18 evaluated case studies and the (b) strength of the attributes, presented as 'score', to conferring resilience as they actively occur in the focal system, relative to other similar and well-understood systems. The 38 attributes of resilience are organized by dimension (ecological, governance and socio-economic) and are ordered by decreasing average importance or score.

highly in the majority (>50%) of case studies. In contrast, *modular infrastructure*, *economic diversity* and *social diversity*—also socio-economic attributes—were scored lower across case studies. Of the ecological attributes, *ecosystem connectivity*, *larval dispersal* and *species diversity* scored highest across many of the case studies, whereas *environmental niche breadth*, *evolutionary potential* and *age structure* scored lowest. With respect to the governance attributes, *participatory*, *leadership and initiative*, *accountability* and *adaptive* governance all scored higher across many of the case studies, whereas the *equitable and inclusive*, *cross-scale integration* and *effective and efficient* attributes scored lower.

3.3 | Attribute data quality

The quality of the data (or the completeness of data and accuracy of information) available for scoring, varied by dimension and attribute (Figure S2). High-quality data were more available to inform many of the scores for the *adult mobility*, *population abundance* and *habitat diversity* attributes within the ecological dimension. Conversely, data quality scores were significantly lower for the *genetic diversity*, *plasticity* and *evolutionary potential* attributes. Within the governance dimension, high-quality data were more often associated with the *polycentric*, *participatory* and *transparent* attributes, whereas lower-quality data tended to inform the *cross-scale integration*, *leadership and initiative* and *equitable and inclusive* attributes. Within the socio-economic dimension, higher-quality data were more often available to inform the scores for the *mobility*, *knowledge access* and *social capital* attributes. In contrast, lower-quality data were more frequently associated with the *modular infrastructure*, *resilience mindset* and *technology transfer* attributes.

3.4 | Attribute typology

An attribute typology was developed based on a combination of attribute importance and score to reduce the dimensionality of the complex data set (Figure 3). *Learning capacity*, *social capital* and *participatory* governance were consistent contributors to the resilience of fishery systems (both in terms of high score and high importance) across the global set of fishery cases, and hence were identified as 'robust sources of resilience'. *Economic diversity*,

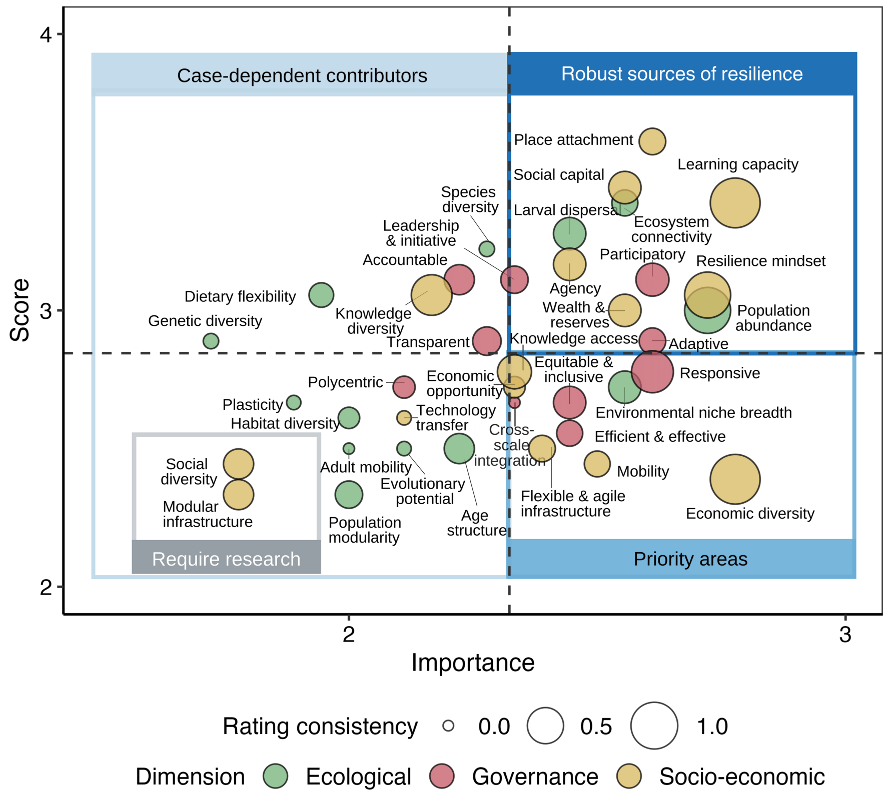


FIGURE 3 A general typology of resilience attributes across fishery case studies. Attributes were assigned to a typology based on whether they are above or below average importance (vertical dashed line) or above or below average score (horizontal dashed line). Averages were calculated across the 18 evaluated case studies. Attributes are as follows: (1) 'robust sources of resilience' if they are consistently important and higher scoring (top-right, dark blue); (2) 'priority areas' if they are consistently important yet lower scoring (bottom-right, medium blue); (3) 'case-dependent contributors' to resilience if they are of lower importance and variable in score (left-half, light blue); or (4) 'require research' if they are both low importance and low scoring (bottom-left subset, grey). Attribute importance was reported using a three-option Likert scale (low: 1, medium: 2 or high: 3). Attribute score was reported using a four-option Likert scale (very low: 1, low: 2, moderate: 3 or high: 4). Point size indicates rating consistency (inverse of variance) in attribute ratings across the 18 evaluated case studies, with smaller points indicating high variability and case dependence and larger points indicating consistency.

environmental niche breadth and *equitable and inclusive* governance were consistently noted as important 'priority areas' for strengthening resilience by case study authors, but were on average scored lower than other attributes of resilience. The importance of many of the species-specific ecological attributes was rated with lower-than-average importance and were noted as 'case-dependent contributors' (variable scores but low importance). These attributes included *adult mobility*, *plasticity*, *genetic diversity* and *dietary flexibility*. For many fisheries, *social diversity* and *modular infrastructure* ranked low in contribution to resilience both in terms of score and importance and 'require research'.

3.5 | Fishery archetypes

The clustering analysis (Figure 4a) revealed five groups or 'archetypes' of case studies (Figure 4b). The major split differentiated case studies with lower (Groups 1–2) and higher (Groups 3–5) governance scores. Below, we describe the five fishery archetypes based on attribute scores.

3.5.1 | Group 1. Ecologically strong, governance constrained

Senegal small pelagics, Moorea reef fish (French Polynesia) and U.S. Atlantic and Gulf of Mexico highly migratory pelagic longline fisheries had consistently lower governance scores, with five governance attributes scored as 'low' across all cases in this cluster (Figure 4; Figure S3). Ecological attribute scores were moderate across studies, although *ecosystem connectivity* was scored consistently high. Socio-economic scores were moderate as well, with higher scores for attributes such as *place attachment*, *learning capacity*, *knowledge diversity* and *social diversity*.

3.5.2 | Group 2. Strong ecological and social processes, despite lower wealth and infrastructure

Kiribati giant clam (*Tridacna* spp., Cardiidae), Madagascar nearshore, Fiji nearshore and Madang reef fish fisheries tended to have higher ecological scores (*species diversity*, *larval dispersal* and *habitat*

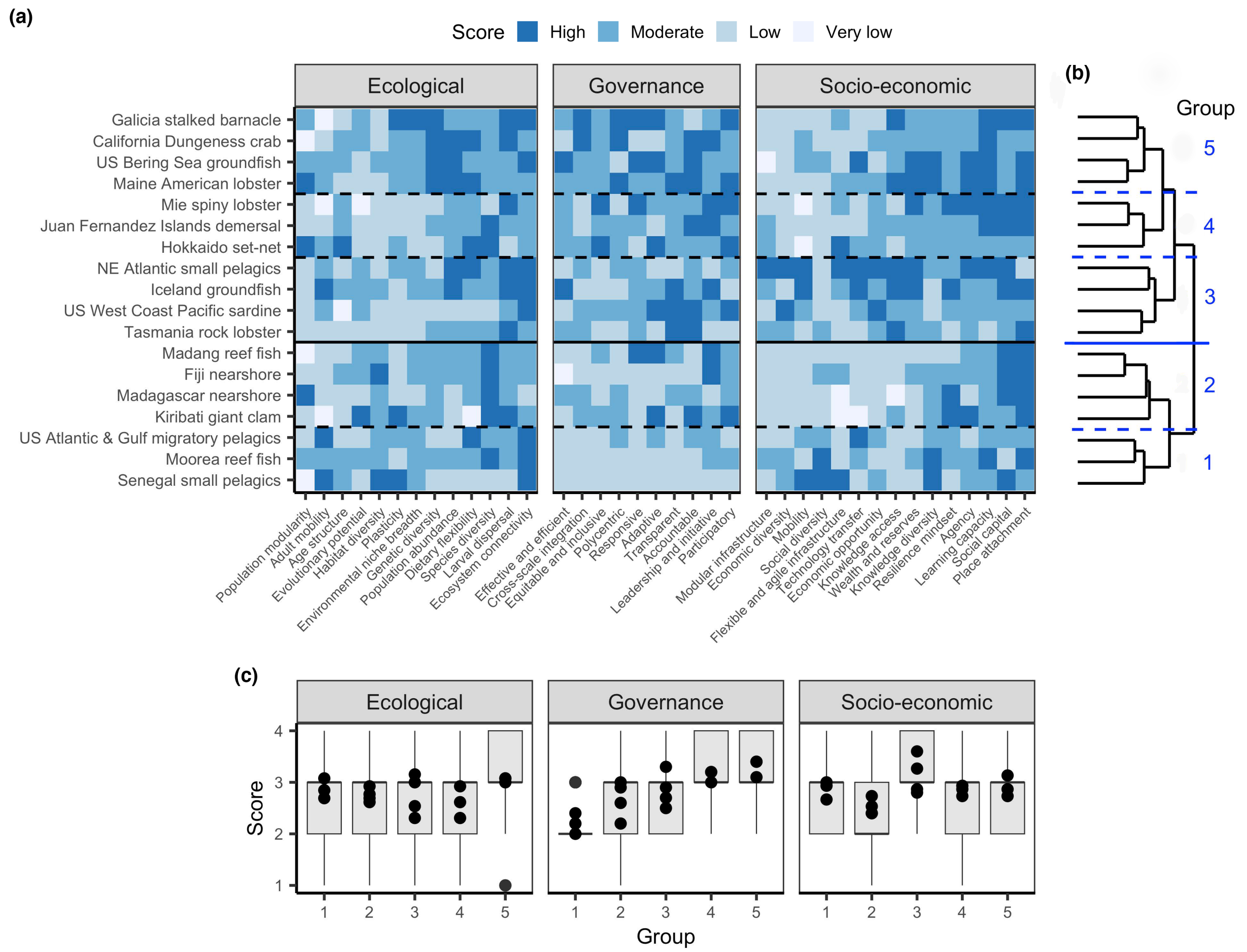


FIGURE 4 Resilience attribute scores by case study and case study groups. In (a), attributes are organized by dimension (ecological, governance and socio-economic) and are ordered by increasing average score. In (a, b), case studies are organized by groups identified through a hierarchical cluster analysis of the resilience attribute scores. One primary split (solid blue and black line) and three secondary splits (dashed blue and black lines) were detected. Groups are numbered in blue and represent fishery archetypes: (1) ecologically strong, governance constrained; (2) strong ecological and social processes, despite lower wealth and infrastructure; (3) economically wealthy and well governed; (4) variable stocks; reliable social processes and governance and (5) enabled by all dimensions. In (c), the distribution of attribute scores is presented by dimension and cluster group. Points show the mean attribute score by case study within each group and dimension.

diversity) and lower socio-economic scores (e.g. for *economic opportunity*, *technology transfer*, *mobility*, *economic diversity* and *modular infrastructure*) (Figure 4; Figure S3). However, this group had consistently high scores for *place attachment* and *social capital*. Scores for governance were more variable, with higher scores for *leadership* and *participatory* governance and lower scores for *equitable and inclusive*, *cross-scale integration* and *efficient and effective* governance.

3.5.3 | Group 3. Economically wealthy and well-governed

Tasmania rock lobster (*Jasus edwardsii*, Palinuridae), U.S. West Coast Pacific sardine (*Sardinops sagax*, Clupeidae), Iceland groundfish and North-East Atlantic small pelagics fisheries had high scores across socio-economic attributes, particularly for *social capital*, *wealth and reserves*, *knowledge access* and *economic opportunity* (Figure 4; Figure S3). This group had moderate scores for ecological and governance attributes. *Ecosystem connectivity* and *larval dispersal* ranked high for many cases in this group as did *accountable* and *transparent* governance.

3.5.4 | Group 4. Variable stocks, reliable social processes and governance

Hokkaido set-net (Japan), Mie spiny lobster (*Panulirus japonicus*, Palinuridae; Japan) and Juan Fernandez Islands demersal (Chile) fisheries scored low to moderate across ecological attributes and higher for governance and socio-economic attributes (Figure 4; Figure S3).

Particularly strong governance attributes were *participatory*, *leadership and initiative* and *equitable and inclusive*. In the socio-economic dimension, this group scored *place attachment*, *social capital* and *learning capacity* highest, while *mobility*, *social diversity* and *economic diversity* scored low.

3.5.5 | Group 5. Enabled by all dimensions

U.S. Bering Sea groundfish, Maine American lobster (U.S.), California Dungeness crab (*Metacarcinus magister*, Cancridae; U.S.) and Galicia stalked barnacle (*Pollicipes pollicipes*, Pollicipedidae; Spain) fisheries had moderate-to-high mean scores for all three dimensions (Figure 4; Figure S3). *Population abundance*, *genetic diversity*, *ecosystem connectivity*, *larval dispersal* and *dietary flexibility* had particularly high scores in the ecological dimension. Governance attributes were scored as having high *participation*, *accountability*, *polycentricity* and *cross-scale integration*. Socio-economic attributes that scored highest across cases include *place attachment*, *learning capacity*, *agency*, *knowledge diversity*, *wealth and reserves* and *knowledge access*, whereas *economic diversity* and *modular infrastructure* scored low for many cases.

4 | DISCUSSION

4.1 | Summary

We assessed the climate resilience attributes across 18 fisheries case studies to understand which attributes were present, important, easy to assess and monitor and how they operate in response to various climate-related stressors. We highlight attributes that were important across case studies as 'robust sources of resilience' or 'priority areas' that may provide foci for interventions to build resilience. Our case studies also demonstrate that certain attributes operate differently across contexts, capacities and spatio-temporal scales ('case-dependent contributors'). We identified five fishery archetypes based on a cluster analysis. These archetypes could provide examples for practitioners to consider as they identify key attributes in their own fishery contexts and prioritize potential actions to improve resilience. In the following sections, we present insights into climate resilience attributes and fishery archetypes, articulate select resilience pathways that are revealed through key attribute linkages, discuss caveats and suggest future research directions to improve climate-resilient fisheries.

4.2 | Attribute typology

The attributes that provide 'robust sources of resilience' are those that practitioners may seek to identify, maintain through management interventions or bolster if they are weak. As climate impacts vary, the utility of a particular attribute may be temporarily elevated or sidelined in a given context. However, because these attributes emerged as important across diverse fisheries and climate stressors, they may represent sources of more general resilience. This means that practitioners may still seek to maintain or promote these attributes, independent of actualized impacts, so that they can be drawn upon in the future in the face of uncertainty. In particular, designing strategies that utilize multiple robust attributes together, such as *learning capacity* and *place attachment*, may foster resilience over longer time scales. For example, preserving culture and values can maintain identity-based *place attachment* and foster the stewardship of natural resources (e.g. Fiji nearshore fisheries), which may improve the availability of ecological attributes to ensure their sustainable conversion to socio-economic assets (e.g. *wealth and reserves*) under many climate scenarios (Kalikoski & Allison, 2010). However, strong *place attachment* may also hinder transformative change, such as relocation, if individuals feel duty bound to 'watch over the land' in the face of escalating climate risks (Singh et al., 2020).

We also identified key 'priority areas', where a deficiency in certain attributes hindered fishery resilience in most of the examined cases. Often fishery practitioners know the climate-ready management interventions needed in the system but political obstacles, lack of support or capacity impede the realization of these structural changes (Holsman et al., 2019). By taking the time to identify and enhance primary inhibiting attributes in the system, practitioners can increase the success of long-term interventions. Such efforts may require the practitioner to work beyond the assumed boundaries of a fishery system. For example, building *economic diversity* or increasing *equitable and inclusive* governance may not be within the jurisdiction or capabilities of fishery managers (e.g. Madagascar nearshore fisheries). Thus, addressing 'priority areas' may require employing collective processes, such as enhancing *social capital*, *cross-scale integration* and *polycentric* governance within the broader social-ecological system. There are a growing number of integrative conceptual and policy frameworks in cogent fields of study—such as sustainable development (Fleming et al., 2017; Kates et al., 2001), 'climate-smart' approaches that combine adaptation and mitigation (Harvey et al., 2014; Julius, 2023), food systems approaches (Ingram, 2011; Tezzo et al., 2021), OneHealth (Jamwal & Phulia, 2021; Zinsstag et al., 2021) and 3D-Wellbeing (Weeratunge et al., 2014; White, 2010). When coupled with calls for more 'policy coherence' (Scobie, 2016) and 'joined-up-government' (Aoki et al., 2023), they open 'windows of opportunity' (Brown et al., 2017) for fishery managers and practitioners to engage productively in this boundary-spanning work.

The attributes that emerged as 'case-dependent contributors' had high variability in scores across case contexts possibly because of the influence of other attributes of resilience. For example, *dietary flexibility* may depend on the strength of *adult mobility*. Furthermore, many of the 'case-dependent contributors' are species-specific ecological attributes, for which ratings of importance and score vary widely with the biology and location of target species or species portfolios. While species-specific attributes such as *genetic diversity* or *evolutionary potential* may not be readily actionable management targets (although a notable exception may be the management of Pacific salmon as an evolutionarily significant unit, ESU; Waples, 1995), they require attention because they modulate population- and ecosystem-scale ecological attributes that affect how target species respond to stressors. Thus, after assessing robust attributes, managers might identify these species-specific ecological case-dependent attributes in their system and use these findings as the foundation for management interventions.

Attributes with consistently low scores and low importance might be a lower priority for management interventions and further applications of this framework. However, we note that the importance and score of these attributes may vary depending on how the fishery system and time scale of the assessment are bounded. For example, *evolutionary potential*, a low-scoring attribute among these case studies, would be more important over very long time scales. Similarly, *modular infrastructure* and *social diversity* may be more relevant when broader fishery supply chains or fishing communities are included in system framings. Prior to deprioritizing these attributes, decision makers should consider how these spatial and temporal considerations could influence scores and importance.

4.3 | Fishery archetypes

The cluster analysis identified five fishery archetypes that highlight how ecological, socio-economic and governance attributes may enable or inhibit resilience to climate change in different marine fishery contexts. Our case studies, and fisheries globally, include a vast array of geographies, target species, fishery scales and management structures. As such, we present these archetypes as an entry point for fishery practitioners, community leaders, NGO partners and others, to identify analogous case studies to facilitate successful management outcomes in their focal fishery.

The archetypes can guide a fishery management group to identify a set of approaches to build resilience that are likely to be applicable to their fishery. A stakeholder from a developing country might, for example, relate to the Group 1 archetype ('ecologically strong, governance constrained'), which typically exemplifies strong attributes of ecological resilience that allow the fishery to persist despite unjust or ineffective governance regimes. In fisheries where high intrinsic ecological resilience can mask ineffective or inequitable governance, focusing on *responsive* and *participatory* governance, both 'robust sources of resilience', can foster supportive governance structures that benefit the fishery (Mason et al., 2023). In fisheries with high *ecological diversity*, such as small-scale coral reef fisheries, *place attachment* and *social capital* can support *leadership* and *participatory* governance, which may be a critical strategy in the face of limited *economic opportunities* outside of the fishery (Group 2: 'strong ecological and social processes, despite lower wealth and infrastructure'). Thus, customary management initiatives, such as those present in the Madang reef fish fishery, may focus on maintaining social attributes such as strong *place attachment*, and working to build and bolster *resilience mindset* and *social capital* as well as finding opportunities to increase alternative *economic opportunities* (Heenan et al., 2015). While the customary management process is capable of implementing measures for resilience in a timely fashion, advancing these techniques to include contextually appropriate tools, such as long-term monitoring and enforcement, may require additional resources; these are often difficult for communities to acquire and may be enhanced through appropriate partnerships.

'Economically wealthy and well governed' fisheries (Group 3) may have foundational capacities, such as flexible and proactive management systems, in place that promotes *technological innovation*, *economic opportunity* and *responsive* governance (Kritzer et al., 2019). Similarly, if a stakeholder has already identified properties of good governance, case studies in Group 4 ('variable stocks, reliable social processes and governance') or Group 5 ('enabled by all dimensions') may illustrate strategies for interventions based on the strength of case-dependent intrinsic ecological resilience attributes in the fishery. For example, in the Galicia stalked barnacle fishery (Group 5), the *agency* of local fishers maintains the ability of rights holders to turn ecological assets into socio-economic *wealth and reserves* (e.g. income or tradable assets). The implementation of Territorial Use Rights for Fisheries (TURFs), where only place-based community members or local residents are allowed to access the resource, creates a sense of ownership and fosters *place attachment* in the fishery. However, it is equally important to assess how some attributes may work in opposition to others, creating limitations or eroding resilience in different contexts. For example, the static geographic boundaries of the Galicia barnacle TURF system restrict the *mobility* of fishers, limiting the *social diversity* in the TURF and the diversity of *economic opportunities* for fishers with low access to alternative income-earning activities. Similarly, profitable, vertically integrated firms in Iceland (Group 3) have ample *wealth and reserves* that expand *adaptive* options, such as buying high-capacity trawlers to increase *mobility*, purchasing more quota to diversify portfolios and relying on reserve wealth and insurance to cope with stock fluctuations. However, these feedbacks reinforce economic inequalities within the individual transferable quota (ITQ) system. In particular, in this system, where the wealthiest firms are most poised to benefit from new *economic opportunities* or withstand losses, these wealthier actors also accrue political power and have strong incentives to maintain the status quo.

4.4 | Pathways to future resilience: Two contrasting examples

The fishery archetypes revealed a suite of potential interactions among attributes, which vary across the archetypes, within which we hypothesized distinct resilience pathways in our case study systems. The proposed pathways are composed of multiple causal relationships between attributes that can amplify or attenuate resilience, depending on the system state. We provide an overview of these linkages, as noted by case study authors (see Appendix 3), as well as two examples of actionable pathways to resilience. These are not the only pathways for achieving climate resilience but are also pathways with broad relevance to fisheries globally.

Across case studies, attributes of resilience influence population and ecosystem flexibility and organization. These, in turn, affect how the size and structure of the fished population change in response to a climate stressor. For example, within a fisheries system, *population abundance* often represents the critical link between the ecological dimension and socio-economic dimension (i.e. the fish available to catch and consume for nutrition or exchange for income or other assets). Thus, fundamental features of effective fisheries management include sustaining healthy populations of fished species and ensuring that fishery benefits can be realized and distributed equitably (e.g. Free et al., 2020; Gaines et al., 2018). Attributes that support socio-economic and governance flexibility played an integral role in the status and distribution of ecological to socio-economic asset conversion; dynamic (*responsive* and *adaptive*) as well as just (*participatory* and *equitable and inclusive*) attributes of governance were particularly important in supporting *effective and efficient* governance in the context of climate change. Collective processes, such as *social capital*, *cross-scale integration* and *polycentric* governance, facilitated access to *knowledge diversity*, *learning capacity* and *wealth and reserves* further altering the ability of the fishery system to both benefit from and maintain ecological assets in relation to disturbance in the short term. These linkages were most frequently identified by case study authors and resulted in two examples of pathways to resilience (Box 1).

In Pathway A, 'resilience through ecological assets and strong communities', strong *social capital*, *place attachment* and a *resilience mindset* led to supportive and flexible governance, despite limited *economic opportunities* outside of the fishery. This pathway is characteristic of small-scale systems, particularly more remote and traditional fishery-dependent contexts where seafood might be consumed for subsistence or shared among community members (e.g. Cinner et al., 2006; Eurich et al., 2023; Quintana et al., 2021; Thomas et al., 2020). In this pathway, fish represent an ecological asset, which leads to non-monetary assets such as health, social capital and other benefits that support community well-being in the face of stressors. While the fishery's ability to create and accumulate economic wealth is limited, benefits tended to be distributed more equitably than in commodity market-oriented fisheries (Pathway B). However, this pathway can break down when communities transition to more globalized economies (Arthur et al., 2022). For example, in the Kiribati giant clam fishery adaptive management has failed on the most developed island compared to the more rural islands, where governance and social processes were more flexible (Eurich et al., 2023). On the developed island, traditional community boundaries are blurred, governance operates more regularly through the central government, which tends to be less adaptive, and the fishery has continued to decline.

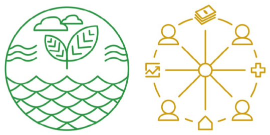
Conversely, in Pathway B, 'resilience through economic assets and effective governance', efficient conversion of fish and invertebrates into economic assets is the primary driver of reinforcing feedback loops that support resilience. Competition for access to fishery benefits combined with *knowledge access* and capital to invest (e.g. *wealth and reserves*) leads to *technology transfer* and often *responsive* governance. These factors together tend to expand adaptive options. For example, landings and market data can allow for prompt responses to environmental or market changes when a baseline period and target objective are properly defined and alternative scenarios and assumptions are explored (Duplisea et al., 2021; Roux et al., 2022). However, *wealth and reserves* and other attributes of resilience may become increasingly concentrated in the most successful actors in this pathway, creating power imbalances and worsened equity outcomes (McClanahan et al., 2021). These feedbacks reinforce economic inequalities in Iceland, where the wealthiest firms are most poised to benefit from new economic opportunities or withstand losses; these wealthier actors also accrue political power and have strong incentives to maintain the system status quo (Mason et al., 2023). Additionally, while Pathway B is effective at maintaining economic assets and learning under certain stressors, these linkages can erode the ability to think nimbly and adaptively (e.g. *resilience mindset*) if persistent desirable outcomes reduce motivations for preparation and adaptation to future change. This occurred in the California Dungeness crab case, where minimal management measures appeared sufficient given the stock's robust ecological resilience, but resulted in lengthier and costlier recovery from an unprecedented combination of climate-driven stressors. Thus, this pathway can create rigidity, where systems optimized for stability under a certain range of conditions become inflexible and vulnerable to collapse under extreme or novel stressors (Carpenter & Brock, 2008); as illustrated in the North-East Atlantic small pelagics fishery (Kapstein et al., 2023; Mason et al., 2023). This is a key concern for fisheries under uncertain future climate conditions.

4.5 | Caveats and limitations

While the case study framework, attribute typology and fishery archetypes presented here can help delineate pathways towards fishery resilience, complexities and questions remain. We were unable to determine if some attributes that commonly scored low were true limitations to fishery resilience or instead scored low because they were difficult to conceptualize or measure (see Section 3.3 and typology 'require research') or were viewed by respondents as being represented to some degree by other higher-ranked attributes. For example, 'case-dependent contributors' *dietary flexibility* and *plasticity* could be considered to be characteristics of *environmental niche breadth*. Fishery complexity also

BOX 1 **Resilience attributes define two pathways of resilience.**

Pathway A. Resilience through ecological assets and strong communities



Fisheries with high *species diversity*, *ecosystem connectivity*, strong social processes, and *participatory* governance (e.g., **Group 2**), exemplify a pathway of resilience. On this path, ecological assets are not being turned into cash income rapidly. Rather, the intrinsic capacities of the fished species along with intact ecosystems create ecological assets, which lead to socio-economic assets, specifically *economic diversity* and investment in *infrastructure*. When bolstered by social attributes, specifically strong *place attachment*, *resilience mindset*, and *social capital*, the actors in the fishery are able to derive benefits from the fishery sustainably and equitably. These benefits increase the resilience capacity of each individual, which can enhance social *agency* and eventually promote *participatory* governance. This interaction creates a positive feedback loop of resource stewardship and community well-being despite limited monetary *wealth and reserves*. Moreover, these capacities can lead to *participatory* governance and strong *social capital*, which further protect ecological assets through adaptive management initiatives.

Pathway B. Resilience through economic assets and effective governance

Several high-capacity, market-oriented industrial fisheries exemplified a reinforcing resilience feedback loop, where ample *wealth and reserves* and *access to knowledge* promote technological innovation, which in turn results in further wealth accumulation, enhanced *learning capacity*, and *economic opportunity* (e.g., **Group 3**). On this path, profit motive and market competition, in conjunction with high *learning capacity* and *access to knowledge*, drive innovation and community and government responsiveness. In these cases, strong management may also stem from the income generated. However, this pathway can also generate or exacerbate economic and power inequalities, whereby actors who already have abundant *wealth and reserves* and *learning capacity* are best poised to reap the benefits of innovation and responsiveness. Further, those with the most economic success may be better engaged or represented to have the greatest voice in the management system, likely to result in management decisions that benefit them and reinforce status quo and maintain inequalities.

Examples of climate resilience in practice

Small-scale coral reef fisheries demonstrate the social and governance processes in **Pathway A** and reflect how strong communities can achieve adaptive management. For example, tropical cyclones in Madagascar and Fiji pose higher risks for both ecological and socio-economic assets, including fishing boats, gear, and the ecosystem, which inhibit offshore fishing activity. In the past, communities that incurred damage from the cyclones were able to activate strong community relationships (*social capital*), traditional *knowledge*, and strong *place attachment* to rebuild *infrastructure*. The community response supports a short-term transition to traditional forest foods and subsistence farming, respectively, that buffers against nutritional shortages while fishing effort is decreased. Similarly, in Kiribati, the resilience of the giant clam fishery depends on the ability of stakeholders to act collectively, with flexibility, to implement traditional governance. Strong *place attachment*, *learning capacity*, and *agency* has led to successful community-driven species-specific regulations, quotas, and adaptive closures. These governance approaches, specifically fisher-driven no-take marine protected areas, have led to a stable giant clam population and associated fishery.

Several fishery cases demonstrate both the success and potential challenges of **Pathway B**. In Iceland, tightly controlled and effective management, paired with supply chains that promote information exchange, allow fisheries actors to rapidly respond to ecological changes. Abundant assets enable stakeholders to translate changes in ecological assets into economic opportunities. Specifically, efficient and profitable fishers with secure harvest rights have economic incentives to respond to stock and market fluctuations. Shared databases, centralized ex-vessel market auctions, and connected markets provide rapid access to landings and market data. This knowledge allows prompt responses to environmental or market changes; fishers can decide where and what to fish to maximize value, or processing firms can expand economic opportunities by specializing in underutilized species. Similarly, other fisheries have ample *wealth and reserves* that expand adaptive options. For example, in the NE Atlantic small pelagic fishery commercial actors incorporated new *technology* to increase *mobility*, purchased more quota to diversify portfolios, and reinvested to cope with population declines of fished species.

created caveats within the fishery archetypes clustering. For example, the U.S. Atlantic and Gulf of Mexico highly migratory pelagic longline fishery clustered within Group 1 due to low governance scores reflecting a general lack of compliance and responsive management strategies by other countries in the international domain and regulatory system (Juan-Jordá et al., 2015). However, the U.S. domestic management system is more *efficient and effective* and *accountable*, which has led to several effective bycatch mitigation measures for the fishery as a direct result of strong legal mandates to protect species of concern (Di Natale, 2021). Furthermore, the cases selected for this study are based on past or existing research. As such, some findings may be an artefact of the case study selection process. For instance, *place attachment*, *social capital* and *learning capacity* were the strongest attributes across the fishery case studies. Researchers often find it more accessible and straightforward to work with fisheries where participants are accepting, receptive and organized or have capable leader(s) and are willing to learn and engage with scientists.

4.6 | Future research and application

Our synthesis highlights several important directions for future research. The potential for bi-directionality in attribute interactions was beyond the scope of our analysis but may be a key driver of tipping points and non-linearities in resilience pathways. For example, the Maine American lobster fishery has self-imposed size and harvest limits since the 1930s, which have helped attain high *population abundance* in the Gulf of Maine and buffer against warming water temperatures during the 2000s (le Bris et al., 2018). But these practices appear to be waning, perhaps due to complacency (Mazur & Johnson, 2020), suggesting that additional incentives or enforcement measures may be needed to maintain the resilience benefits that had been built over time. More comprehensively evaluating destabilizing feedbacks that may lead to systems' state change is a topic that should be prioritized for future research.

Another critical area of research includes understanding inequities in resilience attributes. Specifically, there is a need to examine how and why different attributes are accessed by and beneficial to different groups and how inequities might be overcome. Social equity ensures individuals or subgroups have access to the resilience attributes of a system, providing them with a greater array of plausible climate responses. In contrast, inequity can allow privileged groups within a fishery (with a broader resilience portfolio) to adapt better to changing conditions, and thereby acquire a larger share of fishery benefits. Perceived procedural inequities (unfairness in decision-making processes) can affect compliance with fisheries management regulations (as observed in the Moorea reef fish case study) and can serve as a barrier to effective climate adaptation planning in fisheries (Harper et al., 2023). Measures of procedural equity are included in our analysis via the governance attributes of *accountable*, *equitable and inclusive*, *participatory* and *transparent*. Distributional equity in the context of resilience refers to the extent to which assets and arguably other domains of resilience attributes are distributed fairly. Some of the socio-economic attributes in our analysis—such as access to *economic opportunity* and *knowledge access* and *agency* (i.e. access to self-determination)—indicate general access within the system. In addition, fairness in distribution is broadly captured in the attribute of *equitable and inclusive* governance. However, we did not comprehensively measure how access to resilience attributes is socially differentiated. There is a pressing need for a deeper understanding of pathways that foster equitable resilience in fisheries (Ojea et al., 2020). Future research that considers how access to attributes varies among fishery actors includes distributional equity as a distinct metric alongside score and importance, or prioritizes the perceptions of marginalized groups within a fishery, could help advance this understanding.

Alongside future research, our framework can be directly applied to support climate change resilience planning in fisheries. To this end, we used our framework to design, pilot and refine a public decision support tool for fishery policymakers, managers, stakeholders and communities seeking to increase resilience to climate change. The Climate-Resilient Fisheries Planning Tool (CRFP Tool; https://ClimateResilientFisheries.net/), available online, guides users through the framework presented here, to assess their fishery's climate resilience and identify approaches and priority actions that can be used to improve resilience in their fishery. Specifically, the CRFP Tool supports users through a six-step process based on the methods described here. The process guides users to (1) assess their fishery system, (2) set long-term goals, (3) identify climate impacts, (4) evaluate attributes of climate resilience, (5) evaluate potential climate-resilience actions and (6) identify priority actions. Through this process, the knowledge of multi-dimensional attributes and their relationships can be combined with stakeholders' case-specific context to advance climate resilience across marine fisheries. The CRFP Tool links to case studies described here and thus enables stakeholders to locate their focal system within the archetypes and pathways we have identified and draw appropriate lessons. Additional examples of climate impact-specific interventions and strategies for building specific resilience attributes are available within the CRFP Tool Workbook. As stakeholders continue to develop climate-resilience plans and advance solutions to support healthy marine ecosystems, this approach and continuing synthesis will help strengthen holistic efforts.

5 | CONCLUSION

Building resilience is a complex multi-faceted goal that must be considered and managed at both the global and case-specific scales. Applying resilience-building approaches to the world's diverse fisheries will benefit from the general applied understanding of resilience in practice that this set of 18 comparatively analysed case studies has provided. The empirically informed resilience framework presented here, built on Mason et al. (2022), can help identify climate impacts, attributes and contextual factors that influence the resilience of fisheries to climate change. We also revealed relationships among attributes, from which we observed distinct attribute typologies, fishery archetypes and resilience pathways to demonstrate actionable levers for building resilience. We highlight the need to combine place-based historical perspectives (Mills et al., 2023), inference- and model-based methods and resilience stories (see Appendix 3 for fishery case studies narratives) to better understand the impacts of climate variability on management decisions. Therefore, enabling practitioners and communities to identify their own pathways towards building climate resilience in their fisheries systems, independently, represents a critical future direction of our research.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The data and code that support the findings of this study are available in the Science for Nature and People Partnership repository at https://github.com/Science-for-Nature-and-People/climate-resilient-fisheries.

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