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RESEARCH ARTICLE

Climate resilience and risks of rigidity traps in Iceland's fisheries

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Abstract Iceland's fisheries system is well-governed, data-rich, and has adapted to past ecological change. It thus provides an opportunity to identify social-ecological attributes of climate resilience and interactions among them. We elicited barriers and enabling conditions for adaptation in Iceland's fisheries from semi-structured expert interviews, using projections of fish habitat shifts by mid-century to guide discussion. Interviewees highlighted flexible management, highly connected institutions that facilitate learning, ample assets to expand adaptive options, and cultural comfort with change. However, examining how these attributes interact in reinforcing feedback loops revealed potential rigidity traps, where optimization for resilience to stock shifts may render the system more vulnerable to extreme environmental change and social backlash. This study articulates resilience attributes that Iceland and other fisheries systems might prioritize as the climate changes. It further explores circumstances in which these same attributes risk forming traps, and potential pathways to escape them.

Keywords Climate change · Climate resilience · Fisheries · Rigidity trap · Social-ecological system

INTRODUCTION

Fisheries provide crucial services to human communities, from sustenance to spiritual values. To provide services in dynamic conditions, fisheries must strive to be resilient—a term we approach here as encompassing a social-ecological system's abilities to respond, adapt, and potentially transform in response to change in order to maintain desired pathways (Folke 2016; Chaigneau et al. 2021). The ongoing and projected impacts of climate change have elevated climate resilience as an urgent but challenging policy priority for fisheries (De Young et al. 2012).

Putting resilience into practice is challenging because it is so complex: feedbacks within and between social and ecological dimensions of systems are dynamic and nonlinear; appropriate resilience indicators and the data to measure them remain elusive; and the very definition of resilience is ambiguous and "turbulent" (Davidson et al. 2013; Moser et al. 2019). To engage this complexity, researchers have theorized principles and attributes of resilience that we could observe and potentially strengthen (e.g., Biggs et al. 2012; Whitney et al. 2017; Mason et al. 2021a). We still, however, lack understanding of how these attributes apply to fisheries specifically, which attributes are relevant in different contexts, and, critically, how they interact to confer or inhibit resilience (Whitney et al. 2017; Cinner and Barnes 2019). To move resilience theory toward practice, researchers have called for more empirical examples illustrating how these theorized attributes operate in varied fisheries social-ecological systems (Ojea et al. 2017; Kleisner et al. 2021; Mason et al. 2021a).

Examining interactions among key system attributes could help map out the nonlinearities, thresholds, and feedbacks that are central to characterizing resilience (Biggs et al. 2012; Folke 2016). Mason et al. (2021a) identify an initial typology of attribute interactions that includes *dependencies*, where some attributes enable others; *weakest links*, where lack of certain attributes severely limit resilience even if other attributes are present; and *bidirectional feedbacks*, where too much of an attribute or

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combination of attributes detracts from resilience by creating inflexibility and inertia. Collectively, these suggest that attributes can interact in reinforcing feedback loops, both as virtuous cycles that promote resilience and vicious cycles that erode it. The latter represent a key dynamic of social-ecological traps, a metaphor describing how reinforcing feedbacks lock social-ecological systems into sustained undesirable pathways (Enfors 2013; Tidball et al. 2016).

Concerns about social-ecological traps are increasingly informing fisheries resilience research (Kittinger et al. 2013), following observations of a "gilded trap" in the lucrative but ecologically depauperate Maine lobster fishery, where the system is wholly dependent on a fragile lobster "monoculture" (Steneck et al. 2011) and poverty traps in coral reef fisheries, where impoverished fishers cannot afford to exit a degraded fishery and may have to use increasingly destructive fishing practices (e.g., Cinner 2011). Rigidity traps are yet another form of trap where tightly connected, self-reinforcing structures optimize and stabilize a system for a certain set of conditions but make it inflexible, potentially triggering catastrophic system-wide collapse under sufficient stress (Carpenter and Brock 2008). Rigidity traps are less represented in the fisheries literature, perhaps because such traps are more characteristic of stable, high-capacity systems that might typically be considered management successes. Because climate change could bring novel and extreme stressors that push even such successful-seeming systems over thresholds, understanding how attribute interactions could contribute to various forms of social-ecological traps will be increasingly important to develop resilience strategies across fishery contexts and capacities. Further, social-ecological traps are dynamic, path-dependent processes (Boonstra and DeBoer 2014), so characterizing resilience dynamics in case studies not solely in already entrapped systems but also where traps are latent or nascent can deepen our understanding of how traps form and how to escape them.

Iceland's fisheries present near ideal conditions to explore interactions among resilience attributes and their potential contribution to virtuous resilience cycles or social-ecological traps in a high-capacity system. If, in our attempt to characterize climate resilience in fisheries, we resemble the proverbial drunk searching for their keys under a lamppost, Iceland shines a very bright lamp: detailed scientific surveys and landings data support a comprehensive Individual Transferrable Quota (ITQ) management system. The social, economic, and ecological outcomes of the ITQ system have been widely studied. Finding these keys is salient to Iceland and informative to fisheries worldwide: Iceland is a major fishing nation contributing over 1% of global marine capture production, and fisheries are a domestic economic pillar (FAO 2020). Fish and fishing are central to Iceland's culture, diet, and heritage, so lessons learned here could "unlock" challenges for other fishery-dependent nations. Finally, unlike the prospects for the unfortunate drunk, it is likely that we *can* find these keys here. Iceland has high capacities throughout its system, topping charts of global development, environmental performance, and well-being indicators (OECD 2020; UNDP 2020; Wendling et al. 2020). The fisheries system has already demonstrated adaptive and transformative capabilities. The management system, developed in the 1980s-90 s in response to declining stocks and profits, is today considered a model of economic and ecological success (Gunnlaugsson and Valtysson 2022). The industry has already adapted to decades of environmental variability, including rapidly establishing a lucrative fishery on a novel incursion of Atlantic mackerel (*Scomber scombrus*) in the mid-2000s, albeit sparking international political conflict over harvest rights (Saevaldsson and Gunnlaugsson 2015; Spijkers and Boonstra 2017). Looking to the future, researchers have projected potential increases in some species for Iceland's waters (Campana et al. 2020; Mason et al. 2021b), consistent with a general pattern of poleward shifts and borealization of the Arctic (Cheung et al. 2010; Fossheim et al. 2015). Iceland thus presents an opportunity to explore potential resilience in action, examining opportunities as well as threats as the climate changes.

In this study, we explore resilience attribute dynamics in Iceland's data-rich and high-capacity fisheries system. Based on expert interviews about barriers and enabling conditions for adaptation to projected climate-driven shifts in species distribution and abundance, we identify four themes of reinforcing interactions among attributes that align economic and ecological goals but may create two potential rigidity traps. We present interviewees' suggested interventions for escaping these traps. Finally, we discuss potential actionable resilience attributes for Iceland and other fishery systems to prioritize to bolster resilience and avoid traps.

MATERIALS AND METHODS

Study system: Iceland's ITQ fisheries

Warm Atlantic and cold Arctic currents converge in Iceland's waters, creating a dynamic environment that supports abundant and relatively diverse fish stocks. In addition to interannual and spatial variability, the interactions of these currents create multidecadal warm and cold regimes that alter species productivity, composition, and distribution (Astthorsson et al. 2007), including a warm-water anomaly from the mid-1990s–2010s that drove northward expansions of warmer-water species including Atlantic mackerel as noted above (Valtýsson and Jónsson 2018). Given Iceland's remoteness, harsh environment, and rich marine resources, fisheries have been central to its culture and economy since it was settled in the ninth century (Agnarsson and Arnason 2003). Today, fishing and related industries remain core to Iceland's economy, contributing up to 18% of Iceland's GDP (Sigfusson et al. 2013). Fisheries are predominantly commercial and export-oriented, with an emphasis on quality, sustainability, and innovation in waste reduction and value creation (Gunnlaugsson and Valtysson 2022; Sigfusson 2020).

Fishing activity in Iceland's waters is tightly controlled and monitored under the uniform ITQ system, which covers over 98% of catch and over 30 species. Under the ITQ system, total catch limits are set annually for each species, and rights to harvest a fixed portion of that catch are allocated to firms or vessels according to their quota share. Quota shares are owned permanently or can be bought, sold, and temporarily leased. Catch limits are based on fixed harvest rules or advice from the Marine and Freshwater Research Institute (MFRI), a government agency that monitors and assesses stocks. Discards are prohibited (The Fisheries Management Act 1990; Agnarsson et al. 2016; Gunnlaugsson and Valtysson 2022).

The management system includes several catch-balancing mechanisms beyond quota transferability to buffer for unpredictability and prevent "choke" species with low quota levels from constraining target catch: fishers can bank or borrow a set portion of the following year's quota, and convert quota among species using a standard "cod-equivalent" (The Fisheries Management Act 1990). These measures allow fishers to make strategic decisions to maximize value within their quota allocation, while also maintaining ecological management goals (Knútsson et al. 2016; Oostdijk et al. 2020). All commercial fishing requires a permit, no foreign vessels may own quota, all landings are weighed and recorded, and those data are shared with fishers in real time (Agnarsson et al. 2016; Chambers and Carothers 2017). Centralized fish auctions link landings to buyers and processers throughout Iceland via a virtual marketplace (Knútsson et al. 2015).

This management system is broadly considered a success story in achieving sustainability and profitability. However, social critiques persist (see Gunnlaugsson and Valtysson 2022, for a comprehensive overview of fisheries system structure, recent outcomes, and perceptions). The privatization of harvest rights incentivizes economic efficiency and accordingly the industry grew consolidated and vertically-integrated following ITQ implementation. This reduced overfishing but has been associated with unemployment and depopulation in remote fishery-dependent towns (Agnarsson et al. 2016; Chambers and Carothers 2017). The Icelandic government implemented a community development quota and a small open access coastal fishery to support these towns, but these measures have been criticized as inadequate and the industry remains difficult to enter as a newcomer (Chambers and Carothers 2017; Kokorsch and Benediktsson 2018).

Expert interviews

The first author conducted 18 semi-structured interviews with Iceland fisheries system experts via online videoconference between December 2020 and May 2021. These were recorded and transcribed with the videoconference platform's built-in software. The interviewer also asked research questions, with consent, in 16 in-person meetings during June 2021, predominantly hosted by industry experts who had been less accessible virtually. These meetings included 1–3 experts and presentations on business practices or facility tours. We took detailed notes during these conversations but found it impractical to audio-record due to noise and variable interview locations, so we share paraphrased insights in the subsequent text rather than direct quotes.

We used a purposeful sampling strategy, beginning with an initial base of key informant contacts identified in scoping interviews who held deep expertise across diverse sectors and geographies (Gentles et al. 2015; Sharma 2017). These experts referred us to other individuals or organizations, and we felt confident that this snowball strategy returned a strong cross-section of fishery system representatives and interests when recommendations converged on previous interviewees. The interviewee sample included representatives from eight large quota-owning fishing and/or processing firms or associations, three small boat or processing firms or associations, three value-add or marketing firms, two aquaculture firms, and one tourism company. Six interviewees were natural scientists, three were economists, and two were in social sciences or humanities. Three interviewees represented rural development agencies, two represented government fisheries management agencies, and two were in current or former government positions. The interview sample included two women, two foreign nationals residing in Iceland, and two active fishermen (non quota-holding). Note that categories are not exclusive. In addition to diverse sectors and perspectives we sought a broad geographic distribution of interviewees, with ten institutions or firms from the greater Reykjavik area, three from the south and Westman Islands, four from the Eastfjords, four from the north and Akureyri, and four from the Westfjords represented in the interview sample.

The interviewer first asked interviewees about their expectations of future climate impacts, and then shared projections of ocean temperature and fish habitat redistribution by mid-century to prompt discussion of potential impacts on the fishery system (Mason et al. 2021b). The interviewer then asked about enabling conditions and barriers to adaptation to elicit what resilience attributes might be present or lacking, in interviewees' own words. When interviewees identified specific enabling conditions (or barriers), the interviewer probed further on how those conditions came about and how they enable (or prevent) adaptation, thus eliciting linkages to other attributes or characteristics of Iceland's system. For example, an enabling condition might be that large vessels can travel to follow shifting fish distributions, and a linkage is that financial capital facilitates access to large vessels. While initial questions focused on climate-driven stock shifts, the interviewer also invited interviewees' insights into other climate or non-climate risks. Finally, interviewees were asked what they thought should change in the fisheries system to promote adaptation to climate change, further elucidating feedbacks among or gaps in resilience attributes. Questions were adapted to each interviewee's expertise but aimed for a system-level understanding of ecological, social, economic, and governance factors that enable or constrain climate resilience. The interview instrument, approved by Cornell University's Institutional Review Board (protocol # 1101001927) is available in Appendix S1.

Identification of attributes, linkages, and traps

The first author iteratively reviewed the interview transcripts to identify themes of resilience attributes and linkages. We then matched these emergent themes with applicable terminology from Mason et al.'s (2021a) set of resilience attributes across ecological, social, and governance dimensions of fishery systems. We categorized the attributes to reduce complexity, using broader domains from Cinner and Barnes's (2019) social-ecological resilience framework: assets, flexibility, organization, learning, socio-cognitive constructs, and agency. To continue the above example, when several interviewees highlighted fleets' ability to follow shifting fish stocks (e.g., "*the trawlers, they go everywhere…*"; "*the fleets are incredibly mobile…*"; "*Iceland is not really big, so…people [can] fish anywhere*"), we coded this emergent theme as the "fisher mobility" attribute from Mason et al. (2021a) and categorized it within the "flexibility" domain.

We then mapped out linkages and feedbacks among these attributes based both on interviewees' insights and additional research in the published literature, which we used to better understand and contextualize interviewees' comments and emergent themes (*c.f.* Johnson et al. 2014). Where literature provided additional support for interview insights, we provide citations alongside interview quotes or paraphrases. Although we did not initially set out to identify traps in Iceland's system, bidirectional feedbacks and reinforcing loops emerged strongly from interviewees' perceptions of barriers to adaptation or what needs to change in the fisheries system. Interviewees often referenced how the strengths and enabling conditions they had just discussed might also prevent change in the system. We thus characterized potential traps from interviewees' collective discussion of these dynamics and potential solutions from interviewees' suggested interventions, but did not explicitly discuss the concept of traps during the interviews.

RESULTS

Resilience attributes in Iceland's fisheries system

Although interviewees discussed potential climate impacts ranging from storms that threaten fisher safety to catastrophic slowing of ocean currents that would render Iceland uninhabitable, they expressed confidence about the fishing industry's resilience. Species shift projections were met with nonchalance: as one interviewee put it, *"I'm not particularly worried about this."* Interviewees' descriptions of enabling conditions for adaptation revealed multiple strongly interacting resilience attributes. Four overarching themes of interactions among attributes emerged across multiple interviews; we highlight these below (Fig. 1). In addition to resilience attributes, we identified three themes of "external drivers" that are broader than the fisheries system and seemed to underlie the formation of other resilience attributes. Interviewees often identified these drivers at the end of a string of probing questions (e.g., "What do you think makes the industry so flexible?" "What gives them the confidence to take those risks?"). These were (1) Iceland's high societal development context, (2) its history of a variable environment, and (3) profit seeking incentives under market competition. See Table S1 for a full list of emergent resilience attribute themes and representative quotes from the interviews and Figure S1 for comprehensive linkages among resilience attributes described in interviews.

Theme 1: Responsive and flexible management allows rapid adjustments to changing environmental conditions and species distributions

Iceland's ITQ system facilitates flexibility, directly through regulatory measures, and indirectly through unrestricted mobility (Fig. 1a). Interviewees pointed to quota transferability and catch-balancing mechanisms as facilitating

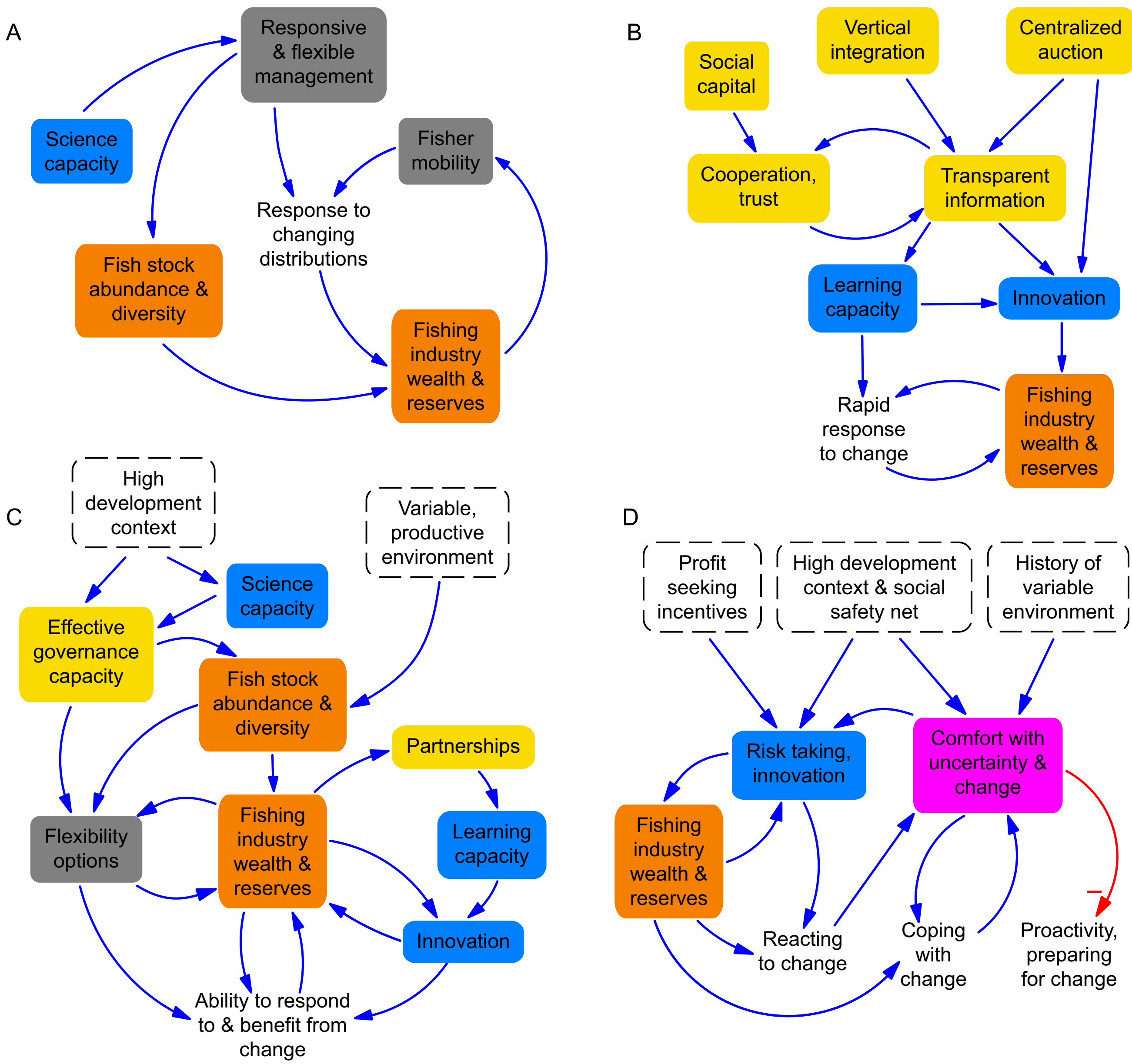

Fig. 1 Interviews revealed four themes of strong and reinforcing interactions among attributes that contribute to resilience: **A** Responsive and flexible management allows rapid adjustments to shifts in species abundance and distribution due to environmental change. **B** Centralized and connected institutional organization creates transparency and access to knowledge, facilitating learning capacity, innovation, and thus responsiveness. **C** Ample assets including abundant stocks and fishing industry wealth provide buffers and enhance flexibility and innovation in multiple reinforcing feedback loops. **D** Cultural comfort with uncertainty and change drives responsiveness but hinders proactivity. Box colors represent resilience domains from Cinner and Barnes (2019): flexibility (gray), organization (yellow), learning (blue), assets (orange) and socio-cognitive constructs (pink). Text boxes with dotted lines represent the three "external drivers" identified in interviews. Red line indicates a negative relationship

responses to fluctuations in catch or distributional changes: "*All the haddock quota and all the cod quota is tradable so the quotas simply follow the resources.*" Because fishing effort, time, and location for quota holders are largely unrestricted, fisher mobility is limited only by costs and vessel capacity. Interviewees were thus confident about larger trawlers' ability to track shifting stocks, but acknowledged that smaller boats would be less mobile.

Additionally, while environmental data are not directly factored into stock assessments, fisheries management is responsive to environmental change via annual catch limit adjustments and dynamic closures that MFRI can immediately implement to protect spawning areas for juvenile fish (Knutsson et al. 2011). High-scientific capacity and data accessibility are key enabling factors in this responsiveness (Fig. 1a). Interviewees highlighted a mechanism to incorporate new species into the quota system based on 3–6 years of catch history, which allows management to adjust to emerging fisheries and incentivizes fishers to experiment and take risks because it represents the lowest-cost opportunity to obtain quota. While this incentive structure could risk overexploitation, regular monitoring puts the management system *"in a good position to be dynamic,"* as an interviewee described, where establishing quota management within a few years would likely stabilize catch. *"We react to [the] issues that climate change might be causing…We're in good shape."*

Theme 2: Centralized and connected institutional organization promotes learning and responsiveness

Iceland's centralized and connected fisheries institutions create stability and transparency: with annual catch limits, real-time data sharing, and centralized auctions, fishers know exactly how much product will be in Iceland's market each year and what other firms are catching. This promotes rapid learning, decision making, and response to change (Fig. 1b). Vertical integration, centralized auctions, and shared databases increase transparency and reduce transaction costs throughout the value chain, enabling firms to quickly recognize and react to market signals or disturbances. For example, interviewees emphasized how quickly Iceland's fishing firms responded to labor strikes, changing trade policies, and the COVID-19 pandemic by pivoting to alternate markets or products. An interviewee explained how connected and transparent organizational structures also promote innovation: new processing companies have used the centralized auctions and "seamless" transport and logistical infrastructure to aggregate and specialize in underutilized species, whereas previously fishers had to discard uncommon species because they had no market.

This connectivity may both stem from and reinforce broader cohesion and trust, or social capital, in Iceland's society (Fig. 1b). The seafood industry recognizes that "Iceland is the brand," where the reputational risks of any one company selling poor-quality or unsustainable fish would affect everyone. Interviewees explained how these social and economic incentives, along with tight social bonds in Iceland's society, create collaboration and openness in the fishing industry that enables knowledge transfer and resource sharing, further facilitated through "innovation clusters" (see Sigfusson 2020). However, some interviewees expressed concern that these tight bonds create insularity, leading to potential missed opportunities for more transformative innovation, for example in alternative fishing gears, marketing, or emerging seafood sectors like aquaculture. Accordingly, interviewees brought up a need for more diverse knowledge sources and viewpoints in the industry: *"You have a very similar type of person running most of these companies…this industry needs to open up to not only women but people from everywhere, with different opinions."*

Theme 3: Abundant assets provide buffers and enhance flexibility

Access to abundant assets underpins and enhances other resilience attributes (Fig. 1c). Capacities for effective governance and scientific research and monitoring—along with Iceland's naturally productive and variable waters—support abundant and diverse fish stocks that buffer against fluctuations in environmental conditions and fishing pressure. The fishing industry's financial wealth and reserves expand the flexibility options that firms can exercise: buying higher-capacity trawlers that can travel further, purchasing more quota to diversify their portfolio, or relying on cash reserves and loans to weather years of poor catch. For some firms we interviewed, portfolio diversification emerged more as a by-product of wealth than a deliberate resilience strategy: up against quota caps for their target species but with excess funds to invest, they purchased quota for additional species. Larger firms also have more time and resources to invest in partnerships with entrepreneurs or universities that can lead to innovation.

Theme 4: Cultural comfort with uncertainty and change drives responsiveness

Interviewees emphasized positive attitudes toward uncertainty and change in Iceland, collectively describing how broad historical and societal forces including profit seeking incentives, Iceland's social safety net, and past experience with variable environmental conditions have already shaped adaptive and innovative mindsets (Fig. 1d). Several interviewees praised the lack of government subsidies in the system, where *"no one is going to help the Icelandic fisheries if they don't help themselves."* Market competition in a dynamic environment thus drives out less innovative firms, while those able to adapt have persisted, growing even more confident in their ability to respond to change. One interviewee explained that capitalizing on new species or taking risks simply makes good business sense, recognizing that access to assets reinforces this behavior: *"The fishing companies have an extremely strong financial backbone…they're very used to taking risks and they're very keen on taking risks to get some kind of edge."* Beyond assets, several interviewees invoked broader cultural norms around optimism, opportunism, and reacting in the moment instead of planning in advance. Many referenced Iceland's "unofficial national motto" *þetta reddast* (loosely, "things will be fine"), which interviewees and scholars attribute to Iceland's harsh environment and history of uncontrollable disasters such as volcanoes and famines (see Eyjolfsdottir and Smith 1996; Minelgaite et al. 2018). *"In Iceland, we are a group of survivors…we are always adapting to new things, somehow,"* said one interviewee, while acknowledging that this mentality favors short-term coping and reactivity over proactivity.

Synthesis: Reinforcing feedbacks stabilize the system but could contribute to rigidity traps

The interactions among the above-described resilience attributes demonstrate how Iceland's fisheries system powerfully aligns ecological and economic goals with reinforcing feedbacks. Effective management has promoted fish stock recovery, which has increased wealth and profits; these outcomes have fostered trust among industry, managers, and scientists, which in turn allows for more precautionary and effective management. These along with other reinforcing interactions among resilience attributes outlined above have enabled the fishery system to respond to and benefit from past environmental change.

Despite these resilience benefits, interviewees' perceptions of barriers to adaptation and needed changes revealed how these reinforcing feedbacks may—perversely—reduce the system's ability to recognize and respond to novel change. This is in part because, as interviewees described, there are resource and motivational barriers to altering any system that is currently satisfactory: *"The problem is, if you're sitting on a system that sort of works and you expect the system to keep working, you're not making any plans for the time when the system stops working. I think that's the catch-22 that we're in right now."* Additionally, and more powerfully, those that benefit from the system may have a vested interest in maintaining the status quo (Freudenburg 2005). Managers are incentivized to maintain the system because it achieves ecological goals; so too is the fishing industry because it brings them wealth, status, and power. Interviewees pointed out that the larger firms have a well-developed capacity to act in their own interests: *"The ones owning the quota, they are very satisfied in their position. And they have a lot of power and a lot of people to work for them. So, it's going to be hard to change that."*

In short, despite the resilience successes described above, Iceland's fishery system exhibits some of the hallmarks of a potential rigidity trap: high connectedness, high homogeneity, extreme effectiveness at focusing on one goal or approach but lower capacity to explore alternatives (Carpenter and Brock 2008). The very factors that make the system work well in its current state—these reinforcing feedbacks to align economic and ecological goals—might

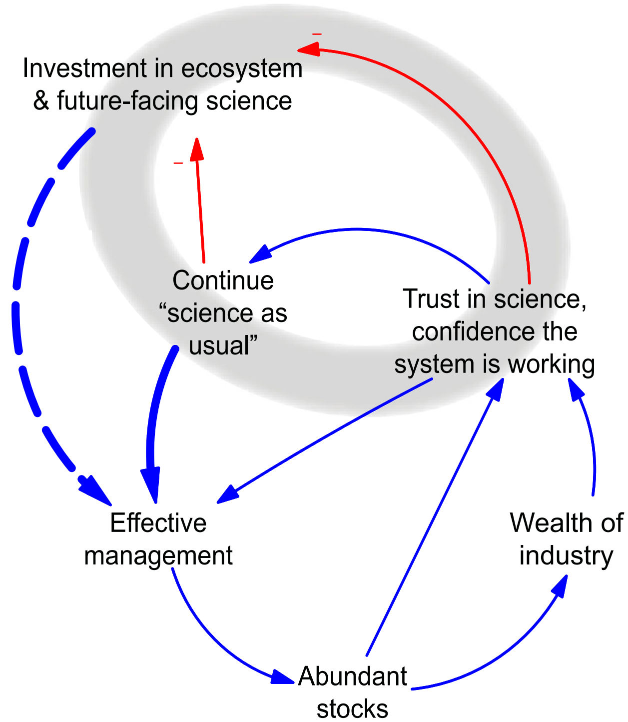

Fig. 2 A potential rigidity trap where underinvestment in ecosystem and climate science could leave Iceland unprepared for more extreme environmental change. Indicators of success in the management system—abundant stocks and a wealthy industry—foster trust and confidence among fishers, scientists, and managers that the management system is working. This creates reinforcing incentives for "science as usual" focused on stock assessments for management of commercial species, while undercutting investment in integrative or future-facing science needed to prepare for climate change. Currently, stock-assessment science appears sufficient to support effective management (bold solid arrow), but future potential ecological and environmental change will likely increase the relative importance of broader science (dashed arrow). Thus, without more investment in broader science, climate change could contribute to breaking the virtuous cycle of effective management, healthy stocks, industry wealth, and trust in the management system. Blue arrows indicate positive relationships, red arrows indicate negative relationships, and the gray circle indicates the trap

also make it vulnerable to novel or extreme change. In discussing risks or barriers to change, interviewees collectively outlined two potential traps: 1) failure to study or prepare for more drastic ecological change beyond species redistribution (Fig. 2), and 2) unresponsiveness to social concerns leading to growing political backlash (Fig. 3). See Appendix S2 for an expanded description of the broader context and historical antecedents of these traps, following Boonstra and de Boer (2014).

Trap 1: Scientific blind spots could leave Iceland unprepared for dramatic ecological change

Even as interviewees downplayed climate risks to fisheries, they expressed concern about constraints in the

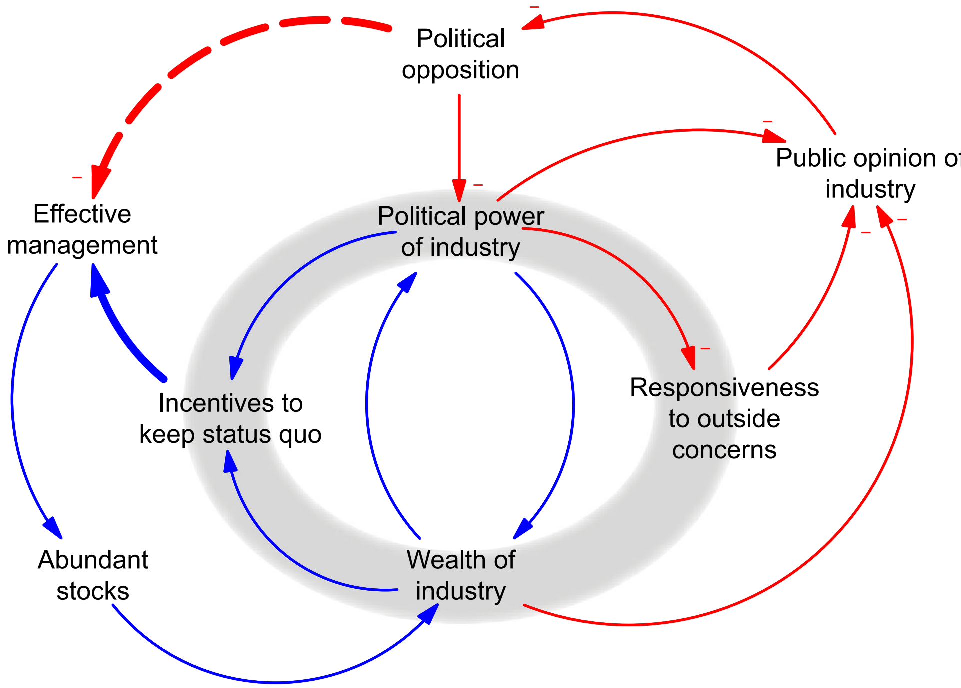

Fig. 3 A potential rigidity trap where lack of responsiveness to social equity and outside concerns may make the fishing system vulnerable to political backlash. The management system effectively aligns ecological and economic incentives such that the system is self-reinforcing. The industry has strong incentives to keep the status quo, supporting effective management (bold solid arrow). However, it has limited incentives to respond to social equity concerns or outside voices such as non-quota holders. This contributes to longstanding debate and dispute over the social impacts of the fishery management system, which has spawned political movements to overturn or modify the system. Currently, these political parties have limited power (dashed arrow), but concerted public mobilization against the management system could erode effective ecological protections and thus the reinforcing feedbacks of healthy stocks and wealthy industry. Blue arrows indicate positive relationships, red arrows indicate negative relationships, and the gray circle indicates the trap

scientific system that could hinder understanding and anticipating broader environmental change. Perceived success of the management system incentivizes a narrow focus on commercial stock assessments and maintaining constant survey methods that managers and the industry are familiar with and trust (Fig. 2). But these methods may not support effective management under changing conditions if fixed surveys do not sufficiently track shifting fish stocks or assumptions about the relationship between the environment and stock status no longer hold. For example, interviewees pointed to a northward shift in haddock (*Melanogrammus aeglefinus*) distribution during the recent warm anomaly that MFRI initially interpreted as decreased stock, therefore, advising lower catch values.

Interviewees were further concerned about neglect of broader climate impacts on the marine ecosystem, including predator–prey dynamics, invasive species, ocean acidification, diseases, and parasites. Even though some of these impacts are already apparent in Iceland's waters, interviewees described "ridiculous" challenges in funding broader climate and ecosystem work relative to commercial stock assessments. Although MFRI hosts a vibrant international community engaged in such research, interviewees lamented that foreign scientists cannot communicate with policymakers and fishermen in their native language, while Icelandic universities have seen declining enrollment in natural science programs. Thus, reinforcing dynamics encourage "science as usual" at the expense of broader, more future-facing science, a potential rigidity trap that has optimized scientific advice under conditions within historical variability, but under extreme ecological change could undermine the feedbacks support effective management (Fig. 2). Interviewees, particularly scientists, recommended more government funding of ecosystem and climate science to monitor changes in species beyond commercial stocks, as well as more sophisticated downscaled climate models to help the fisheries system predict and prepare for future change.

Trap 2: Lack of responsiveness to social equity and outside concerns may generate political backlash

Another risk is one of social backlash leading to political challenges to the ITQ system. The reinforcing ecological and economic successes of the management system have made the fishing industry wealthy and politically powerful, such that there are few incentives to respond to marginalized voices (Fig. 3). Interviewees described how the "endless debate in Iceland" over social impacts of the ITQ system has shifted as the system has matured: Initial critiques came from rural fishing-dependent communities that lost access to fishing and employment when wealthy firms consolidated quota in urban centers. Today, consolidation has slowed and large firms maintain some facilities in remote towns, both for social license and to gain access to multiple ports. These remaining communities largely approve of the industry, which provides jobs and social services. Thus, the industry's critics now come more from the larger urban populace that has never been involved in fishing, and the critiques accordingly focus less on direct impacts of consolidation and more on abstract principles of wealth accumulation in a relatively egalitarian society, how fisheries revenue should be taxed and distributed, and the ethics of private enrichment from a common pool resource.

The reinforcing wealth and political power accumulating to the fishing industry are therefore a target of broad social and political ire. *"If the impression in the population becomes that the quota moguls own everything and you're at their mercy, people will turn on them,"* explained an interviewee. Indeed, two parliamentary parties with fisheries reform platforms have seen growing popularity: a breakaway party from the previously dominant Conservatives proposing time limits on quota ownership and restoring a competitive derby-style fishery, and the quasi-anarchist Pirate Party with an insouciant call to abolish privatization altogether. While not an immediate threat to fisheries management—the Conservative breakaway party gained one seat in the September 2021 parliamentary elections, now representing 8% of the parliamentary vote, while the Pirate Party's vote share remained constant at 10%—these calls may be a bellwether of significant future challenges. *"Is it going to happen in this election? I don't think so. But might it happen in the future? Absolutely,"* said an interviewee. *"And I think the overall economic benefits of the system are so great that anything that jeopardizes it is a bad thing."*

Much like the uncertainties posed by climate change, this political risk represents a potential tipping point. Because the overwhelming majority of the fishing industry is governed under ITQ management, a significant alteration could destabilize the entire fishery system. The reinforcing stability of the current system, particularly the incentives of within-system actors to maintain status quo, reduces its ability to respond to and diffuse social resentment (Fig. 3). Meanwhile, Icelanders have grown less connected to the fishing industry that employs fewer people with consolidation and increasing automation, and the political landscape has grown more fragmented (see Appendix S2 and Eythorsson 2000 for a description of the particular historical and political dynamics that enabled the initial implementation of the ITQ system). An interviewee explained how, if political alterations undo ecological protections and erode trust among industry and management, it would be near-impossible to restore the system and re-align long term sustainability and economic goals: *"If you ruin the system, how are you going to start again? With the parliament as fractured as it is now, the one who comes with the greatest goods for the electorate in the short term will win."*

To ameliorate social backlash, interviewees recommended investment in public relations to communicate the how the fishing industry currently provides societal benefits via Iceland's steep taxes and a fishing fee levied since 2004. Others recommended increasing those fees or directing the revenue toward specific public programs. However, they acknowledged the irony that this could further disadvantage remote communities by redirecting the fishing revenue that supplies their wages and social services to general government funds that largely benefit Reykjavik. Some companies are moving toward public listing on the Icelandic stock market, which could increase—albeit modestly—public ownership of Iceland's fish resources.

Additional interventions to avoid or escape traps

Two additional interventions emerged from the interviews that, while not specific to either of the above traps, could nurture general capacities for renewal and novelty. One was to support smaller boats and processors. *"It's quite important that [the small sector] remains because it adds to value creation, innovation, and resilience because it means there are more marketing chains available,"* explained an interviewee. Although interviewees generally discussed wealth as an enabling condition for innovation, several added nuance that larger companies' innovation tends to be incremental, whereas smaller companies must experiment with bold and different models to compete. These smaller firms may fail, but are more likely than large companies to generate novelty and diversity needed to respond to diverse stressors. One interviewee commented that smaller companies flourished in the wake of COVID-19-related supply chain disruptions, finding alternate marketing chains to sell fresh fish directly to consumers in Europe. In responding to climate change, smaller boats may be less mobile but could catch small amounts of emerging inshore species; smaller processors could specialize in new species or more readily pivot their business models and supply chains. Currently, regulations stipulating that quota can be transferred from large to small boats but not vice versa secures the small boat sector, but smaller processors lack these protections: *"I'm afraid, maybe…the small companies will be left behind in a changing period,"* cautioned one interviewee.

The second set of interventions emphasize investment in innovation, both within the fishing industry and for communities to transition away from fishing. Interviewees emphasized the agency of individual pioneers to instigate business ideas that transform their towns, and a culture that embraces rather than stigmatizes failure: *"People love to try things, trial and error, trial and fail. [This is] completely Icelandic. 'Oh, it didn't work, okay, I'll try something different.'"* While local and national governments agencies currently support this entrepreneurial spirit with small innovation grants, interviewees called for longer-term funds to encourage more transformative ideas, not just "market-ready" projects. Another emerging model is partnerships between seafood firms and nearby universities, where the industry hosts and funds graduate student research. An interviewee described "totally open" initiatives, from developing a seaweed kombucha product to piloting social programs to make immigrant fish processing families feel more welcome. These partnerships provide low-risk experimentation opportunities, diversify knowledge sources, and cultivate the next generation of fishing industry workforce.

DISCUSSION

Collectively, interviewees depicted strong and reinforcing resilience attributes that help maintain sustainable stocks and profits in Iceland's fisheries. Interviewees across a wide spectrum of interests were confident that those attributes—most prominently, flexible, science-based management; centralized and connected networks that promote information exchange; access to natural and material assets; and innovative mindsets—will be effective for near-term climate disruptions such as species range shifts or the introduction of new commercial species. Tracing interactions among attributes revealed that flexible management and resilient mindsets more directly confer climate resilience (Fig. 1a, 1d), while the organizational attributes that create high connectivity confer resilience indirectly via linkages to attributes related to learning and assets (Fig. 1b). Wealth in the fishing industry enabled many other attributes across multiple domains and thus plays a key role in feedback loops (Fig. 1c). Overall, the linkages and feedbacks among attributes emerged as critical to resilience outcomes, both by aligning ecological and economic incentives to stabilize the system and by potentially creating rigidity traps. Interviewees demonstrated how reinforcing resilience attributes have served the fisheries system (or at least those empowered by it) well thus far, but promote reactivity over proactivity. This reinforces the system's existing trajectory and benefits empowered within-system actors (large boats, wealthy consolidated firms, quota holders) at the expense of less empowered actors (smaller boats, smaller firms, aspiring fishery entrants, other outside perspectives) who may represent critical sources of novelty and diversity in the system. These are the very dynamics that could lead the system into rigidity traps.

While some resilience dynamics identified here may be closely tied to Iceland's unique context, a few are directly actionable and could provide models for other fishery systems. Flexible regulatory mechanisms such as catch-quota balancing and regular incorporation of new species into the quota system—when paired with rigorous monitoring to maintain ecological outcomes—could be applied in other rights-based systems to help fishers adjust to fluctuations in species abundance and distribution. Resilience interventions related to learning and knowledge sharing, such as expanding data access or promoting knowledge clusters, could be widely applicable, including in lower-capacity and small-scale fishery settings. Studies of adaptive strategies in small-scale fisheries also emphasize learning, and indeed highlight parallel dynamics to what we observe in Iceland, where close social ties and a shared sense of importance of the fishery promote knowledge exchange and cooperation (e.g., Galappaththi et al. 2021; Gianelli et al. 2021). Therefore, these may represent key resilience pathways across multiple fishery contexts that merit further exploration.

Learning attributes likely represent a key focal area for Iceland to prepare for climate change and avoid traps. Actors within Iceland's system clearly have high learning capacity, but the risk of traps arises when learning and innovation focus on reactivity rather than proactivity, optimizing outcomes for within-system scenarios and actors without attention to deeper underlying issues. Interviewees' calls for future-facing science and expanding monitoring beyond commercial stocks are consistent with broader recommendations for climate-resilient fisheries management, which additionally emphasize the need for structured decision-making frameworks to ensure such information is incorporated into management (Bryndum-Buchholz et al. 2021; Kleisner et al. 2021). A lack of climate studies and climate-informed stock assessments is unfortunately a common challenge even among high-capacity fishery systems and represents a critical priority for quota-managed fisheries worldwide (Tokunaga et al. 2023). Iceland could be poised to lead in this respect given its strong scientific capacity and unusual economic reliance on fisheries.

Interviewees' concerns about insularity in knowledge sources underscore the importance not just of what is learned but also whose knowledge and perspectives are heard. These concerns were couched in terms of missed opportunities for economic gain in the industry, but insularity likely also contributes to broader issues of entrenched inequality and unresponsiveness to societal concerns. There are already efforts underway to pair industry innovation clusters with international sister clusters, which could help expand knowledge exchange (Sigfusson 2020). Dedicated efforts to enhance diversity and equity in these knowledge sharing initiatives as well as to engage more of Iceland's society may be needed to address social equity concerns and alleviate the "endless" fisheries debate. Participatory exercises such as scenario planning or future visioning (e.g., NAMA 2005; Enfors-Kautsky et al. 2018; Merrie et al. 2018) could engage diverse knowledge sources to identify additional resilience strengths and potential traps, and leverage the fisheries system's strong social ties and learning capacity to guide its trajectory toward more equitable and broad shared aspirations.

We acknowledge that despite our efforts to engage a broad spectrum of interests, our own limited interview sample may reinforce insularity of knowledge sources. Given the close ties in Iceland's system, where interviewees freely pointed us to contacts with different viewpoints, we believe that our picture of interviewees' perceptions of resilience is reasonably representative. However, a more comprehensive social-ecological mapping process could identify additional linkages and contextual factors that may mediate the resilience outcomes and formation of traps proposed here (Elsler et al. 2021). Additionally, a systematic analysis of how perceptions of resilience in the fisheries system differs among actors, particularly underrepresented groups, was beyond the scope of our study but could be an informative future effort to diagnose sources of critiques and develop interventions to avoid a potential social/political trap. The scope and timing of our interviews may also have influenced the emphasis on traps: political concerns may have been magnified because we conducted our interviews in the lead-up to the September 2021 elections, and our framing around specific projections of species distribution shifts may have influenced interviewees to focus on shorter-term reactions. However, the responses we heard were consistent with other studies of climate change perceptions among Iceland's fishing industry and society showing confidence based on past reactions to environmental variability and de-prioritization of climate risks relative to day-to-day operational concerns (Seibert et al. 2018; Saviolidis et al. 2020).

As researchers and practitioners navigate climate resilience in other fishery systems, additional comparative studies of how feedback loops emerge among resilience attributes could elucidate if certain attributes consistently seed loops, such that bolstering a few would organically promote others, and if these loops consistently result in traps. Further comparative cases could also reveal patterns of how attributes contribute to adaptive versus transformative capacities (Cinner and Barnes 2019). The emergence of the potential rigidity traps discussed here provides further illustration of trade-offs between general versus specific resilience, and specific resilience versus general well-being, discussed in Chaigneau et al. (2021). With a narrow focus on the fishery system and stock distribution projections, we could conclude that the system is highly resilient. But a broader view of the stressors the system might face revealed that the dynamics contributing to climate resilience for actors currently benefitting from the system also reinforce economic inequality and power imbalances that may be at odds with wider societal aspirations. As such, political interventions to build resilience based on this narrow focus could inadvertently erode general resilience and well-being. Interdisciplinary approaches that can reveal such feedbacks are needed, both to make these trade-offs explicit to decisionmakers, and to identify where they could promote synergies for resilience (Chaigneau et al. 2021).

CONCLUSION

This study provides an empirical exploration of how resilience attributes operate and interact in a high-capacity fisheries system. Expert interviews indicated strong interactions and feedbacks among these attributes that confer resilience to certain stressors (e.g., climate variability), but may form rigidity traps that that undermine its resilience to other stressors (e.g., political backlash). They also revealed tensions in defining resilience for whom and for what. This suggests there could be value in broadening the kinds of forward-looking conversations conducted here—both to acknowledge resilience trade-offs and to find opportunities to leverage Iceland's capacity for innovation to guide the fishery system toward more equitable, inclusive, and adaptive pathways.

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Declarations

Conflict of interest The authors declare no conflicts of interest.

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