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Abigail J. Lynch

Frank J. Rahel

Doug Limpinsel

Suresh A. Sethi

Augustin C. Engman

See next page for additional authors

Authors

Abigail J. Lynch, Frank J. Rahel, Doug Limpinsel, Suresh A. Sethi, Augustin C. Engman, David J. Lawrence, Katherine E. Mills, Wendy Morrison, Jay Jay Peterson, and Mark T. Porath

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Ecological and social strategies for managing fisheries using the Resist-Accept-Direct (RAD) framework

Abigail J. Lynch[1] | Frank J. Rahel[2] | Doug Limpinsel[3] | Suresh A. Sethi[4] | Augustin C. Engman[5] | David J. Lawrence[6] | Katherine E. Mills[7] | Wendy Morrison[8] | Jay O. Peterson[9] | Mark T. Porath[10]

[1]U.S. Geological Survey, National Climate Adaptation Science Center, Reston, Virginia, USA

[2]Department of Zoology and Physiology, Program in Ecology and Evolution, University of Wyoming, Laramie, Wyoming, USA

[3]Habitat Conservation Division, NOAA Fisheries, Anchorage, Alaska, USA

[4]U.S. Geological Survey, New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources and the Environment, Cornell University, Ithaca, New York, USA

[5]Department of Forestry, Wildlife and Fisheries, University of Tennessee, Knoxville, Tennessee, USA

[6]National Park Service, Climate Change Response Program, Fort Collins, Colorado, USA

[7]Gulf of Maine Research Institute, Portland, Maine, USA

[8]Office of Sustainable Fisheries, NOAA Fisheries, Silver Spring, Maryland, USA

[9]Office of Science and Technology, NOAA Fisheries, Silver Spring, Maryland, USA

[10]U.S. Fish & Wildlife Service, Mountain Prairie Region Ecological Services Nebraska Field Office, Wood River, Nebraska, USA

Correspondence

Abigail J. Lynch, U.S. Geological Survey, National Climate Adaptation Science Center, Reston, VA, USA.
Email: ajlynch@usgs.gov

Abstract

Fisheries management is a complex task made even more challenging by rapid and unprecedented socioecological transformations associated with climate change. The Resist-Accept-Direct (RAD) framework can be a useful tool to support fisheries management in facing the high uncertainty and variability associated with aquatic ecosystem transformations. Here, RAD strategies are presented to address ecological goals for aquatic ecosystems and social goals for fisheries. These strategies are mapped on a controllability matrix which explores the ability to guide a system's behaviour towards a desired state based on ecological responsiveness and societal receptivity to change. Understanding and improving the controllability of aquatic systems and fisheries can help managers to maintain the broadest suite of available RAD management strategies.

KEYWORDS

climate adaptation, climate change, fisheries ecosystem transformation, natural resource management, socioecological systems

Abigail J. Lynch and Frank J. Rahel are joint lead authors.

1 | RAPIDLY TRANSFORMING AQUATIC ECOSYSTEMS

Freshwater and marine ecosystems are transforming at unprecedented rates under the influence of climate change (Arimitsu et al., 2021; Halpern et al., 2019; Hollowed et al., 2013; Weiskopf et al., 2020) and other anthropogenic stressors (Best, 2019; Halpern et al., 2008; Reid et al., 2019). Aquatic systems can transform via many mechanisms, but climate change often exacerbates the impacts of other stressors. When these factors interact, aquatic systems can respond in a nonlinear fashion through feedback loops, synergies, threshold effects, and time lag responses, often with uncertain and unpredictable outcomes (Liu et al., 2007; Staudinger et al., 2021). So-called "regime shifts," have been documented in both marine and freshwater systems. For example, Arctic lakes have undergone widespread species changeover and ecological reorganisations as a result of warming temperatures (Smol et al., 2005). The North Pacific and North Atlantic oceans have similarly experienced multiple warm phases that increase sea-surface temperatures and alter trophic productivity, resulting in shifts in the abundance and recruitment of forage and ground fish populations (Laurel et al., 2021; Litzow et al., 2020; Nielsen et al., 2021; Pershing et al., 2015, 2021).

These rapid changes impact the services that aquatic ecosystems provide, including provisioning services (e.g. food production, water supplies, livelihoods), regulating / maintenance services (e.g. climate regulation) and cultural services (e.g. support for cultural and spiritual beliefs, recreation) (Lipton et al., 2018; Maes et al., 2014). Although we acknowledge that fish have other important ecosystem roles (e.g. Lynch et al., 2021a), here, our focus is on fisheries, which we consider to be socioecological systems that encompass targeted fish populations, the ecosystem that supports those fish populations, the stakeholders involved in the system (including fishers, regulators, and other stakeholders), and the sociopolitical processes governing stakeholders.

There are diverse examples across biomes of fisheries being transformed by climate change (Figure 1). In the Gulf of Alaska, shifts in climate coupled with fisheries exploitation have been linked to the transformation of a system formerly dominated by shrimp, Pacific herring *Clupea pallasii* Valenciennes, and capelin *Mallotus villosus* (Müller) to one dominated by groundfish species (Anderson & Piatt, 1999; Litzow et al., 2006, 2014). More recently, changing climate patterns have diminished oceanic mixing which has led to persistent, unprecedented heatwaves in the Gulf of Alaska, dramatically altered trophic dynamics, declines in Pacific cod *Gadus macrocephalus* Tilesius stocks, and subsequent reductions in harvest levels (Barbeaux et al., 2020). Likewise, in the Gulf of Maine, both climate impacts and fishing pressure have been linked to declines in Atlantic cod *G. morhua* Linnaeus and rapid increase in American lobster *Homarus americanus* H. Milne Edwards populations (Goode et al., 2019; Le Bris, 2018; Pershing et al., 2015, 2021). And, in Caribbean freshwaters, extreme drought induced by climate change has been associated with a species invasion to an urban stream ecosystem from a reservoir source population; this invasion shifted the assemblage composition from indigenous to non-indigenous species dominance and had negative consequences for an indigenous fish population with recreational fishing value (Ramírez et al., 2018). Such transformations can lead to reduced harvest and eventual fishery closures, impacting fishing revenues and necessitating adaptations by fishers (Szymkowiak, 2020).

Fisheries management is profoundly complicated by these rapid and substantial socioecological system changes (Voss et al., 2014). Traditional management approaches may no longer be effective in maintaining once-desired outcomes. System controllability (i.e. the ability to guide a system's behaviour towards a desired state through the manipulation of ecological and social variables) constrains the set of available management options. Given the above issues, the Resist-Accept-Direct (RAD) framework can be a useful tool to support fisheries management in the face of great uncertainty and variability associated with aquatic ecosystem transformation. As a holistic framework encompassing both ecological and social processes that combine to govern fishery dynamics, the RAD approach to managing transformative system change is useful for implementing ecosystem approaches to fisheries management (sensu Hilborn, 2004; Link, 2002; Pikitch et al., 2004). The objectives of this article are to: (1) introduce the RAD framework in the context of both ecological and social processes that define marine and freshwater fisheries, (2) share examples of existing RAD strategies for transforming fisheries, and (3) provide insights into how system controllability affects the feasibility of RAD management options for marine and freshwater fisheries.

2 | RAD STRATEGIES FOR FISHERIES

The RAD framework (Aplet & Cole, 2010; Lynch et al., 2021b; Schuurman et al., 2022; Thompson et al., 2021) provides fisheries managers with three overarching management pathways to address transforming aquatic ecosystems:

- *Resist* the trajectory of change, working to maintain the current or to return to historical ecosystem configuration (i.e. its composition, structure, or function) and ecosystem services;
- *Accept* the trajectory, allowing the ecosystem to change autonomously; or,
- *Direct* the trajectory by actively shaping the change in the ecosystem towards a preferred new configuration and ecosystem service flows.

The RAD framework is particularly useful in framing management responses to ecosystem transformations because it encompasses the entire decision space available to a manager. Temporal scales (e.g. the speed of system change, decision timelines), spatial scales (i.e. small compared to larger ecosystems), and the magnitude of anticipated change factor into RAD strategy selection (Magness et al., 2022b; Thompson et al., 2021). Ecological, societal, and

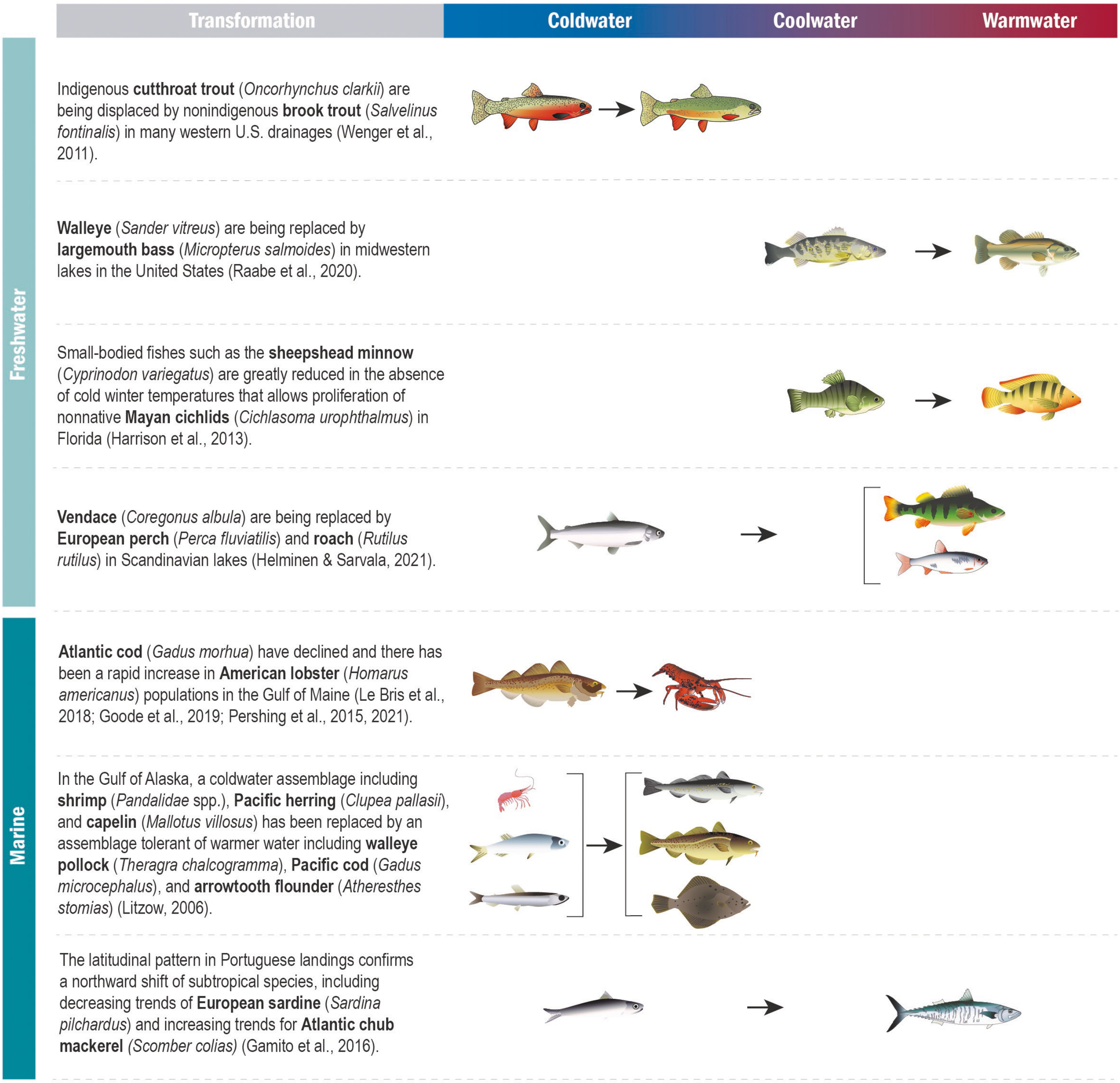

FIGURE 1 Examples of fisheries transformations associated with climate change, especially warming temperatures. Symbols courtesy of and modified from the Integration and Application Network, University of Maryland Center for Environmental Science (Gamito et al., 2016; Goode et al., 2019; Harrison et al., 2013; Helminen & Sarvala, 2021; Le Bris et al., 2018; Litzow, 2006; Pershing et al., 2015, 2021; Raabe et al., 2020; Wenger et al., 2011)

financial factors also contribute to the feasibility of success for RAD strategies (Lynch et al., 2021b). Familiar adaptive management processes can be modified to fit within and help operationalize the RAD management framework (Lynch et al., 2022) if plausible socioecological trajectories are identified (Magness et al., 2022a) and the internal and external factors that shape RAD decisions are acknowledged (Clifford et al., 2022). For freshwater and marine fisheries transformations induced by climate change, management actions involving stocking, harvest regulations, habitat improvements, and community manipulations can be readily applied within the RAD framework (Dassow et al., 2022; Embke et al., 2022; Feiner et al., 2022; Kocik et al., 2022; Psuty, 2022; Rahel, 2022).

Fisheries function as coupled socioecological systems, such that RAD approaches for fisheries fall into two broad categories: (1) RAD strategies for ecological goals and (2) RAD strategies for social goals (Table 1). Ecological strategies encompass management actions to influence the state or dynamics of the ecological system composition, structure, and function. Social strategies encompass management actions aimed at harvest, livelihoods, and cultural goals associated with fisheries. Equity issues are implicit in any reallocation of access, wealth,

TABLE 1 Examples of ecological and social strategies for fisheries management to implement different RAD (Resist-Accept-Direct) pathways in relation to ecosystem type. For a more detailed examination of inland recreational RAD strategies, see Rahel (2022). Icons adapted from Paukert et al. (2021)

RAD pathway	Resist	Accept	Direct
Ecological strategies	Compensatory stocking to maintain fishery Watershed protection to reduce eutrophication Suppress undesirable species favored by climate change Riparian shading to cool water Flow management Restore stream network connectivity Reduce groundwater withdrawals Reduce hardened shorelines, promote living shorelines	Monitor to detect unacceptable system changes that may warrant switching to other strategies Cease stocking species disfavored by climate change	Deliberately introduce species outside native range that are adapted to new conditions Assist migration of impacted species to better suited environments Establish ecosystem engineering species that promote desired ecological function Foster migration of saltmarsh spawning/nursery habitat further inland
Social strategies	Prioritize stakeholder communication and education to promote cooperation Promote watershed- and fisheries-friendly water and land use practices Support 'put-and-take' fisheries for species no longer capable of natural recruitment	Adjust harvest levels and implement a precautionary approach to maintain fishery at reduced levels Monitor to detect unacceptable system change that may warrant switching to other strategies Close fishery during biologically sensitive periods (e.g., warm spells) Establish fishery for prevalent species Seek to enhance economic value given reduced harvest of traditional species Utilize aquaculture to replace lost wild capture fisheries Establish marine protected areas to minimize impact to species disadvantaged by climate change	Promote transition to species favored by climate change Develop aquaculture for *new* species adapted to changing conditions

Lakes and reservoirs , streams and rivers , estuaries and coasts , and offshore welfare, and resources and need to be considered when evaluating social RAD strategies (Kourantidou et al., 2021; Shultz et al., 2022). For both ecological goals and social goals, we can envision management actions that fall into either *resist*, *accept*, or *direct* pathways for managing fisheries in a changing climate (Table 1). To date, *resist* pathways have been more common for promoting ecological goals, whereas *accept* pathways have been more common for social goals.

The partitioning of RAD strategies by social and ecological goals is not always clear-cut as the same strategy can impact both. For example, implementation of a marine protected area can have an ecological objective of maintaining population age structure and a social objective of improving catch per unit effort outside the protected area. However, even in such situations, the process of classifying strategies can help to identify the available options to manage under ecosystem transformations. In transforming aquatic systems, fisheries management will need to consider both ecological and social strategies; neither can operate successfully in isolation.

2.1 | RAD strategies for ecological goals

RESIST—Ecological strategies to *resist* climate-driven fisheries transformations include measures to protect or restore habitats as well as efforts to maintain extant populations or reintroduce extirpated populations through stocking. Habitat-focused strategies occur across multiple and nested scales (e.g. stream reaches, riparian area, watersheds; estuaries, bays, coastlines) in aquatic systems. Examples of large-scale actions include preventing water quality degradation from nutrient and pollutant input with conservation easements that minimise watershed development (Jacobson et al., 2013), planting riparian vegetation to reduce stream warming (Thomas et al., 2016), and managing water flow to emulate historical flow regimes (Thompson et al., 2012a). Examples of resistance actions at local scales include depositing sediment to elevate and maintain tidal wetlands as sea levels rise (Ford et al., 1999), removing algae on corals to reduce competition and promote coral recruitment (Ceccarelli et al., 2018), deploying artificial reef structures and stocking corals in marine environments (Nieves-Ortiz et al., 2021), and reducing the impact of flooding and intense storm events on fish nursery habitats by reconnecting floodplains through addition of woody debris and beaver-dam analogues in riverine environments (Thompson, et al., 2012b). Supplementation of sportfish or threatened and endangered species populations from hatchery stocks—ideally in conjunction with other resistance strategies (e.g. water quality improvements, fish passage/dam removal, invasive species removal)—may help to maintain economically, ecologically, and/or culturally important fisheries that are declining due to climate change and other anthropogenic drivers (Lorenzen et al., 2013). This approach of strategic resistance is being employed in the midwestern United States (U.S.), where fisheries managers are maintaining walleye *Sander vitreus* (Mitchill) fisheries despite little-to-no natural recruitment (Raabe et al., 2020). Similarly, supplementation hatcheries are another approach to relieve harvest pressure on wild populations (Trushenski et al., 2018).

ACCEPT—Ecological strategies to *accept* fisheries transformations involve acknowledging that ecological changes are not readily reversible, and therefore management efforts can either continue operating under business-as-usual or evolve with transforming ecosystem conditions. While *accept* is often considered the default choice [i.e. if a system transformation is unobserved (failure to monitor) or unheeded (failure to act)], it is important to note that it can be an active, deliberate choice. Acceptance can involve the discontinuation of resistance efforts (e.g. supplemental stocking or habitat restoration) or it can involve the initiation of new management actions. For example, changing spawning phenologies driven by warming climate may require alterations to the opening and closing dates of fishing seasons to protect spawners (Peer & Miller, 2014; Tufts et al., 2019). Managers may have to accept that flow or thermal conditions may occasionally become inhospitable to fishes, and thus conserving groundwater regimes to enhance connectivity to refuges or recolonization sources becomes important for population persistence (LeMoine et al., 2020). However, enhanced connectivity can also promote the spread of undesirable species (Rahel, 2013).

DIRECT—Ecological strategies to *direct* fisheries transformations are not new to fisheries managers. Fisheries management has a strong history of manipulations of fish assemblages, food webs, and habitat to *direct* transformations towards conditions that support fisheries in novel configurations. For example, deliberate introductions of new species or entire assemblages is a common means for *directing* reservoir fish assemblages to configurations that provide recreational fisheries. Management upstream of dams often focuses on establishing novel, self-sustaining food webs via populations of lake-adapted, sometimes non-indigenous, sport and forage fishes (e.g. largemouth bass *Micropterus salmoides* (Lacepède), bluegill *Lepomis macrochirus* Rafinesque), while novel, sometimes non-indigenous, trout fisheries are a common management strategy for tailwaters below dams in North America (Hubert & Quist, 2010). *Direct* strategies specifically related to climate-driven transformation are less common but they can build on this long management history. Deliberate introduction of species to systems that are outside of their historical range is one possible course of action. Although rarely employed, upstream translocations of fish and other aquatic organisms above barriers is another action that could result in high biodiversity and ecosystems functioning in novel ecosystems and could be used to save thermally sensitive species from extinction (Galloway et al., 2016). Such introductions will need to be done with extreme caution given the mounting concerns that introduced species can become invasive, imperil other species (particularly in previously fishless areas), and cause extensive ecological harm (Karasov-Olson, 2021; Rahel & Smith, 2018).

2.2 | RAD strategies for social goals

RESIST—Social strategies to *resist* fisheries transformations include measures that will maintain fishing opportunities and harvest levels to sustain livelihoods and cultural goals. The loss of fishing opportunities can be stemmed by stockings from production hatcheries to provide or enhance opportunities for recreational anglers (Trushenski et al., 2018). Precautionary harvest regulations may be adopted that strengthen population resilience (i.e. age structures and genetic diversity) to better withstand environmental variability and sustain ongoing fishing during periods of environmental change (Free et al., 2020; Munguía-Vega et al., 2015; Planque et al., 2010). *Resist* strategies can maintain sustainable harvest levels by supporting healthy meta-populations to stabilise populations or species via portfolio effects, and similarly, fishing portfolios can stabilise revenues derived by fishers and communities (i.e. catch diversity dampens economic variability; Hilborn et al., 2003; Kasperski & Holland, 2013; Schindler et al., 2010; Sethi et al., 2014).

ACCEPT—Social strategies to *accept* fisheries transformations include a variety of strategies that enable fisheries to adjust to ecosystem changes. Acceptance can be a de facto strategy if managers are unaware that fisheries are being altered by climate change or are unwilling/unable to address such changes. But acceptance can also be a deliberate strategy if managers recognise that changes have occurred and then attempt to manage as best they can under the new conditions. In recreational fisheries, this could, for example, involve promoting fishing for warmwater largemouth bass in warming lakes that were previously managed for coolwater walleye fisheries (Dassow et al., 2022). In commercial fisheries, this could involve diversification of fishing opportunities as some fisheries fail, such as the refocusing on salmon when the Cook Inlet crab and shrimp fisheries collapsed from large-scale climate-driven oceanographic changes (Anderson & Piatt, 1999; Mantua & Hare, 2002). Fishers may also modify their fishing practices to reduce bycatch of non-target species or "choke" species (i.e. species in multispecies fisheries with low quotas that can constrain catch of target species), particularly as climate change affects the location and productivity of target species (Dunn et al., 2016; Lewison et al., 2015). In addition, the ability of commercial harvesters to switch target species can dampen impacts of variability and buffer against changing species availability (Finkbeiner, 2015; Fisher et al., 2021), but this flexibility may come at a cost for such things as additional equipment, permits, and labour. Management actions that adapt harvest levels to match changing stock productivity are key to supporting sustainable fisheries with ongoing harvest opportunities as ecosystem conditions change (Gaines et al., 2018; Holsman et al., 2019; Kasperski & Holland, 2013; Walters & Martell, 2005). Adjusting fishing practices to focus on quality over quantity, direct marketing, or a shortened supply chain could maintain income as catch levels decrease (Stoll et al., 2015). Additionally, the development of aquaculture for *existing species* that cannot sustain wild fisheries could be considered as an important acceptance strategy (Lorenzen, 2006; Stoll et al., 2019). Furthermore, strategies for *accepting* ecosystem change need to include adaptation of fishery management institutions. Institutions will likely need to increase responsiveness by incorporating adaptive measures into existing or new management processes (e.g. dynamic ocean management to reduce bycatch; Hazen et al., 2018; temperature-triggered temporary closures for recreational coldwater fisheries; Jeanson et al., 2021). In addition, it may be necessary to adjust jurisdictional authority over a fishery as stocks shift across boundaries (Holsman et al., 2019; Pinsky et al., 2018). For example, Makah Treaty fishing rights are geographically limited to the extent of usual and accustomed fishing grounds and stations but, as climate change drives range shifts in commercially and culturally important fish species, Makah fishers may face decreased access to these treaty resources if they are unable to follow fish outside the treaty boundaries (Cucuzza et al., 2021). Similarly, climate may impact recreational fisheries operations, participation, and motivation (Cantrill et al., 2019; Townhill et al., 2019).

DIRECT—Social strategies to *direct* fisheries transformation involve measures that drive social systems towards novel configurations and resource opportunities to replace lost ecosystem services. Precautionary harvest moratoriums for species moving into new habitat areas provide a period for stocks to become established while relevant scientific information and management measures are developed (Stram & Evans, 2009). In addition, selective harvest measures, such as catch and release requirements or size-based rules, can facilitate higher productivity or successful establishment of species in new locations (Le Bris et al., 2018), eventually leading to fishing opportunities. When ecosystem change cannot be controlled, strategies can be employed to *direct* fisher responses in the context of those changes. For example, programmes to support livelihood diversification can reduce reliance on declining resources by facilitating job and career opportunities in complementary activities (Cusack et al., 2021; Ojea et al., 2020). In addition, the development of alternative industries such as aquaculture for *new species* adapted to the changing ecological conditions can sustain certain ecosystem services (e.g. food provision) and social functions (e.g. livelihoods) while enabling some operational controls on ecosystem conditions experienced by the industry (e.g. shellfish hatcheries buffering incoming seawater to control aragonite saturation levels detrimental to larval survival; Barton et al., 2015).

3 | CONTROLLABILITY SCENARIOS

Controllability (i.e. the ability to guide a system's behaviour towards a desired state through the manipulation of input variables; Liu et al., 2011) affects the feasibility of RAD strategies and determines what management options are available to address ecosystem transformation. Here, we view controllability on two axes of influence where the first axis is the ability to influence the ecological system and its trajectory, and the second axis is the ability to influence the social system and its dynamics in terms of social norms, societal values, and economics.

Four controllability scenarios result from this socioecological controllability matrix (Figure 2):

- *Cope*—When ecological responsiveness and societal receptivity to change is low, managers can *cope* with aquatic ecosystem transformation, employing ecological *accept* and social *resist* strategies. For example, when extreme heatwaves led to a severe decline of

Pacific cod in the Gulf of Alaska, the response was to *accept* the ecological change by reducing the harvest quota until the stock recovers (Barbeaux et al., 2020).

- *Engineer*—When social systems are averse to change but ecological systems can be manipulated, managers can *engineer* their domain, employing any ecological and social *resist* strategies. Examples would be enhancing riparian vegetation to prevent warming of salmonid streams (Justice et al., 2017; Lawrence et al., 2014; Thomas et al., 2016) or the release of cool reservoir water to support salmon spawning migrations that would otherwise be harmed by excessively warm temperatures (e.g. spring-run Chinook salmon *Oncorhynchus tshawytscha* (Walbaum) in California; Thompson et al., 2012a).
- *Innovate*—When societal receptivity to change is high but ecological systems are not responsive to intervention, managers can *innovate* for the new management frontier, employing ecological *accept* strategies and any social RAD strategies. *Directing* fisheries efforts to species favoured by climate change or moving from capture fisheries to aquaculture would fall into this category.
- *Create*—When both social and ecological controllability are high, managers can *create* diverse options, employing any ecological and social RAD strategies such as introductions of species better suited for the new ecological conditions.

Ultimately, real world situations may not fit nicely into these four idealised scenarios, but the scenarios can help orient planning discussions because they emphasise that both ecological and social RAD strategies need to be considered. Maintaining a nimble and iterative fisheries management process is critical for effectively addressing ecosystem transformation. We envision "triple loop" adaptive management, whereby higher-level ecosystem management goals and objectives are periodically updated to reflect changes in social and ecological systems, to play a key role in operationalizing RAD strategies under transforming ecosystems (Lynch et al., 2022; Pahl-Wostl, 2009). Below are two case studies involving management of trout in the Rocky Mountains and Pacific salmon fisheries in Alaska that provide examples of RAD strategies portfolios across these four scenarios (Figures 3 and 4).

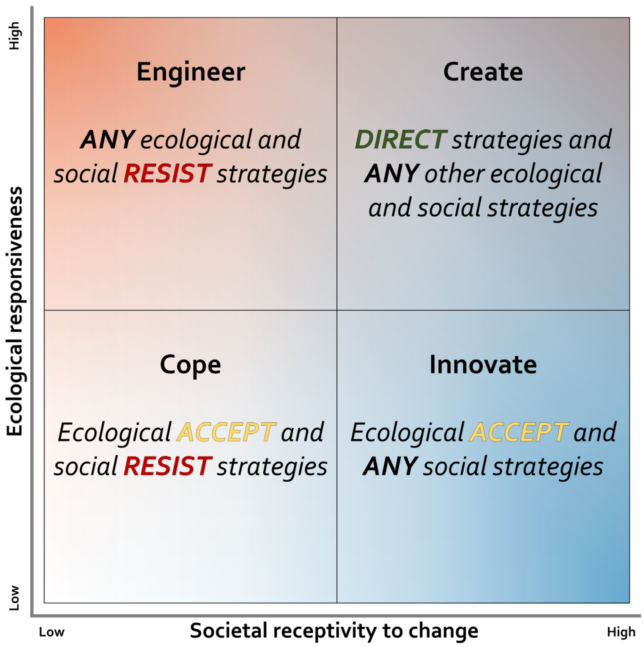

FIGURE 2 RAD strategies across the controllability spectrum of ecological responsiveness and societal receptivity to change. *Resist* strategies could be attempted in any scenario; however, ecological and social *resist* strategies are ultimately futile for fisheries transformed by rapid, persistent drivers of change and where ecological responsiveness is low

3.1 | Case study: Recreational fisheries in a changing Rocky Mountain region

Cutthroat trout *Oncorhynchus clarkii* (Richardson) represent an important coldwater recreational fishery in the Rocky Mountain region, supporting local and predominantly rural economies. Anglers often pay outfitters a premium to fish river habitats occupied primarily by indigenous cutthroat trout, compared to fisheries dominated by non-indigenous trout (Pitts et al., 2012). Climate change is causing stream warming, changing hydrology, and facilitating climate-mediated hybridization and competition between indigenous and

FIGURE 3 Various subspecies of cutthroat trout sustain highly valuable recreational fisheries in western North America. Shown is the Rio Grande cutthroat trout *Oncorhynchus clarkii virginalis* (C. F. Girard), the southernmost subspecies. Threatened by human population growth, climate change, and non-indigenous species, these fish now occupy <12% of their historical range (Bakevich et al., 2019). [credit: C. Springer]

FIGURE 4 Purse seiners commercially fish for Pacific salmon (*Oncorhynchus* spp.) by a hatchery in Prince William Sound, Alaska, U.S. [credit: S.A. Sethi]

non-indigenous trout; all to the detriment of cutthroat trout fisheries (Isaak et al., 2018). These changes threaten to transform indigenous trout fisheries to systems dominated by non-indigenous trout or other species (e.g. smallmouth bass *Micropterus dolomieu* Lacépède; Lawrence et al., 2015).

Cutthroat trout fisheries will vary in ecological responsiveness to different RAD interventions, determined by climate change velocity, spatial context (i.e. trailing edge, centre, leading edge of shifting cutthroat trout distributions), and the presence of non-indigenous species. At the same time, social receptivity to change in cutthroat trout fisheries will determine the RAD strategies that can be employed. Together, these dimensions can be used to examine potential RAD strategies within the four scenarios (Figure 2).

- *Cope*—Where ecological responsiveness is low, and social receptivity to change is low, *accept* strategies, such as switching to catch-and-release fisheries, reduced creel limits, and fishery closures during warm spells, all help maintain a cutthroat trout fishery while recognising constraints on manipulating the ecological system supporting the fishery.
- *Engineer*—Where responsiveness of the ecological system is high, but social receptivity to change is low, RAD strategies to *resist*, both ecologically and socially, include riparian shade enhancement, barriers to non-indigenous trout incursion, and non-indigenous trout removal.
- *Innovate*—In situations of low ecological responsiveness but high social receptivity to change, managers can promote the harvest of species favoured by climate change such as non-indigenous trout (Kovach et al., 2018) or coolwater species (Rubenson & Olden, 2020).
- *Create*—When ecological responsiveness and societal receptivity to change are high, managers can consider actions that *direct* fisheries to new states. These can include intentional introductions of more thermally tolerant, non-indigenous trout species, shifting from coldwater to coolwater fisheries, or establishing trout populations above natural migration barriers where they historically did not occur (Galloway et al., 2016). *Directing* fisheries to new states will require a significant risk evaluation (Karasov-Olson et al., 2021) and an evaluation of the capacity of indigenous cutthroat species to adapt to climate changes before these more extreme approaches are exercised (Thurman et al., 2020). Ultimately, there is flexibility to employ any of the ecological and social RAD strategies in the other scenarios provided they do not conflict with efforts to manage other species. For example, translocation of trout populations to fishless waters may conflict with efforts to conserve other taxa, such as amphibians (Knapp et al., 2007).

When climate change is driving transformation in a cutthroat trout fishery, simultaneously examining the dimensions of ecological responsiveness and social receptivity to change allows managers to consider the full range of ecological and social RAD strategies under various scenarios (i.e. engineer, cope, innovate, and create). Ecological responsiveness may include evaluating climate velocity for the local fishery (i.e. slow change makes ecological *resist* strategies more feasible; fast change may preclude them), while social receptivity to change may include evaluating angler preferences (e.g. an existing fishery with indigenous and non-indigenous trout components may be more receptive to change than an indigenous-only fishery). Clearly, constraints and opportunities to use these strategies will vary by local context, but considering all options, rather than adhering to one regardless of cost and efficacy, will enhance success at responding to transformations in cutthroat trout fisheries.

3.2 | Case study: Navigating transforming ecosystems in Alaskan salmon fisheries

Five Pacific salmon species, Chinook, chum *O. keta* (Walbaum), coho *O. kisutch* (Walbaum), pink *O. gorbuscha* (Walbaum), sockeye *O. nerka* (Walbaum), contribute substantially to commercial, sport, and subsistence fisheries throughout the state of Alaska (Figure 4). These anadromous fishes are exposed to a suite of climate-driven and anthropogenic stressors in coastal watersheds and marine environments throughout their life cycle. Salmon-bearing ecosystems in Alaska span the spectrum of low to high ecological controllability and social receptivity to management changes. Stakeholders are utilising a portfolio of RAD strategies to navigate rapidly changing marine and freshwater ecosystems.

- *Cope*—Environmental change has transformed marine and freshwater conditions at scales sufficient to interrupt salmon spawning in remote regions where ecological *resist* strategies such as hatchery supplementation are infeasible. For example, chum and Chinook salmon contribute to important subsistence harvest resources for communities throughout the Yukon River drainage, yet heatwaves cause pre-spawning mortality in warming rivers (Westley, 2020). Similarly, Chinook salmon populations have declined dramatically over the past decade in these regions and the root causes have proved difficult to identify (Ohlberger et al., 2018). In these cases where ecological controllability is low and where salmon stakeholders rely heavily on subsistence harvests, managers have had to *accept* ecological changes and attempt to *resist* loss of subsistence harvest opportunities by restricting commercial fisheries on chum and Chinook salmon as well as reducing bycatch of these species in marine commercial fisheries through bycatch caps.
- *Engineer*—Social norms and regulatory statutes support large salmon hatcheries in Alaska, although debate continues as to the risks hatchery programmes present for wild salmon populations (e.g. Rand et al., 2012). Nevertheless, with 1.7 billion juveniles stocked annually across the state, hatchery supplementation to buffer against variable and in some cases declining wild salmon recruitment is a primary ecological and social *resist* strategy employed by salmon managers to maintain harvest opportunities in the face of rapidly changing environmental conditions (Wilson, 2021).
- *Innovate*—In some regions of Alaska, stakeholders have had to *accept* ecological changes that are underpinning continued declines in salmon stocks, but social receptivity to change among some stakeholder groups is high. This has opened the door to social *direct* strategies to adapt to system changes. For example, some salmon fishers in southeast Alaska are changing business practices to vertically integrate and market high-value seafood products directly to consumers, generating new value and transforming the fishery towards different seafood supply chains (e.g. Bolton et al., 2016; Sitka Salmon Shares, https://sitkasalmonshares.com/).
- *Create*—Ecological *direct* strategies involve steering ecosystems and species assemblages into new, more desirable configurations through species introductions or habitat manipulation efforts such as altering disturbance regimes. These actions are difficult, if not impossible, to implement in open marine systems compared with freshwater systems (see recreational fisheries case study above), although social *direct* strategies may still be possible. Ecosystem managers are *resisting* ecological change to maintain salmon fishing opportunities in urban areas of southcentral Alaska by restoring river connectivity in degraded watersheds (O'Doherty et al., 2020; Sethi et al., 2017). Similarly, managers are collaborating with a new and broader mix of stakeholders to *direct* societal change towards a conservation stewardship ethic and mixed-use access for salmon watersheds through collaborative research and improved land-use decision-making forums (Walker et al., 2021).

Warming climate and changing hydrology is transforming salmon-bearing watersheds across Alaska. Furthermore, as urbanisation has progressed, the bundle of ecosystem services demanded from salmon-bearing watersheds has changed significantly. In particular, previously low human use in coastal watersheds and a focus on commercial salmon harvests have now been replaced by demand for sport and personal-use salmon harvests, and land-use for housing, business, road works, and trail use. RAD provides a framework for identifying the combination of ecological and social actions applicable for managing Pacific salmon at different spatial scales in a changing climate.

4 | IMPROVING CONTROLLABILITY

To maintain the broadest suite of available RAD management strategies, fisheries managers can focus on improving controllability. This focus can shake the decision paralysis that often leads to futile *resist* strategies (i.e. those that do not achieve desired outcomes) or inevitable *accept* strategies (i.e. those with only one possible outcome). But, both ecological responsiveness and societal receptivity to change are substantial hurdles. Low societal receptivity to change is common, and can limit management actions to social *resist* strategies whereas high social receptivity allows for social *accept* and *direct* strategies (Figure 2). Low ecological responsiveness to intervention limits options to ecological *accept* strategies whereas high ecological responsiveness opens the door to *resist* and *direct* strategies.

To move from low controllability to high controllability scenarios, managers will need to assess the current status of their socioecological system and the timescales required to improve controllability. Both social and ecological change can be rapid and interact to drive ecosystem transformation (Beever et al., 2019). Furthermore, positioning along either of these axes may change overtime. For example, initial resistance to social change may be replaced by acceptance as fishers experience increasingly dire economic consequences due to ecosystem transformations or as social and economic conditions change to make alternative options more desirable. Or, technological advances may make ecological manipulations more viable, such as the development of thermally tolerant genotypes for species declining in a warming climate (Van Oppen et al., 2015; Morikawa & Palumbi, 2019; e.g. heat-tolerant corals; Buerger et al., 2020; Caruso et al., 2021).

Controlling the ecological system state presumes a working knowledge of biotic and abiotic drivers and their relationships with each other in influencing system dynamics. While we may have a general knowledge of ecological cause and effects, this understanding may be based on previous system states, and not relevant for new or altered trajectories. This lack of stationarity in ecological conditions is a primary motivation for adopting the RAD management framework (Thompson et al., 2021). The increasing acknowledgement of this non-stationarity and the importance of interacting ecosystem factors has led to the call for moving from single species management to ecosystem-based fisheries management (Barbeaux et al., 2020; Hilborn, 2004; Link, 2002; Pikitch et al., 2004). The RAD management framework fits decidedly within ecosystem-based fisheries management, but with a focus on managing those ecosystems through transformations. Case in point, the ability to change an ecosystem trajectory is a complex process of ecological functions influenced by social, economic, and policy factors. Advances in control theory and network analysis show promise for improving predictive controllability for simplified ecological systems where economic and social elements are incorporated (Benavides et al., 2015). Still, socioecological systems are rarely simple or well understood. Approaching these challenges within the RAD framework can help guide decisions and improve system knowledge and controllability.

Controlling the social systems governing fisheries is even less straightforward than controlling the ecological systems. The actions of fisheries stakeholders are motivated by political and regulatory systems, economic factors, norms, and value systems. Thus, the structure and scale of social systems drive receptivity to management interventions and can affect the feasibility of RAD options for both social and ecological processes (Clifford et al., 2022). Fishery stocks are common pool resources and coordination among stakeholder groups is a prerequisite for effective management (Ostrom, 1990). The number and diversity of stakeholder groups involved in a socioecological system can affect receptivity to management interventions (Grimble & Wellard, 1997). Smaller fisheries with fewer stakeholder groups may achieve consent more readily and may enable a greater range of RAD options. For example, managing inland recreational fisheries under transforming lake ecosystems may require coordination with a handful of stakeholder groups such as local angling clubs and lake associations (Rahel, 2022). In contrast, marine and coastal fisheries are often large in scale and encompass commercial, recreational, and subsistence fishers, in addition to stakeholders from other ocean-use activities such as tourism or energy (e.g. Psuty, 2022). A case in point involves the Atlantic goliath grouper *Epinephelus itajara* (Lichtenstein). Overexploitation led to a fishery closure and as the population recovered, a tourism industry developed for divers seeking to see and photograph these enormous fish. Efforts to re-establish a fishery were resisted by the dive-tourism industry, which argued that the fish should be managed as a non-extractive resource with a commercial value greater than that gained through fishing (Koenig et al., 2020). That said, even small fishery systems can face stakeholder conflict where specific groups dominate the management process with self-interested behaviour that prevents deliberation and progress in implementing RAD options. Thus, stakeholder communication, coordination, and education will feature heavily in defining the feasibility of both ecological and social RAD options (Clifford et al., 2022; Davies et al., 2015).

4.1 | Ecological responsiveness

Ecological responsiveness (i.e. our ability to control the trajectory of ecosystem change) is likely to be strongly dependent on spatial scale and system complexity. Controllability in large-scale aquatic systems is particularly challenging. Stream reaches are more likely to be controllable than entire watersheds; small lakes are likely more controllable than large lakes; and marine systems, which are large and complex, are relatively uncontrollable.

There are a number of tools and promising innovations that can help to clarify ecological responsiveness through improving understanding of system dynamics. First, technological advancements including remotely sensed data, autonomous underwater vehicles, drone-based data collection, and environmental DNA samplers have increased our ability to monitor ecosystem changes and responses to management actions (Toonen & Bush, 2020; Wang et al., 2021). Second, even in situations that are data-limited, rapidly expanding fields of data science as well as emerging new artificial intelligence techniques and cloud-based computing data storage may help us to understand mechanisms and functions of aquatic systems and fisheries (Bradley et al., 2019). Increasing computational capabilities (e.g. Bayesian belief networks, accessible machine learning application software, and management strategy evaluations) can also advance decision analysis by helping optimise management choices given multiple objectives and information uncertainty (Elith et al., 2008; Kaplan et al., 2021; Marcot et al., 2006). To the extent that models can be developed that simulate ecosystem processes, management actions can be tested using the models before on-the-ground manipulations are undertaken (Gomes, 2019). For example, trophic models can be used to predict the response of lake ecosystems to changes in nutrient loadings as a result of changes in land-use practices (Weng et al., 2020). Similarly, in response to repeated climate-forced ecological perturbations, a management strategy evaluation that combines downscaled or global climate models with climate-enhanced biological models (and socio-economic models in some cases) can be used to explore realistic options to lessen impacts on species and identify potential novel opportunities to better manage fish and fisheries (e.g. in the Gulf of Alaska, A'mar et al., 2009; along the U.S. West Coast, Haltuch et al., 2019; and Smith et al., 2021; in the Bering Sea, Hollowed et al., 2020).

With better understanding of system dynamics, interventions to manipulate those systems and improve controllability are being cautiously considered. For example, translocations and novel genetic tools, such as gene editing, with their far-reaching ethical implications, are being examined for application in agricultural systems (Karavolias et al., 2021) and coral restoration (Van Oppen et al., 2015), and could be more broadly considered to facilitate species and biological community adaptation to climate change.

4.2 | Societal receptivity to change

Societal receptivity to change is a moving target. For example, "shifting baselines" is a common phenomenon in fisheries and can alter societal receptivity on the order of generations (Jackson et al., 2001). However, sometimes even stable environmental policy can undergo sudden jumps or dramatic change very quickly (Repetto, 2006). For example, the U.S. had a Congressional moratorium on new catch share programmes (also called dedicated access privilege programmes) in place from 1996 to 2002. In the years that directly followed, many new catch share programmes were quickly enacted across the country (Baker, 1999; also see: NOAA Fisheries Catch Share Programs by Council Region, https://www.fisheries.noaa.gov/national/sustainable-fisheries/catch-share-programs-council-region).

In addition to facilitating stakeholder coordination, several considerations related to the structure of governance systems may help to improve the receptivity of social systems to RAD options under transforming ecosystems. First, governance systems need to accommodate the spatial and temporal scale of ecosystem transformation, for example, by aligning management jurisdictions to ecologically relevant scales and/or facilitating transboundary governance forums (Cumming et al., 2006; Pinsky et al., 2018). This may be particularly important in marine systems where large-scale redistributions of species continue to accelerate (Ojea et al., 2020) and for species with highly migratory life histories (Kocik et al., 2022; Miller et al., 2013). Similarly, efforts to ensure that RAD strategies persist across governance leadership changes are also necessary to align the temporal stability of management processes with ecosystem dynamics (e.g. Castrejón et al., 2014).

Second, dedicated access privileges are in effect for many large marine fisheries and other fisheries are considering implementing similar policies. While there is evidence that catch shares may support sustainable harvests (Costello et al., 2008; Melnychuk et al., 2012), policies which set up rigid access entitlements may restrict opportunities for course corrections under transforming ecosystems, particularly for species with highly migratory life histories as well as those with shifting distributions (e.g. Acheson et al., 2015). In the face of rapid ecosystem change, perceptions of permanent entitlements may lock managers into status quo management to satisfy historical access claims. This could hamper support for fisher livelihood adaptation under *direct* strategies to respond to transforming ecosystems (e.g. Criddle, 2012). Requiring periodic policy reviews and instituting sunset dates for entitlements can provide options to either renew existing policies or alter the course in response to ecosystem change (Lynch et al., 2021b).

5 | HUMILITY AND AGILITY

Managing fisheries within transforming aquatic systems will require both humility and agility, attributes that are essential for current and future fisheries sustainability. Ecosystem transformations can make fisheries managers feel powerless and incapable of meaningful intervention when they have little control over the transforming systems in which they work. Although fisheries managers cannot substantially change global climate trajectories, they can play a part in adaptation solutions. Fisheries managers can help guide responses to the socioecological transformations wrought by climate change (Table 1). The RAD framework can empower fisheries managers to act in the face of uncertainty through system transformation by helping identify feasible actions and shifting focus towards improving controllability (ecological responsiveness and/or societal receptivity to change), thereby altering the decision landscape.

It is also important to recognise that there are "windows of opportunity" to implement any RAD strategy (Magness et al., 2022b). While rash decisions are rarely constructive, delayed action can increase the risk of irreversible change to aquatic ecosystems and can result in lost opportunities for *resist* or *direct* strategies and lost time to prepare for adapting to ecosystem changes under an *accept* strategy (Lynch et al., 2021b). Particularly, when a window of opportunity is short or management is for an endangered species, paralysis can equate to higher economic costs, increased losses to fisheries, and greater consequences to aquatic ecosystems. It may be necessary to act quickly to implement *resist* strategies in an open system, such as culling an undesirable species expanding its range with warming waters, before such interventions become ineffective. On the other hand, managers of a more closed or smaller-scale system (i.e. with greater ecological responsiveness) may have more flexibility to evaluate alternative approaches before selecting and implementing one. Optimising these windows of opportunity can give fisheries managers the ability to move beyond futile *resist* or inevitable *accept* approaches and open up a diverse portfolio of ecological and social RAD strategies.

While the focus of this piece has centred on climate change as the driver of aquatic ecosystem transformation, the RAD approach to management can provide a useful framework to address any impactful pressures on fisheries. Transforming ecosystems as driven by changing climate or any other stressors behave in unpredictable manners, presenting stakeholders with the daunting prospects of managing under high system variability and high uncertainty. Yet, through iterative and deliberate management, RAD approaches provide a useful framework for pressing ahead. With an understanding of a system's ecological responsiveness and societal receptivity to change (Figure 2), managers can identify ecological and social RAD strategies (Table 1) suitable for use in their system context. Pragmatically, ecological, societal, and financial feasibility considerations will constrain the availability of actions to implement desired RAD strategies (Lynch et al., 2021b). Thus, a cost-benefit analysis stage to assess potential actions will be an important operational step for implementing RAD approaches to managing transforming fisheries. If the set of available options is insufficient, managers may seek to address the controllability of the systems they manage to expand the potential set of feasible management actions and potentially open up new RAD strategies. Once a RAD strategy and associated management actions are implemented, iterative monitoring, experimentation, evaluation, and adjustments can be made, along with periodic re-evaluation of higher-level management goals and relevant RAD strategies in an ongoing cycle (Lynch et al., 2022).

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CONFLICT OF INTEREST

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ORCID

Abigail J. Lynch https://orcid.org/0000-0001-8449-8392
Frank J. Rahel https://orcid.org/0000-0002-0932-3485
Suresh A. Sethi https://orcid.org/0000-0002-0053-1827
Augustin C. Engman https://orcid.org/0000-0003-2064-7680
David J. Lawrence https://orcid.org/0000-0002-1457-9944
Katherine E. Mills https://orcid.org/0000-0001-6078-7747
Jay O. Peterson https://orcid.org/0000-0001-6130-5519
Mark T. Porath https://orcid.org/0000-0001-6952-349X

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