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Resist, accept, and direct responses to biological invasions: A social–ecological perspective

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Abstract

Biological invasions represent an important and unique case of ecological transformation that can strongly influence species and entire ecosystems. Challenges in managing invasions arise on multiple fronts, ranging from diverse and often divergent values associated with native and introduced species, logistical constraints, and transformation via other change agents (e.g., climate and land-use change). We address biological invasions considering the Resist-Accept-Direct (RAD) framework for addressing ecological transformation. Because RAD is focused on decisions, we address both social and ecological factors that influence preferences for decision alternatives. We address social factors first as these can constrain the range of alternatives considered in an ecological context. Next, we address ecological dynamics by modeling trajectories from RAD alternatives in a two-species scenario involving impacts of introduced brook trout (*Salvelinus fontinalis*) on native bull trout (*S. confluentus*). Results reveal that decision alternatives aligned with each of the major components of RAD can produce positive outcomes. In a management context, these findings highlight the value of investing in early engagement to fully identify decision alternatives, formalizing models of system dynamics to understand ecological trajectories, and applying this knowledge to set the stage for longer term efforts to address biological invasions.

KEYWORDS
biological invasions, ecological transformation, managing impact modifiers, Resist-Accept-Direct, social-ecological systems

1 | INTRODUCTION

Rapid transformation of the Earth's social and ecological systems has led to a call for new frameworks for addressing change (Reyers et al., 2018). A recent response to this is the Resist-Accept-Direct (RAD) framework (Lynch et al., 2021, Thompson et al., 2021; Schuurman et al., 2022) which explicitly acknowledges the distinctive objectives associated with *resisting*, *accepting*, or *directing* change. RAD offers a simple and effective means through which stakeholders can envision more intentional decisions regarding what is desirable or attainable in a world where the prospects of change and transformation are increasingly likely. Ecological transformation can be defined as a major and irreversible shift in multiple features of ecosystems, which include changes in ecological communities (Crausbay et al., 2022). RAD considers management responses to transformation in terms of (1) *resisting* trajectories of change by acting to maintain a contemporary state or restore prior ecological conditions, (2) *accepting* trajectories of change without interventions, (3) *directing* changes through interventions intended to shape ecological conditions toward new desired conditions or states (Aplet & McKinley, 2017; Schuurman et al., 2022). As such, RAD provides a clear statement of three distinctive approaches for managing ecological transformation that have direct relevance to management decision-making. What this looks like in practice is still an open question for many applications. Here, we focus on application of RAD for managing biological invasions.

Biological invasions (Table 1) represent an important and unique case of ecological transformation (Davis et al., 2001). As introduced species become increasingly prominent members of ecosystems, the need for considering a broad range of approaches to managing them has become apparent (Dunham et al., 2020). Management of biological invasions can be aligned with stages of the invasion process itself (Figure 1). Assuming an introduced species is undesirable (a point we return to below), the best approach to management is prevention. Prevention avoids the need for subsequent stages of management and the chance that an introduced species has undesirable impacts on receiving ecosystems or species. If prevention fails, early detection and rapid removal is a commonly prescribed alternative (Reaser et al., 2020). Again, early detection and rapid removal is preferable because it should require less effort to remove or eradicate an introduced species earlier in the invasion process, assuming it is detected in time. Although managing biological invasions in the early stages makes good sense, many invasions nonetheless proceed to later stages, where a species is established and may spread to additional locations (secondary spread, Figure 1). In this case, complete eradication, containment, and even partial removal of a species are more difficult and costly. At this stage, one may consider managing the impacts of introduced species rather than directly controlling their populations by managing impact modifiers (MIM, Table 1; Dunham et al., 2020; García-Díaz et al., 2021a, b).

In this paper, we explore and attempt to integrate RAD into approaches for managing introduced species (see also Alofs & Wehrly, 2022). Our intent is to show how aligning these approaches can provide novel guidance that managers can use in more effectively addressing introduced species in the face of multiple and sometimes competing values. We begin by outlining the social factors that fundamentally frame the issues, as it is arguably important to consider these first in addressing ecological problems, rather than relegating them to post hoc analyses of why purely ecologically framed solutions succeed or fail (Bennett et al., 2017; Magness et al., 2022). With these social considerations in mind, we then move to an ecological case study of managing an introduced sportfish (brook trout, *Salvelinus fontinalis*) that potentially threatens a native congener (bull trout, *S. confluentus*). In this exercise, we adapt a two-population model to evaluate outcomes for managing these species and their possible interactions framed by RAD decision alternatives (Benjamin et al., 2017). Finally, we discuss our review of social factors and outcomes from our modeled ecological scenarios in light of the contribution RAD concepts provide to managing biological invasions.

2 | SOCIAL FOUNDATIONS OF MANAGING BIOLOGICAL INVASIONS

RAD is founded on formulation of decision alternatives that can be addressed within the frameworks of structured decision-making and adaptive management (Gregory et al., 2012, Conroy & Peterson, 2013; Lynch et al., 2022a, b). These frameworks are focused on addressing fundamental objectives specified by stakeholders, so it is important to understand how social factors define the

TABLE 1 Selected terms related to biological invasions as used and defined herein

Term	Definition
Biotic resistance	The reduction in invasion success caused by the negative interactions with native (recipient) communities, most often through competition, predation, herbivory and/or pathogens
Early detection and rapid response	A coordinated set of actions to find and eradicate potential invasive species in a specific location before they spread and cause damage
Establishment	The process of an introduced species in a new habitat successfully producing viable offspring with the likelihood of continued survival
Hybridization	The process by which interbreeding individuals from genetically distinct populations produce a hybrid
Introduced species	A species that is intentionally or unintentionally transported to a new geographic area by humans
Invasion	A series of sequential stages (transport, introduction, establishment, spread, and integration) through which individuals or populations need to pass to be considered invasive
Invasive species	Introduced species whose introduction in a particular location causes or is likely to cause undesirable economic or environmental impacts, or negative impacts to human, animal, or plant health
Managing Impact Modifiers (MIM)	Management actions designed to modify undesirable influences of introduced species without direct control
Nonnative species	Populations that have become introduced and often established outside their native ranges but do not necessarily cause impacts so to be considered “invasive”
Pathway	Any means, intentional or unintentional, that allows the entry or spread of an introduced species

Note: These are intended to align with definitions in use within the jurisdiction of the United States (Beck et al., 2008; Iannone et al., 2021) and more generally applied to describe invasion processes and types of species (Olden et al., 2021). A newer approach (managing impact modifiers or MIM, Dunham et al., 2020) is also defined. Terms applied to species in the context of biological invasions are used inconsistently in the literature, but, in a management context (Beck et al., 2008), they can have specific meaning for decisions and thus we provide definitions used herein to be clear on such implications.

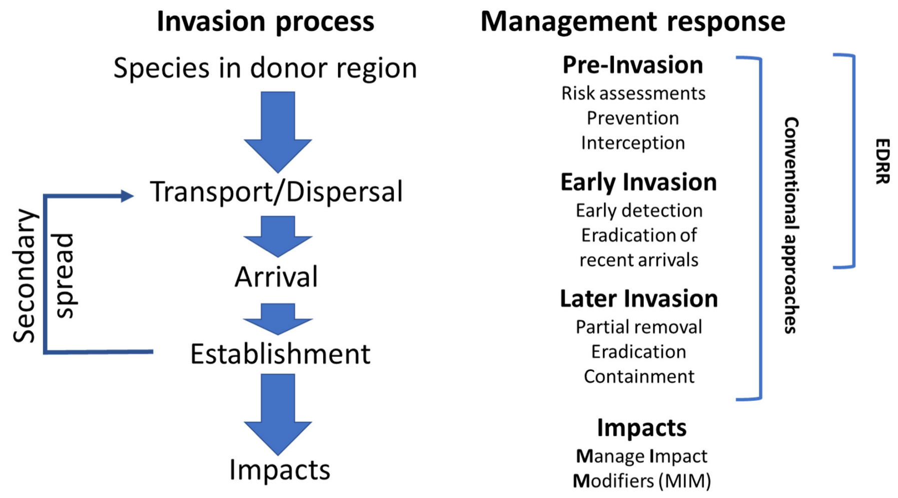

FIGURE 1 Outline of processes involved with biological invasions and associated management responses. Invasions start with arrival of an introduced species from a donor region (e.g., its native range or range within a prior invasion). Unidirectional arrows (lengths adjusted to match text) indicate the general sequencing of events, but more complex series of events (including management interventions) are possible. The simple sequence is as follows: (1) the species can be actively transported or dispersed to arrive in new locations, potentially establishing new populations and spreading further (secondary spread); (2) following establishment, potential impacts from the introduced species are realized for species and ecosystems. Management responses associated with each stage of invasions are summarized on the right. Conventional approaches to control, including early detection and rapid removal (EDRR) are shown. In addition to these approaches, managing impact modifiers (MIM) is also included (see narrative for details). Modified from Dunham et al. (2020)

management decision space stakeholders operate within (Clifford et al., 2022). More specifically, preferences for RAD alternatives (i.e., *resist*, *accept*, or *direct* change) in part derive from internal mental models held by individuals. As articulated by Clifford et al. (2022), mental models are shaped by individual worldviews (subjective emotional and psychological influences), cultural influences (shared, social influences on behaviors), and understanding of the environmental system (through individual or collective experiences and formal scientific investigation). These internal factors (mental models) interact with external factors (e.g., scientific uncertainty, social feasibility, institutional context, and financial resources) to define the decision space – the set of alternative choices available for making decisions (decision alternatives; Clifford et al., 2022). In the context of biological invasions, it is important to examine these factors as they can and likely do influence the range of decision alternatives considered.

Here, we focus on internal factors, unique to the individual, that collectively shape the decision space for responding to biological invasions. Viewed through a social lens, divergent views of how to respond to biological invasions may be less about the specific management responses (Figure 1) and more about fundamental differences in beliefs and worldviews about how introduced species interact with social and ecological systems. In other words, debates about management alternatives are likely more tied to the underlying values held by managers (as well as scientists, stakeholders, and the public, e.g., Anderson & Lambert, 2019). In support of this notion, an analysis of literature on social dimensions of biological invasions found that conflict about introduced species management was primarily due to differing value systems and that risk perceptions were a lesser, secondary influence (Estévez et al., 2015). A common point of divergence in value systems is the fact that many introduced species are highly valued, leading to widespread intentional introduction and reluctance to engage in efforts to control them. This is particularly true of freshwater fishes. For example, intentional introductions and invasions of salmon and trout in South America provide important economic benefits (e.g., aquaculture and recreational and commercial fisheries), yet these species can pose serious threats to many native fishes and ecosystems (Arismendi et al., 2014; De Leaniz et al., 2010; Habit et al., 2010). Similarly, in some cases, management strategies to reduce introduced trout to support native trout fisheries in the United States have drawn opposition from local anglers who enjoy the recreational opportunities that the introduced fish offer (Quist & Hubert, 2004), whereas in other cases of fisheries for, native trout are more highly valued (Pitts et al., 2012).

In addition to individual and cultural influences on mental models that can drive decisions for managing biological invasions, a third and important contributor to mental models is the understanding of the environmental system (Clifford et al., 2022). Social science research has shown that individuals can vary widely in their knowledge of introduced species, impacts, and consequent preferences for managing them (Niemiec et al., 2017; Shackleton et al., 2019). For example, a survey of stakeholder perceptions of introduced species (including fishes) in Spain revealed strongly different levels of knowledge about introduced species, perceptions of their value, attitudes toward their control, and willingness to pay for control measures such as eradication (García-Llorente et al., 2008). In many cases, stakeholders did not recognize known introduced species (i.e., introduced species were often thought to be native).

In this section, we highlighted internal factors (mental models) that operate in concert with external influences (scientific uncertainty, institutional context, financial resources, and social feasibility). These factors define the decision space for managers facing RAD decisions (Clifford et al., 2022). More explicit consideration of mental models that shape how people view species (introduced or native) can act as a starting point for incorporating human dimensions into the process of formulating decision alternatives for managing biological invasions (Estévez et al., 2015; Shackleton et al., 2019; Lynch et al., 2022a, b). Through understanding the human dimensions of invasions, practitioners can identify a potentially broader range of decision alternatives (see below) for managing invasions that more effectively address invasion trajectories and are representative of the perspectives of stakeholders and rights holders (Ooft, 2008). This elevates the management of biological invasions from a purely conventional, ecological problem to a more integrated social-ecological issue and a broader range of solutions as envisioned by the RAD framework.

3 | ECOLOGICAL ISSUES

From the preceding discussion, it is clear a host of social influences and values can strongly contribute to decisions regarding tactics practitioners employ to address invasions (i.e., decision alternatives). These likely act through all stages of the invasion process (Figure 1). In this section, we focus on ecological processes using a hypothetical case study of local coexistence (syntopy) between a native species and an ecologically similar introduced species (Melbourne et al., 2007). Decision alternatives for addressing the problem are aligned with components of RAD (Table 2). As such, this example illustrates what application of RAD might look like in practice. Because our example was hypothetical, we do not address individual preferences for different alternatives based on social factors discussed above. In practice, individuals vary widely in their views of introduced species as described above. Furthermore, it is possible that these preferences may change with new information or experience with the effectiveness of decision alternatives (e.g., double or triple loop learning; Runge et al., 2013; Lynch et al., 2022a, b).

3.1 | Case study: Coexistence or control?

To specifically illustrate the potential consequences of RAD approaches to managing invasions, we consider the example of invasion of introduced brook trout and responses of a native congener (bull trout) in the western United States (Benjamin et al., 2017). Bull trout is listed as Threatened under the US Endangered Species Act (USFWS, 2015). Brook trout do not naturally occur within the native range of bull trout, but the species has been introduced widely to support popular recreational fisheries (Bahls, 1992; Dunham et al., 2004; Wiley, 2003). Although mechanisms of interactions between brook trout and bull trout likely vary considerably in space and time, the two species can potentially interact through interspecific competition, predation, hybridization (hybrids of the two species are generally sterile) and possibly transmission of pathogens (USFWS, 2015).

Interactions between introduced brook trout and native bull trout can influence demographic rates (e.g., growth, survival, and reproduction) of each species throughout the life cycle, which ultimately determines population persistence (Figure 2, modified from Benjamin et al., 2017). We employed a variation of an existing demographic model (Benjamin et al., 2017) to evaluate the general scenarios we identified for interactions between an introduced species and a native species (Table 2). Our point was not to use the model to precisely anticipate actual outcomes of decision alternatives, but

TABLE 2 A selection of potential scenarios for managing an introduced species in the context of managing impacts on an affected native species

Scenario	RAD strategy	Invasion stage	Decision	Tactics
R1	*Resist*	Preinvasion	Prevent initial introduction	Education, regulations, enforcement
R2	*Resist*	Early invasion	Removal	Surveillance to detect initial invasions, rapid response
R3	*Resist*	All	Control	Partial or periodic removal
R4	*Resist*	Later invasion	Removal	Full eradication
A1	*Accept*	All	No action	Allow invasion to occur without efforts to control
A2	*Accept*	Later invasion	Manage Impact Modifiers (MIM)	Manage physical environment to favor native species without control of introduced species
A3	*Accept*	Later invasion	MIM	Enhance life-history expression of native species to provide competitive advantage over introduced species without control of introduced species
D1	Direct	All	Translocation	Reintroduction or assisted migration of native species to a currently unoccupied location without the introduced species present

Note: Each scenario is paired with the most closely aligned Resist-Accept-Direct (RAD) framework to managing the trajectory of the invasion from preinvasion to later stages. Note that each scenario may include elements of more than one RAD approach. Decisions to take actions ranging from no action to a host of action-based alternatives are listed and briefly described. Specific actions or tactics associated with each decision are described.

rather to show how each can lead to different trajectories based on a reasonable population model and inputs of parameters from the available scientific literature and expert opinion.

3.2 | Model formulation

The dynamics of native and introduced trout were modeled using a deterministic, stage-based matrix model that allowed the two species to compete (Benjamin et al., 2017). For bull trout, we considered eight life-history stages separated into two expressions (resident and migratory; Figure 2a). Within the model, these two expressions are simplifications of movement patterns commonly observed for bull trout across the species' native range (Rieman & McIntyre, 1993). Here, resident fish are defined as those individuals that complete their life cycle within natal habitats. Migratory fish are those that move to exploit growth opportunities outside of their natal habitat and are often larger, and larger females are more fecund. For brook trout, we considered five life-history stages of resident-only expression (Figure 2b), which is often observed for this species where it is not native (Dunham et al., 2002). Brook trout can out-compete bull trout for resources (Gunckel et al., 2002, McMahon et al., 2007; Rodtka & Volpe, 2007). Competition between species was accounted for using a density-dependent survival function modified from Lee and Rieman (1997; Table S1). The model operates on an annual time step and was run over 30 years. Individuals in each stage transition to the next stage based on survival rates. Demographic vital rates used in the model were based on previous studies of bull trout and brook trout (Benjamin et al., 2017, Table S1). Model simulations were run on an annual time step in R using the package *popbio* (Stubben & Milligan, 2007).

3.3 | Model simulations

We applied the model (Figure 2) to a host of scenarios representing decision alternatives to evaluate their consequences for persistence of native bull trout (Table S2). These included representations of each of the generalized scenarios aligned with RAD (Table 3). Penalties identified below were based on stakeholder assessments that originated in a previous study (Benjamin et al., 2017).

For *resist*, four scenarios were focused on preventing invasion from occurring or removing introduced species at early or late stages of the invasion process (Figure 1). We assumed earlier stage invasions would have a starting (Year 1) brook trout to bull trout abundance ratio of 0.5:1, and later stage invasions would be 2:1. Scenario R1 simulated a barrier that would prevent brook trout from invading but would also no longer allow migratory life-history expression of native bull trout (Fausch et al., 2009). For R2 and R4, during the first year, brook trout were completely eradicated from a stream under earlier and later stages of invasion, respectively. Eradication is often done using a piscicide, thus, bull trout would need to be removed and held during piscicide treatments (Buktenica et al., 2013). To account for this, we assumed a 5% penalty on each life stage of bull trout during the first year. R3 simulated partial removal (control, in invasive species management parlance) of brook trout typically done through mechanical means (e.g., electrofishing, Meyer et al., 2006, Shepard et al., 2014, or direct removal via snorkeling and spearing, Banish et al., 2019). We simulated removal of brook trout based on electrofishing capture efficiencies used in previous models (Peterson et al., 2008). Because bull trout can also experience negative effects during capture, we penalized each life stage by 2.5%. Partial removal was done under late invasions during the first 3 years of simulations.

Accepting an invasion could result in no action being taken to control the introduced species and/or restoring conditions that may benefit the native species. Three scenarios were simulated to represent management actions of acceptance of the brook trout invasion. First, earlier (0.5:1 brook trout: bull trout) and later (late; 2:1) stage invasions were allowed to "play out" without any action to control brook trout or enhance conditions for the native fish. Second, to mimic potential actions that would improve spawning and rearing habitat for bull trout, we increased survival of their egg, juvenile, and resident subadult stages by 25% and adult fecundity by 10% (favor native species without control of introduced species; Table 2, A2). Third, to mimic actions, such as improving connectivity or downstream habitat conditions, that would benefit the migratory life history of bull trout, we increased the survival of migrant subadults and adults by 25% and the fecundity of adults by 10% (enhanced migratory life-history expression of native species; Table 2, A3). For Direct (translocation; Table 2, D1), a reintroduction of a bull trout population was simulated by adding 100 subadult fish for three alternating years (year 1,3,5).

3.4 | Simulated outcomes

Modeled outcomes for decision scenarios (Figure 3) for bull trout changed over time. In the short term (<15 years), controlling brook trout (*resist* scenarios) had the greatest effect on the number of adult bull trout. In the long term (>15 years), the scenarios with best outcomes for bull trout were improving habitat conditions without controlling brook trout (*accept* scenarios). Preventing invasion using barriers (R1), which eliminated the migratory component of bull trout, led to a decline of bull trout abundance. As expected, scenarios of accepting the invasion without improving habitat to benefit bull trout (A1 early, A1 late) led to continued declines of bull trout (while supporting brook trout). Lastly, reintroducing bull trout into an unoccupied stream resulted in a small, positive trend on bull trout abundance.

Our modeled outcomes suggest that some *accept* approaches, particularly those involving MIM, may be effective to conserve bull trout under the threat of introduced brook trout. Although we focused on bull trout (due to the mandate for recovering this threatened native species), it is worth mentioning that this alternative provides some value to individuals who value brook trout. Promoting migratory opportunities may provide a long-term opportunity for native and introduced trout to coexist. This may not be surprising, given a migratory life history is important to the persistence of bull trout

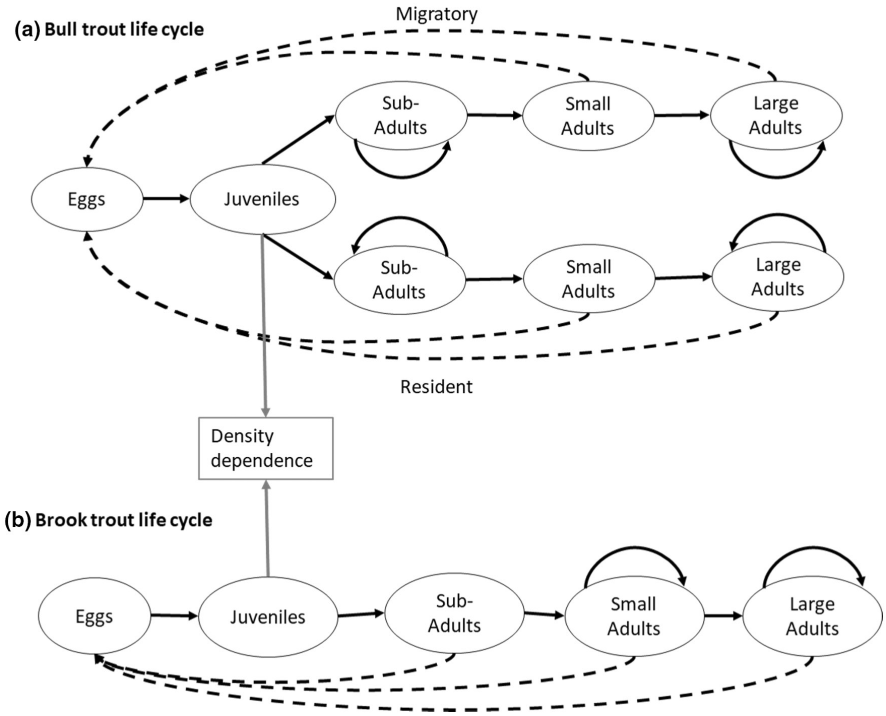

FIGURE 2 Diagram showing life cycles modeled for bull trout (*Salvelinus confluentus*); (a) and brook trout (*S. fontinalis*); (b). Bull trout typically have migratory and resident expression, whereas brook trout typically express only resident life history. Solid lines denote transitions from one stage to the next or persistence within a stage, and dotted lines denote reproductive output. Demographic rates are provided in Table S1. See Benjamin et al. (2017) for detailed model description

TABLE 3 Summary of decision scenarios related to *resist* (R), *accept* (A), and *direct* (D) tactics for managing native bull trout (*Salvelinus confluentus*) in the face of invasion by introduced brook trout (*S. fontinalis*). Specific actions associated with each decision, as well as model formulations are summarized (see Tables S1 and S2 for details)

Scenario	Decision	Model
R1	Installation of a downstream barrier to prevent upstream invasion	Persistence of bull trout upstream of the barrier without contributions from individuals that could migrate between downstream areas and the population upstream
R2	Brook trout eradication	Early-stage detection of brook trout invasion and eradication
R3	Control	Partial (electrofishing) removal of brook trout based on capture efficiencies (50%–65%; Peterson et al., 2008) over three consecutive years
R4	Brook trout eradication	Late-stage invasion and eradication of brook trout
A1	No action	Model persistence of bull trout without control of established brook trout under early and late invasion
A2	MIM	Enhance spawning and rearing habitat (e.g., cold water) to increase survival of early life stages of bull trout without control of established brook trout
A3	MIM	Enhance life-history expression to increase survival of migratory bull trout without control of established brook trout
D1	Translocation	Reintroduction or assisted migration of bull trout to a presently unoccupied location without brook trout present

(Brenkman & Corbett, 2005; Rieman & McIntyre, 1993; Warnock & Rasmussen, 2013). The importance of migratory expression was further supported by the decline in adult bull trout when a barrier was installed, although the effects of a barrier on bull trout could be mitigated if adult bull trout could be manually moved on an annual basis (Benjamin et al., 2017). This analysis assumes migratory destinations have sufficient habitat (e.g., temperatures, stream flows) and prey resources to support growth, if not then individuals may skip spawning one or more years until sufficient growth is achieved to support gamete production (Benjamin et al., 2020).

Resist management options to control introduced fish are common in current practice but may not always be necessary to conserve bull trout, at least in some of the scenarios we considered here. We considered two common approaches, partial (Meyer et al., 2006; Peterson et al., 2008) or complete (Buktenica et al., 2013) removal of brook trout, both of which can be effective for bull trout conservation. This may not be surprising given the known negative effects brook trout can have on bull trout populations (USFWS, 2015). However, these approaches, along with barrier installation, can be compromised by natural or human-assisted recolonization by brook trout, which we did not simulate. If brook trout recolonization was included in the model, it could negate the outcomes of the *resist* simulations (i.e., the negative influences of brook trout on bull trout would re-emerge upon return of brook trout to the system).

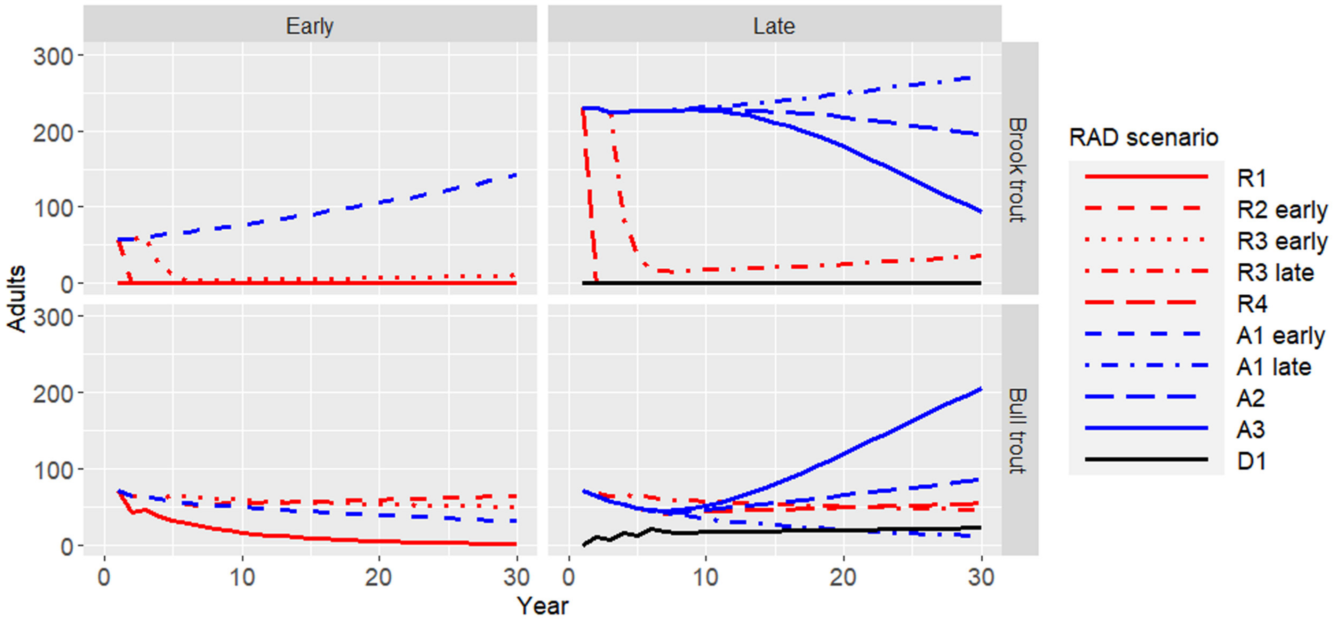

FIGURE 3 Number of adult brook trout (*Salvelinus fontinalis*; top) and bull trout (*S. confluentus*; bottom) over 30 years under each *Resist* (R), *Accept* (A), and *Direct* (D) decision scenario (described in Tables 1 and 2). Simulated management outcomes during earlier stages of invasion (brook trout to bull trout abundance ratio of 0.5:1) and later stage invasions (brook trout to bull trout ratio of 2:1) are shown

The *direct* scenario we considered showed a relatively modest, but positive response of bull trout. This should not be interpreted to mean that all *direct* options (i.e., translocations) have similar effects. Variable outcomes can emerge depending on the recipient system, release strategy and number of individuals released. Modeled outcomes from hypothetical translocations and empirical reviews of past attempted translocations highlight these factors as important for influencing their success (Benjamin et al., 2019; Brignon et al., 2018; Hayes & Banish, 2017).

4 | DISCUSSION

Although RAD does not perfectly align with many decision alternatives for managing biological invasions (Tables 2 and 3), it provides an intelligible rubric for explicitly identifying decisions that are often not acknowledged in practice (Schuurman et al., 2022). Preferences for decision alternatives are based in part on preexisting knowledge, values, and perspectives of individuals (Clifford et al., 2022), so it is important to consider both social and ecological factors that influence their formulations (Lynch et al., 2022a, b). Furthermore, perspectives of individuals are often in place before ecological problems are recognized or assessments are conducted, and thus our reason for describing their importance before considering a full spectrum of ecologically formulated decision alternatives for addressing a biological invasion. Whereas ecological models such as those employed in the case study herein can provide critical information (e.g., modeled outcomes of decision alternatives) for decision *support*, actual decision-*making* is a product of a much broader spectrum of considerations (Clifford et al., 2022; Conroy & Peterson, 2013; Gregory et al., 2012). Decisions that are made in practice are partly a consequence of which decision alternatives are brought into consideration and social factors can play a role in determining which alternatives are included. Here, we discuss these issues in the context of our specific example, and when possible, we point to broader insights that highlight the potential value of RAD for biological invasions.

In our modeled outcomes from RAD alternatives for managing introduced brook trout and recovery of native bull trout, we found that *resist*, *accept*, and *direct* alternatives (Tables 2 and 3) can all lead to desirable outcomes with respect to the native species (Figure 3). Given widespread concerns over ecological and social consequences of invasive species and their impacts (Olden et al., 2021), it should be no surprise that *resist* is an important component of conventional management actions (Figure 1). In the case of bull trout, some RAD alternatives (e.g., *accept* displacement of an existing bull trout population with brook trout) may not be acceptable from an institutional or regulatory perspective, as the species is afforded protections under the U.S. Endangered Species Act (e.g., the Act mandates avoidance of actions that harm a listed species). Even within this regulatory instrument, however, there are diverse provisions that allow for considerable flexibility in terms of implementation to recover threatened and endangered species (Dunham et al., 2016; Henson et al., 2018). These calls for broader implementation of provisions within existing regulations are consistent with the value of embracing a broader range of alternatives as specified by RAD.

In the context of biological invasions, the *accept* alternative is not well-represented in contemporary ecological literature (Dunham et al., 2020; García-Díaz et al., 2021b), but our modeled scenarios indicated that positive ecological outcomes (e.g., maintain or increase abundance of bull trout) can be realized through this alternative. This included benefits from increasing availability of cold-water habitat favoring bull trout and improving the expression of migratory life histories of bull trout, without control of brook trout (Figure 3). In practice, *accept* is a common decision for the problem we considered because a host of factors limit the capacity of practitioners to address introduced brook trout in most locations (leading to adoption of "no action" or A1 by default, Table 2). For example, common justifications for "no-action" include but are not limited to (1) situations where managers and/or the public have a preference for introduced over native species, or are content with either ecologically similar species; (2) the ecological, social, or institutional environment constrains the ability to successfully eradicate introduced species; (3) funding or logistical constraints severely limit the capacity to eradicate introduced species, (4) collateral damage associated with eradication is unacceptable, or (5) trade-offs are difficult to resolve (e.g., the costs and benefits of isolating native populations to protect them from invasions, Fausch et al., 2009). Our analysis shows that adverse outcomes from at least some *accept* decision alternatives are not inevitable, and, in fact, that benefits for native species are possible in some scenarios. We are not aware of examples of *accept* alternatives that involve actions such as those specified by A2 (favor native species without control of introduced species) and A3 (enhanced migratory life-history expression of native species; Tables 2 and 3) that have been intentionally implemented to benefit native bull trout without control of introduced brook trout (but seen Thornton et al., 2017), but these alternatives offer some promise when *resist* is not an option.

The third alternative we considered, *direct*, represents a different departure from commonly accepted alternatives for managing introduced species. We focused on translocating the native species (bull trout) outside of its historical range as an alternative. For bull trout, nearly all translocation efforts have focused on reintroductions within the species' historical range (Hayes & Banish, 2017). Although translocations of trout far beyond historical ranges have been undeniably successful in establishing populations on a global scale (Arismendi et al., 2014; Crawford & Muir, 2008), stakeholder support for such translocations to benefit native species for conservation purposes is often quite low (Kemp et al., 2015).

In the case of bull trout, there are many examples of proposed reintroductions and feasibility assessments (Benjamin et al., 2017; Brignon et al., 2018; Benjamin et al., 2019; Dunham et al., 2011), and although the ecological success of these efforts has yet to be fully realized (Hayes & Banish, 2017), they can be characterized as social successes in terms of the decision process where not only ecological, but social and institutional considerations were aligned (Dunham et al., 2016). Well-documented translocations of bull trout outside of the species historical range are few, but there is at least one case of a long-established population resulting from human-assisted colonization above a natural waterfall (South Fork of the Skykomish River, WA; USFWS, 2015). Newer assessments of such translocations (Karasov-Olson et al., 2021) and at least one emergency translocation (Galloway et al., 2016) may provide further examples to learn from in the future.

Our analysis of translocation of bull trout to a novel location indicates that it is a potentially viable alternative. Under the conditions modeled here, however, population growth is slow, with decades needed to attain increased numbers of individuals. Given the relatively long-generation time of bull trout and the time it takes to produce larger, more fecund individuals that can greatly increase potential recruitment, it is perhaps no surprise that many relatively recent translocations of the species have yet to yield measurable results (Hayes & Banish, 2017). There are a host of other factors that can explain the lack of success in extant reintroductions (Benjamin et al., 2019; Hayes & Banish, 2017), but time is likely a factor as well. In contrast to the current situation for bull trout, other threatened native fishes have been completely recovered through a strategy involving a mix of conservation of extant populations, reintroductions, and translocations to novel habitats (Dunham et al., 2016). These examples of successful conservation outcomes have involved the full spectrum of RAD alternatives or portfolios of RAD (Magness et al., 2022) applied to different portions within and outside of the historical range of a species.

4.1 | Management implications

Developments in many concepts discussed here have occurred rapidly and may be difficult to track in practice. Accordingly, we end with a series of implications for managers to consider relative to the concepts presented here:

- *A RAD approach to managing invasions opens the dialogue to a broader range of decision alternatives*. Conventional approaches to managing biological invasions of freshwater fishes (or any species or ecosystem) focus on solutions early in the invasion process (e.g., early detection and rapid removal) or control within systems that are more easily contained (e.g., smaller, closed systems as opposed to large, open systems). While these approaches are reasonable in many settings, RAD is a useful starting point for considering a more complete portfolio of approaches across transforming ecosystems, regardless of whether the change agent is biological invasions, other influences, or both.
- *Upstream engagement*. When engaging stakeholders and rights holders in the process to identify fundamental objectives and decision alternatives to attain them, encourage early and open discussion of their perspectives, preferences, and needs (e.g., "upstream engagement," Magness et al., 2022; Wilsdon & Willis, 2004; Yung et al., 2013). Consider reaching out further into surrounding communities to better understand social contexts before identifying specific problems and solutions. Such efforts can lead to inclusion of a broader range of decision alternatives and potentially greater acceptance of decisions that are ultimately implemented. Consider these social outcomes as a measure of success equal to ecological outcomes. In other words,

consider the decision-making process to be as important as realized outcomes from implementing a selected alternative (Conroy & Peterson, 2013; Gregory et al., 2012).

- *Formalize models of system dynamics*. Following upstream engagement, consider additional effort to work with managers to provide a common understanding of system dynamics. In structured decision-making, this usually involves co-production of formal, quantitative models that are employed to simulate consequences of decision alternatives, including an assessment of future trajectories (e.g., climate change, land-use change), model uncertainties, and sensitivity to uncertainties about model structure or inputs (Conroy & Peterson, 2013; Gregory et al., 2012; Lynch et al., 2022a, b). While this process of knowledge co-production can produce many benefits (e.g., inclusion of a broad range of perspectives, social buy-in or acceptance), there can be substantial costs involved as well, such as the time, funding, and personal commitments needed to deliver meaningful results (Lemos et al., 2018). Deliberate consideration of the benefits and costs of co-production can help to identify when it is warranted.
- *Long-term engagement*. Even in cases of successful prevention or control of introduced species, management of biological invasions is a long-term process. The reality of ecological transformation and social changes (e.g., changes in how stakeholders and rights holders perceive the issues and solutions regarding management of introduced species) is important to consider if more than short-term, incremental success is needed. From an institutional perspective, institutional policies, staff turnover, and other changes can create discontinuities that lead to loss of shared objectives, foster conflicts, and weaken trust (Stern & Coleman, 2015).

Management implications highlighted above derive from our review of social and ecological factors that influence decisions for managing biological invasions as framed by RAD. An overarching theme is that a more integrated social-ecological approach can help to identify a broader range of approaches to managing biological invasions, with the hope of realizing improved outcomes. Although we presented both social and ecological components of RAD (see also Lynch et al., 2022a, b) for managing biological invasions, our treatment of these was necessarily selective. Full accounting of the complexity inherent within social-ecological systems is a truly daunting prospect (e.g., Dunham et al., 2016; Güneralp & Barlas, 2003; Linders et al., 2020). These complexities should not act as a barrier, however, as our review points to a host of factors that can be productively addressed to get started on the path to more fully addressing the complex challenge of biological invasions.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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