RAD Adaptive Management for Transforming Ecosystems

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Intensifying global change is propelling many ecosystems toward irreversible transformations. Natural resource managers face the complex task of conserving these important resources under unprecedented conditions and expanding uncertainty. As once familiar ecological conditions disappear, traditional management approaches that assume the future will reflect the past are becoming increasingly untenable. In the present article, we place adaptive management within the resist–accept–direct (RAD) framework to assist informed risk taking for transforming ecosystems. This approach empowers managers to use familiar techniques associated with adaptive management in the unfamiliar territory of ecosystem transformation. By providing a common lexicon, it gives decision makers agency to revisit objectives, consider new system trajectories, and discuss RAD strategies in relation to current system state and direction of change. Operationalizing RAD adaptive management requires periodic review and update of management actions and objectives; monitoring, experimentation, and pilot studies; and bet hedging to better identify and tolerate associated risks.

Keywords: contemporary climate change, nonstationarity, natural resource management, climate adaptation, loop learning, loop leaps

Natural resource managers face a daunting task: maintaining dynamic and often unpredictable ecological systems within some desired range of conditions frequently defined in terms of historical observations. Adaptive management has helped guide managers in this task by employing an iterative approach to foster learning and refine objectives and potential actions for more effective decision making (Holling 1978, Walters and Hilborn 1978, Williams 2011). As a management philosophy, adaptive management generally operates under a number of elemental premises, including the ability to (1) clearly define desired management outcomes; (2) characterize structural uncertainty by a set of competing, testable models; and (3) adequately influence or control the system (controllability; Williams et al. 2007). Although variation around a stable mean (stationarity; Milly et al. 2008) is not a formally defined assumption of adaptive management, it is often implicit in either the system models or the objective-setting process (Williams and Brown 2012). Many of these considerations can hinder adaptive management from broader usage (Westgate et al. 2013).

Although climate-smart conservation has effectively drawn adaptive management into the climate change arena (Stein et al. 2014), ecosystem transformation poses some direct challenges to adaptive management's basic tenets—namely stationarity, characterizing uncertainty, and controllability (Williams and Brown 2016). A transforming ecosystem is one exhibiting shifts in multiple components that are not easily reversed through management actions (see Schuurman et al. 2021). Anthropogenic ecological trajectories and ecosystem transformations are now recognized to be occurring at rates that render the historical range of variability less and less relevant as a management target (Walters and Holling 1990, Millar et al. 2007, Wiens et al. 2012, Schuurman et al. 2021). However, a dominant assumption that the future system behavior will mimic past behavior remains in management approaches (Nichols et al. 2011, Beever et al. 2013, Schuurman et al. 2021).

To facilitate a transition to managing ecosystems in which past experiences no longer suffice, we place adaptive management within the resist–accept–direct (RAD) conceptual framework (Lynch et al. 2021, Thompson et al. 2021, Schuurman et al. 2021). The RAD framework is a simple, flexible tool to help managers make informed, purposeful choices about how to *resist, accept,* or *direct* changes in ecosystems; the tool applies both on public and private lands (Schuurman et al. 2020). We build from a strong body of adaptive-management and loop-learning literature (Flood and Romm 1996, Williams et al. 2007, Pahl-Wostl 2009, Williams and Brown 2014, 2016, 2018), but emphasize that managing transforming ecosystems requires an explicit

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Box 1. Using a compass and a gyroscope to navigate a transforming world.

The resist–accept–direct (RAD) framework (Lynch et al. 2021, Schuurman et al. 2021, Thompson et al. 2021) can help a manager navigate a transforming world like a compass helps one navigate toward a specific destination, providing guidance on when a management pathway needs redirecting because it will no longer effectively reach the desired destination. *Surveillance* monitoring, experimentation, and pilot studies are essential components of this process.

Adaptive management can help maintain a management pathway like a gyroscope is used to maintain a heading. It offers iteratively improved precision along an identified pathway that leads to a predefined desired outcome via feedback loops of technical learning, institutional learning, and changing values and beliefs over decades (and perhaps longer). *Targeted* monitoring is necessary to evaluate and adjust management actions.

Note that Lee (1994) originally proposed the compass as an analogy for adaptive management and the gyroscope as an analogy for public and stakeholder participation in democratic decision processes. Lee's intent was to focus on improving social learning. At that time, most managers viewed ecosystems as stationary, and adaptive management was often implemented with the single-loop model, focused on technical solutions (Walters 1986).

In the present article, we flip the original analogy because current system states are now acknowledged to be more complex, with multiple plausible ecological trajectories (Laycock 1991, Tausch et al. 1993) and multiple management pathways (Magness et al. 2021). In addition, adaptive management has further evolved to embrace social inputs, so multiple learning loops (Pahl-Wostl 2009, Williams and Brown 2018) are needed in the conceptual space originally occupied in Lee's compass–gyroscope analogy (figure 1).

understanding of the current functions and trajectory, a marked shift from conventional interpretations of adaptive management (box 1). We present a case study from the Mojave Desert (box 2) on how to operationalize RAD adaptive management. And, we conclude by acknowledging that although risks may be reduced, there is no one pathway to one final state amid a transforming world. RAD adaptive management is an iterative process that requires periodic review and update of management actions and objectives; monitoring, experimentation, and pilot studies; and bet hedging to support informed risk taking.

Staying the course

Adaptive management is generally defined as a six-step cycle of assessing, designing, implementing, monitoring, evaluating, and adjusting that allows managers to work iteratively toward improved understanding and improved management over time (Williams et al. 2007). Adaptive management was initially envisioned as a single loop (Walters and Hilborn 1978) that incorporates technical learning. Later, a second loop (Argyris and Schön 1978) was added to incorporate institutional learning and, together with the single loop, composes the six-step cycle that is most familiar to natural resource managers (Williams and Brown 2018). A third loop (Pahl-Wostl 2009) was later suggested to allow updates to underlying values and beliefs (see Williams and Brown 2018).

Within this adaptive-management cycle, every step is intended to refine and improve movement toward a predefined management target. If the identified objectives continue to be feasible, continued *targeted* monitoring ("designed around testable hypotheses over defined areas"; Sparrow et al. 2020, p. 1706), experimentation, and pilot studies can be used incrementally to improve management action without questioning the underlying assumptions (figure 1, inner loop). Even in this stationary situation, it is important to recognize the need to consider both near-term and temporally distant planning horizons (Walters 1986). For example, the Great Lakes lampricide program considers the immediate impacts on the treated tributaries, as well as the longer-term lake-level benefits of sea lamprey (*Petromyzon marinus*) control measures (Siefkes et al. 2014). Similarly, a US Fish and Wildlife Service management program for midcontinent mallards (*Anas platyrhynchos*) employs adaptive harvest by iteratively examining relationships between waterfowl populations, harvest, and broader societal processes to improve hunting regulations with each new increment of learning (Johnson et al. 2015). Such processes must be revisited frequently because directional change can quickly derail management pathways.

Adjusting the course

If management objectives are no longer feasible but the current RAD pathway is still considered the appropriate strategy, managers can still operate in the six-step adaptive-management cycle. This involves revisiting assumptions about cause–effect relationships and adjusting management objectives to align with feasible outcomes (figure 1, middle loop). Interventions may need to change or intensify to maintain a system state, if the system is subject to escalating directional drivers. *Targeted* monitoring, experimentation, and pilot studies can be used to test and refine potential management interventions that may later be implemented at broader scales (Nichols and Williams 2006). For example, comparing tree seedling densities after different prescribed fire treatments can guide actions for expanding the area of a functional grassland system and serve as metrics of success when directing transformation of a forest ecosystem to grassland (Davis et al. 2019). Managers may choose in this loop to be forward looking, and perhaps assess species'

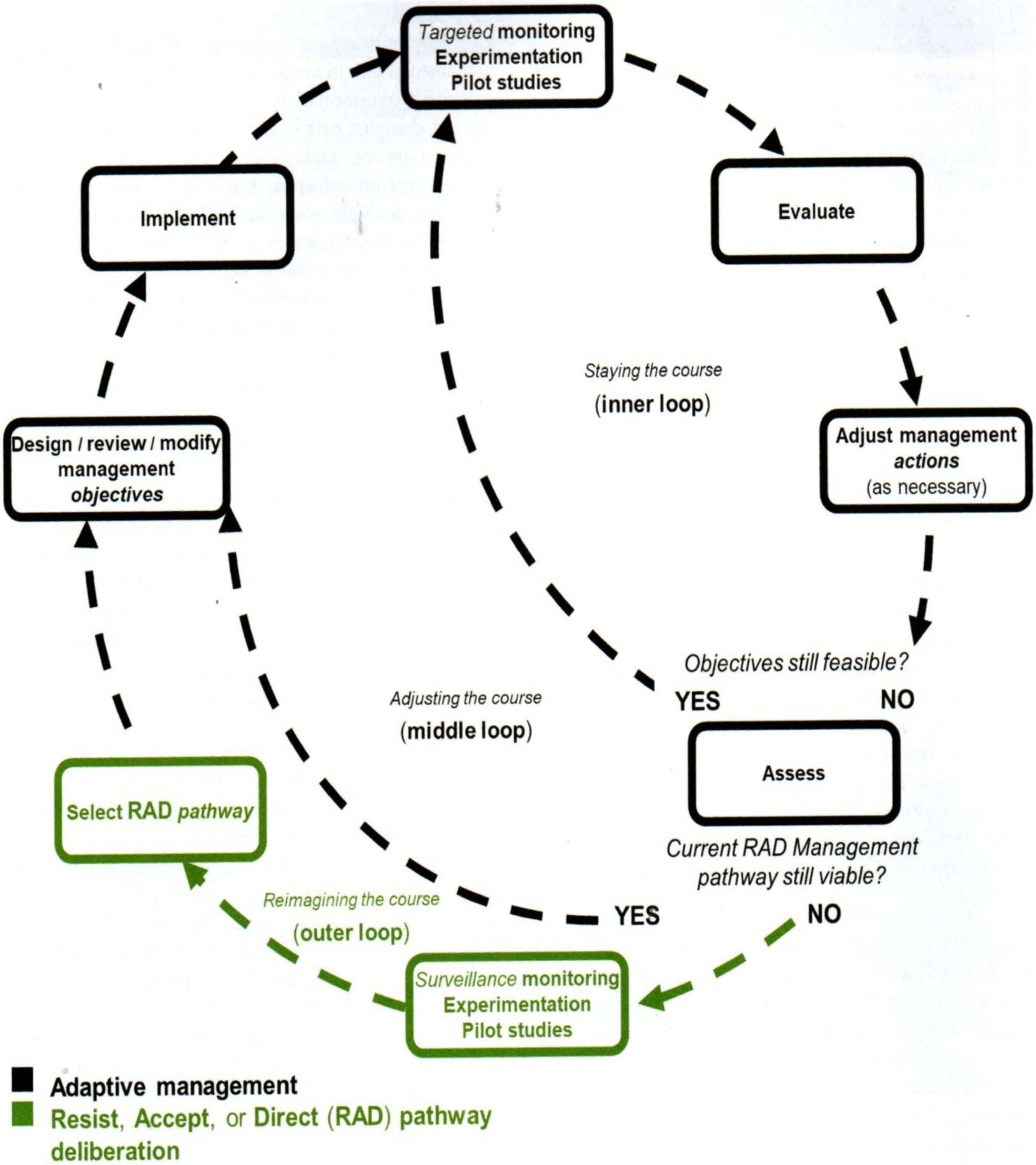


Figure 1. Adaptive management is generally defined as a six-step cycle (black). The resist–accept–direct (RAD) framework (green) can be overlaid on this process to assist informed risk taking for transforming ecosystems.

adaptive capacity (Thurman et al. 2020) or climate-change vulnerability (Foden et al. 2019) on the basis of their attributes or observed status and trends (Nicotra et al. 2015).

Reimagining the course

In the six-step adaptive-management model, the management pathway does not need to change, because fundamental drivers of ecological condition are considered stationary. However, as ecosystems become vulnerable to irreversible transformation, decision makers will need to refocus on emerging processes such as altered hydrology, loss of topsoil, or marine acidification, or on critical components such as keystone, foundation, or invasive species. More fundamentally, they will need to identify alternative acceptable (or least unacceptable) outcomes if previous management objectives become infeasible (Crausbay et al. 2021). Including stakeholders and rightsholders in RAD deliberations can help identify the existing knowledge base and community values to determine feasible and desirable system trajectories, given ecological, economic, and sociopolitical constraints (Lynch

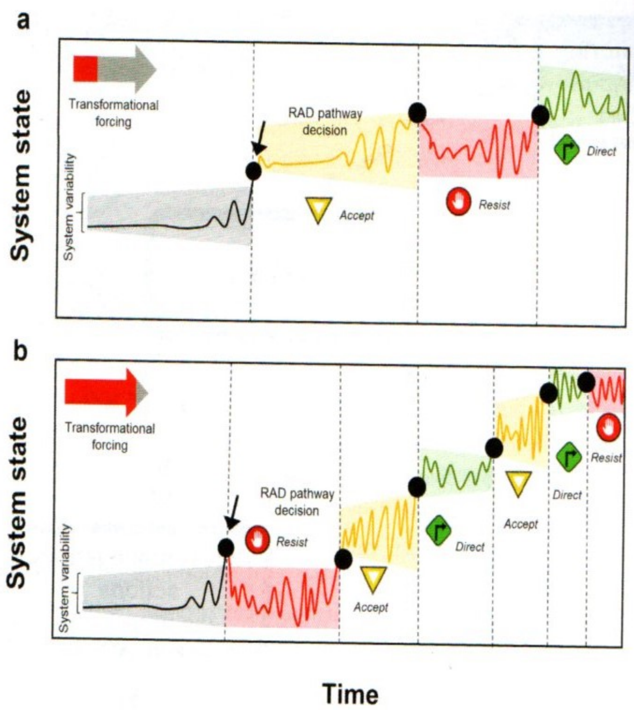


Figure 2. Heuristic decision pathways using adaptive management that begin with a current ecosystem (grey) affected by (a) moderate or (b) strong transformational forcings that drive outer-loop decisions (black dots) to* resist *(red time periods),* accept *(yellow), or* direct *(green) the trajectory of change. Under continued transformation, ecosystems depart farther in multidimensional space from starting conditions and system variability may increase in some cases. Stronger transformational forces may require revisiting the outer loop more frequently because the rate of ecosystem transformations is likely to increase.

et al. 2021). RAD deliberations can be a standalone process or integrated into other existing planning processes such as scenario planning (Peterson et al. 2003), structured decision making (Conroy and Peterson 2013), and climate-smart conservation (Stein et al. 2014). Climate-smart conservation is a particularly good complement for RAD adaptive management because it is built on a foundation of adaptive management and explicitly acknowledges the need to manage for change, not just persistence (NPS 2021).

Managers and other decision makers can collaboratively examine multiple pathways within the RAD framework to address transformations in ecosystem structure, function, and services. If a management pathway is no longer viable, assessment of alternative options can help reduce uncertainties about system trajectories, drivers, and responses to potential management interventions (figure 1, outer loop). For example, prescribed fire can be used in some locations to experimentally assess how changing wildfire regimes shape current and future ecosystems by linking fire behavior to fire effects in real time (Hiers et al. 2020). Likewise, common gardens may be used to explore which species (Berend et al. 2019) or plant genotypes (Flanagan et al. 2018) are best suited for managed relocation (Crausbay et al. 2021).

Loop leaps

Inevitably, setting goals for the distant future will require a fundamental shift in management thinking to accommodate ecosystem transformation. Openness to continued learning and changing pathways is necessary because ecological surprises are inevitable (Walker and Salt 2012). Adaptive management objectives for transforming ecosystems need to explore multiple, plausible ecological trajectories (Noy-Meir 1975, Bestelmeyer et al. 2003, Crausbay et al. 2021, Magness et al. 2021), and strategies may shift as ecological surprises manifest themselves (Williams and Jackson 2007). Management culture may need to shift to a mindset that encourages risk taking, nimble responses, and a greater commitment to learning through science-based processes; Crausbay and colleagues (2021) defined many science priorities raised by the information needs of this new management outlook.

The uncertainties associated with ecological transformation will make it increasingly difficult to identify pathways that are simultaneously ecologically viable, socially acceptable, and economically feasible (Lynch et al. 2021). Multiple decision points in RAD adaptive management provide opportunity to reassess 1) whether the objectives are still feasible and 2) whether the currently pursued RAD pathway is still viable (figure 1). Should a change in course be warranted, the management trajectory can be reset to a different course through a loop leap (figure 2).

Needing to know when to leap the nested management loops, either to revisit objectives along the same RAD strategy pathway (figure 1, middle loop) or to consider new system trajectories and RAD strategies (figure 1, outer loop), presents new challenges that may require different approaches for different systems. The knowledge necessary for loop leaps comes from establishing effective monitoring programs to refine plausible future trajectories, identifying nearby ecological tipping points (Dakos et al. 2019, Magness et al. 2021), designing experiments to examine system thresholds, or planning pilot studies to test alternative management actions (table 1).

Loop leaps may be needed more frequently where transformations are happening more rapidly because of the magnitude of climate-change exposure, frequency of extreme climate events, and other drivers of change. In extreme cases, the outer loop may need frequent visitation, shifting among RAD strategies over time (figure 2). Even within a particular management jurisdiction, transformational forces can vary. For instance, environmental conditions are likely to deteriorate more rapidly at the trailing edge of a shifting species' range than at the center (Hampe and Petit 2005). As one illustration, the endangered American burying beetle (*Nicrophorus americanus*) requires uncompacted, moist (nonsaturated) soil to bury carrion and uses different habitat types in northern and southern regions of the Great Plains in the United States, which vary in both temperature and precipitation (Leasure and Hoback 2017). As the frequency, duration, and intensity of drought conditions across

Box 2. A case study of RAD adaptive management in the Mojave Desert.

The Mojave Desert is the driest region of North America, and experiences extreme seasonal temperature variability; summer temperatures can exceed 54 degrees Celsius (129 degrees Fahrenheit) and winter temperatures can fall below freezing. The region is characterized by large topographic and elevational variability, ranging from –85 meters (m; –279 feet) to over 3500 m (over 11,000 feet). The large topographic variability and dearth of surface water account for the high numbers of endemic species, threatened and endangered species, and isolated and unique ecosystems (NatureServe 2021). Over the past three decades, the Mojave has experienced rapid anthropogenic development, which is likely to increase as cities in the region grow. Drivers of ecosystem transformation are wide ranging and include introduced species, groundwater pumping, and climate change. A decline in species richness and distributions over the last century (Iknayan and Beissinger 2018, Riddell et al. 2021) is expected to intensify as the Mojave becomes warmer and drier with increasingly frequent extreme-weather events (Seager et al. 2007, Diffenbaugh et al. 2008, Cook et al. 2015).

Water is the most limiting resource in the Mojave. Because both uncertainty (future hydrological regimes) and controllability (water is highly manipulated in managed portions of deserts) are high, adaptive management may be particularly useful when discussing water-related RAD actions in arid landscapes (Allen et al. 2011). However, the Mojave presents four major challenges that successful (RAD-based) adaptation must overcome: (1) multiple competing demands on limited resources that will likely intensify in the future; (2) multiple jurisdictions include several federal agencies, Tribal nations, states, and local municipalities; (3) changing policy directives from new political administrations that alter or shift implementation of management strategies; and (4) slow ecological processes that may require multidecadal timescales before *a priori* management triggers are met. The temporal mismatch between ecosystem processes and management actions presents a challenge for all managers; however, the RAD pathway provides a framework for before, during, and after (figure 2). In this Mojave case study, we use desert springs to illustrate two spatial scales of application for RAD adaptive management.

Ash Meadows National Wildlife Refuge (NWR) comprises numerous desert springs; it possesses unique flora and fauna and has the highest concentration of endemic species in the United States, 26 endemic species inhabit the 9700-hectare (24,000-acre) refuge, including 12 species federally listed as threatened or endangered (Sada 1990). Legislative directives (i.e., US Endangered Species Act) require managers to preserve listed species and habitats (figure 3a). Management objectives, which have been focused on increasing the population size of the endangered Devils Hole pupfish (*Cyprinodon diabolis*) that occurs in only one spring, have been pursued using various actions such as supplemental feeding and habitat manipulation (figure 1, inner loop). The population size continues to decline (Hausner et al. 2014), however, and a refugial population has been created elsewhere as a safeguard. Objectives, which currently include maintaining a viable population *in situ*, may need modification (e.g., to *ex situ*) to meet metrics of success (figure 1, middle loop). Reconsideration of the current RAD pathway (implicitly, *resist*) could be triggered by either continued declines in population size or prohibitive costs (figure 1, outer loop).

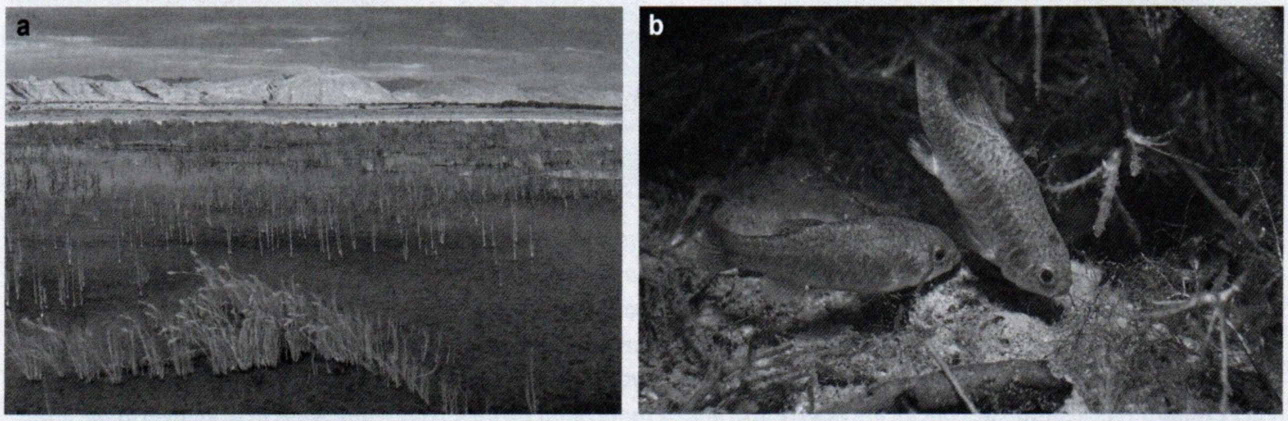


Figure 3. (a) Alkali seep at Ash Meadows National Wildlife Refuge in southern Nevada, a biodiversity hotspot and one of the largest remaining oases in the Mojave Desert. The refuge provides rare spring and wetland habitats for 26 endemic species, 12 of which are federally threatened or endangered. Photograph: Peter Pearsall/USFWS. (b) The Shoshone pupfish (*Cyprinodon nevadensis shoshone*) historically occurred in Shoshone Spring and throughout its outlet creek in Inyo County, southern California. Photograph: Steven David Johnson.

At broader spatial extents, desert-spring biota throughout the Mojave are threatened by numerous invasive aquatic species (Parker et al. 2021). In some springs, managers have *accepted* transformation of entire fauna into assemblages composed almost entirely of invasive species, particularly when alternative actions are hindered by recreational objectives. Warm desert springs often represent the only swimming holes in rural communities. At other springs, managers have *resisted* change by maintaining or restoring native species by various actions such as invasive species removal and water treatments (figure 1, inner loop).

Metrics of progress indicate that the response of native species to these strategies vary across the Mojave (Parker et al. 2021). Objectives may need revisions to meet the goal of a robust native spring fauna in the Mojave, a metric of success (figure 1, middle loop). For example, objectives could shift to efforts aimed at increasing native species distribution by creating new spring habitats to be stocked with natives (figure 3b). This strategy as a bet-hedging technique is already used in the Mojave, where managers have *directed* change by establishing multiple refugial populations of imperiled species in artificially constructed aquatic environments (figures 3c, 3d). *Surveillance* monitoring could be used to track the status of existing springs in the Mojave, whereas *targeted* monitoring could be used to manage artificial spring

Box 2. Continued.

habitats (Wintle et al. 2010). Reconsideration of this RAD pathway could be triggered by continued declines of native spring species or if water availability becomes reduced to a level at which human use is prioritized over allocation of water for conservation (figure 1, outer loop).

Integrating adaptive management into the RAD decision-making space presents opportunities to address considerations of environmental justice (Crausbay et al. 2021). The Mojave has racially and ethnically diverse populations, a wide rural–urban divide, and a history of inequities associated with past natural resource management decisions. Environmental justice concerns center around equitable distribution of environmental benefits and burdens, which can be incorporated into multiple decision points along the RAD pathway. Effective inclusion of these considerations into planning processes is often an agency requirement, a moral imperative, and can improve the chances for long-term success by incorporating a broader range of knowledge and perspectives into management decisions (Stirling 2008, Daley and Reames 2015, Magness et al. 2021). Specifically, consulting and engaging Tribal and other underrepresented populations in a genuine and respectful way that is meaningful to them is most effective, from clear responsibilities for the different parties at the outset on through the development and implementation of the work. In addition, explicit acknowledgement of the unequal distribution of past environmental burdens in the Mojave can act as a starting point for discussions about how to improve future decision making. For example, in Las Vegas, Nevada, affluent neighborhoods that contain more parks and landscaping are cooler and less climatically stressed than lower-income communities (*sensu* Smith et al. 2020). Managers can promote more equitable outcomes by recognizing past injustices, following environmental-justice requirements and best practices, and including multiple perspectives in decision making. For instance, in situations in which resistance may be more desirable (use of scarce water resources to maintain riparian forests), *resist* actions should be equitably allocated among communities regardless of economic status, ethnicity, or geographic location.

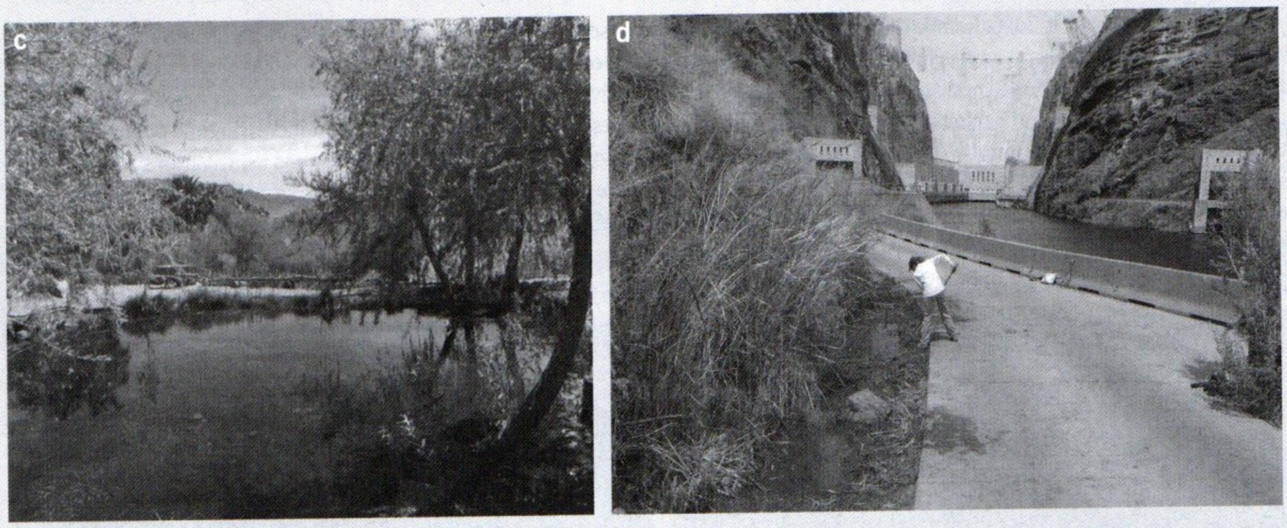
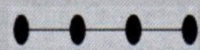


Figure 3. Continued. (c) Excessive water diversion for agriculture and other human use resulted in severe habitat loss, and the Shoshone pupfish was presumed extinct until a single population was rediscovered in a drainage canal in the mid-1980s. Today, Shoshone pupfish numbers have rebounded because of collaborative efforts among multiple entities (Shoshone Village, The Amargosa Conservancy, agencies, universities) to create, stock, and maintain spring-fed ponds for the species. Photograph: Susan Sorrells. (d) Similarly, maintenance of aquatic habitats created for refugial populations of the imperiled relict Leopard Frog (**Lithobates onca*****), previously distributed throughout springs, creeks, and seeps in drainages of the lower Colorado River watershed, is necessary. Photograph: USFWS.***

Although our case study depicts a (relatively) straightforward path along a theoretical model, we acknowledge that, in reality, events rarely unfold according to plan. Still, several key messages from the Mojave can be applied more broadly. First, small-scale pilot studies may be easier to initiate on private lands. For example, nonprofit organizations that act as land managers are often less constrained by federal mandates, such as the National Environmental Policy Act, and their decision-making process is typically faster. These nimble organizations have more flexibility when executing RAD options and, therefore, can be a good platform for pilot studies associated with adaptive management. Second, when working with multiple partners across a landscape, some communities may be more open to experimenting with RAD approaches. These communities can provide opportunities to test not only ecological interventions but also different engagement and communication methods for enhancing stakeholder and rightsholder relationships and collaboration. For example, some Tribal Nations in the Mojave have expressed a willingness to experiment with constructing solar energy facilities that use novel wildlife-friendly designs (DOI 2020). Third, participatory planning processes designed to serve as a compass will be most effective when drawing from a comprehensive suite of stakeholders and rightsholders (box 1). Broad participation from community members such as private landowners, conservation organizations, off-road recreationists, Tribes, and agencies was key to successful implementation of RAD actions in the Mojave, and this pattern is likely to hold for other rural communities embedded within landscapes in which adaptive management occurs. Finally, one-third of human populations live in countries characterized by water stress (Vörösmarty et al. 2010), and water scarcity is projected to increase globally because of a changing climate, population growth, and economic development (Hoekstra et al. 2012). Unconventional approaches highlighted in our case study may offer insight to natural resource managers in other arid environments.

Table 1. Loops within the resist-accept-direct (RAD) adaptive-management framework with their purpose, typical actors, iteration frequency, and potential information-gathering approaches that can be used for navigating the loops.

Loop	Purpose	Actors	Relative iteration frequency	Information gathering approaches
Outer Reimagining the course	Navigate the existing knowledge base to identify desired ecosystem futures and relevant RAD strategies given ecological, economic, and social constraints	Policy makers, stakeholders, managers		*Surveillance* monitoring to refine plausible future trajectories, experiments and pilot studies to examine potential RAD pathway changes
Middle Adjusting the course	Develop management objectives under the current RAD pathway in order to achieve desired ecosystem futures	Stakeholders, managers		*Targeted* monitoring to identify ecological tipping points, experiments to examine system thresholds
Inner Staying the course	Implement, monitor, evaluate, and adjust actions to iteratively improve management effectiveness and achieve management objectives	Managers		*Targeted* monitoring to evaluate progress toward management objectives, pilot studies and experimentation to test alternative management actions

Note: Although we depict iterations occurring at regular frequencies, the middle- and outer-loop iterations may be triggered by regular revisit schedules, detected by crossed thresholds, or linked to contingencies defined through planning processes.

the Great Plains are difficult to accurately model (Feng et al. 2017), conserving the American Burying Beetle may require more nimble and slightly different responses in different areas of its range.

Who bears the burden of implementation and opportunity costs when loop leaps occur will depend on the RAD pathway selected. For example, an *accept* objective may only result in monitoring costs for public-land managers but may involve substantial financial or social consequences for other stakeholders and rightsholders if it leads to loss or degradation of ecosystem services. Potential trigger points (Mulder et al. 1999) for loop leaps and socioeconomic and environmental-justice implications for potential pathways are considerations across any option (Magness et al. 2021). Because learning is ongoing through the process, timing of reevaluation can be refined (figure 2).

As a specific example, Devils Tower National Monument in northeast Wyoming, in the United States, is centered on a massive igneous monolith rising above the surrounding plains, which Native peoples consider sacred and have lived and held ceremonies beside for thousands of years. The whole management unit—including a complex of ponderosa pine (*Pinus ponderosa*) forest and woodland, some with a bur oak (*Quercus macrocarpa*) understory, and meadows flanking the base of the tower—is an ethnographic landscape, and modern connections between Native American culture and the tower are maintained through personal and group ceremonies and practices. Preserving ethnographic resources, including meadows used as ceremonial sites, is therefore a management priority. However, a recent climate change scenario planning process highlighted the possibility of strong future shifts in the forest–meadow ratio that might affect an important ceremonial space. In recognition of the potential need to *resist* or *direct*, rather than *accept*, managers identified ways in which their monitoring approaches could be updated specifically to be more sensitive to changes in tree recruitment that could trigger different forest management approaches (Schuurman et al. 2019).

Operationalizing RAD adaptive management

Although the need to address directional system change has long been acknowledged in adaptive management (Williams and Brown 2012), in our collective experience, resource managers either have not yet widely embraced it or are still seeking guidance and tools for managing under rapid change. Our simple RAD adaptive management approach uses the familiar to confront the unfamiliar. It combines iterative planning with stakeholders and rightsholders to choose a RAD strategy with adaptive-management practices to craft management objectives and implement actions.

At the most fundamental level, stakeholders, rightsholders, managers, and policy makers will have to decide whether to *resist, accept,* or *direct* ecosystem change, and what indicators to monitor that would alert them when a loop leap is needed (see table 1). For example, under *resist* and *direct* strategies, iterative and adaptive management approaches provide a process to improve learning by doing (Walters and Holling 1990) and satisfy management objectives (figure 1, inner loop) or shift management objectives (figure 1, middle loop). In contrast, under an *accept* strategy, management may focus instead on *surveillance* monitoring (figure 1, outer loop) that could detect system change or thresholds that show the need for a *direct* or *resist* strategy. Alternatively, management might focus on experimentation to speed learning about *direct* or *resist* strategies (figure 1, outer loop).

The choice of pathway will be influenced by an understanding of the current rates of transformation, plausible future trajectories of transformation, and realistic expectations for management action (Magness et al. 2021). The rate of transformation is context dependent but there is potential for rapid ecological transformation, even within a management timeframe (figure 2). Mass coral reef bleaching, drought-induced tree mortality, and cyanobacteria blooms in lakes are just a few examples of abrupt changes in marine, terrestrial, and aquatic ecosystems that can happen over very short timescales (Turner et al. 2020).

Time itself may dictate the feasibility of any given RAD pathway. In some cases, *resist* strategies may be the only feasible choice, given near-term decision requirements. However, substantial conservation challenges can arise from temporal mismatch in the function and scale of social and ecological systems (Young 2002, Beever et al. 2019). Sustaining interest, funding, and political will warrant understanding and communicating the implications of timescales for any RAD deliberation.

This time element for transformational adaptation (Kates et al. 2012) is driven by a wider set of institutions, stakeholders, and rightsholders than those tied directly to an individual RAD decision (Magness et al. 2021). Societal and institutional frameworks, values, rules, and knowledge in governance structures constrain the capacity for transformational choices (Wise et al. 2014, Gorddard et al. 2016). Consequently, there is a much larger societal decision-making realm that contains multi-level loops of learning that constrain RAD decisions (Clifford et al. 2021, Magness et al. 2021). Similar future-looking approaches have been effectively implemented for social and institutional dimensions (Colloff et al. 2017, van Kerkhoff et al. 2019). The generally slower rate at which social values and beliefs change may hinder adoption of *accept* or *direct* strategies (Gorddard et al. 2016, Colloff et al. 2017), but it is important to note that social change can also happen rapidly (Repetto 2006).

To help others steward transforming ecosystems, we provide the following guideposts for consideration:

Review and update management actions and objectives periodically. In the face of increasingly pervasive and frequent ecosystem transformations, managers may need to iteratively update actions and objectives to anticipate or adapt to transformation (Nichols et al. 2011, Fisichelli et al. 2016) because historical conditions no longer serve as useful precedent. Through the RAD framework, actions and objectives can be updated at multiple scales to better suit existing conditions and examine the feasibility of achieving specific desired conditions. To facilitate these course corrections, managers can schedule reassessments into their planning processes. These reassessments can be time-based, linked to a tipping point, or tied to conditions that suggest change is, ultimately, probable but with unpredictable timing.

The US State Wildlife Action Plan (SWAP) program, for example, requires each state to review and, if necessary, revise plans for conserving fish, wildlife, and habitats at least every 10 years. This provision is designed to incorporate new information and changing circumstances on a regular basis. And, the SWAP program includes inherent accountability because it is a condition for funding through the State and Tribal Wildlife Grant Program.

Monitor, experiment, and conduct pilot studies. Navigating ecosystem transformations with the RAD framework will likely require both greater humility and also increased willingness to make potentially unprecedented decisions in the face of high uncertainty associated with no-analog climates and novel communities. Managers may see future shifts in their information needs from a focus on the target resource's dynamics to include, at least, *surveillance* monitoring of ecological processes and system functioning (Wintle et al. 2010) to refine understanding of plausible future system trajectories and more frequent assessments of the adequacy of *targeted* monitoring and observation methods. Reassessment of *targeted* monitoring requires asking whether traditional tools and approaches are still tenable for providing the necessary information to achieve management objectives, or whether system observability has declined sufficiently under unfolding ecosystem transformations to warrant a change in monitoring approaches. In many situations, these information needs will require greater collaborations across agencies and with academic partners, because the manager's organization may not have the expertise or resources required to effectively monitor the most informative indicators of system change. Cross agency–academic, manager–researcher relationships are particularly valuable for investigation-based efforts that include data interpretation from monitoring, experimentation, and pilot projects.

Experimental approaches can test, confirm, and improve our understanding of the ecological outcomes of climate signals. For example, snow fences are used *in situ* to simulate warmer soil temperature effects on subarctic vegetation growth and permafrost (Johansson et al. 2013) and arctic microbial activity and nitrogen mineralization (Schimel et al. 2004). Passive heating chambers and fertilizer simulate the effects of warmer air temperatures and changing nutrient dynamics on tree seedlings planted above the treeline (Angulo et al. 2019). This kind of experimentation can provide an early warning indication of potential effects. Such a preview increases the window of opportunity for directing change. However, experiments are in no way predictive, only suggestive (Stephens et al. 2015).

Pilot studies, in contrast, can take the form of demonstration projects as proof of concept or as conventional experiments to demonstrate efficacy of a particular management action; these activities may be particularly important for gaining political and social buy-in, given that a greater diversity of values will typically be involved when revisiting middle and outer loops (Magness et al. 2021). For example, to help *resist*, rainwater catchments can recharge drying springs in southern Nevada, in the United States (box 2; Tambe et al.

2012). To help *direct*, soil inoculation with mycorrhizal fungi can improve bigleaf mahogany (*Swietenia macrophylla*) seedling response to drought stress (Rajan et al. 2020). Subsequent interactions with cyanobacteria facilitate the formation of biological soil crust in deserts, essentially accelerating ecological processes (Wang et al. 2009). In exploring another *direct* option, field transplanting to novel sites coupled with climate suitability models validates the feasibility of assisted colonization of lichens, immobile species with high microclimate sensitivity (Brooker et al. 2018).

Experimentation and pilot studies can be used in tandem to set the stage for selecting among RAD options. For example, van Oppen and colleagues (2015) initially proposed sequential experiments to assess the feasibility of enhancing stress tolerance in corals by accelerating natural processes, a concept they termed "assisted evolution." These experiments were actualized at Australia's National Sea Simulator, where heat-tolerant corals are being created by cross breeding, gene editing, selective breeding through multigenerational rearing in overheated conditions, and manipulating their microbiome. Although these laboratory experiments show promising results, a national committee is considering pilot field studies that may include corralling and steering coral spawn toward degraded reefs and farming hardier corals for transplanting purposes (Cornwall 2019).

Employ bet hedging. In some cases, it may be possible to employ multiple RAD strategies simultaneously in different management areas or sequentially in the same areas (Schuurman et al. 2021). *Resist* approaches may attempt to maintain current conditions as long as possible; *accept* or *direct* approaches can simultaneously be employed to explore potential future trajectories elsewhere in the landscape or ecoregion. For example, iteratively increasing temperatures favor warm-water sport fish species such as largemouth bass (*Micropterus salmoides*) over cool-water species such as walleye (*Sander vitreus*; Tingley et al. 2019). Across a region in which walleye fisheries are declining, management actions could include *resist* strategies, such as stocking to compensate for reduced natural reproduction of walleye; hybrid strategies (somewhere between *resist* and *accept*), such as reduced creel limits to allow a walleye fishery to persist, albeit at lower levels; or *direct* strategies such as stocking warm-tolerant species such as saugeye (*Sander canadensis* × *vitreus*) to maintain similar functions of a top predator in the ecosystem. As we learn about potential climate futures and ecosystem transformation intensifies, adaptive management efforts can be allocated to those RAD approaches deemed likely to be most compatible with stakeholder desires (box 2).

Informed risk taking

Planning in the face of uncertainty is inherently risky, especially with a paucity of information or when the climate trajectory is unclear. Making choices is a critical part of all planning processes. However, implementation in a changing world requires different types of information to support effective decision making within the middle and outer loops and also whether (and, if so, when) to leap between loops. Addressing these additional information needs will be a balancing act and likely require increased coordination across agencies and partners to maximize information sharing with limited resources. It is an open question as to how a manager or program should most effectively allocate limited science resources under each RAD pathway between the demands for informing the pathway decisions (i.e., figure 1, outer loop) versus refining objectives (i.e., figure 1, middle loop) and adjusting management actions (i.e., figure 1, inner loop).

These information needs will be particularly novel when managers deliberately *direct* the trajectory of change away from historical conditions. Not only may there be high uncertainty about the feasibility (and perhaps desirability) of stewarding the outcome, the ecological trajectory and outcome may differ from what is expected (figure 2). Management pathways can help describe current understanding about the timing and series of interventions needed to shape the ecological trajectory toward a desired future condition (Magness et al. 2021).

Although informed risk taking is a long-term goal of adaptive management, the magnitude of uncertainty associated with strong ecological trajectories and ecosystem transformation overwhelms the existing quantitative-decision approaches. For instance, to reduce uncertainty and better inform future decisions, multidisciplinary adaptive strategies couple coarse-scale global climate models with fine-scale regional ecosystem and socioeconomic models (Hollowed et al. 2020). Testing both species and management responses to ecosystem trajectories under current climate-change scenarios help identify better management practices that need to evolve under future ecosystem states to minimize impacts on fisheries, coastal communities, and economies (Holsman et al. 2019, 2020).

Fortunately, periodic review and update of management actions and objectives, complemented by monitoring, experimentation, pilot studies, and bet hedging, can better identify and increase tolerance for risks. Acknowledging that trajectories, objectives, and actions will change because of uncertainty can increase cooperation in the management process and provide the confidence to adapt with ecosystem transformation. Although risks may be reduced, uncertainty will never be eliminated from an "uncontrollable," nonstationary world, so navigating ecosystem transformation successfully is not a path traversed once to a final state but, rather, a perpetual journey iterating through the RAD adaptive management cycle (figures 1 and 2). Adding adaptive management and associated technical expertise among management agencies and their collaborators can increase capacity and help streamline uptake of these planning approaches in a transforming world.

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