RAD Decisions in Rad Landscapes:
Black Ridge Canyons Wilderness

Final Report

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“We need to strive for every lofty goal we have...we haven’t hit the point where we’re ready to give up on these things nor do we think we have to.” –Bureau of Land Management Staff Member

Executive Summary

Climate change is contributing to unprecedented rates of ecological transformation worldwide. Shifts in species distributions and altered structural complexity of habitat has implications for ecosystem function and human relationships. The 1964 Wilderness Act was passed to preserve undeveloped large landscapes in their "natural" condition and for the continued recreational, cultural, and spiritual benefit of the people. Nevertheless, wilderness is still vulnerable to the direct and indirect impacts of climate change. Using active management to respond to climate change challenges in wilderness is complicated by the very protections afforded to wilderness that limit human impacts. This conundrum manifests as a wicked problem for land stewards who are grappling with how to prepare for or respond to climate change-driven ecological transformation.

In the Black Ridge Canyons Wilderness (BRCW) of southwest Colorado, USA, climate change is impacting habitat conditions for native amphibians and exacerbating adverse interactions between native and invasive amphibian species. This report summarizes research and activities relevant to the *RAD Decisions in Rad Landscapes: Black Ridge Canyons Wilderness* case study. The overarching goal of this case study was to provide Bureau of Land Management (BLM) staff and their partners with knowledge and tools to support intentional and transparent decision-making for ephemeral riparian communities in the BRCW through climate change-driven ecological transformation. Scientists from the Aldo Leopold Wilderness Research Institute (ALWRI) conducted research to illuminate the potential ecological consequences of climate change for ephemeral riparian communities as well as managers' perceived ability to respond to ecological change. Additionally, scientists at AWLRI facilitated a 2-day workshop which engaged BLM staff and their partners in an adaptive management process to clarify values and desired conditions, generate decision alternatives under the RAD framework, and evaluate the potential social, legal, and ecological implications of various decision alternatives for native amphibian communities within the BRCW.

Workshop activities and discussions were informed by the biological and social science research conducted prior to the workshop. Biological analyses included expert-informed ecological interpretation of three projected climate scenarios: hotter and drier, warmer and wetter, and hotter but no change from recent mean precipitation amounts. Across scenarios, several transformation themes emerged, including habitat replacement by non-native invasive or upland vegetation, shift from long hydroperiods to short hydroperiods associated with increasing evaporation and sediment deposition, and altered competitive pressure from invasive bullfrogs. Impacts to native amphibians were expected to range from localized population decline to widespread species loss and declines in species richness. Social science research included individual interviews with managers and management partners on their perceived capacity to address climate change challenges. Many interviewees felt the path forward to conserving native amphibians was unclear and that their ability to address climate

change challenges in wilderness was limited by capacity constraints and the potential for litigation.

During the workshop, attendees participated in a range of facilitated discussions and small-group activities to inform an iterative process of generating and evaluating decision alternatives to address climate change challenges for ephemeral riparian communities. Workshop participants representing multiple agencies and organizations contributed their unique perspectives, which enabled a rich discussion of values and desired conditions for the BRCW as well as perceived benefits and drawbacks of deliberately choosing to intervene (resist or direct) or not intervene (accept) to conserve ephemeral riparian communities. When exploring the RAD framework, workshop participants generated more resist and accept strategies than direct decision alternatives. Resist and accept alternatives were most familiar to workshop participants, however, participants questioned the ability of these strategies to remain effective over the long-term under ongoing climate change.

The process and tools introduced in the workshop were created to support forward-thinking and intentional decision-making regarding climate change-driven ecological transformation in the BRCW. Specific recommendations were not provided as part of this workshop with the intention that practitioners, land stewards, and partners can use this process in a way that best fits their unique needs and limitations. Adhering to a standardized process that explicitly integrates the evaluation of RAD alternatives can increase transparency in decision-making, thereby fostering collaboration and supporting defensible decision-making under climate change.

Key take-aways

- Ecological conditions in ephemeral riparian systems in the BRCW are expected to transform under climate change in a variety of ways that may threaten the persistence of native amphibian species
- Managers generally feel limited in their capacity to respond to climate change in the BRCW
- Management actions which constitute trammeling (Table 1) may be necessary to preserve historical characteristics within ephemeral riparian communities
- There is a high degree of uncertainty regarding the effectiveness of any single decision alternative as a long-term strategy for conserving native flora and fauna through climate change
- Familiar resist or accept options may no longer be effective long-term options to achieve desired conditions in the BRCW
- Direct actions, such as translocating native amphibians, are risky but may be necessary to fulfill long-term desired conditions

RAD Decisions in Rad Landscapes: Project Background

Ecological Transformation

Climate change has contributed to unprecedented shifts in ecological patterns and processes (McElwee et al. 2023). Altered ecosystem structure and function directly and indirectly impacts relationships among people and the environment. When compounded by existing stressors and threats such as wildfire, pests, disease, invasive species, and human development, ecological change may become irreversible. Ecological transformation, or the emergence of new ecosystem states that differ from known historical conditions, makes it difficult for land stewards and partners to delineate management goals and adhere to current management strategies (Stein et al. 2013). Growing concern and recognition that traditional or familiar stewardship strategies may no longer support resilient ecological communities has driven land stewards and their partners to seek alternative solutions to address complex problems under climate change (Magness et al. 2012; Schwartz et al. 2012; Schuurman et al. 2022).

Managing for Climate Change in Wilderness: A Wicked Problem

Climate change-driven ecological transformation is a diffuse and complex issue impacting landscapes globally, regardless of jurisdiction and protection status. In the United States, the National Wilderness Preservation System (NWPS) includes over 100 million acres of land afforded the highest level of protection of all public lands in the United States. Guiding policy under the 1964 Wilderness Act mandates that lands designated as part of the NWPS be preserved in their natural state, wherein the character of the landscape is primarily influenced by the forces of nature and absent of human development or trammeling (Public Law 88-577; Wilderness Act 1964). In addition, the NWPS is managed to preserve opportunities for solitude or primitive recreational experiences and other features of value, such as ecological processes and cultural features that existed upon designation (Table 1). Nevertheless, despite these high levels of protection, the NWPS remains susceptible to climate change-driven challenges such as increasing temperatures, altered precipitation events, and altered disturbance regimes. Challenges related to climate change threaten several tenets of the NWPS, including the natural condition of wilderness, or the quality of an ecological system to be free from the impacts of modern civilization. Cascading effects of increased human development, including climate change, were not anticipated when the 1964 Wilderness Act was signed into law. Lack of guidance and sometimes competing priorities outlined under the Wilderness Act have created a conundrum for land stewards, rightsholders, and partners attempting to address climate change-related impacts within the NWPS. Furthermore, the same high levels of protection afforded to wilderness to protect lands from direct human impacts are often dually perceived as constraints to addressing climate change-driven threats, including ecological transformation. Whether or not to pursue active management, which may involve trammeling, to address transforming wilderness systems is considered a “wicked problem”, or a problem that is seemingly intractable due to the high degree of complexity and uncertainty associated with balancing sometimes competing mandates, objectives, and values (Head 2019; Rittel & Webber 1973).

Table 1: List and descriptions of the five guiding tenets of the National Wilderness Preservation System.

Wilderness Character Quality	**Definition**	**Example Measures that Detract from Quality**
Natural	Wilderness patterns and processes are largely free from the influence of modern civilization	Presence of non-native species, air pollutants, water pollutants
Untrammeled	Wilderness is free from the impacts of human activity or manipulation	Mechanical forest treatments, wildfire suppression, fish stocking
Undeveloped	Wilderness does not contain structures, installations, or other evidence of human presence or occupation	Dams, use of motorized or mechanized equipment, recreational kiosks
Solitude or Primitive and Unconfined Recreation	Wilderness provides opportunities for solitude and primitive recreational experiences unhindered by the impacts of modern civilization	Light pollution, recreation facilities, user-created campsites and trails
Other Features of Value	Wilderness preserves ecological, geological, or other features of scientific, educational, scenic, or historical value	Vandalism of existing cultural features, loss of iconic plant or animal species, deterioration of iconic geological features

Untangling the Wicked Problem: RAD

The Resist-Accept-Direct Framework (RAD) encompasses the range of available choices for addressing expected or observed ecological transformation: 1) Resist the transformation by maintaining historical conditions through efforts such as restoration, 2) Accept the transformation by intentionally allowing ecological structure and function to change autonomously, or, 3) Direct the transformation by actively shaping ecological change toward a preferred new condition (Schuurman et al. 2022; Figure 1). RAD has a unique advantage for wilderness managers because of its incorporation of acceptance as a possible strategy. However, instead of accepting ecosystem change implicitly, RAD provides a decision space wherein the relative value of acceptance can be fully examined and compared to alternative resist or direct strategies. Explicit and intentional planning fosters transparency in decision-making, a quality which is particularly pertinent in federally designated wilderness where active management is highly scrutinized. By intentionally choosing to resist, accept, or direct observed or anticipated ecological change, land stewards can begin to generate defensible solutions for addressing climate change challenges in wilderness.

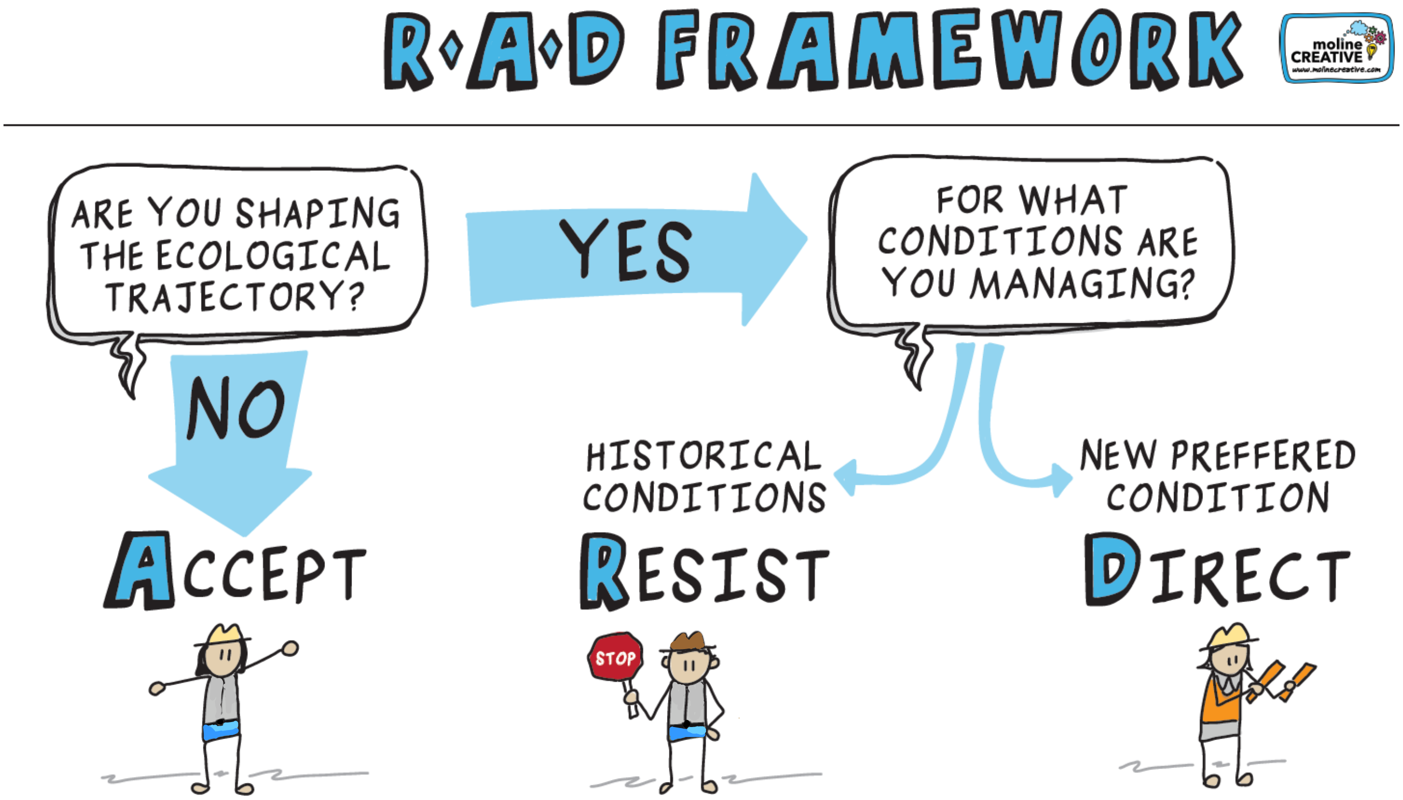


Figure 1: Decision points to guide the use and implementation of the resist-accept-direct (RAD) framework for responding to observed or expected ecological transformation under climate change.

Project Objectives

To unravel the wicked problem of addressing climate change in federally designated wilderness, scientists at the Aldo Leopold Wilderness Research Institute (ALWRI) led an effort that used the RAD framework as a tool to both illuminate a decision-space and evaluate management goals to address climate change-driven ecological transformation for four case studies, one per wilderness-administering agency. The Black Ridge Canyons Wilderness (BRCW) was nominated by Bureau of Land Management (BLM) staff as a case study that represented common challenges staff face when attempting to address climate change impacts in wilderness. Through this project and workshop, a process was developed to illustrate the utility of the RAD framework for adaptive decision-making for ephemeral riparian communities in the BRCW. Scientists at ALWRI worked with regional, state, and national-level management staff and their partners to identify values and desired conditions, explore the RAD decision space to meet those desired conditions, and evaluate social-ecological trade-offs inherent in pursuing RAD strategies.

This *RAD Decisions in Rad Landscapes* project had three primary goals:

1) **Generate a widely applicable process of how to use the RAD framework in designated wilderness.**

2) **Provide science and decision support for management challenges related to climate change in wilderness.**

3) **Advance our understanding of the trade-offs, uncertainties, opportunities, and limitations for addressing climate change impacts within designated wilderness.**

Project Stages

To accomplish overarching project goals, four project stages were completed for all four case studies, (Table 2): 1) information gathering to identify case study partners and to better understand current conditions within wilderness and challenges impacting wilderness management, 2) biological and social science investigation to assess the impacts of climate change-driven transformation and perceived constraints to addressing related challenges in wilderness, 3) facilitated workshop to clarify values and desired conditions as well as evaluate a RAD decision-space for current and future climate change challenges, 4) final reporting to summarize and deliver results of science analyses and comprehensive summaries of workshop activities. Each stage of the project was designed to inform and contribute to an adaptive management process using RAD as a tool to support intentional decision-making around climate change-driven transformation. This report summarizes the first three stages of the project specific to the Black Ridge Canyons Wilderness case study.

Table 2: Project stages and descriptions for the RAD Decisions in Rad Landscapes project, 2022-2025.

Information Gathering	Investigate Transformation	Apply RAD to Planning Process	Final Reporting
Build Advisory Team **Synthesize Current Methods and Processes** **Establish Partners** **Site Visits** **Select Case Studies**	**Social Implications of and Perspectives Around Climate Change** • Interviews with managers, rightsholders, partners, and decision-makers **Biological Forecasts Under Climate Change** • Climate change and landscape change modeling • Clarify ecological transformation(s)	**Workshop to Apply and Evaluate RAD Decision Alternatives** • Identify and evaluate values and desired conditions • Generate RAD alternatives • Illuminate socio-ecological consequences of alternatives for wilderness management	**Post-Workshop Reports** **General Technical Report** **Peer-Reviewed Publications**

Information Gathering:
Black Ridge Canyons Wilderness

The Black Ridge Canyons Wilderness Case Study

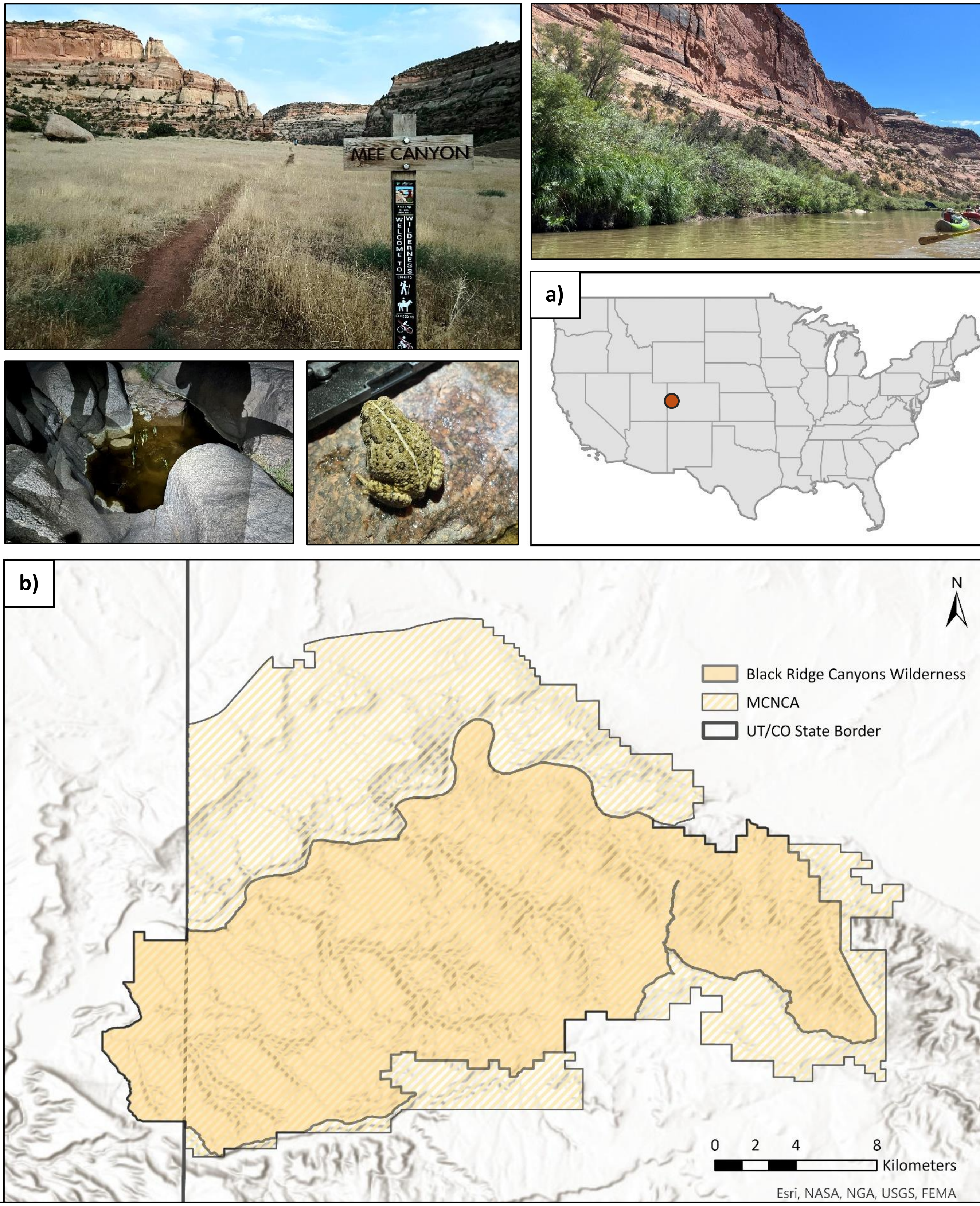
The BRCW is located within the McInnis Canyons National Conservation Area (MCNCA) in southwestern Colorado and eastern Utah, USA (Box 1). The wilderness is approximately 75,000 acres in size and has a climate typical of the arid Colorado Plateau. The plateau is incised by several canyons supporting a high diversity of plant and animal communities. At higher elevations, sparse pinyon-juniper woodlands dominate the overstory. In the canyons, riparian communities are influenced by the ephemeral supply of spring runoff and storm events. Native amphibians, including the red-spotted toad, Woodhouse's toad, and canyon treefrog, persist in isolated and ephemeral freshwater streams and pools that collect in low-lying depressions in canyon bottoms.

The western slope of the Rocky Mountains in Colorado, USA, is experiencing one of the most rapid warming trends in the United States (Clow 2010; Rangwala et al. 2012; Marvel et al. 2023). Due to its high climate exposure, the BRCW is projected to be one of the most vulnerable wilderness areas to the impacts of climate change (Aycrigg et al. 2021). Riparian communities within the BRCW are particularly vulnerable to ecological change under climate change. In particular, native amphibian species that exist within ephemeral pools along canyon bottoms are highly responsive to change in both abiotic and biotic environmental properties. Some amphibian species with higher adaptive capacity, such as Woodhouse's and red-spotted toads, may tolerate moderate changes in habitat conditions, including drying and increased temperatures, by adjusting the timing and duration of life history events. More vulnerable species with limited adaptive capacity, such as the canyon treefrog, may become extirpated because of degrading habitat quality. Subsequent changes in species richness and population abundance of native amphibians serve as strong indicators of overall ecosystem health as habitat conditions change under a warming climate. Nevertheless, limited ecological data on native amphibian populations and their habitat as well as uncertainty associated with shifting ecological baselines under climate change have made it difficult for managers and decision-makers to confidently identify and prescribe beneficial management strategies for ephemeral riparian communities.

Existing and emerging stressors

Influential non-climatic ecological threats to ephemeral riparian communities include invasive flora and fauna. In upland plant communities, non-native, invasive cheatgrass (*Bromus tectorum*) has contributed to altered fire regimes. In turn, altered fire regimes further facilitate the spread of cheatgrass and other annual invasive plants throughout the Colorado Plateau ecoregion. Increasing wildfire frequency is expected to lead to soil destabilization and erosion which may impact riparian communities down-canyon by reducing pool depth and habitat availability. In riparian plant communities, non-native, invasive tamarisk (*Tamarix spp*.) is a large shrub that readily outcompetes native riparian vegetation and can prevent establishment of native species by altering soil characteristics. Invasive American bullfrogs (*Lithobates catesbeianus*) further disrupt native amphibian populations in ephemeral riparian habitat. Bullfrogs may directly compete with native species for resources, prey on native species, and can spread the fungal pathogen *Batrachochytrium dendrobatidis*.

Climate change is expected to exacerbate the impacts of pre-existing stressors for riparian communities. Increasing temperatures, fluctuating precipitation patterns, and decreasing humidity and soil moisture anticipated throughout western Colorado will likely contribute to altered disturbance regimes, decrease hydroperiods of ephemeral stream and pool habitat, and may accelerate the spread of invasive species in the wilderness. Rapidly changing ecological conditions may impact the effectiveness of current management strategies. Conserving native riparian communities in an era of climate change will require managers to think beyond familiar management approaches within wilderness and carefully consider the social-ecological trade-offs inherent in deliberately choosing to resist, accept, or direct observed ecological change. The 2004 Resource Management Plan (RMP) accompanying the designation of the BRCW describes objectives meant to guide management activities in the wilderness (US DOI BLM 2004), including actions to reduce the spread of noxious weeds and preserve native plant and animal diversity. Nevertheless, climate change was not explicitly accounted for in the RMP.



Box 1: Location of the McInnis Canyons National Conservation Area (MCNCA) represented by the orange dot (a) and the Black Ridge Canyons Wilderness (BRCW) in Colorado and Utah, USA (b). Top row, left to right: images of the entrance to Mee Canyon within the BRCW and the Colorado River shoreline along the northern boundary of the BRCW. Middle row, left to right: image of ephemeral canyon pool habitat and a native Woodhouse's toad.

Investigate Transformation:
Black Ridge Canyons Wilderness

Climate Scenarios and Potential Ecological Futures

To investigate how climate change may impact ephemeral riparian communities in the BRCW, ALWRI personnel convened a team of experts to construct a series of divergent climate scenarios and discuss emerging ecological futures. The team of experts consisted of a group of scientists and managers with local- and subject-level expertise in the southwestern region of the United States. Together, the team identified climate metrics most likely to influence ephemeral riparian communities (Table 3), created a suite of divergent and plausible climate scenarios, and discussed how climate scenarios may differentially impact native amphibians and their habitat at multiple spatial scales.

Table 3: Climate metrics evaluated to investigate potential ecological changes to riparian communities in the Black Ridge Canyons Wilderness, Colorado, USA, under climate change.

Metric	Season(s) Assessed	Description
Temperature	summer	The mean of daily mean temperatures (^oF), computed as the mean of daily high and low temperatures
Precipitation	winter, spring, summer	Accumulated total precipitation (inches) in all forms for each season
Heat Index	annual	Total number of days exceeding or equal to either 90^oF or 100^oF each year
Climatic Water Deficit (CWD)	spring, summer	Evaporative demand (inches/season) that exceeds available soil moisture calculated as the difference between potential and actual evapotranspiration
Vapor Pressure Deficit (VPD)	annual	Atmospheric demand for water (kPa) calculated from daily differences between how much moisture the air holds and how much moisture the air could hold if the air were saturated

Climate change projections

Climate change projections were made using the Future Climate Scenarios tool from the Climate Toolbox (Hegewisch and Rangwala 2024). Climate models used in analyses were chosen based on their performance in reproducing historical climate conditions for the southwestern United States (RPA 2020). Two emissions scenarios—representative concentration pathways (RCP) 4.5 and 8.5—were included in climate modeling to capture a range of likely trends in future emissions. From the resulting 23 climate models, both mid-century (2040-2069) and end-of-century (2070-2099) projections were examined, however, mid-century projections were used to define climate scenarios for further discussion. In total, three climate scenarios were described that diverged in their projections for future temperature and precipitation: warmer and wetter, hotter, and hotter and drier (Figure 2; Appendix A).

Mean projections for each climate metric were examined relative to historical metric means from 1971-2000. Under the Warm/Wet Scenario, precipitation is expected to increase as compared to historical totals and summer temperatures are expected to increase by an average of 4^{o}F. Under the Hot Scenario, precipitation totals are not expected to deviate more than 5% from historical levels and summer temperatures are expected to increase by an average of 6^{o}F. Under the Hot/Dry Scenario, precipitation amount decreases from historical totals and summer temperatures increase by an average of 7^{o}F. Summaries for each climate metric for each scenario were calculated as the mean of all model projections for each timestep.

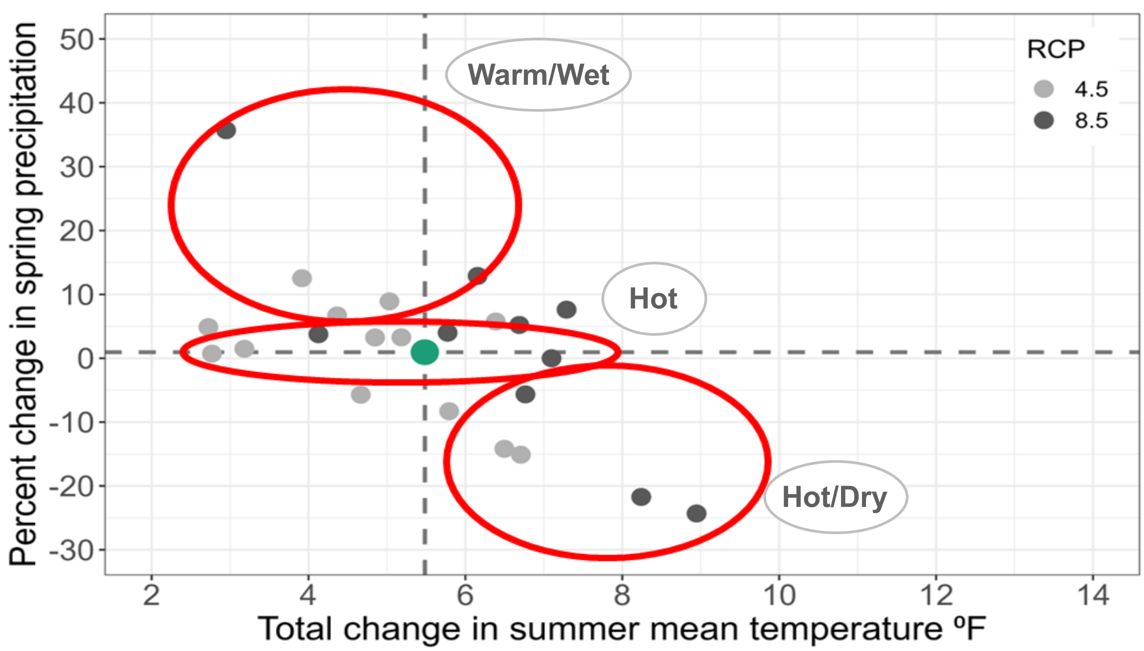
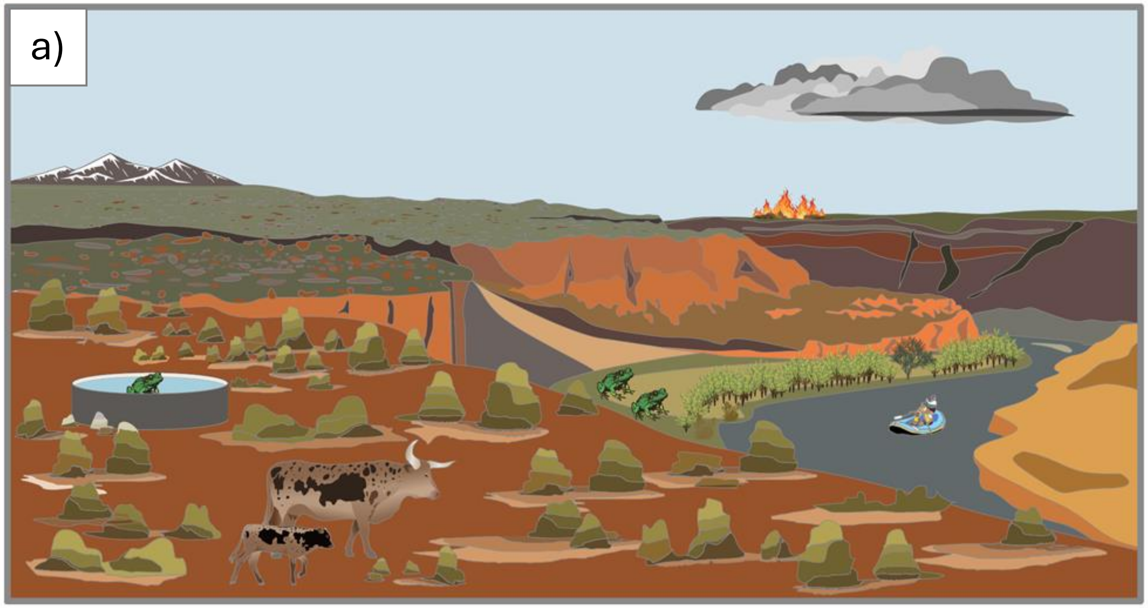
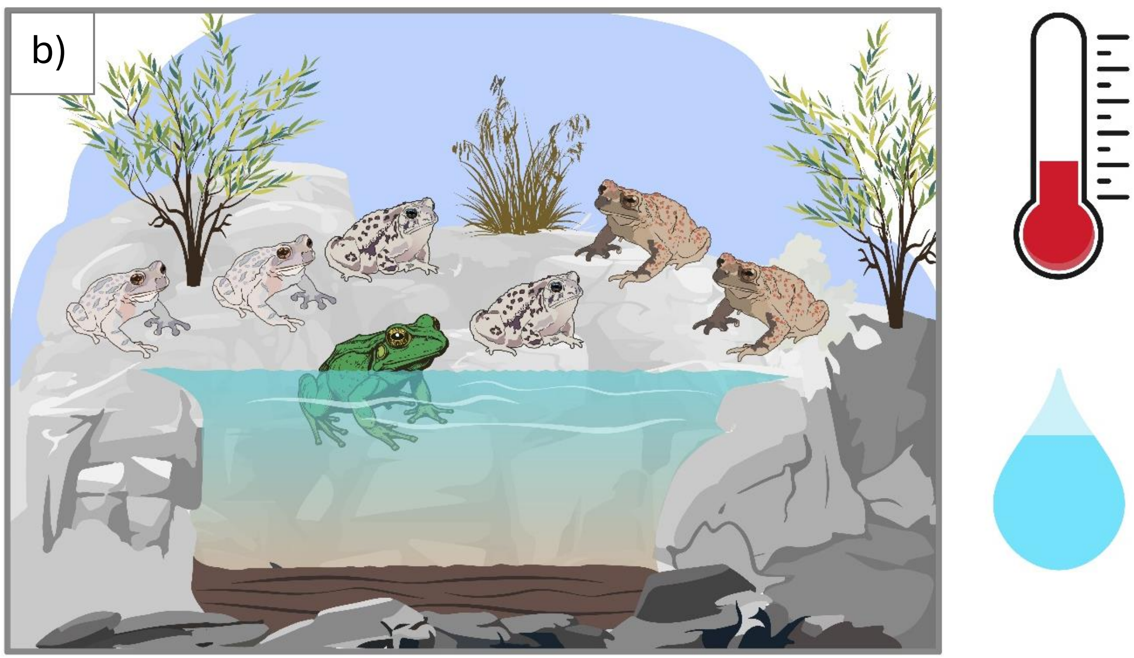


Figure 2: Three climate scenarios chosen to investigate impacts of climate change on riparian communities within the Black Ridge Canyons Wilderness. Scenarios were delineated from mid-century (2040-2069) model projections. In this example, the green point represents the mean of all model projections for total change in summer temperature and percent change in spring precipitation.

For each climate scenario, the interdisciplinary team of local- and subject-matter experts discussed potential future impacts to ephemeral riparian communities. Facilitated discussions for each scenario investigated potential biotic and abiotic drivers of ecological change and anticipated ecological outcomes. In particular, the following topics were highlighted in discussion: disturbance events (e.g. wildfire and convective summer storms), hydrology (e.g. spring runoff and pool hydroperiod), native amphibians (richness and abundance), invasive bullfrogs, and disease. Both landscape-level and site-specific impacts were considered during discussion (Box 2).





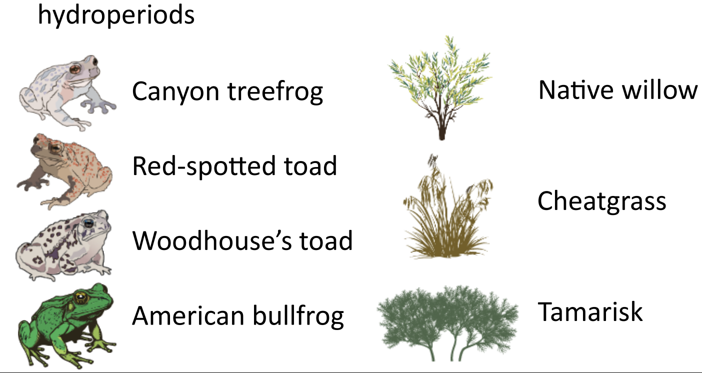
Box 2: Current baseline climate, land use, disturbance, and species assemblages in the Black Ridge Canyons Wilderness, Colorado, USA. Graphics represent current landscape-level conditions (a), and site-specific conditions of ephemeral pools (b). Non-native, invasive plant species (cheatgrass, tamarisk) and invasive bullfrogs represented. Three climate scenarios were generated to describe potential ecological transformations at both spatial scales. Key transformations examined for each scale include:

Landscape (a):

1) **Disturbance regime change**, including wildfire and summer convective storm patterns
2) **Non-native, invasive species** persistence or expansion and replacement of native species
3) **Precipitation pattern changes** including conversion of winter snowfall to rain

Ephemeral Pools (b):

1) **Altered patterns of amphibian species diversity** including species richness and abundance
2) **Conversion of riparian vegetation** to upland or non-native invasive vegetation
3) **Conversion of deepwater pools** characterized by long hydroperiods to shallow pools characterized by short hydroperiods



Characterizing Ecological Transformation

Model and prediction uncertainty

The following summaries represent plausible futures that are subject to further discussion with continued advances in our understanding of climate change trends and subsequent impacts to ecological communities. Climate scenarios and potential ecological futures were generated with the best available data and by leveraging expert knowledge, however, uncertainty in direct and indirect causal relationships persists. A set of plausible, divergent scenarios was created to account for uncertainty associated with predicting future climate and ecological change. However, unanticipated interactions or events could lead to additional outcomes not considered as part of this process. Furthermore, several ecological futures may emerge from a single climate scenario. The ecological futures presented here are meant to be used as reference points for further refinement as new knowledge and data sources become available.

Climate scenarios

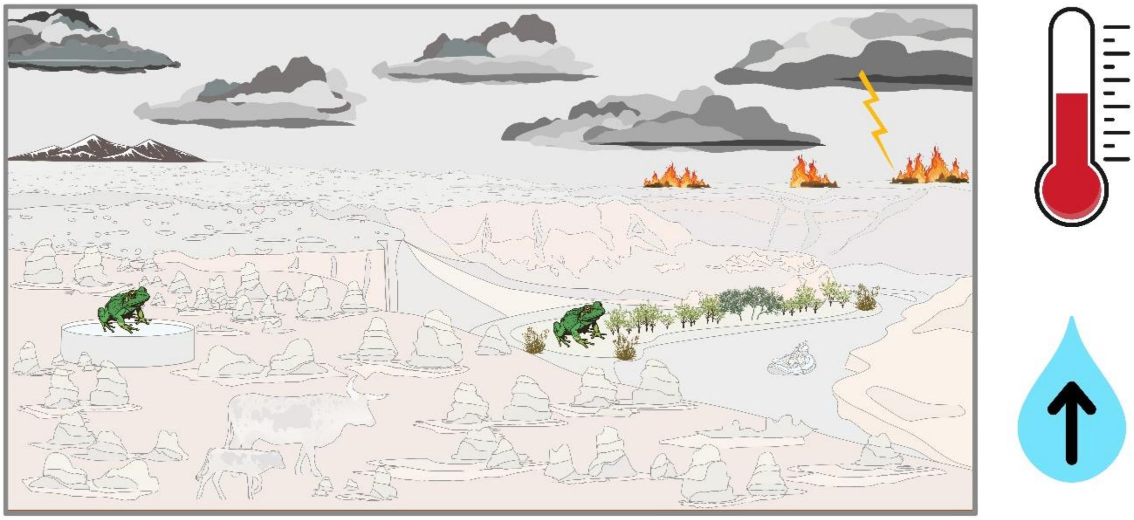
Our selection of climate scenarios captured divergence in future projections of precipitation amount, type, and timing. Nevertheless, the direction of change in derived climate metrics that are strongly influenced by temperature, such as climatic water deficit and vapor pressure deficit, was consistent across scenarios. Similarities in trends for water balance metrics indicated that, although precipitation amount may be projected to increase or decrease, increasing temperatures could play a larger role in shaping ecological futures for the BRCW. Across climate scenarios, mean summer temperature, heat indices, climatic water deficit, and vapor pressure deficit all increased, indicating that conditions will continue to dry despite stabilized or increasing precipitation amount.

Potential ecological futures and transformation themes

Although the direction of change for climate metrics associated with water availability and heat stress were similar across scenarios, there were differences in the magnitude of change across those metrics. Consequentially, anticipated differences among potential ecological futures were largely attributed to the seasonality and magnitude of ecological change, rather than the direction of change. For example, wildfire frequency was expected to increase under each climate scenario, however, under the Hot/Dry Scenario, experts anticipated that wildfire frequency may ultimately stabilize due to decreasing fuel loads. In comparison, wildfire frequency was expected to continue to increase for the Warm/Wet and Hot scenarios where higher projected precipitation amount may maintain greater biomass and fuel loads that promote fire spread.

Despite differences in the magnitude of change, there were commonalities in overarching transformation themes (Box 2). At the landscape-level, expected changes to ecological patterns and processes were represented by changing disturbance regimes, conversion of upland and riparian native plant communities to non-native plant communities, and shifts in the timing of precipitation as well as decreases in the amount of precipitation falling as snow (Box 3). At the site-specific level of ephemeral canyon pools, communities were expected to experience shifts in the richness and abundance of native amphibians, conversion of riparian native plant communities to upland or non-native plant communities, and decreases in pool depth and hydroperiod (Box 4). Experts anticipated that increased wildfire frequency may lead to increased sedimentation into canyon bottoms. Increased sedimentation may fill ephemeral pools, reducing the number of deep pools and subsequently reducing habitat overall for native amphibians, particularly those that rely on persistent sources of deeper water (canyon treefrogs). Additionally, increased sediment accompanied by increasing temperatures may facilitate the spread of upland and non-native invasive species (e.g. tamarisk and cheatgrass) into canyon bottoms. The replacement of native riparian vegetation in canyon bottoms by upland or non-native invasives may reduce shading of canyon pools, further accelerating water evaporation and decreasing pool hydroperiods. Subsequent habitat loss for native amphibians may lead to overcrowding of remaining suitable habitat, reduce reproductive success for native amphibians, and increase opportunities for competitive exclusion by bullfrogs. Under wetter climate scenarios that may facilitate the spread of bullfrogs into canyons, direct predation of bullfrogs on native amphibians as well as transmission of fungal pathogen *Batrachochytrium dendrobatidis* may exacerbate already stressful conditions for native amphibians, resulting in reduced native amphibian species richness and population abundance.

Warm/Wet Scenario

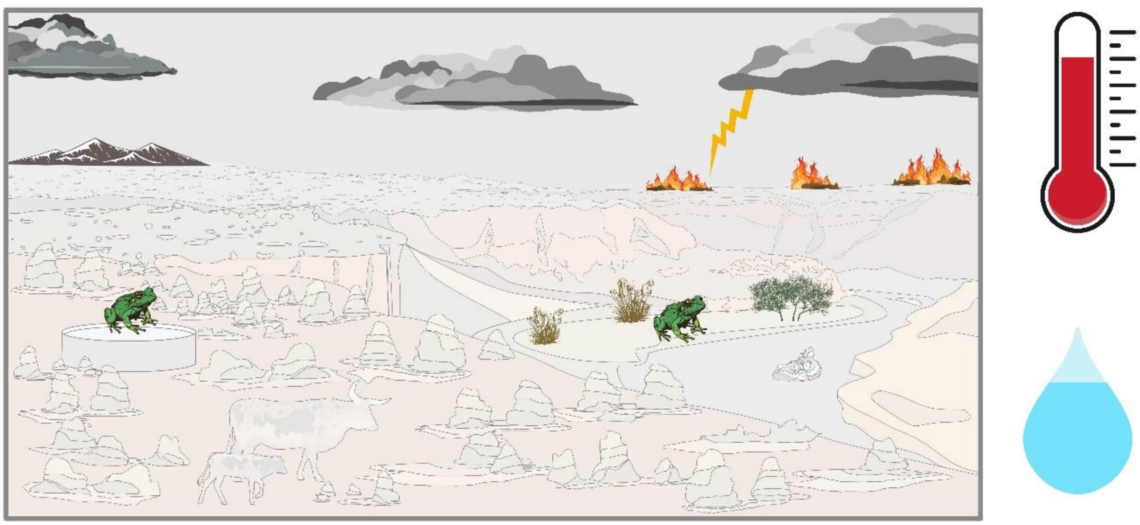


Disturbance: Wildfire intensity and frequency increases. Summer storms become more intense.

Invasives: Gradual displacement of native riparian vegetation by non-native, invasive species. Persistent presence of bullfrogs along Colorado River.

Precipitation: Sustained but decreasing snow accumulation.

Hot Scenario

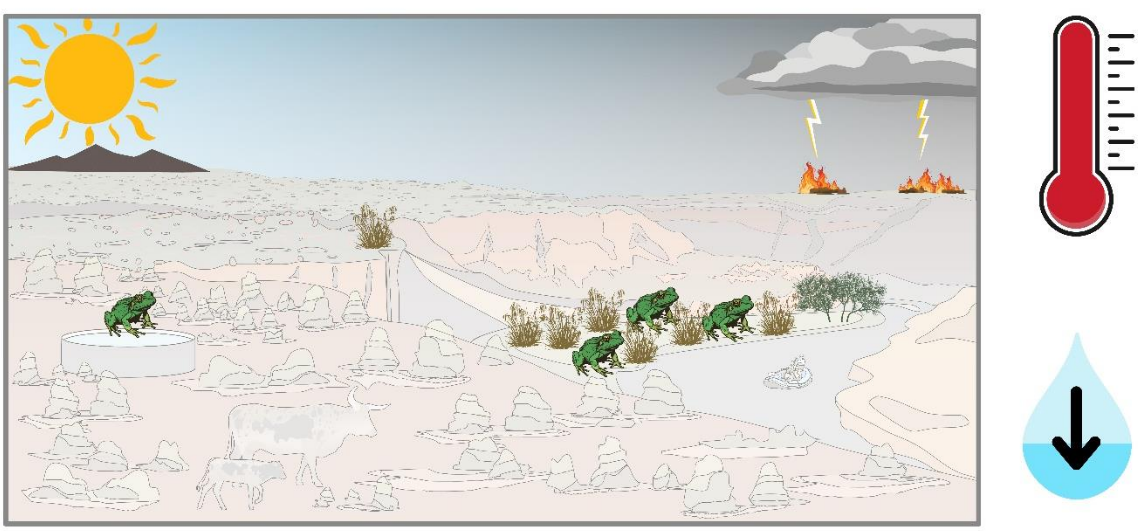


Disturbance: Wildfire intensity and frequency increases. Variable summer storm precipitation.

Invasives: Moderate rate of replacement of native riparian vegetation by non-native invasive upland and riparian species. Persistent presence of bullfrogs along Colorado River.

Precipitation: Shift towards majority winter precipitation occurring as rain.

Hot/Dry Scenario



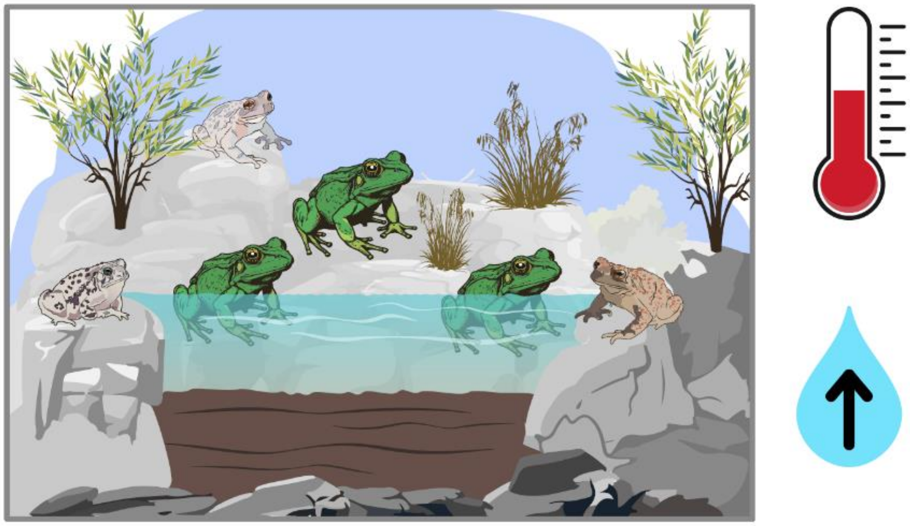
Disturbance: Frequent wildfire characterized by rapid spread. High intensity storm events.

Invasives: Rapid replacement of native riparian vegetation by non-native invasive upland and riparian species. Bullfrog presence restricted to Colorado River shoreline.

Precipitation: Majority conversion of winter snow accumulation to rain.

Box 3: Anticipated landscape-scale changes in ecological properties under three climate change scenarios: Warm/Wet, Hot, Hot/Dry, for the Black Ridge Canyons Wilderness, Colorado, USA.

Warm/Wet Scenario

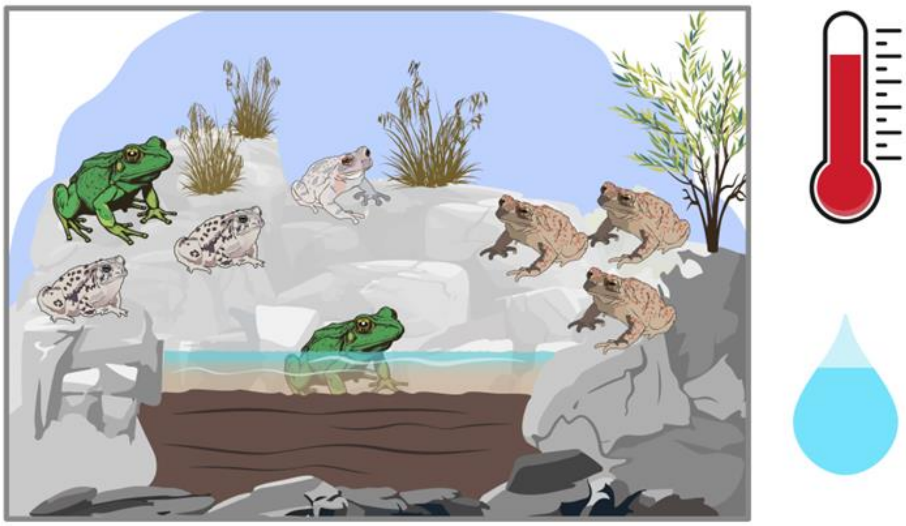


Amphibians: Diversity of native species retained but population abundance of all species declines within pools. Bullfrogs highly mobile and may travel further up into canyons.

Riparian Vegetation: Riparian vegetation continues to persist, however non-native invasive species begin to creep in.

Hydroperiod: Water level reduced in deeper pool and hydroperiod shortened.

Hot Scenario

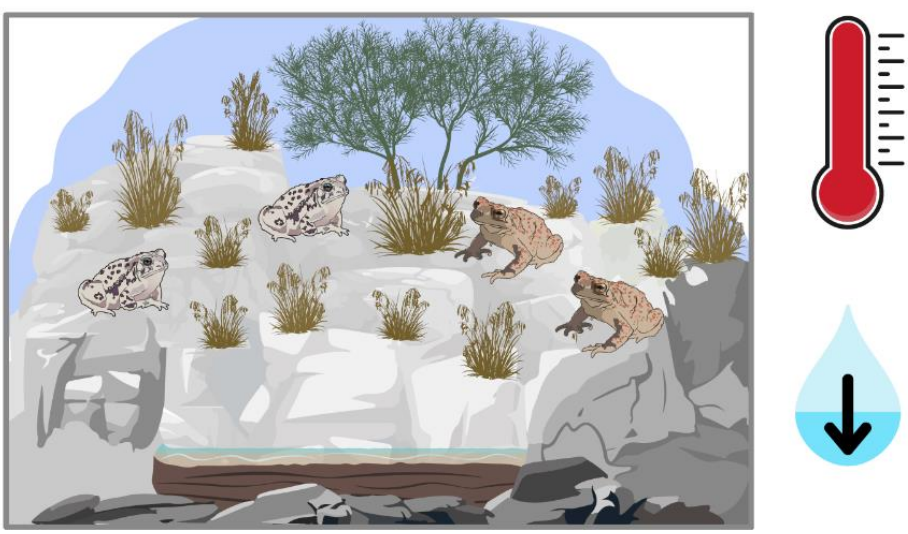


Amphibians: Diversity of native species retained but population abundance of particularly vulnerable species may decline. Bullfrogs invade areas of canyons closest to perennial water sources.

Riparian Vegetation: Non-native invasive species begin to replace native riparian vegetation

Hydroperiod: Water level reduced in deeper pools and hydroperiod shortened.

Hot/Dry Scenario



Amphibians: Both diversity and abundance of all native species declines. No presence of bullfrogs in ephemeral pools.

Riparian Vegetation: Replacement of native riparian vegetation by non-native invasive upland and riparian species.

Hydroperiod: Complete loss of deep pools and significantly decreased hydroperiods.

Box 4: Anticipated site-specific changes in ecological properties of ephemeral canyon pools under three climate change scenarios: Warm/Wet, Hot, Hot/Dry, for the Black Ridge Canyons Wilderness, Colorado, USA.

Understanding Manager Perceptions of Climate Change and Feasibility of Response Actions

To learn how managers and partnering subject-matter experts are experiencing climate change and ecological transformation, as well as their perceptions of response options, we conducted five semi-structured interviews. A semi-structured interview approach uses the same list of questions (or interview guide) for all participants and allows room for exploration into unique topics brought up by each participant. This approach ensures comparable results across participants while also allowing for unique insights and freedom of response (Kvale & Brinkmann 2009). Interviews were conducted with key BLM staff from the Colorado state office, field offices, and BLM National Conservation Areas (NCA) and with key subject matter experts. In particular, we were interested in understanding perceptions of (1) how climate change is affecting areas within and around the BRCW, (2) feasibility of management actions to support conservation of native ephemeral riparian communities, and (3) real and perceived constraints and opportunities for climate change adaptive actions within the BRCW.

All interviews were conducted virtually between October 18, 2023, and November 21, 2023, and lasted an average of 45 minutes. Interviews were recorded and transcribed verbatim. Identities for all transcripts were removed to ensure participant confidentiality. All deidentified transcripts were uploaded into NVivo—a qualitative data analysis software, which helps researchers organize data. Qualitative thematic analysis was conducted with open or inductive coding in which the researcher identifies distinct concepts and themes for data categorization (Williams & Moser 2019). These concepts and themes were then considered together as they relate to larger trends, or themes, across the data (Braun & Clark 2012). See Appendix B for interview quotes that pertain to each theme.

Perceived effects of climate change within and surrounding the BRCW and feasibility of conservation actions

Managers and partners perceive summers as lasting longer and becoming hotter and drier, which alters many aspects of the social-ecological system within and around the BRCW. In particular, managers are noticing temperatures getting hotter earlier in the year and staying hot for longer periods. With prolonged heat, there is increased seasonal drought, and managers are observing vegetation desiccation earlier in the year. One manager also noted changing monsoonal patterns. As a result of some of these changes, managers have observed a lack of post-fire recovery among native plant species, increased invasive species, and several negative impacts to ephemeral riparian communities, including inability of native amphibians to complete reproductive cycles as well as diminishing food sources and habitat due to reduced pool hydroperiods. In addition to changes among wildlife and vegetation, one manager noted increased visitor use during the shoulder seasons, which are becoming increasingly concentrated as the number of hot summer days increases.

Managers noted that although they may not spend much time focused explicitly on climate change (e.g., reading about or planning for it), much of their project work is impacted by the effects of changing climatic conditions, such as prolonged drought. Additionally, due to changing climate, invasive species, and historical fire suppression, managers noted that the tools that traditionally worked well for fire management and restoration are no longer reliable. For instance, observed increased seasonal drought and the pervasiveness of invasive cheatgrass have made it necessary to suppress lightning-ignited fires within the BRCW. However, suppressing fires is a trammeling action, and therefore can be perceived as undesirable in wilderness. Managers expressed that changing climate—particularly prolonged periods of heat and drought—make restoration planning and implementation difficult, especially as it relates to selecting seeds and planting native vegetation.

Constraints to addressing climate change challenges

Managers discussed several physical and institutional constraints that make addressing climate change challenges difficult for amphibian conservation within the BRCW. First, it is physically difficult to access the canyons due to their remoteness and lack of roads. Trips into the wilderness typically require extensive preparation and then multiple days of travel and substantial gear. Additionally, managers noted a lack of funding and staffing capacity to do monitoring, research, and management within the wilderness. Lack of staff capacity was largely attributed to staff attrition, restructuring of the field office, and decreased ability to attract and hire new staff because of increasing costs of living near the duty station. Given the lack of capacity, efforts to learn about and conserve native amphibians within the BRCW is not prioritized as much as ongoing litigations, Resource Management Plan evaluations, grazing permit renewals, and other important projects. Although some native amphibians are species of concern for the state of Colorado, they are not federally listed as threatened or endangered, which further impacts the ability of managers to justify allocating resources for species conservation efforts. Finally, some staff expressed a hesitancy to engage in management activities in wilderness due to a general lack of understanding about what actions were allowable and potential for litigation.

Opportunities for climate adaptation in wilderness

Despite the perceived constraints to addressing climate change challenges, managers identified unique opportunities for research and management within the wilderness. Some managers thought that the wilderness offers an opportunity for anecdotal and empirical research about the effects of climate change, where things are allowed to change more autonomously. Additionally, one manager mentioned that in some cases, it may be easier to find funding for work within wilderness as opposed to outside of wilderness. They noted that there are a few funding sources within the state of Colorado that specifically fund work within wilderness. Lastly, managers noted that the community and other agencies are invested and interested in doing work within the BRCW. By leveraging new and existing partnerships, managers may be able to fill gaps where staff capacity is currently lacking.

An Iterative Process Using the RAD Framework for Climate-Informed Adaptation Planning:

Black Ridge Canyons Wilderness

Learning Objectives

A 2-day, in-person workshop was implemented to support overarching project goals to inform and evaluate a decision space using the RAD framework and to support climate-informed adaption planning in wilderness. During the workshop, participants followed an adaptive management process incorporating the RAD framework to generate and evaluate decision alternatives for ephemeral stream communities in the BRCW under a changing climate. The workshop was structured around four learning objectives:

1) Orient the Black Ridge Canyons Wilderness case study in the broader challenge of wilderness management in an era of climate change
2) Identify desired conditions surrounding the focal ecological transformation that reflects all perspectives
3) Understand the utility of RAD as a tool for responding to ecological transformation in wilderness
4) Develop a feasible and repeatable workflow to evaluate RAD decision alternatives

Each learning objective was achieved through a combination of scientific inquiry (described above), facilitated discussion, and small group activities. Both biological and social science investigations were leveraged to better understand how ecological conditions may change in the BRCW and how land stewards and their partners perceive this change and their ability to prepare for or respond to climate change-driven transformation. Preliminary and final results of science investigations were shared with workshop participants to characterize potential ecological transformation for ephemeral riparian communities and to encourage further discussion concerning real and perceived constraints and opportunities to conserve riparian systems. Facilitated small-group activities and discussion encouraged co-production of ideas and decision alternatives that were examined further with additional decision-support tools.

Workshop Participants

Workshop participants encompassed a diverse range of positions and organizations involved with planning and programs in the larger McInnis Canyons National Conservation Area (MCNCA), which includes the BRCW. The MCNCA is administered by the Bureau of Land Management (DOI BLM). BLM staff who attended the workshop included program specialists, biologists, interns, and leadership at the regional, state, and national levels. Collaborating organizations such as the USDA Forest Service, Colorado Parks and Wildlife, the non-profit Colorado Canyons Association, and Colorado Mesa University were also represented. In total, 19 individuals attended the workshop.

Applying the RAD Framework

The RAD framework is a tool meant to support decision-making in an era of ecological transformation under climate change. Using the RAD framework, land stewards can generate a broad range of decision alternatives to deliberately intervene or not intervene to address climate change threats (Crausbay et al. 2021; Schuurman et al. 2022). During the workshop, a generalized adaptive management process was used to increase the applicability of the RAD framework as a tool for strategic planning and project management (Figure 3). Adaptive management is an iterative, structured decision-making process that seeks to reduce uncertainty associated with implementing divergent management strategies, particularly through climate change (Johnson 1999). Incorporating RAD into an adaptive management process is consistent with previous efforts by Lynch et al. (2022) and Crausbay et al. (2021).

In a rapidly changing landscape where information is limited and the future is uncertain, adaptive management helps land stewards move forward by incorporating learning into decision-making (McFadden et al. 2011). By critically evaluating RAD decision alternatives and monitoring the successes and shortcomings of decisions to meet desired conditions, knowledge is generated along each revolution of the adaptive management wheel. During the workshop, we sought to complete five stages (out of seven) of an iterative adaptive management approach (Figure 3): 1) Clarify observed climate change threats and persistent ecological stressors, 2) Identify values and desired conditions, 3) Clarify potential ecological transformation(s) that threaten values and desired conditions, 4) Generate a suite of decision alternatives to address transformation using the RAD framework, and 5) Evaluate the potential socio-ecological consequences of choosing to resist, accept, or direct perceived climate change-driven threats. Subsequent stages of adaptive management, including implementing a decision alternative(s) and monitoring action effectiveness, are next steps to be completed beyond the workshop.

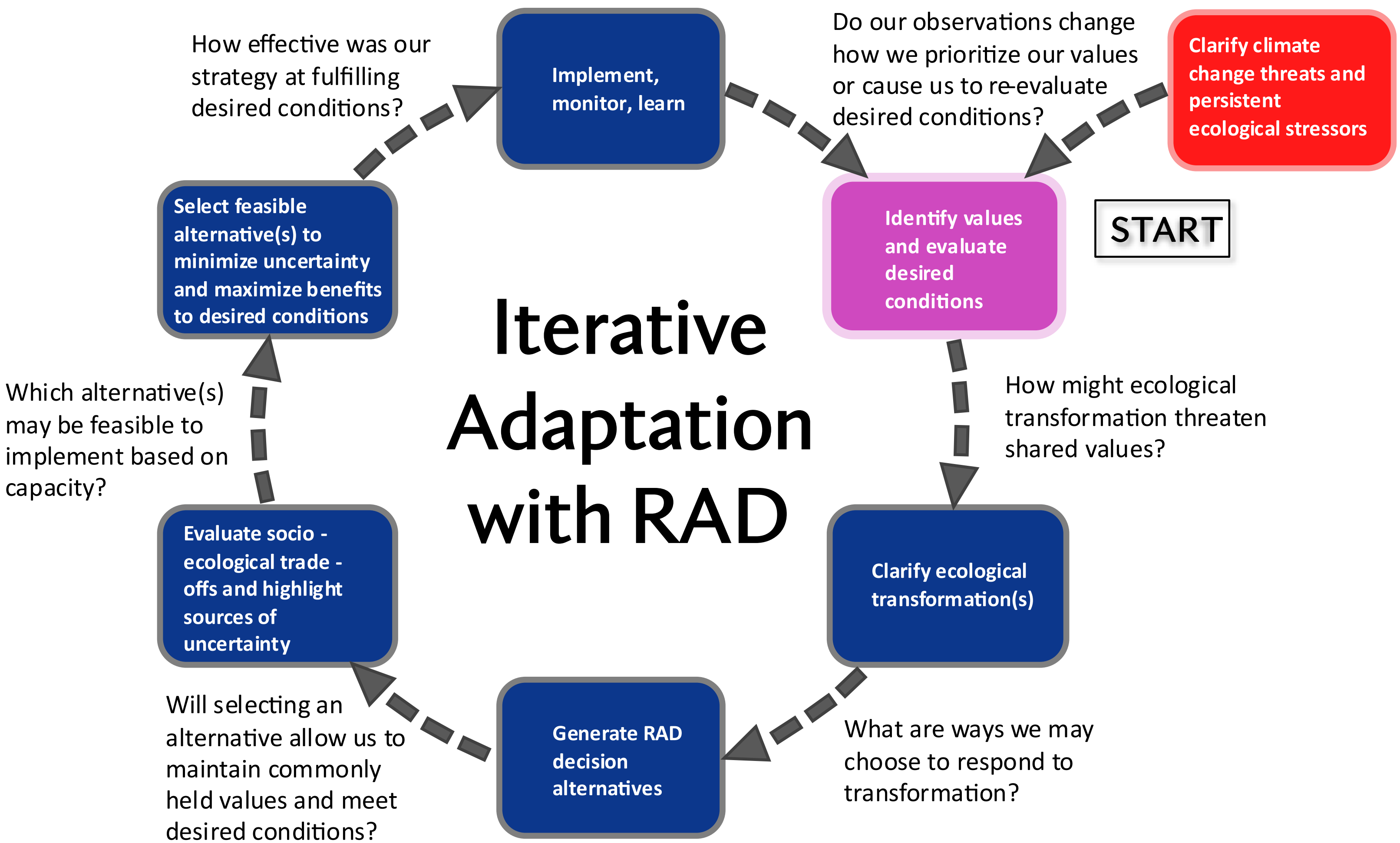


Figure 3: Iterative planning process using the resist-accept-direct (RAD) framework as a tool for climate-informed adaptation for federally designated wilderness.

Learning Objective 1: Orient the Black Ridge Canyons Wilderness in the Broader Challenge of Wilderness Management in an Era of Climate Change

To orient workshop participants to the broader challenge of managing wilderness in an era of climate change, ALWRI scientists discussed how specific challenges faced by ephemeral riparian communities in the BRCW represent a wicked problem. Facilitators identified existing and anticipated ecological stressors that may contribute to ecological transformation and shared preliminary results from the semi-structured interviews described above to summarize how managers perceive the feasibility of implementing actions to respond to transformation. Since not all workshop participants participated in an interview or work within the BRCW, this helped lay a foundation of shared knowledge about conditions within the BRCW and how they relate to national-level challenges.

The Wicked Problem Statement: Black Ridge Canyons Wilderness

In the Black Ridge Canyons Wilderness in southwestern Colorado, USA, natural and human-caused disturbances compounded by climate change are causing irreversible changes in ephemeral riparian communities. Loss of stream and pool habitat threatens native toad and frog species and may exacerbate competitive pressure from invasive bullfrogs. Subsequent changes in population abundance of native amphibians serves as a strong indicator of overall ecosystem health as habitat conditions change under climate change. Nevertheless, limited ecological data on native amphibian populations and their habitat as well as uncertainty associated with shifting ecological baselines under climate change have made it difficult for managers to confidently identify and prescribe effective management strategies for ephemeral riparian communities. Furthermore, lack of staff capacity and inability to justify allocating staff time and resources to benefit non-T&E species has impacted the potential for land stewards to prioritize conservation efforts for native amphibians and their habitat. Additionally, complex policy stipulations under the Wilderness Act may contribute to an overall hesitancy to engage in management activities that may constitute trammeling. To conserve sensitive riparian species under climate change while also upholding the intent of the Wilderness Act, land stewards are tasked with identifying and balancing multi-faceted trade-offs involving impacts to wilderness character, social and ecological values, and real and perceived institutional constraints.

Learning Objective 2: Identify Desired Conditions Surrounding the Focal Ecological Transformation that Reflects all Perspectives

How individuals perceive and understand ecological transformation and contribute to a decision space is influenced by unique life experiences and values. Several internal and external factors inform individual perspectives and values including personal worldviews, cultural norms and traditions, and institutional demands or constraints (Clifford et al. 2022). Desired conditions in place-based adaptation planning may differ substantially among participants involved in planning efforts (Stern et al. 2023). Discussing solutions to climate change-driven ecological transformation can therefore become contentious when someone's values are impacted by proposed management actions or inaction. By engaging with and illuminating the multi-faceted values of impacted stakeholders and rightsholders, land stewards can build a decision space that is inclusive of the diverse perspectives of affected groups and increase transparency in decision-making. Additionally, new vulnerabilities and opportunities may emerge that may strengthen strategic planning and generate new decision alternatives that were not previously considered (O'Brien et al. 2024). Such co-production efforts can accelerate knowledge transfer and promote sustained interest and support for continued planning as environmental conditions change and new threats emerge (Stern et al. 2023). With climate change-driven transformation, achieving or maintaining previously held desired conditions may no longer be feasible or prioritization of values or desired conditions may shift. Appropriately communicating future uncertainty and re-evaluating the dynamic feasibility to achieve desired conditions under climate change remains a critical component of decision-making.

Activity: Values and Desired Conditions

To establish a participatory decision space inclusive of the diverse perspectives of land stewards as well as impacted stakeholders, workshop participants were asked to contribute their unique values and desired conditions for the BRCW during a facilitated, large-group discussion. Values and desired conditions were recorded by workshop facilitators prior to presenting findings of the biological science analyses described above. After results of the biological analyses were presented, workshop participants were asked to revisit previously stated desired conditions to evaluate whether they believed these conditions were threatened by climate change and if new desired conditions emerged.

Values for the Black Ridge Canyons Wilderness

Given their pre-existing knowledge of and experience in the BRCW, workshop participants discussed what they valued about the BRCW broadly. Contributed values fell into multiple themes that included: recreation, natural communities and features, education and connection to place, and inspirational space (Table 4). Of their stated values, participants were particularly concerned about degrading habitat and native species losses through climate change.

Table 4: Values for the Black Ridge Canyons Wilderness, CO, USA, contributed by land stewards and their partners during a workshop to evaluate climate adaptive decision-making in wilderness.

Value Theme	Description	Illustrative Quotation
Recreation	BRCW offers unique recreational opportunities due to the feelings of solitude and remoteness while being near Grand Junction.	"Mee Canyon is our back door…Accessibility to this wilderness area is just really great for our community. You really feel like once you're out there, you're miles and miles and hours and hours from anybody that's around."
Natural communities and features	BRCW provides viable, defensible habitat for wildlife and has unique geologic features.	"It's viable habitat and given that it's in a wilderness…it's the defensible kind where it's likely to be habitat for a while."
		"The geology of the BRCW is one of those other features of value. The arches in Rattlesnake [Canyon], those are other features of value that all contribute to wilderness character."
Education and connection to place	BRCW offers outstanding opportunities for education, community outreach, and volunteer stewardship. These opportunities foster place attachment and interest in stewardship.	"Education and outreach: I really value that [BRCW] is a springboard for early scientists, whether they're interning at our agency or they're working at CMU... [They] really get to be a part of this place and that conservation piece."
Inspirational space	BRCW is an inspirational space for visitors, specifically for art and science.	"With some of our education trips that we've taken into the Canyons, students were inspired: drawing, journalling, poems. It may be an important place for inspiring teachers, scientists, and artists."

Desired conditions for the Black Ridge Canyons Wilderness

Workshop participants generated desired conditions for the BRCW based on the values described in the previous exercise and on pre-existing goals and objectives. Discussion of desired conditions was, in part, grounded in the 2004 Colorado Canyons NCA/Black Ridge Canyons Wilderness Resource Management Plan (RMP) and the Wilderness Act. The 2004 RMP considers the physical, social (i.e., recreation), and administrative settings of each zone of the NCA including zones within wilderness (DOI BLM 2004). Desired outcomes for the BRCW as outlined in the RMP largely included benefits for visitor experience such as increased physical and spiritual health, outdoor knowledge and skill, awareness and appreciation of nature, sense of community pride, and stewardship. One environmental benefit for the BRCW highlighted in the RMP included “greater retention of distinctive natural landscape features” (DOI BLM 2004).

Some workshop participants cautioned against changing the desired outcomes and benefits described in the RMP or “moving the goalposts”. Rather, these participants felt that staff should focus on the new and changing management actions needed to achieve existing desired conditions. Other participants thought that desired conditions may need to be reevaluated after considering climate change impacts to ephemeral riparian communities, particularly when considering native species threatened by rapid invasion of non-native species and habitat loss.

Workshop participants also discussed the management paradigm of desired conditions generally and whether desired conditions were appropriate and achievable. One question raised was if “desired conditions are appropriate in wilderness”, where natural systems are meant to exist or change without human interference. Another participant reflected that the management paradigm of desired conditions, thresholds, and triggers is inherently reactive. To be more proactive, but still work within the same management paradigm, this participant suggested making triggers and thresholds more conservative; or, allowing for less change before management response. Participants felt that the ability to achieve or reevaluate desired conditions was limited by several factors, including budget, technical knowledge, and staffing capacity. However, participants identified that there may be opportunity to leverage outside partner support to meet objectives and establish long-term monitoring and inventory programs.

In addition to the desired outcomes and benefits outlined in the RMP, participants identified three more desired conditions for the BRCW: maintain thriving populations of native flora and fauna, leadership of innovative management, and to keep wilderness wild.

Maintain thriving populations of native flora and fauna

Building on values of natural communities and features, there was a large consensus among workshop participants to continue to see “native flora and fauna species thrive” through climate change in the BRCW. Native flora and fauna thriving meant preserving native species and reducing the likelihood that these species would be replaced by non-native species such as cheatgrass, tamarisk, Russian olive, and bullfrogs. Participants felt that native species were important parts of the historical natural quality of the wilderness. And one participant felt managers should use historical conditions “as a gauge” for their “reference vision” of this desired condition.

Leadership of innovative management

One participant wanted the “wilderness and the [McInnis Canyons] NCA [to be] an example of people on the forefront of decision-making and management” when considering climate adaptation planning. As part of this desired condition, management paradigms for the BRCW would need to be more proactive and less reactive. This desired condition also included engaging in research to contribute to proactive planning and leveraging partnerships to do so.

Keep wilderness wild

Several participants wanted to maintain the feeling of wildness within the BRCW. Participants described the difficult balance of encouraging recreation within the wilderness for increased community support with maintaining opportunities for solitude. For example, one participant stated: “Part of wilderness is keeping it wild, and that solitude aspect. We want to encourage education and outreach and recreation…How do we do that while also keeping it wild?” For some participants, wildness primarily meant maintaining opportunities for solitude, and for others, it meant allowing the land to be untrammeled.

Influence of anticipated climate change impacts on values and desired conditions

After being presented a summary of anticipated impacts of climate change on ephemeral riparian communities, workshop participants were asked if they were concerned about any of their previously stated values and if the desired conditions still felt feasible. Participants agreed that even though future conditions felt grim, there was a need to strive for desired conditions with the help of partners. Some participants felt that, although the identified desired conditions still felt feasible now, they may not be as feasible in ten years. To address this, some participants suggested that desired conditions could be continually evaluated over time as conditions on the ground change. A partner subject matter expert emphasized that more fine-scale species and habitat monitoring would be beneficial for better understanding how conditions on the ground are changing in relation to desired conditions. Another viewpoint expressed, however, was that desired conditions are meant to be aspirational and questioned if they need to be feasible at all.

One workshop participant felt that climate change and ecological transformation underscored the need to work across space and time and recognize how desired conditions for the BRCW fit into desired conditions for the broader landscape. They felt that if native amphibians could be protected from transformation anywhere, it should be with wilderness where other threats to habitat (e.g., human development) are minimal. They remarked that a landscape scale approach to desired conditions diverges from historic management paradigms and requires more collaboration and community support.

Another workshop participant added a desired condition to the list: “a well-staffed management agency", with specialists who can make desired conditions achievable. Several participants did not feel that the MCNCA currently has the staff to make this achievable. Others were more optimistic that current staffing levels could achieve desired conditions, because staff are dedicated and often find ways to achieve projects they are passionate about. Other participants emphasized the importance of partnerships that help fill gaps in BLM staff capacity.

Learning Objective 3: Understand the Utility of RAD as a Tool for Responding to Ecological Transformation

Since European settlement, ecological systems within the United States have been managed under the assumption of stationarity, or the tendency of environments to fluctuate within a range of historically known conditions (Jackson & Hobbs 2009; Magness et al. 2022; Young & Duchicela 2020). With this understanding, environmental properties may change in response to disturbance events, such as wildfire, but also return to a known reference or stable state following disturbance. Increasingly, however, land stewards are observing a shift in ecosystem state beyond a historical natural range of variability (Schuurman et al. 2022). Once ecological communities have crossed a threshold, it is often infeasible to restore historical ecosystem structure and function (Milly et al. 2008; Suding and Hobbs 2009). Management techniques that may have been previously employed to restore ecosystems following perturbation or strategies to promote resiliency through disturbance may no longer be effective at achieving desired conditions. Land stewards are therefore increasingly challenged to generate novel solutions to meet management mandates and objectives as the character of the landscapes they manage continue to shift.

Decision alternatives for wilderness in an era of climate change

The RAD framework was developed in response to the need for further guidance in responding to ecological transformation under climate change. Rather than defaulting to familiar actions or strategies, the RAD framework provides a space for land stewards to evaluate the opportunities and costs of choosing to deliberately act to intervene (resist or direct) alongside the deliberate decision to not intervene (accept) with observed climate change-driven ecological transformation. This is particularly pertinent for federally designated wilderness, where accepting ecological change may be a familiar strategy due to real and perceived barriers to using active management (Cravens et al. 2024). Nevertheless, although active management is highly scrutinized in wilderness, such activities are not strictly prohibited. In some instances, resist strategies may be necessary to preserve or recover special status species, such as those listed under the Endangered Species Act. Direct strategies are often less familiar and may be viewed as high-risk strategies because few real-world examples exist outside manipulative experimental trials such as common garden and greenhouse experiments (Cravens et al. 2024). By carefully considering all potential alternatives and their implications for wilderness character qualities, land stewards may justify the use of minimum allowable tools to meet desired conditions in rapidly changing wilderness landscapes.

Activity: Generating RAD Decision Alternatives

Before introducing the RAD framework, workshop participants were divided into small groups of 6-7 and asked to generate potential management responses to the target transformations for ephemeral riparian communities in the BRCW. Participants were encouraged to freely generate decisions, regardless of capacity limitations, constraints, or risks. Nine themes of response strategies emerged from exercises and ensuing conversations: invasive species control, grazing management within wilderness, water retention strategies, inventory and monitoring, captive breeding and release into previously unoccupied habitat, increased communication, relationship building with private landowners, restrictions and enforcement, and impactful restoration planning (Table 5). Following this exercise, workshop facilitators introduced the RAD framework and asked participants to sort their decision alternatives into resist-accept-direct categories they felt best represented the intent of each alternative. If participants felt a decision alternative fit multiple categories, they were allowed to classify that alternative as such.

Workshop participants generated several decision alternatives that resisted ecological change to ephemeral riparian communities, including removing bullfrogs, treating non-native invasive plant species with herbicide, adding shade structures to reduce evaporation from ephemeral pools, restoration planting, and supplemental water drops. Accept strategies, or strategies that did not include active management, largely consisted of research and monitoring efforts. Direct strategies included actions to either create new habitat in areas outside the canyons or wilderness and assisted migration strategies to move vulnerable species to new areas where climate and habitat conditions are anticipated to remain more suitable through climate change. Participants identified several alternatives that could inform multiple resist-accept-direct strategies, including increasing communication and collaboration among partners, education and outreach with community members and recreationists, flexible access and enforcement, and creating detailed planning documents.

When asked why resist strategies may have been more common, some participants felt that resistance was often the nature of their jobs. Additionally, some participants felt that solving the "problem" of ecological transformation naturally led to ideas to resist change. Other participants expressed that they felt more comfortable with resist and accept strategies in the form of monitoring because direct strategies felt too risky given the lack of successful real-world examples. One participant expressed that they did not want to be responsible for directing change "in the wrong direction", thereby making matters worse. Additionally, one participant expressed a concern for increased risk of litigation using a direct strategy, particularly considering the potential legal challenges of relatively untested actions.

Table 5: Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for native ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Invasive species control	Eliminate source populations of bullfrogs upstream of wilderness and with support of partners	X		
	Largescale herbicide treatment of invasive plant species	X		
Grazing management within wilderness	More flexible and proactive grazing management	X		
	Stop grazing within wilderness	X		
	Restraint and enforcement for grazing permittees to ensure proper cattle rotation and to maintain infrastructure	X		
Water retention strategies	Shade structures over pools	X		
	Plant native vegetation to shade pools	X		
	Beaver dam analogs upstream of wilderness to create new habitat			X
	Beaver dam analogs / Zeedyk structures outside wilderness to create new habitat			X
	Snow fences	X		
	Supplemental water to canyons	X		

Table 5 (continued): Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for native ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Inventory and monitoring	Fine scale inventory and monitoring to learn about system changes		X	
Captive breeding and release into new, previously unoccupied habitat (ex-situ conservation)	Move species out of unsuitable habitat in critical situations			X
	Work with local golf courses to remove bullfrogs and relocate native amphibians to golf courses			X
	Captive breeding and release into new habitat			X
Increased communication	Improve communication with public about beavers within the NCA	X	X	X
	Improve communication with the public about native amphibians	X	X	X
	Communicate story of the MCNCA and BRCW to inspire people to care about climate change and native amphibians	X	X	X
	Improve communication with other agencies and among BLM offices to learn from successes and mistakes	X	X	X
Relationship building with landowners	Build and expand relationships with adjacent private landowners to create buy-in	X	X	X

Table 5 (continued): Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for native ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Restrictions and enforcement	Enforce requirements with permittees and build shared understanding around enforcement and ecosystem health	X	X	X
	Proactive restrictions on recreation access (e.g., permits) to decrease existing non-climate stressors within and outside wilderness	X	X	X
Impactful restoration planning	Create a detailed restoration plan that carries the same weight as the RMP.	X	X	X

Learning Objective 4: Develop a Feasible and Repeatable Workflow to Evaluate RAD Decision Alternatives

Selecting and applying decision alternatives generated using the RAD framework can be challenging if the ecological transformation is poorly understood or if institutional constraints impact the ability of managers to feasibly pursue certain alternatives. Ecological modeling and experimentation may help to characterize potential transformations; however, uncertainty often persists. Despite constraints and sources of uncertainty, land stewards are tasked with responding to ecological transformation to fulfill institutional mandates and objectives.

Balancing social-ecological trade-offs

In addition to grappling with uncertainty, wilderness stewards must also balance social-ecological trade-offs inherent in decision-making under climate change. These trade-offs are a negotiation of the unique values each member of the planning or project team contributes balanced with policy requirements under guiding strategic management plans and legal documents, such as the National Environmental Policy Act (NEPA) and the Wilderness Act. In federally designated wilderness, selecting and implementing a decision alternative should minimize undesirable outcomes as well as impacts that may degrade wilderness character. For example, preserving special status, iconic species may be considered a high priority for managers to fulfill requirements pursuant to the Endangered Species Act (16 U.S.C. 1531-1544) as well as to maintain or preserve the natural quality of wilderness. Nevertheless, the type of management action pursued to support species persistence may conflict with policy under the Wilderness Act. Resist strategies are often used for single-species preservation and may involve habitat restoration or species reintroductions to historical habitat. However, resist actions often require trammeling of wilderness to meet necessary targets for viable populations. Furthermore, under climate change, it is becoming less common that single actions will be sufficient to support species persistence, thereby necessitating more intensive management efforts (Evans et al. 2016). In the long-term, a resist strategy may reduce undesirable outcomes associated with species loss, but this strategy may also degrade wilderness character through multiple acts of trammeling. Under an accept strategy, where no active management takes place, wilderness character may not be degraded by trammeling; however, the natural quality of wilderness may be compromised if an iconic species is lost. Finally, under a direct strategy, individuals or populations may be translocated to other areas of the landscape where they may persist autonomously as habitat conditions shift under climate change. Trammeling may be required to translocate the species to more suitable habitat within or outside wilderness, however, unlike the resist strategy, it may be less likely that this strategy will entail repeated acts of trammeling to meet target population requirements if the species can be self-sustaining within its introduced range. For management decisions to be defensible, it is critical to explicitly account for all potential impacts of implementing a decision alternative.

The Futures Wheel: An exercise to illuminate trade-offs

To help clarify sources of uncertainty and socio-ecological trade-offs inherent in climate change-informed decision-making, we used the Futures Wheel tool to evaluate the potential outcomes and tradeoffs of a resist, accept, and direct strategy within the BRCW. The Futures Wheel is a structured brainstorming tool used to describe multi-level potential outcomes of addressing social-ecological change (Bengston 2015; Bengston et al. 2022). There are many ways to design and apply the Futures Wheel, however, in its basic structure, it requires users to define multiple arcs of potential consequences that stem from a central problem or event. Perceived positive, negative, and neutral consequences are all considered along each arc and individual arcs describe a hierarchy of connected consequences. First order consequences occur as a direct result of the central decision point or event. Second order consequences are triggered by first order consequences. Third order and all subsequent consequences are directly informed by the preceding order. Arcs are extended as far as necessary, such that all potential consequences have been identified for each arc. The purpose of building arcs is to clarify all potential impacts, likely or unlikely, that stem from a central problem or event. By following this process, users can reduce unforeseen impacts and identify consequences that may be particularly beneficial or catastrophic (Bengston et al. 2022). Furthermore, by explicitly describing and recording all potential implications of implementing a decision, this process fosters transparency in decision-making. After all arcs have been completed, users can score each consequence by the likelihood that it may occur and its perceived desirability (Table 6). Final scores can then be summarized across the wheel to generate a quantitative understanding of the drawbacks and opportunities of a central problem or event.

Activity: Applying the Futures Wheel to RAD Decision Alternatives

To further evaluate decision alternatives generated during the workshop, a Futures Wheel was used to illuminate all potential consequences (positive, negative, or neutral) of selecting either a resist, accept, or direct action to address ecological transformation for ephemeral riparian communities in the BRCW. Workshop participants were divided into small groups which represented a range of positions, tenure, and affiliations. Each group constructed one wheel focused on either a resist, accept, or direct alternative (Box 5). Decision alternatives were placed at the center of each wheel such that subsequent arcs described direct and indirect implications associated with implementing each alternative. Workshop participants were encouraged to consider a range of potential consequences, including social, legal, and ecological consequences. Participants then scored each unique consequence by its likelihood and desirability and a group consensus score was recorded (Table 6). Likelihood described the perceived possibility that each consequence would come to pass and was scored on a scale from 1-9. Desirability described perceived appeal of each potential consequence and was scored along a weighted scale such that perceived catastrophic consequences received a score of -50 and triumphant consequences received a score of 50. Scores were summarized by both the average and mode for likelihood and desirability for each wheel and summaries were used to evaluate whether each alternative may sufficiently balance socio-ecological trade-offs and achieve desired conditions for ephemeral riparian communities in the BRCW.

Table 6: Scoring method for a Future's Wheel activity examining the implications of choosing to resist, accept, or direct ecological transformation in native ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

Likelihood		**Desirability**	
9	Extremely likely	50	Triumph
8	Very likely	5	Extremely desirable
7	Likely	4	Very desirable
6	Somewhat likely	3	Desirable
5	Uncertain	2	Somewhat desirable
4	Somewhat unlikely	1	Minimally desirable
3	Unlikely	0	Neutral
2	Very unlikely	-1	Minimally undesirable
1	Extremely unlikely	-2	Somewhat undesirable
		-3	Undesirable
		-4	Very undesirable
		-5	Extremely undesirable
		-50	Catastrophe

RESIST

Reduce competitive and predatory pressure on native amphibians by removing bullfrogs from upstream source populations on public and private land within and outside the Black Ridge Canyons Wilderness. Methods of capture and removal include netting and hand capture. All age classes of bullfrogs will be removed. Access to sites will include a diverse range of options and effort (water, land, road).

Likelihood	*Desirability*
Mean: Somewhat Likely (6)	Mean: Somewhat Desirable to Desirable (2.7)
Mode: Highly Likely (9)	Mode: Extremely Desirable (5)

ACCEPT

In lieu of implementing active management, fund and support monitoring of changing ecological conditions to understand how climate change is impacting native ephemeral riparian communities in the Black Ridge Canyons Wilderness. Work would include audio inventory and temporary installation (up to 5 years) of ecological monitoring equipment such as temperature loggers, acoustic monitors, and water depth sensors. This work would necessitate travel to monitoring sites about 3 times/year. Access to sites would be from the Colorado river and requires boat or raft use.

Likelihood	*Desirability*
Mean: Uncertain to Somewhat Likely (5.8)	Mean: Extremely Undesirable to Catastrophic (-23.1)
Mode: Uncertain (5) and Highly Likely (9)	Mode: Catastrophic (-50)

DIRECT

Conserve native amphibians by moving individuals from historical habitat to new, currently unoccupied natural water sources expected to maintain optimal habitat conditions within and outside the Black Ridge Canyons Wilderness. Collect about 30% of viable wilderness populations. Collect tadpoles only from native range. Use a combination of the following introduction strategies: 1) introduce directly to new habitat, 2) observation in controlled tank environments. This strategy also requires removal of all age classes of bullfrogs in areas of new, introduced habitat using net or hand capture methods.

Likelihood	*Desirability*
Mean: Uncertain to Somewhat Likely (5.3)	Mean: Extremely Undesirable (-6.8)
Mode: Unlikely (3)	Mode: Undesirable (-3) to Catastrophic (-50)

Box 5: Alternative actions proposed to resist, accept, or direct anticipated ecological transformation for native ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA. Workshop participants scored each decision alternative using the Futures Wheel tool to evaluate the likelihood and desirability of potential cascading social-ecological consequences.

Resist: Removal of bullfrogs

The resist decision alternative focused on reducing competitive and predatory pressure by bullfrogs on native amphibian species. Overall, implications of this strategy were viewed as somewhat to highly likely and somewhat desirable to desirable based on ratings of individual implications (Figure 4). Ecological, recreational, educational, and institutional implications were identified in potential cascading effects of removing bullfrogs.

Workshop participants felt the resist strategy was ecologically desirable as it would reduce bullfrog populations and consequently reduce competition with native amphibians and potential for disease spread. Along one arc, participants identified that focusing only on the removal of bullfrogs may not account for changes in habitat due to climate change. Although competition and risk of disease may be decreased, this arc suggests that additional actions may be needed to address habitat transformation.

Workshop participants identified several social implications associated with the resist strategy. First, participants felt recreation experiences would likely be enhanced by opportunities to participate in citizen science efforts associated with bullfrog removal. This would result in increased community awareness about the removal project, the BLM, and other related topics, which would be highly desirable and likely. Additionally, participants also recognized that removal work would likely require more campsite use for administrative purposes, which may displace recreational visitors. However, participants felt that displacement would be extremely unlikely. If recreational visitors were displaced, then participants felt the BLM would need to provide public outreach and education about the need for more administrative sites. Legal implications were not identified for this action; however, other institutional implications were identified. Participants recognized that implementing this action would result in workload increases for staff including training and volunteer recruitment, which they scored extremely likely. This increased workload would require significant amounts of volunteer and staff time, and could result in heightened liability, which is minimally undesirable.

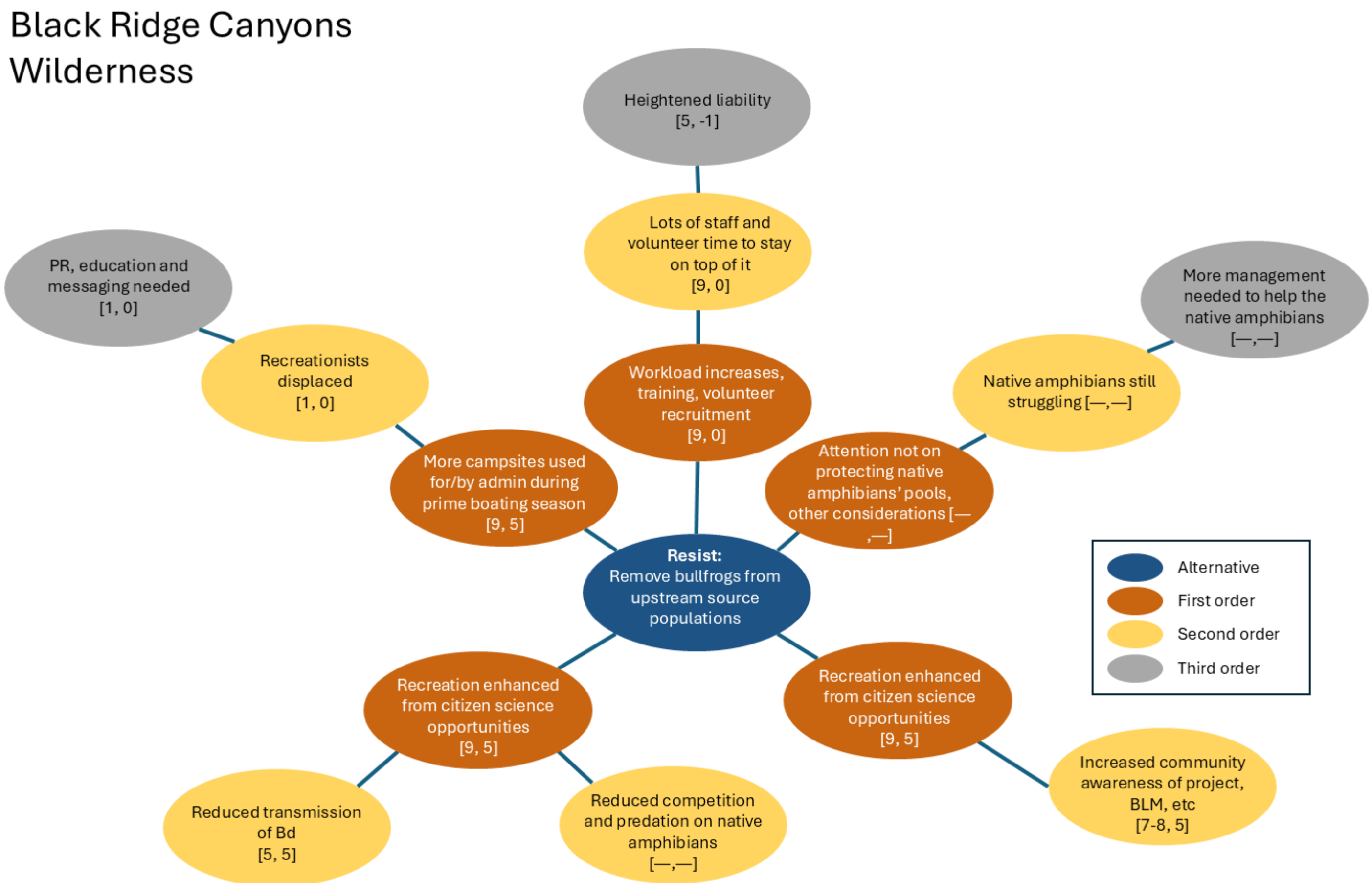


Figure 4: A Futures Wheel used to illuminate the potential cascading implications of choosing to resist anticipated ecological transformation through the removal of bullfrogs (blue circle) from ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA. Implications (orange, yellow, and gray circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets). Some implications were not scored (dashes) because of time constraints.

Accept: Research, inventory, and monitoring

The accept action focused on monitoring environmental and population changes while allowing for ecological change to occur without management intervention. Overall, implications of this alternative were viewed as uncertain to somewhat likely. The desirability of these implications was viewed as extremely undesirable to catastrophic (Figure 5). Ecological, recreational, institutional, and legal implications were identified in potential cascading effects of monitoring the transformation. Generally, this strategy was seen as a good short-term solution for understanding the system more as it changes, but participants did not feel like this was a viable long-term solution.

Workshop participants felt the ecological implications of this acceptance strategy would be catastrophic. Participants indicated that not actively responding would result in risk of increasing bullfrog populations in ephemeral canyon habitat. Increased presence of bullfrogs could result in increased disease transmission to native amphibians and, subsequently, decreased population abundance. A decrease in native amphibians would mean a failure to meet objectives for the MCNCA and the BRCW. As a group, participants rated each of these implications as extremely likely and catastrophic.

Workshop participants identified several social implications of the accept strategy. In particular, participants felt that the presence of data loggers could detract from feelings of solitude within the wilderness and could require a need for educating the public about the monitoring work and pique public interest in the equipment. Increased public interest could result in a risk of equipment vandalism (unlikely but catastrophic) and increased visits to the canyon pools, which could cause trampling of riparian vegetation (somewhat likely and undesirable) and disturbance of native amphibians (very unlikely but extremely undesirable).

Workshop participants also identified legal and institutional implications for this strategy. Participants recognized that temporary installation of monitoring equipment would require the completion NEPA requirements and a Minimum Requirements Analysis (MRA) using the Minimum Requirements Analysis Framework (MRAF). Going through these processes would take staff time to complete when staff capacity is already low, and there could be costs associated with staff time and other resources to complete these processes. Additionally, participants identified that this strategy would not likely result in potential for litigation, but if litigation did occur, it would be undesirable. Additionally, participants recognized that equipment installation and monitoring would cost time and money, and it was uncertain if equipment loss could occur from flash floods, which would be catastrophic.

Black Ridge Canyons Wilderness

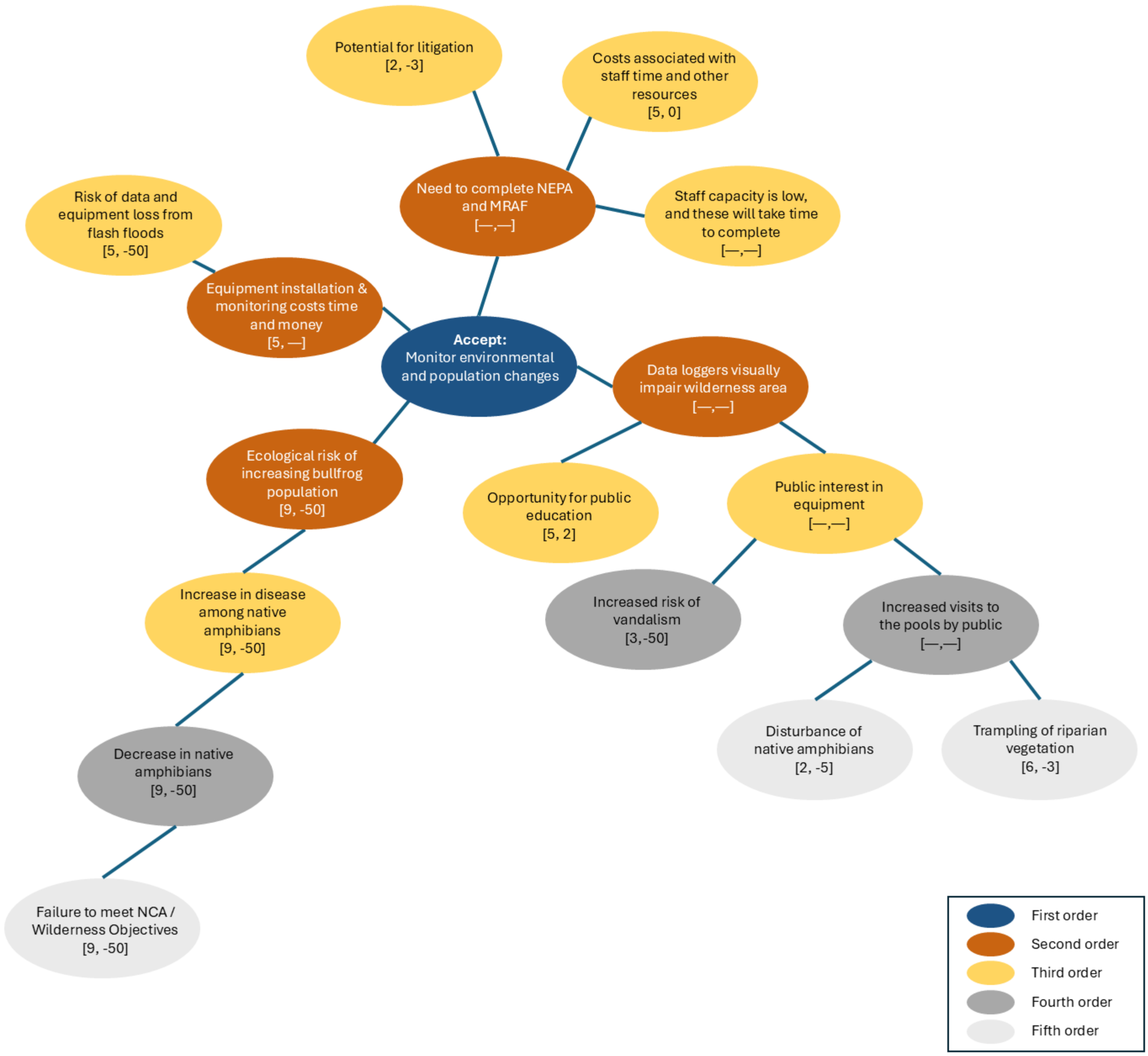


Figure 5: A Futures Wheel used to illuminate the potential cascading implications of choosing to accept ecological transformation and engage in research and monitoring to learn from ecological change (blue circle) in ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA. Implications (orange, yellow, and gray circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets). Some implications were not scored (dashes) because of time constraints.

Direct: Assisted migration of native amphibians

The direct alternative focused on ex-situ conservation, or relocating a portion of the native amphibian populations from threatened wilderness habitat to new habitat where climate stressors may be reduced. Implications of this strategy were viewed as uncertain to somewhat likely. Overall desirability of these implications was viewed as extremely undesirable (Figure 6). Ecological, recreational, educational, and stakeholder partnership implications were identified in potential cascading effects of ex-situ conservation.

Participants identified several ecological implications for the direct strategy. Participants felt that by moving populations there was a somewhat likely risk of introducing disease into areas it did not previously exist, which they deemed catastrophic. Participants also felt that, although unlikely, there was a chance that population viability analyses used to estimate the appropriate number of individuals to conserve and move from native habitat could be incorrect, subsequently resulting in harm or potential extirpation of native amphibian populations within the BRCW. Because moving native species may also degrade the natural quality of wilderness and require trammeling, participants felt it would be likely that the BLM would be litigated, which would be very undesirable. Participants also indicated that there could be undesirable impacts to other native flora and fauna and other unintended environmental consequences which would be catastrophic. Finally, participants did acknowledge that this strategy could likely be successful and result in redundant native amphibian populations that are resilient, which would be a triumph.

Social implications of this direct strategy were also identified. Participants noted that although somewhat unlikely there could be somewhat undesirable interactions between new populations and existing recreation in introduction areas. This could result in an undesirable need to ask the public to change their recreation behavior, and result in negative perceptions and relationships with the public, funders, and partners. Within the BRCW, removal of native amphibians could be considered a loss of naturalness and take away from experiences of solitude, which would be somewhat undesirable. On the positive side, a direct strategy could improve community relations and create new volunteer opportunities and increase interest, support, and stewardship, which was an implication that was viewed as likely and extremely desirable. This action could also very likely create research and learning opportunities for these and other amphibian species which would be extremely desirable. From a management perspective, there could be implications related to introducing sensitive species for the private landowners or agency managing introduction areas, which although viewed as unlikely, would be undesirable.

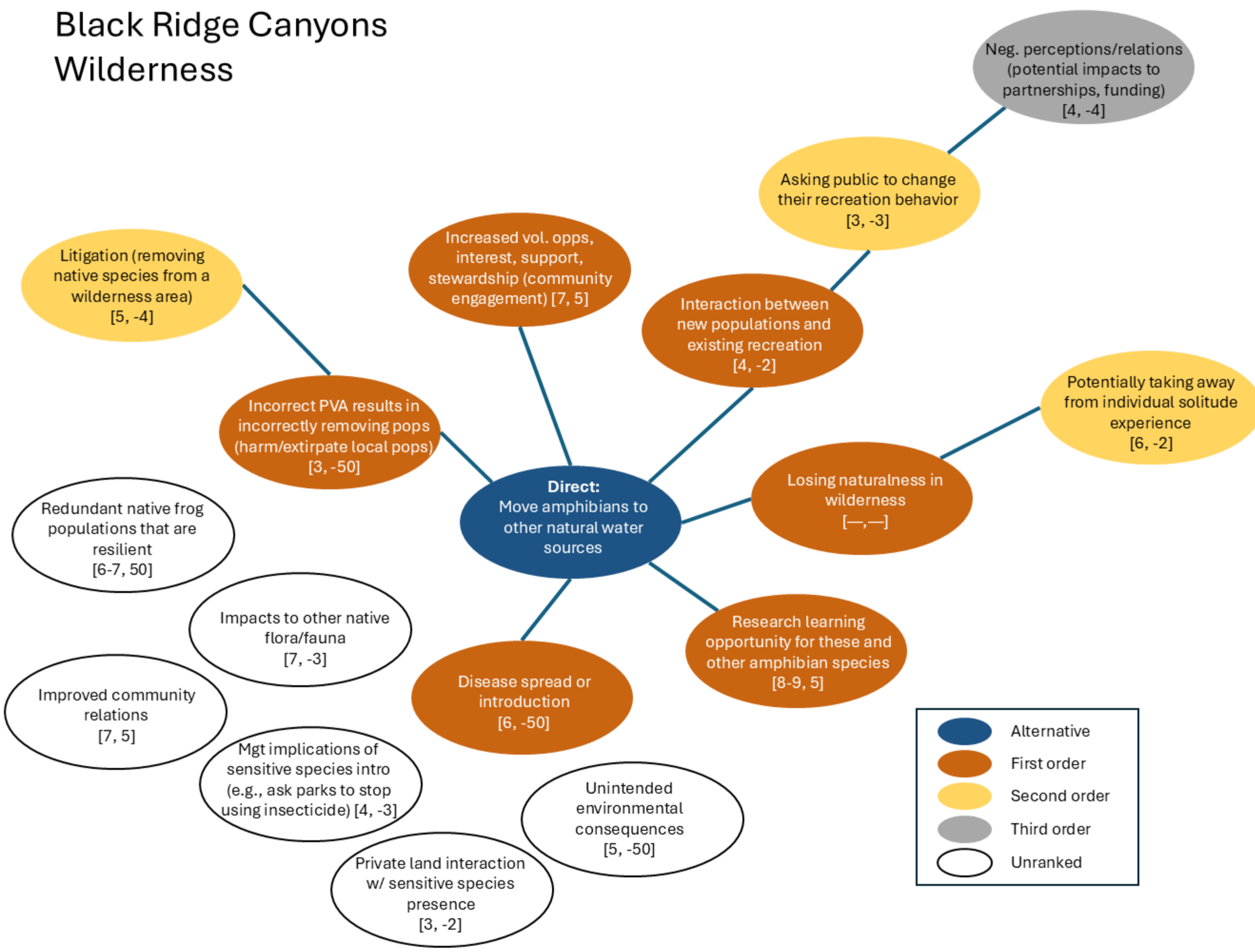


Figure 6: A Futures Wheel used to illuminate the potential cascading implications of choosing to direct ecological transformation by moving native amphibians from ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA, to new habitat that may be less susceptible to climate stressors (blue circle). Implications (orange, yellow, gray, and white circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).

Key take-aways and findings from the Futures Wheel exercise

- Resistance through bullfrog removal may be a more desirable short-term strategy; however, it does not address longer-term threats such as climate change driven habitat transformation
- The accept strategy was determined to be an appropriate interim solution, with an emphasis on more precise species and habitat monitoring to inform future decisions to resist or direct
- Although several of the potential implications of the direct strategy were considered undesirable, it may be the most effective at conserving native species through climate change
- None of the decision alternatives were rated as highly likely nor highly unlikely, indicating there was a high degree of uncertainty in anticipated outcomes for any alternative

Conclusions and Considerations for Future Work

Addressing climate change challenges in federally designated wilderness is a wicked problem faced by land stewards throughout the United States. The purpose of this case study was to begin to untangle this wicked problem by examining the biological and social impacts of climate change and by introducing an iterative process that land stewards and their partners may use to be more mindful in their response to climate change-driven ecological transformation. The case study described in this report specifically addresses the wicked problem of managing for projected ecological transformation in ephemeral riparian communities in the Black Ridge Canyons Wilderness (BRCW), CO, USA. Scientists at the Aldo Leopold Wilderness Research Institute (ALWRI) researched both the potential ecological consequences of projected climate change to ephemeral riparian communities as well how those consequences are observed by land stewards and their perceived capacity to respond. Following this research, ALWRI scientists facilitated a 2-day workshop with Bureau of Land Management (BLM) staff and their partners to introduce an adaptive management process incorporating the RAD framework to generate and evaluate a decision space for addressing climate change-driven transformation.

Workshop participants valued the unique recreational experiences and natural environment of the BRCW as well as opportunities for education and outreach programs in collaboration with existing partners from local organizations and educational institutions. These values contributed to the desire to see native communities continue to thrive in the BRCW, maintain opportunities for solitude, and serve as national leaders for climate adaptation planning for other BLM NCAs. Although climate change is anticipated to negatively impact ephemeral riparian communities within the wilderness and within-agency capacity to allocate resources to respond to climate change challenges remains low, workshop participants remained optimistic about their ability to conserve vulnerable species and described a variety of alternative actions to achieve desired conditions.

Workshop participants generated decision alternatives that largely focused on resisting anticipated ecological change in ephemeral riparian communities. Nevertheless, participants also generated several strategies that did not involve active management, such as building partnerships and engaging in further research and monitoring, that could be used to inform current and future planning. Although resist strategies were common, when participants further evaluated contrasting RAD alternatives, they felt that no single action was extremely desirable and that uncertainty about long-term future outcomes was high among all alternative actions. Participants felt a resist strategy to remove bullfrogs may be a good short-term solution but may not meet long-term objectives of native species conservation and would require significant trammeling in wilderness to remain effective over time. Similarly, participants felt an accept strategy which included research and monitoring would be beneficial in the short-term to learn about population dynamics and responses to climate change. Nevertheless, long-term application of an accept strategy without also engaging in active management may lead to native species losses, resulting in a failure to meet wilderness objectives. Alternatively, although participants initially felt direct strategies (e.g. moving native species to new locations outside their native range) may be the inherently risky, they determined that these strategies may have more beneficial long-term implications for species conservation through climate change. To apply these tools and proceed to the next phase of selecting and implementing R-A-D alternative actions, participants expressed a need to pursue additional research to fill knowledge gaps, identify ecological trigger points, and devise timelines and strategies for incorporating climate-informed adaptive decision-making into existing planning processes.

Filling Knowledge Gaps

Land stewards are often tasked with making decisions with incomplete knowledge and high uncertainty in rapidly changing landscapes. The tools outlined in this report are meant to support high-risk decision-making under climate change, however, the ability to anticipate ecological change as well as the effectiveness of management activities to address change and meet desired conditions hinges on the ability of managers to continue to learn and adapt. Research and monitoring are necessary activities to accelerate learning. Workshop participants identified a need to monitor trends in ecological patterns and processes within the BRCW that may impact ephemeral riparian communities. Future efforts may include installing remote data loggers to regularly collect information on pool depth and temperature, repeated measures of native and invasive amphibians to evaluate changes in species composition, and plant inventory and analysis. Participants also discussed potential for an experimental breeding program outside wilderness for native amphibians to assess the efficacy of either bolstering existing populations or to support assisted migration efforts. Establishing these research and monitoring programs will support proactive planning and help land stewards avoid the pitfall of responding to irreversible or catastrophic change after it has occurred. For these programs to be successful, strong partnerships with collaborating academic institutions, volunteer organizations, state agencies, and non-profit organizations may be necessary to overcome obstacles related to capacity.

Identifying Ecological Thresholds or Trigger Points

When and where to apply RAD decision alternatives remains a complex topic that requires further consideration. Workshop participants indicated that identifying ecological thresholds may be important to better plan for change and select appropriate management strategies through time. Nevertheless, recent studies have indicated that ecological thresholds are difficult to define and are rarely detected by empirical data (Hillebrand et al. 2020). Rather, ecological transformation has been described as a continuum of irreversible change that may increase in magnitude over time (Hillebrand et al. 2020). In that respect, it may be more appropriate for land stewards to identify specific features or ecological processes that, if degraded or lost, might trigger management actions. Limits of acceptable change (LAC) is one example of a tool wilderness managers may use to decide if or when to implement management actions to either resist or direct observed ecological change (Stankey and McCool 1984). LAC was initially developed to inform the management of recreation in wilderness. More recently the LAC tool has been revisited to understand how it can be applied in a multi-use framework (McCool and Cole 1997). Wilderness managers may use this tool or develop their own to decide how much ecological change may be acceptable and to justify when active management may be necessary to minimize undesirable outcomes.

Timelines for Application

For any climate adaptation process to be successful in the long-term, it is important to establish a timeline to revisit and re-evaluate key decisions and desired conditions on a recurring basis (Stein et al. 2014). There are several obstacles that can make it difficult to adhere to re-evaluation timelines, including insufficient resources or capacity, turnover in leadership and staffing, and competing priorities. Some of these obstacles can be overcome by developing and maintaining partnerships, planning ahead to secure appropriate resources and tools, keeping detailed and accessible records, and designating appropriate timelines that may coincide with existing planning revisions or amendments (Månsson et al. 2023). Throughout this case study, land stewards highlighted the need for continued and growing partnerships, identified knowledge gaps and uncertainties for further investigation, and evaluated desired conditions and potential outcomes of divergent decision alternatives. To reduce potential redundancy with existing efforts and streamline decision-making, the skills acquired during the workshop can be used to support existing planning and projects.

Incorporating RAD into Existing Planning

The RAD framework design is intentionally simple so that it can be applied to existing planning strategies and processes (Schuurman et al. 2022). While similar discussions and conversations may already be a part of existing protocols, the process outlined in this report allows land stewards to build a transparent, repeatable process that can be applied in a wide variety of contexts to support more defensible decision-making. For example, the RAD framework may be used to structure decision alternatives as required under the National Environmental Policy Act (NEPA). The accept option of RAD aligns well with the no-action alternative for NEPA, whereas the resist and direct options may be considered alternative actions. For a Minimum Requirements Analysis (MRA), RAD may similarly be used to generate divergent decision alternatives for further evaluation. Additionally, the Futures Wheel exercise can illuminate impacts of each decision alternative when determining whether action may be necessary to achieve specific objectives or improve certain wilderness character qualities. In conclusion, the skills and tools explored for this case study and introduced during the workshop are intended to support increasingly complex decision-making in wilderness by integrating adaptation thinking into existing planning processes.

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APPENDIX

Appendix A

Detailed results of the biological analysis of climate change impacts to ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA. Results include projected changes in select climate metrics relevant to native amphibians and their habitat for three climate scenarios: warm/wet, hot, hot/dry. Additional summaries describe anticipated ecological transformations at two spatial scales (landscape and local) associated with each scenario, derived through structured conversations with local and subject-matter experts.

Appendix B

Key themes about climate change and climate-informed adaption responses derived from a series of five semi-structured interviews of land stewards and their partners focused on impacts to ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

APPENDIX A

Building Climate Scenarios and Describing Potential Ecological Futures for the BRCW

To investigate how climate change may impact ephemeral riparian communities in the BRCW, ALWRI personnel convened a team of experts to construct a series of divergent climate scenarios and discuss emerging ecological futures. The team of experts consisted of a group of scientists and managers with local- and subject-level expertise in the southwestern region of the United States and for amphibian species. Together, the team identified climate metrics most likely to influence ephemeral riparian communities (Figure 1), constructed a suite of divergent and plausible climate scenarios, and discussed how climate change scenarios may differentially impact native amphibians and their habitat at multiple spatial scales.

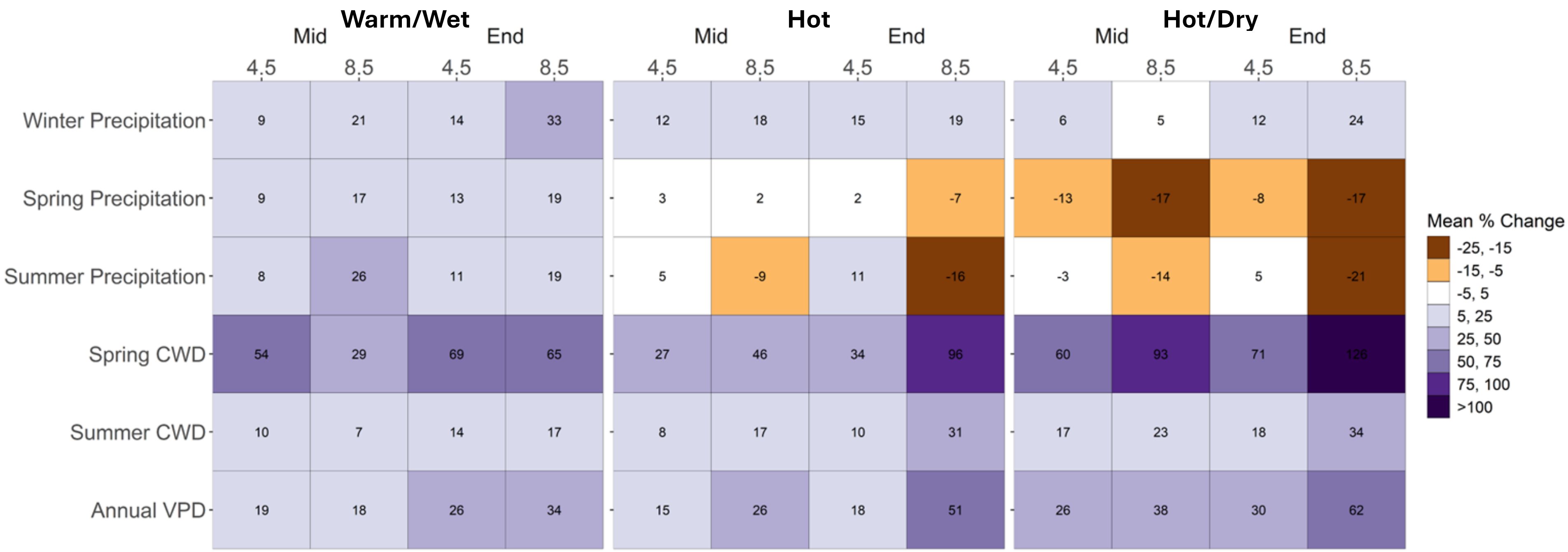

Figure 1: Mean percent change of hydrologic climate metrics from historical means (1971-2000) to projected means for the Black Ridge Canyons Wilderness, Colorado, USA. Projections represent three divergent climate scenarios designated by summer temperature and precipitation: Warm/Wet, Hot, and Hot/Dry. Projections were made for both mid-century (2040-2069) and end-of-century (2070-2099) timesteps and for two emissions scenarios: RCP 4.5 and 8.5. Means for each metric within each scenario encompass all model projections for each climate metric, timestep, and emissions scenario.

Warm/Wet Scenario

Under this scenario, projected precipitation is expected to increase as compared to recent historical levels. Temperature, particularly summer mean temperature, is also expected to increase in this scenario.

Climate Summary

In the Warm/Wet Scenario, projected summer temperature increases by an average of 4 ^{o}F by mid-century and spring precipitation increases between 9 and 15% from the historical mean (Table 1). Summer precipitation also increases up to 25% on average. The number of days above 90 ^{o}F is projected to increase by 37-43 days/year on average by mid-century. Despite increases in spring and summer precipitation, spring climatic water deficit increases 28-53% by mid-century and summer climatic water deficit increases 7-10% in this scenario, indicating increasing evaporative demand. Concurrently, annual vapor pressure deficit also increases up to 19% from historical means in this scenario, indicating that the air is becoming drier. Winter precipitation increases in this scenario by 0.19-0.44” by mid-century, a 9-21% increase from the historical mean.

Table 1: Projections for nine climate metrics under a Warm/Wet climate scenario. Projections were made for both mid-century (2040-2069) and end-of-century (2070-2099) timesteps and included two emissions scenarios: RCP 4.5 and 8.5. Cell values represent averages across model projections for each climate metric x RCP emissions scenario x timestep combination.

	Mid-Century		**End of Century**	
	4.5	8.5	4.5	8.5
Winter Precipitation (inches)	+0.19”	+0.44”	+0.29”	+0.68”
Spring Precipitation (inches)	+0.55”	+0.55”	+0.42”	+0.60”
Summer Precipitation (inches)	+0.20”	+0.62”	+0.25”	+0.47”
Spring CWD (inches/season)	+1.79”	+0.96”	+2.31”	+2.18”
Summer CWD (inches/season)	+1.40”	+1.04”	+1.97”	+2.44”
Summer Mean Temperature (^{o}F)	+4.44 ^{o}F	+4.41 ^{o}F	+5.92 ^{o}F	+7.75 ^{o}F
Annual Heat Index 90F (days)	+36.67	+43.17	+48.50	+64.97
Annual Heat Index 100F (days)	+4.67	+6.07	+9.0	+26.43
Annual VPD (kPa)	+0.25	+0.23	+0.34	+0.44

Potential Ecological Transformations

Landscape-Level Change

In the Warm/Wet Scenario, increased precipitation may allow native plant communities to persist and initially outcompete non-native invasives. Nevertheless, increasing drying conditions and increasing intensity of summer convective storms coupled with persistent presence of high-biomass fuels may lead to increasing frequency and intensity of wildfire. Sedimentation events may increase when bare soil exposed by wildfire is eroded by subsequent storms and spring runoff.

Site-Specific Change

Increased sediment in canyon bottoms may fill deeper pools, reducing overall water depth and subsequently reducing habitat amount. Additionally, increasing precipitation and subsequent presence of water early in the year may facilitate the movement of American bullfrogs further into canyons where they may not have been observed historically. With the spread of bullfrogs, native amphibian species may be vulnerable to direct predation, heightened competition over diminishing resources, and exposure to the fungal pathogen *Batrachochytrium dendrobatidis*. Although conditions within the canyons may not allow bullfrogs to persist throughout the summer, introduction of chytrid further into the canyon may have lasting impacts on native amphibians even their absence. All species of native amphibians could be adversely affected in this scenario. As a result, overall native amphibian population abundance is anticipated to decline for all species, however richness may be retained if habitat conditions allow native species to remain resilient to habitat variability and seasonal interactions with bullfrogs.

Hot Scenario

Under this scenario, projected precipitation is anticipated to fluctuate less than 5% from historical levels. Summer mean temperature is expected to increase significantly.

Climate Summary

In the Hot Scenario, projected summer temperature increases by an average of 3.5 to 6.5 ^{o}F by mid-century, however, spring precipitation changes less than 5% from the historical mean (Table 2). Summer precipitation is variable, either increasing slightly or decreasing. Additionally, the number of days above 90 ^{o}F is projected to increase by 32-49 days/year on average by mid-century. With little change in spring precipitation alongside increasing summer temperatures, spring climatic water deficit increases 28-46% by mid-century and summer climatic water deficit increases 8-17% in this scenario, indicating increasing evaporative demand. Concurrently, annual vapor pressure deficit also increases up to 26% from historical means in this scenario, indicating that the air is becoming drier. Unlike spring precipitation, winter precipitation increases in this scenario by 0.26-0.37” by mid-century, a 12-18% increase from the historical mean.

Table 2: Projections for nine climate metrics under a Hot climate scenario. Projections were made for both mid-century (2040-2069) and end-of-century (2070-2099) timesteps and included two emissions scenarios: RCP 4.5 and 8.5. Cell values represent averages across model projections for each climate metric x RCP emissions scenario x timestep combination.

	Mid-Century		End of Century	
	4.5	8.5	4.5	8.5
Winter Precipitation (inches)	+0.26”	+0.37”	+0.32”	+0.41”
Spring Precipitation (inches)	+0.08”	+0.14”	+0.08”	-0.22”
Summer Precipitation (inches)	+0.12”	-0.23”	+0.26”	-0.37”
Spring CWD (inches/season)	+0.92”	+1.53”	+1.14”	+3.23”
Summer CWD (inches/season)	+1.22”	+2.46”	+1.44”	+4.39”
Summer Mean Temperature (^{o}F)	+3.46 ^{o}F	+6.44 ^{o}F	+4.47 ^{o}F	+11.15 ^{o}F
Annual Heat Index 90F (days)	+32.67	+49.05	+39.78	+80.50
Annual Heat Index 100F (days)	+2.9	+10.35	+4.5	+39.3
Annual VPD (kPa)	+0.19	+0.34	+0.23	+0.66

Potential Ecological Transformations

Landscape-Level Change

In the Hot Scenario, maintenance of historical precipitation totals may slow the loss or replacement of native vegetation by upland or non-native, invasive species. Increasing temperatures, vapor pressure deficit, and climatic water deficit in the spring and summer, signal rapidly drying conditions for plant communities. As a result, native riparian communities may experience range retractions where drying is most extreme. Variability in timing of precipitation is likely to increase as well as intensity of individual storm events which may increase the likelihood of lightning strikes. Drying climatic conditions coupled with high intensity storms could contribute to increased wildfire frequency and intensity. Sedimentation events may increase when bare soil exposed by wildfire is eroded by subsequent storms and spring runoff.

Site-Specific Change

Increased sediment in canyon bottoms may begin to fill deeper pools, reducing capacity for water retention. Additionally, increased drying conditions are likely to lead to shortened hydroperiods. Sediment deposition coupled with increased drying conditions may allow native upland and non-native invasive plant species to establish in canyon bottoms and begin to replace native riparian communities. There may also be opportunities for American bullfrogs to invade canyons in this scenario, however, rapid drying of pools may limit invasion to areas of the canyon closest to perennial water sources. Where bullfrog invasion occurs, native amphibian species may be vulnerable to direct predation, heightened competition over diminishing resources, and exposure to the fungal pathogen *Batrachochytrium dendrobatidis*. Population density of native amphibians may increase due to decreased habitat amount, subsequently increasing competition pressure over resources and potentially increasing disease transmission. Nevertheless, native amphibians may continue to persist in areas where bullfrogs do not invade. As a result, richness and abundance of all native amphibian species may be variable but populations may remain resilient to change.

Hot/Dry Scenario

Under this scenario, projected precipitation is anticipated to decrease as compared to historical totals. Projected summer temperatures for this scenario are hotter than either the Warm/Wet or Hot scenarios.

Climate Summary

In the Hot/Dry Scenario, projected summer temperature increases by an average of 6 to 8 ^{o}F by mid-century and spring precipitation decreases 8-17% from the historical mean Table 3). Summer precipitation also decreases up to -14% on average. Additionally, the number of days above 90 ^{o}F is projected to increase by 46-60 days/year on average by mid-century. With decreasing spring precipitation alongside increasing summer temperatures, spring climatic water deficit increases 60-93% by mid-century and summer climatic water deficit increases 17-23% in this scenario, indicating rapidly increasing evaporative demand. Concurrently, annual vapor pressure deficit also increases up to 38% from historical means in this scenario, indicating that the air will become drier. Unlike spring precipitation, winter precipitation increases a small amount in this scenario by 0.13-0.10” by mid-century, a 4.5-6% increase from the historical mean.

Table 3: Projections for nine climate metrics under a Hot/Dry climate scenario. Projections were made for both mid-century (2040-2069) and end-of-century (2070-2099) timesteps and included two emissions scenarios: RCP 4.5 and 8.5. Cell values represent averages across model projections for each climate metric x RCP emissions scenario x timestep combination.

	Mid-Century		**End of Century**	
	4.5	8.5	4.5	8.5
Winter Precipitation (inches)	+0.13”	+0.10”	+0.25”	+0.51”
Spring Precipitation (inches)	-0.40”	-0.54”	-0.26”	-0.53”
Summer Precipitation (inches)	+0.04”	-0.34”	+0.06”	-0.46”
Spring CWD (inches/season)	+2.00”	+3.12”	+2.36”	+4.21”
Summer CWD (inches/season)	+2.49”	+3.29”	+2.62”	+4.83”
Summer Mean Temperature (^{o}F)	+6.33 ^{o}F	+7.98 ^{o}F	+7.10 ^{o}F	+11.86 ^{o}F
Annual Heat Index 90F (days)	+46.43	+60.40	+53.57	+86.10
Annual Heat Index 100F (days)	+5.50	+13.15	+8.37	+51.15
Annual VPD (kPa)	+0.33	+0.49	+0.39	+0.79

Potential Ecological Transformations

Landscape-Level Change

In the Hot/Dry Scenario, decline in precipitation totals coupled with increasing summer temperatures create extremely dry conditions that have the potential to negatively impact historical ecological patterns and processes. Variability in timing of precipitation is likely to increase as well as intensity of individual storm events. Rapid drying conditions coupled with high intensity summer convective storms may initially lead to more frequent wildfire and overcome native upland and riparian plant community resilience. Sedimentation events may initially increase when bare soil exposed by wildfire is eroded by subsequent storms and spring runoff, however, wildfire may become less intense over time as native perennial grasses, shrubs, and trees are replaced by cheatgrass and other annual upland invasives. Non-native invasive species, such as cheatgrass, may opportunistically spread rapidly under this scenario and generate a positive feedback loop, wherein cheatgrass drives changing wildfire regimes that subsequently allow it to spread. Additionally, sedimentation may eventually decrease under this scenario with frequent, but likely less intense, wildfire in fine grass fuels as compared to other scenarios in which higher-biomass fuels are maintained.

Site-Specific Change

Extreme drying conditions are likely to lead to low water levels and shortened hydroperiods within ephemeral canyon pools. American bullfrogs will not invade canyons in this scenario, as hydrologic conditions of pools are not sufficient to support bullfrog persistence. Rather, bullfrogs will remain in perennial water sources, such as the shoreline of the Colorado River. Riparian plant communities are likely to be replaced by upland or non-native invasive species within canyon bottoms. Loss of native riparian vegetation could lead to a loss of habitat shading, increased water temperature of ephemeral pools, and rapid evaporation. It is plausible that deep pool habitat for native amphibians will be lost, impacting reproductive success of native amphibians. Only species that have the adaptive capacity to reproduce under stressful habitat conditions, such as Woodhouse's and red-spotted toads, are expected to persist, though at reduced population abundance. Sensitive species, such as canyon treefrogs, are expected to become extirpated under this scenario.

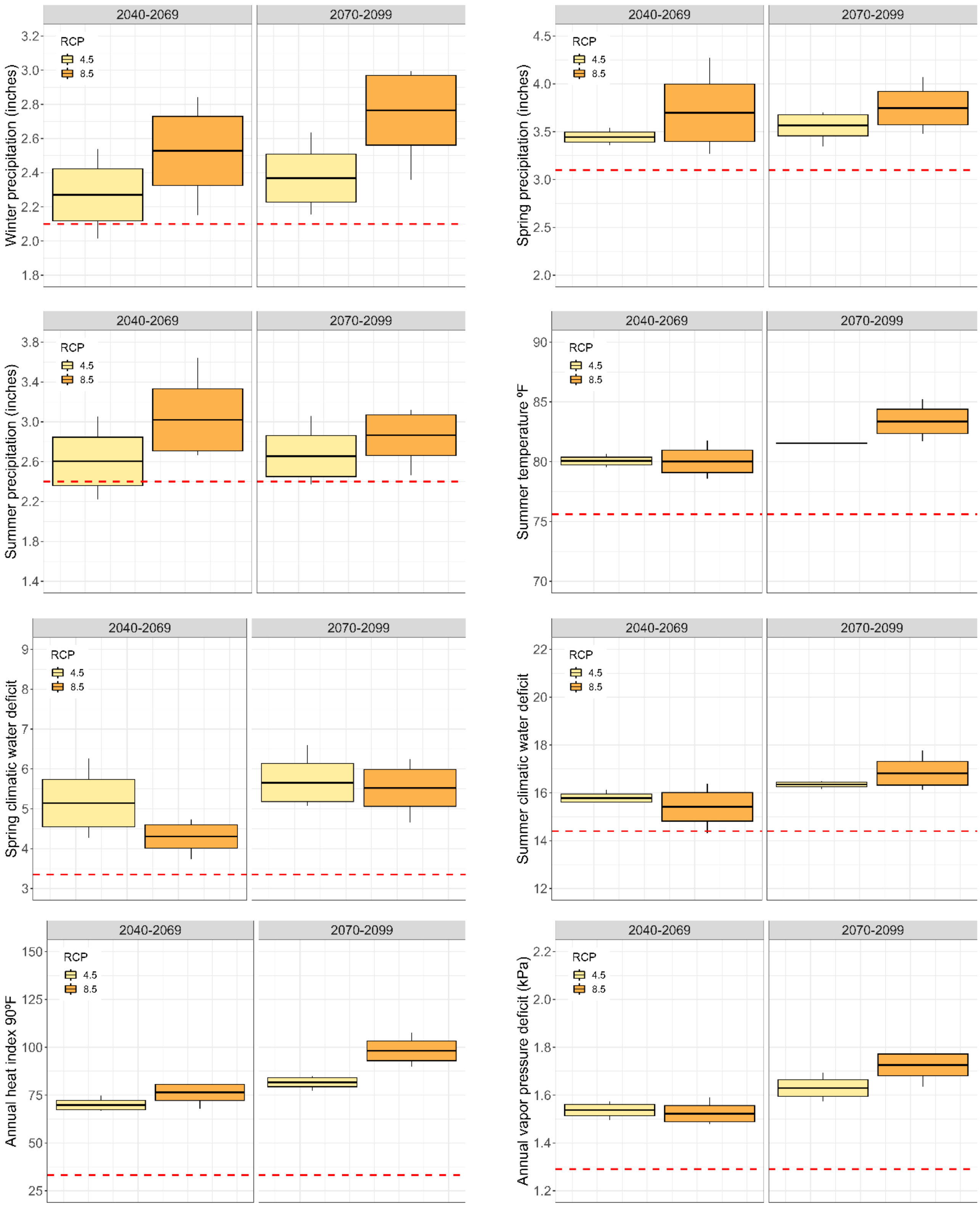

Figure 2: Projected mean change ± standard error for eight climate metrics under climate change for the Warm/Wet Scenario in the Black Ridge Canyons Wilderness, USA. Red dashed lines indicate historical averages (1971-2000).

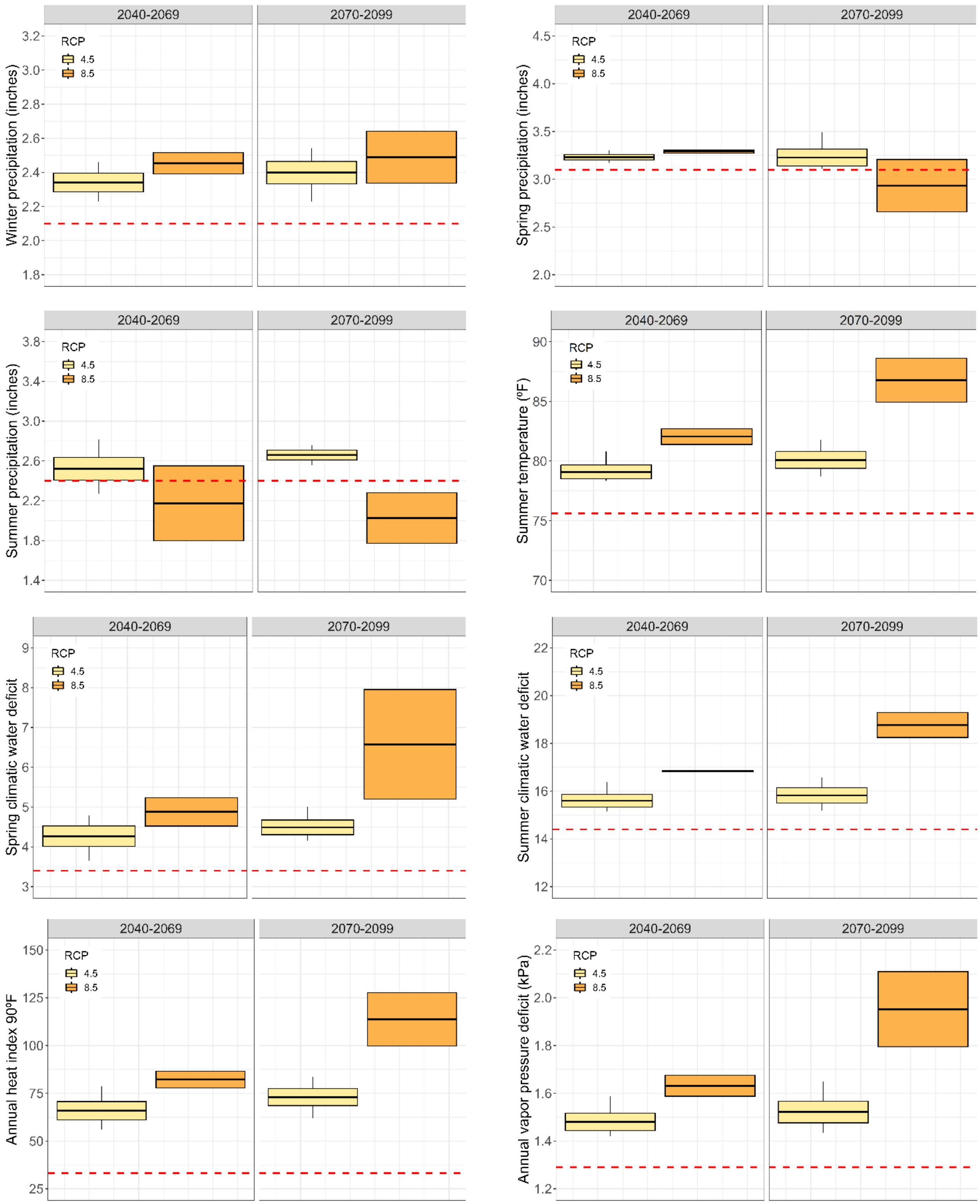

Figure 3: Projected mean change ± standard error for eight climate metrics under climate change for the Hot Scenario in the Black Ridge Canyons Wilderness, USA. Red dashed lines indicate historical averages (1971-2000).

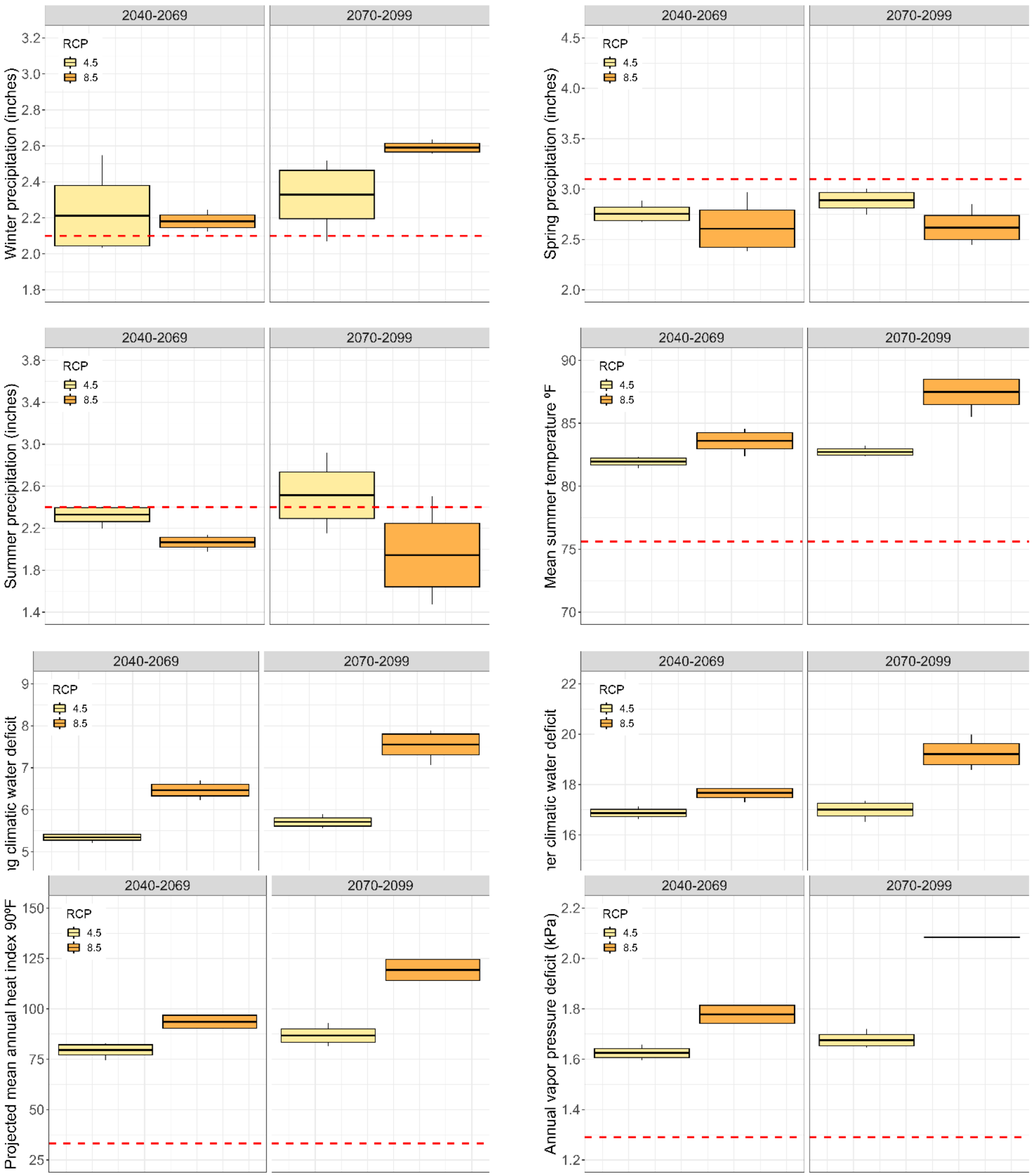

Figure 4: Projected mean change ± standard error for eight climate metrics under climate change for the Hot/Dry Scenario in the Black Ridge Canyons Wilderness, USA. Red dashed lines indicate historical averages (1971-2000).

APPENDIX B

Table 1. Key themes about climate change and climate-informed adaption responses derived from a series of five semi-structured interviews of land stewards and their partners focused on impacts to ephemeral riparian communities in the Black Ridge Canyons Wilderness, CO, USA.

Theme	Code	Representative Quotation
Managers and partners perceive summers are becoming longer, hotter, and drier, which alters many aspects of the social-ecological system within and around the Black Ridge Canyons Wilderness.	Rapid and sustained warming	"What we're seeing is it's getting hotter quicker in the year. It's getting a lot hotter for a lot longer. So instead of, you know, three days of 105-110 degrees (F), we're experiencing that over three weeks now." (BLM2)
	Increased drought	"Things are getting drier. Things are dying sooner, getting drier." (BLM2)
		"Historically, this last decade or so we've been in drought in both NCAs." (BLM1)
	Changing monsoon patterns	"Weather patterns, especially in the Southwest, when you used to get pretty regular monsoons that would come in, from pretty Memorial Day through Labor Day, now, it's not so guaranteed." (BLM4)
	Lack of post-fire recovery	"After fire, we weren't seeing pinyon and juniper come back the way it used to." (BLM3)
	Increased invasive species	"You can see [climate change] from invasive species out-competing native species, whether it's aquatic or terrestrial." (BLM4)
	Negative impacts to wildlife	"I think changing climate is a huge threat because these canyons are very ephemeral. The water comes through in the spring, if we're lucky, they'll get some more throughout rainfall that comes through, but it's getting hotter and we have periods of drought. And a lot of these amphibians, when you think about these canyons, they're almost like an island for them. They can't really move. There's no gene flow between one Canyon to the next.

		So, the amphibians that live in these canyons rely on those temporary water sources" (BLM_Partner1)
	Increased shoulder season visitor use	"We're seeing shifts in recreational use…specifically…shoulder season recreational use. So, it's not in the middle of summer, but in the spring and fall, we have heavy recreational use through the National Conservation Area and the wilderness. And that's becoming increasingly concentrated. So, where we used to have that spring season that will last several months, that same amount of recreational use, or arguably more since COVID, is happening in a more concentrated time." (BLM1)
Climate change touches all aspects of land managers' jobs, even if the work is not explicitly focused on climate change.	Impacts of climate change are baked into seemingly unrelated projects	"Probably all the project work that I do, I don't think it would be too far fetched to say that climate change is a factor in the issues we're facing. I'm working on a reservoir proposal…it's augmenting the water supply in the White River Basin in Colorado. But I don't think it's too far fetched that the reason that proposal exists is because of climate change." (BLM1)
	Climate change challenges planning efforts	"With NEPA, we analyze the impacts or potential impacts projects will have on federal lands…With that any impact we have, we definitely have to restore it. With things getting hotter for longer, we don't know how our stuff's going to respond. It is going to be harder to anticipate a lot of that…With climate change, are certain seeding practices more appropriate as temperatures get hot? You know, instead of hand seeding, is it more appropriate for us to drill seed? Is watering going to be needed for certain things?" (BLM2)
	The past is not an analog for the future	"Anyone in land management is dealing with climate change, whether it's fires and fire behavior, whether it's

		restoration. What we used to do, what maybe worked really well, the tools that were really tried and true are not necessarily tried and true anymore. So, I think you'd be hard pressed to find anyone in land management that's not seeing some shifting in their job. In, you know, the way they do it and what things are on the table." (BLM 3)
Climate change is making it increasingly difficult to manage for untrammeled, especially when it comes to fire.		"So, the wilderness is untrammeled by man, but at the same time, given the existing conditions in both these areas [Black Ridge Canyons Wilderness and Dominguez Escalante NCA] of historic drought and plentiful cheat grass, most of the time it makes sense to suppress wildfire…I'm finding that it's increasingly rare to have those kinds of fires that we're able to manage to actually benefit the resource." (BLM1)
There are several physical and institutional barriers that make climate change adaptive amphibian conservation within the Black Ridge Canyons difficult.	Physically difficult to access	"The remoteness might be difficult for some projects depending on what we're doing. It's pretty remote. It's difficult to get to…Just a quick visit is a multiday thing that requires a bunch of gear." (BLM2)
	Lack of funding	"I think, for BLM at least, and being in the shoes of an actual decision maker, you're taking into account: How much is this going to cost? We have to look at existing funding levels, and what do we have the resources for? We're only limited by what we actually have the funding to implement and the staffing to implement." (BLM1)
	Lack of staff capacity	"Our office is pretty bare bones right now. A lot of folks are moving on to other positions. So it really gives us more of a workload until those positions are filled. So less people, larger workloads, folks with institutional knowledge retiring or moving on, and the restructuring of our office, which—fewer people more workloads. We

		don't have time to do a lot of reading. We don't have time to do a lot of studying. We don't have time to do a lot of the really interesting projects that can help us do a lot of this research because we're trying to keep the lights on." (BLM2)
	Conserving native amphibians is in nicety, not a necessity	"As much as we would love to work on these kinds of fun projects [conserving native amphibians], because yes, this is a fun project. The reality is we have tons of grazing permit renewals. We have to do land health assessments, right of way renewals, RMP evaluations." (BLM4)
	Lack of understanding about what is acceptable in wilderness	"Right now, if I'm being honest, my knowledge base. I don't know exactly what I can do [in wilderness]." (BLM2)
	Leery about litigation	"Some interventions we know would get challenged by wilderness advocacy groups. I don't know if I would be as comfortable with [those kinds of interventions in wilderness] as much as I would be outside of the wilderness." (BLM1)
Although wilderness may constrain climate adaptive work with native amphibians, it also provides unique opportunities	Opportunity to learn about the effects climate change	"So, we don't necessarily know how our systems are going to react [to climate change]. The wilderness has offered us the opportunity to be able to see, to be able to do studies. I keep thinking about the fire restoration efforts we did. You know, we did ten-year monitoring; we did a whole bunch of seed plantings. It offered us the ability to see: these plants do come up from seed, if you are able to have the environment meet XYZ. So studies in the wilderness I think could be very beneficial." (BLM2)
	Wilderness-specific funding opportunities	"Sometimes wilderness may be a little bit easier because there are opportunities for outside funding sources for wilderness specific work…We have an assistance agreement with Society for Wilderness Stewardship, but

		more specifically for Colorado right now…there’s a big pot of money actually available through the National Fish and Wildlife Foundation for wilderness work in Colorado.”
	Partners are excited to do research and project work within the Black Ridge Canyons Wilderness	“It hasn’t been hard to find partners who want to do work there.” (BLM2).