Adaptation in the Face of Environmental Change

Supporting Information for BLM Planning in Colorado

U.S. DEPARTMENT OF THE INTERIOR
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COLORADO STATE UNIVERSITY

COLORADO NATURAL HERITAGE PROGRAM

Adaptation in the Face of Environmental Change

Supporting Information for Colorado BLM

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CNHP's mission is to advance the conservation of Colorado's native species and ecosystems through science, planning, and education for the benefit of current and future generations.

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EXECUTIVE SUMMARY

In 2013, the Colorado office of the Bureau of Land Management (BLM) contacted the Colorado Natural Heritage Program (CNHP) for assistance in conducting a climate change vulnerability assessment to help focus attention on the highest priority species and habitats. In 2015, CNHP completed vulnerability assessments for 98 species and 20 ecological systems (CNHP 2015). That assessment highlighted two clear priorities for BLM management in Colorado: pinyon-juniper woodlands and native fish. Since the vulnerability assessment was completed, we have continued to work with Colorado BLM to expand our understanding of climate impacts on ***pinyon-juniper woodlands*** and ***fisheries***, and to develop data products designed to feed into BLM planning processes at the Field Office scale, using the ***San Luis Valley Field Office*** as a pilot.

Pinyon-Juniper

CNHP (2015) ranked pinyon-juniper woodlands as highly vulnerable to climate change in Colorado. Primary factors contributing to the high ranking are interactions of drought, fire, and insect-caused mortality (which is likely to increase with changing climate), and currently degraded conditions which have reduced resilience to disturbance. We developed spatial ecological response models for each of the dominant tree species (two-needle pinyon, *Pinus edulis*; Utah juniper, *Juniperus osteosperma*; and one-seed juniper, *Juniperus monosperma*) to identify areas where suitable climate is: a) currently present and likely to persist, b) not currently present but likely to become suitable, and c) currently present but unlikely to remain suitable. The ecological response models can be used to identify potential intervention points where specific management approaches will be needed to achieve management goals under future climate conditions. Weather patterns are projected to change in a direction that is less favorable for pinyon, so that juniper may become more dominant; thus, this habitat may be unable to persist or expand in its current form. This would have implications for pinyon-juniper obligate birds, some of which are experiencing population declines.

Cold Water Fisheries

In collaboration with BLM fisheries biologists, we determined that the most important climate-related information needs for fisheries management were an improved understanding of *how to evaluate* potential habitat improvement projects through a climate lens, and a means to determine *where* projects would most likely be successful over the long term. BLM fisheries managers highlighted the particular need for cold-water fisheries (native and non-native species) management decisions in the near term, so we defined target species for additional assessment as:

- Cutthroat trout (*Oncorhynchus clarkii*)
- Rainbow trout (*Oncorhynchus mykiss*)
- Brook trout (*Salvelinus fontinalis*)

- Brown trout (*Salmo trutta*)
- Bluehead sucker (*Catostomus discobolus*)
- Mountain whitefish (*Prosopium williamsoni*)

We modified an existing decision support framework (Nelson et al. 2016) to support evaluation of fisheries projects through a climate lens and offer a suite of potential adaptation strategies. We also modeled current and future (2040) habitat suitability for the target fish species. Amount of optimal habitat (in stream kilometers) is projected to decline for all species. Sub-optimal habitat is projected to increase for rainbow trout and increase slightly for cutthroat and brook trout, but decrease for the other species. Unsuitable habitat is projected to increase for all species.

San Luis Valley Field Office Case Study

The overall objective of conducting the vulnerability assessment and the subsequent expanded analyses reported herein was to assist BLM with improved planning and decision-making. As a pilot effort to work out how we might best offer support, we collaborated with resource scientists, planners, and managers in the San Luis Valley Field Office (SLVFO) to understand their planning process and highest priority information needs for their current planning efforts. We identified the following ecological systems as the most significant needs for climate-related information (not in prioritized order):

- Pinyon-juniper forests and woodlands
- Sagebrush
- Montane grasslands
- Winterfat shrub-grasslands
- Streams and riparian
- Wetlands, seeps, springs, and irrigated meadows

Building on methods developed with other partners (Rondeau et al. 2017, TNC 2018), we evaluated potential climate impacts within the San Luis Valley using four climate scenarios (Hot & Dry, Hot & Wet, Feast & Famine, and Warm & Wet). For each target system, we identified: key environmental requirements or influences (e.g., winter moisture, frequency of growing season drought), scored degree of positive or negative change projected for each, and determined relative vulnerability in the San Luis Valley. Not surprisingly, the systems with the highest relative vulnerability (Highly Vulnerable) were streams/riparian and wetlands/seeps/springs/meadows. Compared to vulnerability at the statewide scale (CNHP 2015), these water-based systems are more vulnerable in the SLV than they are in the mountain and West Slope regions, with the exception of West Slope riparian, which scored as Highly Vulnerable. SLV and statewide vulnerability scores were comparable for other systems except Pinyon-juniper. Pinyon-juniper is highly vulnerable at the statewide scale, but scored low for vulnerability within the SLV. This suggests that the SLV may be an important refugia for pinyon-juniper persistence in Colorado.

Acknowledgements

Funding for this work was generously provided by Colorado Bureau of Land Management. We are grateful for the collaboration and expertise offered by many BLM staff. First and Foremost: Bruce Rittenhouse, who conceived of this work, got it funded, and herded it around many obstacles! BLM Fisheries Experts: Jay Thompson, Dave Gilbert, Russ Japuntich, Tom Fresques, and Josh Ryan. San Luis Valley Field Office: Melissa Garcia, Heather Salaz, Doug Simon, Jill Lucero, Ryan Williams, Melissa Shawcroft, Sue Swift-Miller, Clayton Davey, Alex Mullins, Ricky Martinez, Ben Billings, Nancy Keohane, Negussie Tedela, Eduardo Duran, Jeff Williams, Leon Montoya, Paul Minow, Rebecca Morris, Sean Noonan, and Martin Weimer. Thanks go also to Joe Vieira for his engagement, guidance, and encouragement, and to Joel Humphreys and Robin Sell for sharing their expertise.

Our work was done in collaboration with a team of social scientists, who conducted parallel studies focused on human livelihoods and community values. Thanks to them for raising our consciousness on the social aspects of vulnerability! Colorado State University: Shannon McNeeley, Tyler Beeton, Trevor Even. Western State Colorado University: Corrie Knapp, John Gioia, and Julia Nave.

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INTRODUCTION

In 2013, the Colorado office of the Bureau of Land Management (BLM) was charged with developing a climate change adaptation strategy for BLM lands within the state. They contacted the Colorado Natural Heritage Program (CNHP) for assistance in conducting a vulnerability assessment to help focus attention on the highest priority species and habitats. In 2015, the CNHP completed vulnerability assessments for 98 species and 20 ecological systems (CNHP 2015). Of the three terrestrial ecosystem types that constitute the majority of Colorado BLM surface acres (pinyon-juniper woodland, sagebrush, and desert shrubland), pinyon-juniper woodlands was ranked as considerably more vulnerable than the others. Because BLM is responsible for more than half of Colorado's pinyon-juniper acreage, this system is a clear priority. Of the animal species assessed, fish were ranked as significantly more vulnerable than other groups, with four species scoring in the highly vulnerable category, and all the remaining fish species scoring in the extremely vulnerable category.

The ultimate goal of conducting vulnerability assessments is to identify specific impacts that may occur, and to develop strategies that allow managers to anticipate and respond appropriately—in other words, strategies for adapting to climate change. Before we can develop adaptation strategies, two key questions must be addressed: 1) how will climate change? and 2) where will climate change? Climate scientists have developed a range of models (Global Circulation Models, or GCMs) that describe how temperature and precipitation regimes may change, and where those changes are likely to occur. A fair bit of uncertainty remains, both at the global scale and especially at more local scales. Therefore, managers must be prepared to make decisions now based on a range of potential future climate conditions. To facilitate this, we have worked over several years with a variety of partners (e.g., The Nature Conservancy, North Central Climate Adaptation Science Center, Western Water Assessment, federal and state agencies, landowners, and others) to define scenarios that describe different but equally plausible climate futures on a mid-Century timeframe for Colorado.

Since the vulnerability assessment was completed, we have continued to work with Colorado BLM to expand our understanding of climate impacts on ***pinyon-juniper woodlands*** and ***fish*** using these climate scenarios, and to develop data products designed to feed into BLM planning processes at the Field Office scale, using the ***San Luis Valley Field Office*** as a pilot. These efforts are the subject of this report.

Pinyon-Juniper Woodlands

CNHP (2015) ranked pinyon-juniper woodlands as highly vulnerable to climate change in Colorado. Primary factors contributing to the high ranking are the vulnerability of these woodlands to the interaction of drought, fire, and insect-caused mortality (which is likely to increase with changing climate), and the extent to which the current landscape condition of the habitat has been impacted by anthropogenic disturbance (i.e., degraded conditions in many stands have already reduced resilience to disturbance). Precipitation and temperature patterns are projected to change in a direction that is less favorable for pinyon, so that juniper may become more dominant; this habitat may be unable to persist or expand in its current form. This would have implications for pinyon-juniper obligate birds, some of which are experiencing population declines.

To identify locations most likely to experience changed conditions for pinyon-juniper woodlands, we developed spatial ecological response models for each of the dominant tree species (two-needle pinyon, *Pinus edulis*; Utah juniper, *Juniperus osteosperma*; and one-seed juniper, *Juniperus monosperma*). This series of models (maps) depicts areas where suitable climate is: a) currently present and likely to persist, b) not currently present but likely to be emergent—i.e., new areas where climate will become suitable, and c) currently present but unlikely to remain in place—i.e., likely to be threatened or lost. The ecological response models can be used to identify potential intervention points where specific management approaches will be needed to achieve management goals under future climate conditions. Actions that increase ecosystem resilience and enhance the adaptive capacity of component species will cushion their vulnerability to changing climate conditions.

In order to address uncertainty in future climate projections, while ensuring that adaptation options are robust under a variety of possible outcomes, we used four scenarios of projected future climate that cover a range of potential conditions (hotter and drier, hotter and wetter, warmer and wetter, or increased inter-annual variability, which we refer to as feast and famine). To guard against the potential for maladaptive management, the consequences of various potential outcomes can be considered in the context of each scenario, and evaluated to determine which actions are most likely to produce an acceptable outcome under all scenarios, or under a single scenario. This approach can help focus management actions on strategies that are effective under both current and future climates.

Overview of Pinyon-Juniper Ecology

The distribution of the pinyon-juniper ecosystem is centered in the Colorado Plateau, spanning significant portions of Utah, Colorado, New Mexico, and Arizona (Figure 1). In Colorado pinyon-juniper forms the characteristic woodland of western mesas and valleys, where it is typically found at elevations ranging from 4,900 - 8,000 ft. on dry mountains and foothills. These western Colorado woodlands are common on BLM lands. Pinyon-juniper woodlands also occur in the foothills of southeastern Colorado and extend out onto shale breaks in the plains. In the canyons and tablelands of the southeast, pinyon is absent, and juniper alone forms woodlands and savannas.

Pinyon pine (*Pinus edulis*) and juniper form the canopy. In western pinyon-juniper woodlands of lower elevations, Utah juniper (*Juniperus osteosperma*) is prevalent and Rocky Mountain juniper (*J. scopulorum*) may codominate or replace it at higher elevations. In southeastern Colorado pinyon-juniper woodlands one-seed juniper (*J. monosperma*) replaces Utah juniper. Sagebrush shrubland is frequently adjacent at lower elevations, while at higher elevations pinyon-juniper woodland mixes with oak shrubland and ponderosa pine woodland.

Depending on substrate and elevation, pinyon-juniper stands are variable in structure and composition. Soil depths may range from shallow to deep and textures are highly variable; this variation has a significant effect on soil water availability. Mesic areas are generally pinyon-dominated, while junipers are able to dominate on drier sites (Gottfried 1992). Juniper tends to be more abundant at the lower elevations, pinyon tends to be more abundant at the higher elevations, and the two species share dominance within a broad middle-elevation zone (Woodin and Lindsey 1954, Heil et al. 1993).

Both pinyon pine and juniper are fairly slow growing, and can live for hundreds of years, a life cycle that is well adapted to xeric habitats, but is less suitable for quickly changing conditions. Although individuals of both species become reproductive after a few decades, most seed production is due to mature trees of 75 years of age or older (Gottfried 1992). Both species reproduce only from seeds, and do not re-sprout after fire. Cone production of mature pinyon pine takes three growing seasons, and the large seeds have a fairly short life span of 1-2 years (Ronco 1990). Juniper cones (often called berries) may require 1-2 years of ripening before they can germinate (Gottfried 1992). The smaller seeds of juniper are generally long-lived, surviving as long as 45 years. Birds are important dispersers of both pinyon pine and juniper seed (Gottfried 1992).

These evergreen woodlands are adapted to cold winter minimum temperatures and low rainfall. In Colorado, the range of annual average precipitation for these woodlands is about 10-23 in (25-60 cm), with a mean of 16 in (40 cm). Annual mean winter temperatures are below freezing, although summers are generally warm. The pinyon-juniper ecosystem has large ecological amplitude; warmer conditions may allow expansion, as has already occurred in the past centuries, as long as there are periodic cooler, wetter years for recruitment. A 40% decline in pinyon pine cone production was associated with an average 2.3°F increase in summer temperatures in New Mexico and Oklahoma sites (Redmond et al. 2012). Warming temperatures may reduce recruitment for pinyon pine, accelerate drought-induced mortality (Adams et al. 2017) and increase overall mortality rates in drought-stressed trees (Adams et al. 2009).

Barger et al. (2009) found that pinyon pine growth was strongly dependent on sufficient precipitation prior to the growing season (winter through early summer), and cooler June temperatures. Both of these variables are predicted to change in a direction that is less favorable for pinyon pine. Drought can result in widespread tree die-off, especially of the more susceptible pinyon pine (Breshears et al. 2008, Redmond et al. 2015). Clifford et al. (2013) detected a strong threshold at 23.6 in (60 cm) cumulative precipitation over a two-year drought period (i.e., essentially normal annual precipitation for pinyon pine). Sites above this threshold experienced little pinyon die-off, while sites receiving less precipitation included areas with high levels of mortality. Mortality of pinyon trees was extensive in the area during the 2002-2003 drought and bark beetle outbreak, but in areas where juniper and shrub species provide microsites for seedling establishment, pinyon may be able to persist (Redmond and Barger 2013). Patterns of precipitation and temperature (i.e., cool, wet periods) appear to be more important in recruitment events than history of livestock grazing (Barger et al. 2009).

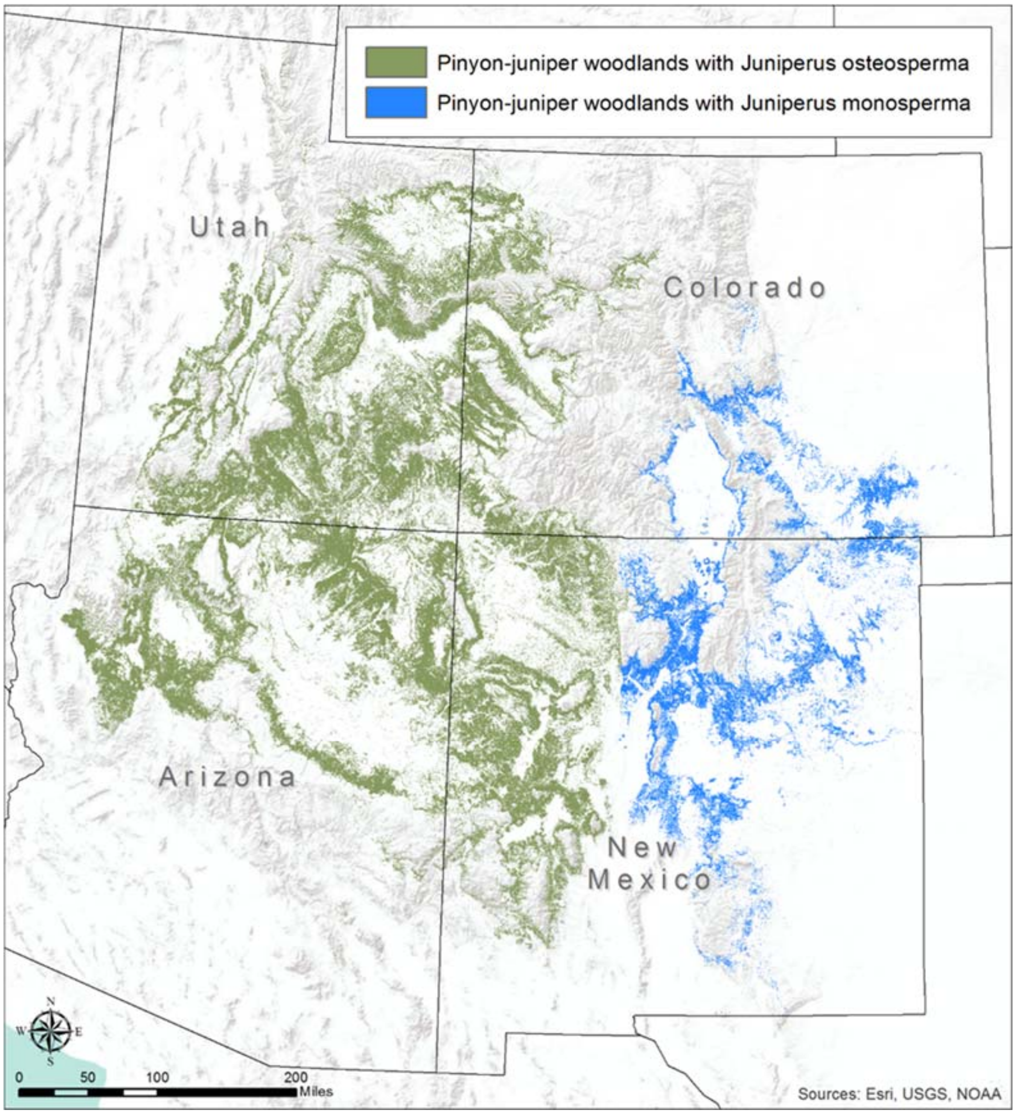


Figure 1. Distribution of two-needle pinyon pine with Utah juniper and one-seed juniper.

Climate Scenarios

With the assistance of climate scientist Imtiaz Rangwala (Western Water Assessment, University of Colorado), we selected four Global Circulation Models (GCMs) from an available set of 72 models run under two Representative Concentration Pathways—4.5 (lower future greenhouse gas emissions) and 8.5 (higher future greenhouse gas emissions). These models were chosen because they remain reasonably constant in their trajectory with regard to temperature and precipitation change during the period from now until the end of the 21st century (Figure 2), and because they represent the four possible combinations of warmer vs. hotter (no models predict cooler future conditions), and wetter vs. drier future conditions. We used the outputs from these models to define scenarios that describe different, but equally plausible, future climate conditions for an area encompassing the current distribution of two-needle pinyon pine (Table 1, Figure 1).

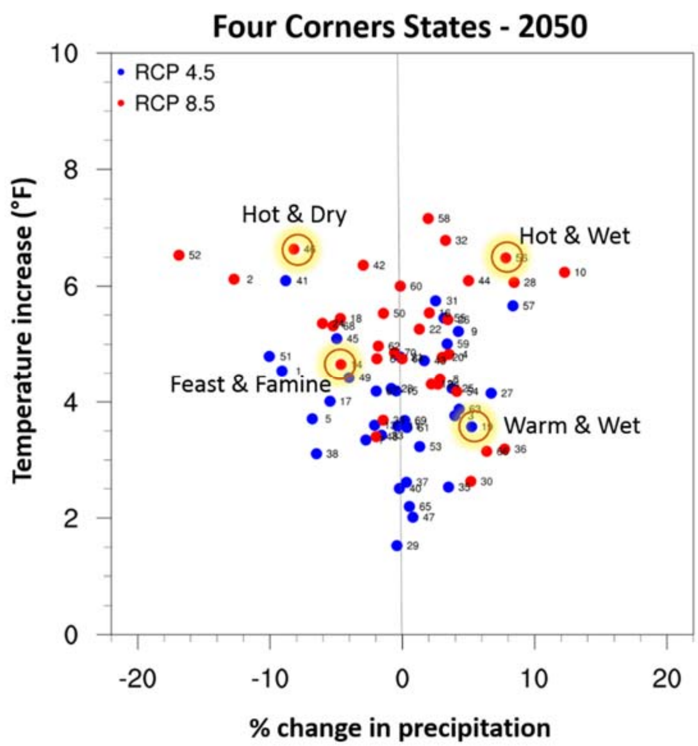


Figure 2. Change in temperature and precipitation of selected climate models.

GCM/RCP combinations used in the scenarios: Hot & Dry = hadgem2-es.rcp85; Hot & Wet = miroc-esm.rcp85; Warm & Wet = cnrm-cm5.rcp45; Feast & Famine = cesm1-bgc.rcp85.

In order to translate predicted changes in temperature and precipitation into ecosystem response models, we needed to assess:

- how altered temperature and precipitation patterns may manifest in on-the-ground conditions across seasons and years, and
- how pinyon pine and juniper species may respond to those altered weather patterns.

CNHP ecologists reviewed available literature, consulted with climate scientists and other experts, and applied their own field expertise to interpret climate data, other habitat variables, and known life history components of these species. Characterizations of basic climate-related consequences for each scenario are summarized in Table 1.

Table 1. Climate-related consequences of four climate scenarios for Pinyon-juniper.

Scenario	Statewide Effects (compared to 1971-2000 baseline)
Hot & Dry	**More fires, insect outbreaks, more frequent and longer droughts, monsoon lost.** Annual mean temperature increase of >6°F, with temperatures warming most in summer and fall. This, combined with a decrease in annual precipitation, results in snowline moving up in elevation by about 1500 ft, as well as frequent severe multi-year droughts. Winters are >20% wetter, but other seasons 3-18% drier, and summer monsoon decreases by 20%. Runoff peak flows are 2 weeks earlier, and volume decreases substantially (>15%).
Hot & Wet	**Even more advanced phenology, novel ecosystems.** Annual mean temperature increase of >6°F, with temperatures warming at similar levels across all seasons, combined with an 18% increase in annual precipitation. Even with increased winter precipitation, permanent snow lines are likely to be more than 1200 ft higher, and rain on snow events more frequent. Spring precipitation is 30% higher, and higher temperatures mean that peak runoff will be 2 weeks earlier. Summer monsoon decreases by almost 10%.
Warm & Wet	**Monsoon remains, but with earlier runoff, advanced phenology, more invasive species.** Annual mean temperature increase about 5°F with temperatures warming most in winter, combined with a 6% increase in annual precipitation results in a +600 ft elevation change for permanent snow lines. Drought frequency is similar to the recent past. Peak runoff is 1-2 weeks earlier, but with volumes generally unchanged. Summer monsoon remains similar to historic levels.
Feast & Famine	**Warmer (moderately hot) and somewhat drier, with large year to year variation in precipitation.** Annual mean temperature increase of over 4°F, with temperatures warming most in winter may lead to a +900 ft elevation change for permanent snow lines and frequent severe droughts. Annual precipitation shows little overall change (2%) but with large year-to-year variation. Winter and spring are likely to be wetter (11% and 3%), but other seasons drier, including a 5% reduction in monsoon moisture. Peak runoff may be 1-2 weeks earlier, with reduced volume (5-10%). Note that for the Colorado portion of pinyon pine distribution, this scenario has little change in average annual precipitation, but is effectively drier due to warmer temperatures.

Conceptual Classification of Future Habitat

To aid in modeling future spatial distribution of suitable conditions for pinyon and juniper species, we defined potential future habitat categories. Development of the future habitat categories initially considered all possible combinations of a variety of factors, including current suitability, current occupation, direction of change, and proximity to source of seed. These combinations were simplified and rolled up into three final potential future habitat categories—***Persistent***, ***Emergent***, and ***Threatened/Lost***—in addition to the category of unsuitable, using the general rationale shown in Figure 3. Within each category, multiple adaptation actions may be linked to particular conditions and situations, with associated adaptation strategies (Table 2).

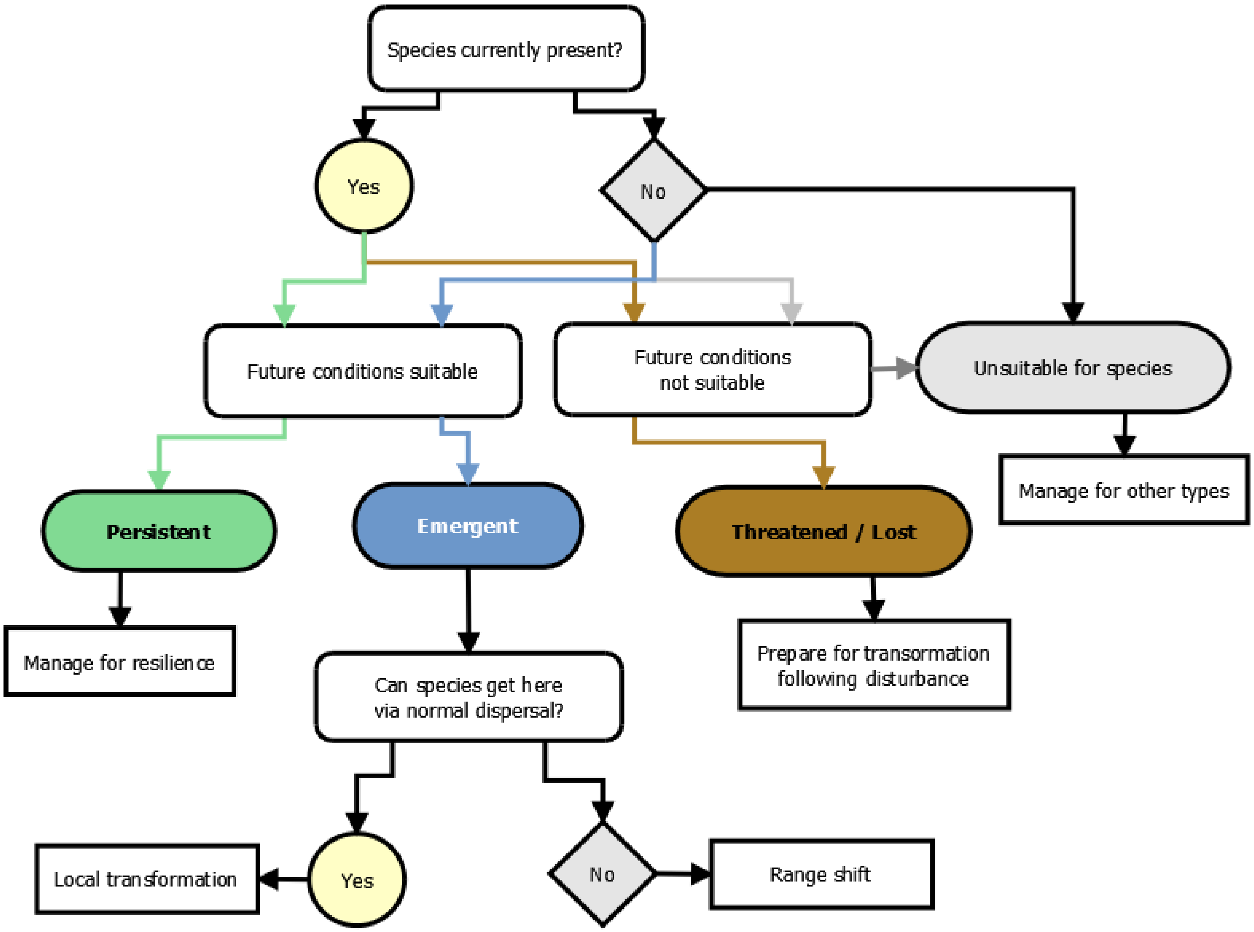


Figure 3. Decision tree for determination of future habitat category.

Table 2. Map category descriptions and sample adaptive strategies.

Map Category	Description	General adaptive strategy	Details
Persistent	Areas where each species (PIED, JUOS, JUMO, and P-J assemblage) is currently present, and where future bioclimatic conditions (climate, soils, etc.) will be suitable for the persistence of the species through mid-century.	Identify/protect/restore/enhance areas that will persist; manage for ecological resilience (*sensu* Gunderson 2000).	Map and identify the persistent areas, where climatic conditions are likely to remain stable under all future scenarios.

Map Category	Description	General adaptive strategy	Details
Emergent (Areas that are not currently occupied, but that will be suitable for the species in the future).	*Local transformation:* improving, stable, or newly suitable habitat near existing sources, such that the species should be able to establish under normal migration rates*	Allow transformation, with assistance (planting) as needed, in areas that are getting better for a particular species or ecosystem.	For pinyon, incorporate presence of seed dispersers. Identify areas where the transformation may be in conflict with other ecosystems of concern (e.g., juniper into sagebrush).
	Range shift: future suitable habitat not within a likely distance to be colonized under normal migration rates*	Consider assisted migration, unless there are conflicting resource issues.	Assisted migration means planting seedlings in areas where the species would not naturally disperse within the time frame under consideration. Genetic considerations may be important.
Threatened / Lost	Areas where the species is currently present, but where future climate conditions are not likely to be suitable for the species. High likelihood of eventual loss, or failure to re-establish following disturbance events.	Reduce management actions that disturb soils; consider allowing post-disturbance transformation. Triage areas that are decreasing in suitability for a particular species or ecosystem – we can't save everything	Develop management plans that move toward expected future conditions (e.g., using a seed mix containing species expected to thrive in the area under future conditions for restoration projects). Map and identify areas that potentially will be lost under all future scenarios vs. areas lost only under certain future conditions
Not suitable	Areas that are not now, and will not become, suitable for the species.	Manage for other types.	

*Normal migration rates via seed rain (deposition by gravity, wind, animals, etc.) could be estimated by average distance per year migration of each species required to reach current distribution from its position during glaciation.

Ecological Response Models

The purpose of the ecological response models was to determine where environmental conditions for pinyon pine and juniper species may improve or deteriorate, based on our best understanding of how each species may respond to projected future climate variables under the four chosen scenarios. Distribution models of the dominant tree species (two-needle pinyon, Utah juniper, and one-seed juniper) under recent conditions (1970-2000) were constructed using known locations for each species in combination with climate data. The models were then projected, using climate data for mid- 21st century in place of the modeled historic-range climate data, and used to produce a probability surface of future habitat suitability. Non-climate habitat suitability factors were incorporated in the models as well (e.g., soils, aspect, and other elevation-derived data); these factors do not change under future scenarios. Key environmental factors are different for each species (Table 3) and are consequently expected to produce different patterns of future habitat suitability. Detailed methods of model construction and testing are in Appendix A.

Table 3. Most important environmental variables influencing the models for pinyon pine, Utah juniper, and one-seed juniper.

	Top 3 variables influencing the models			Other variables with some influence
Species	**1**	**2**	**3**	
Pinyon Pine	Summer mean temp	Winter precip	Summer precip	Available water supply, soil pH, % organic matter, percent sand.
Utah Juniper	Winter precip	Summer precip	Summer mean temp	Winter max temp, % organic matter, pH, % silt, available water supply, slope.
One-seed Juniper	Summer precip	Winter max temp	Summer max temp	Spring precip, autumn precip, % organic matter, % clay, pH, and % silt.

It is important to note that both pinyon and juniper are long-lived species reaching reproductive age only after many decades. Therefore, the lag time between when an area becomes suitable or unsuitable, and the presence or absence of these species on a site may be considerable. In addition, myriad physical and ecological factors other than climate may influence the actual distribution of any species. **Thus, the proper interpretation of these maps is that *climate may be suitable* for species establishment and persistence, *not* that the species *will be there*.**

Models of potential future suitability for Two-needle Pinyon Pine (*Pinus edulis*)

Results of the response of pinyon pine under four possible future climate scenarios are shown in Figures 4 through 8. Although the effect extent is variable by scenario, future conditions are generally expected to be worse for pinyon pine in lower elevation western valleys and slopes. The hotter scenarios show greater expected loss. Currently occupied areas above about 6,500 feet on the west slope are projected to remain suitable at mid-century. Areas at similar elevations in northwestern Colorado that are currently beyond the range of pinyon pine are expected to become or remain suitable for the species. Higher elevation areas (above 7,500-8,500 ft, depending on location) that currently lack pinyon pine may show increasing suitability for the species, although the lag effect of slow dispersal and growth is likely to prevent expansion of pinyon pine to much higher montane elevations for an extended period of time.

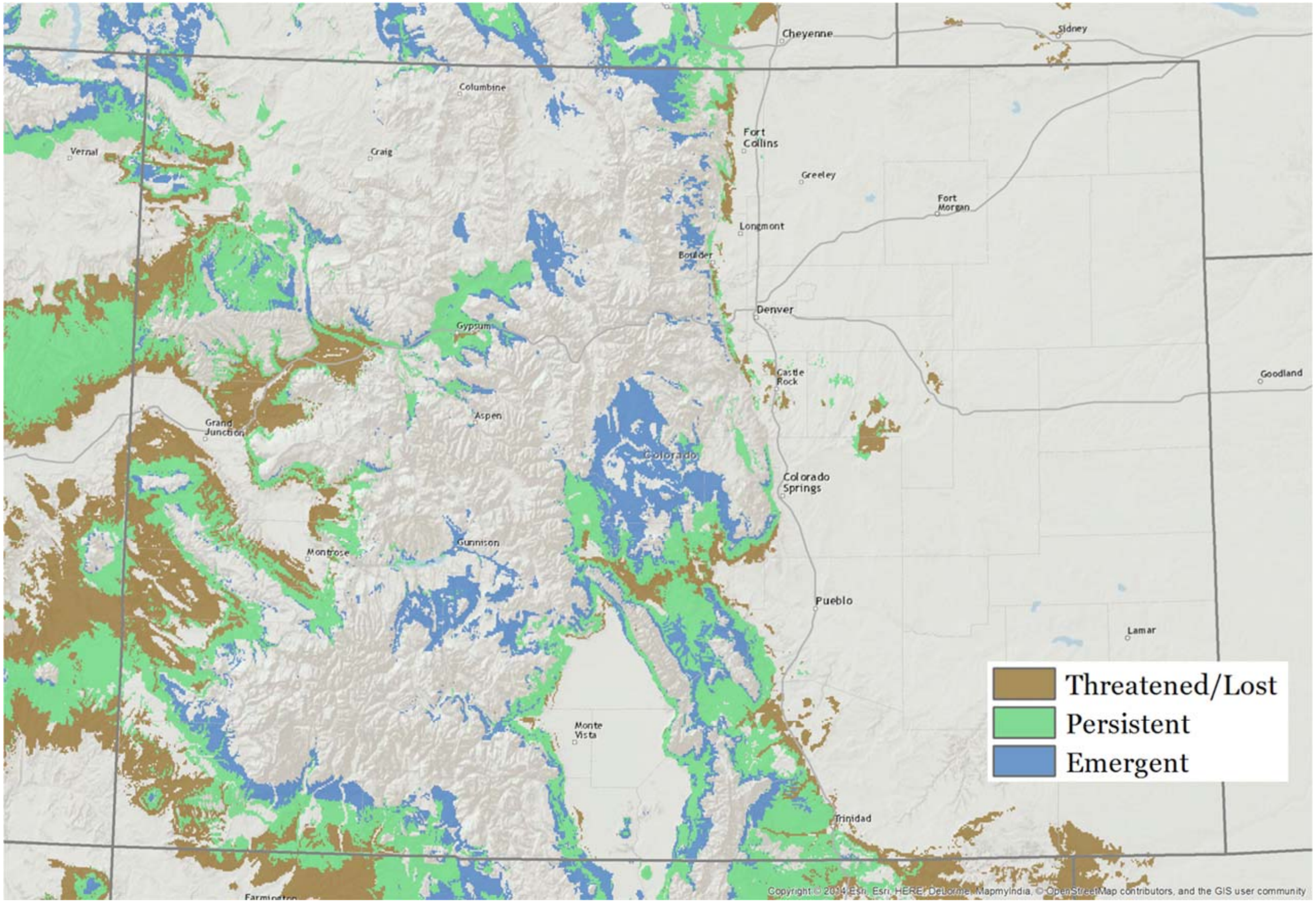


Figure 4. Modeled future suitability for pinyon pine in Colorado under the Hot & Dry climate scenario.

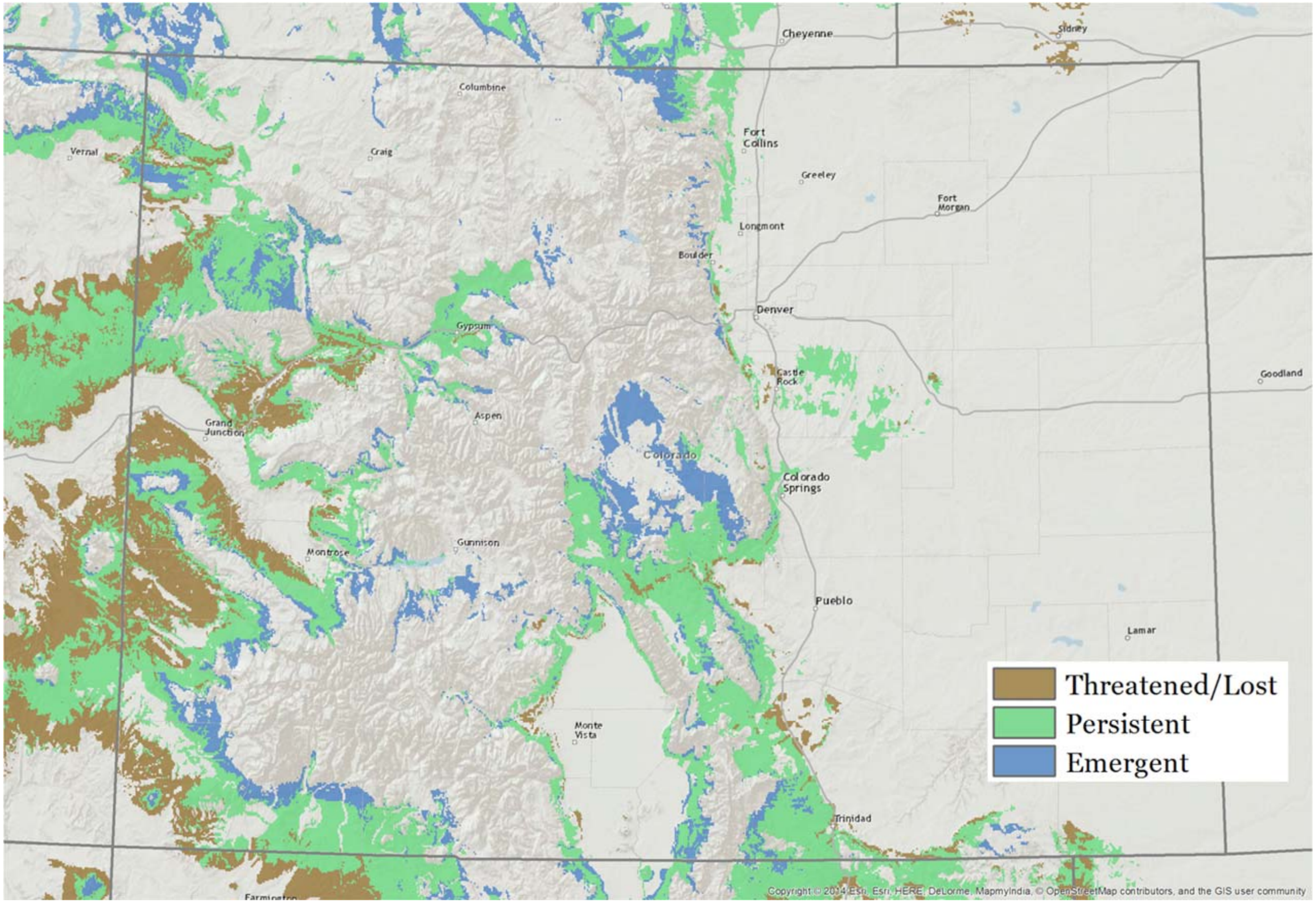


Figure 5. Modeled future suitability for pinyon pine in Colorado under the Hot & Wet climate scenario.

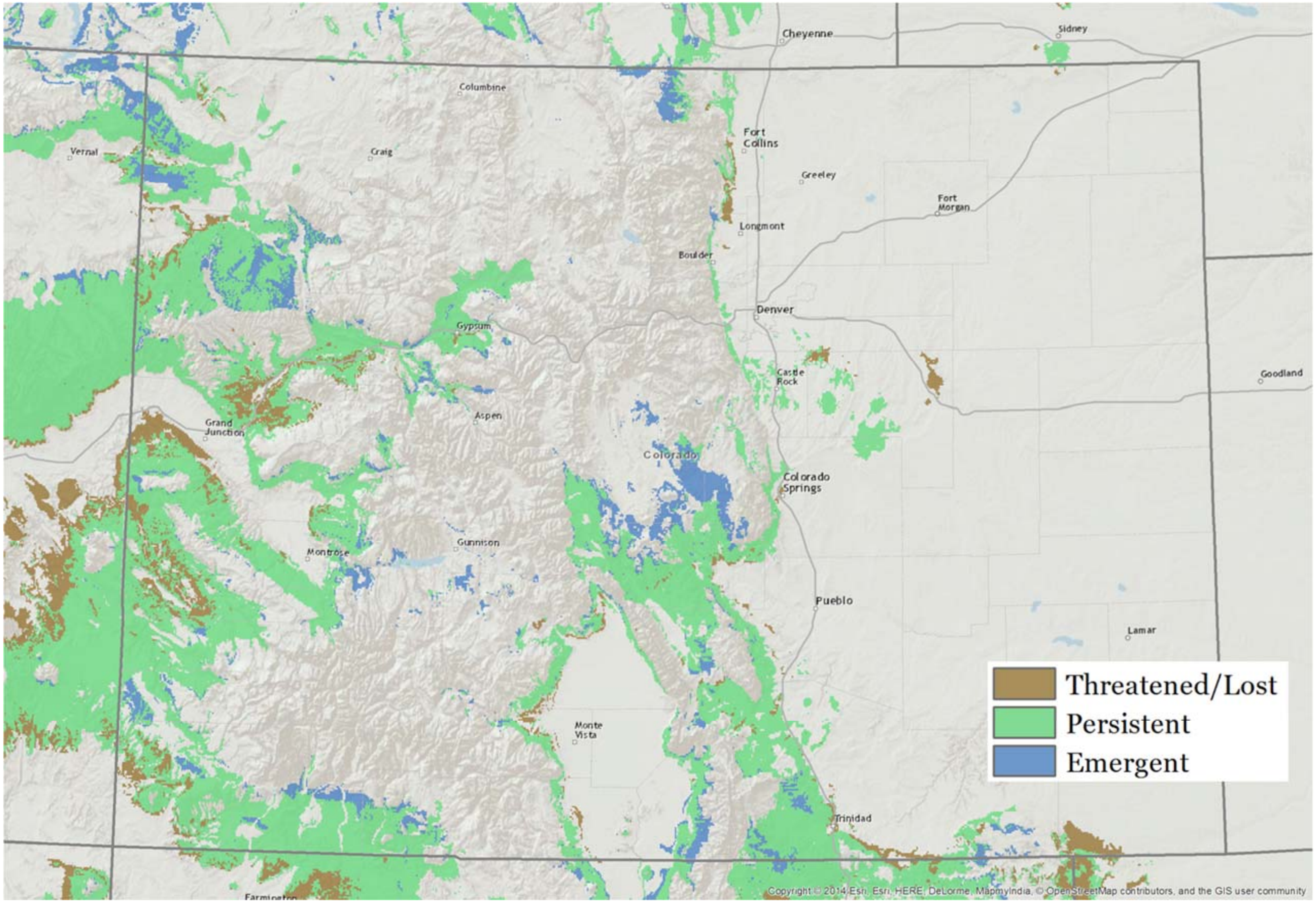


Figure 6. Modeled future suitability for pinyon pine in Colorado under the Warm & Wet climate scenario.

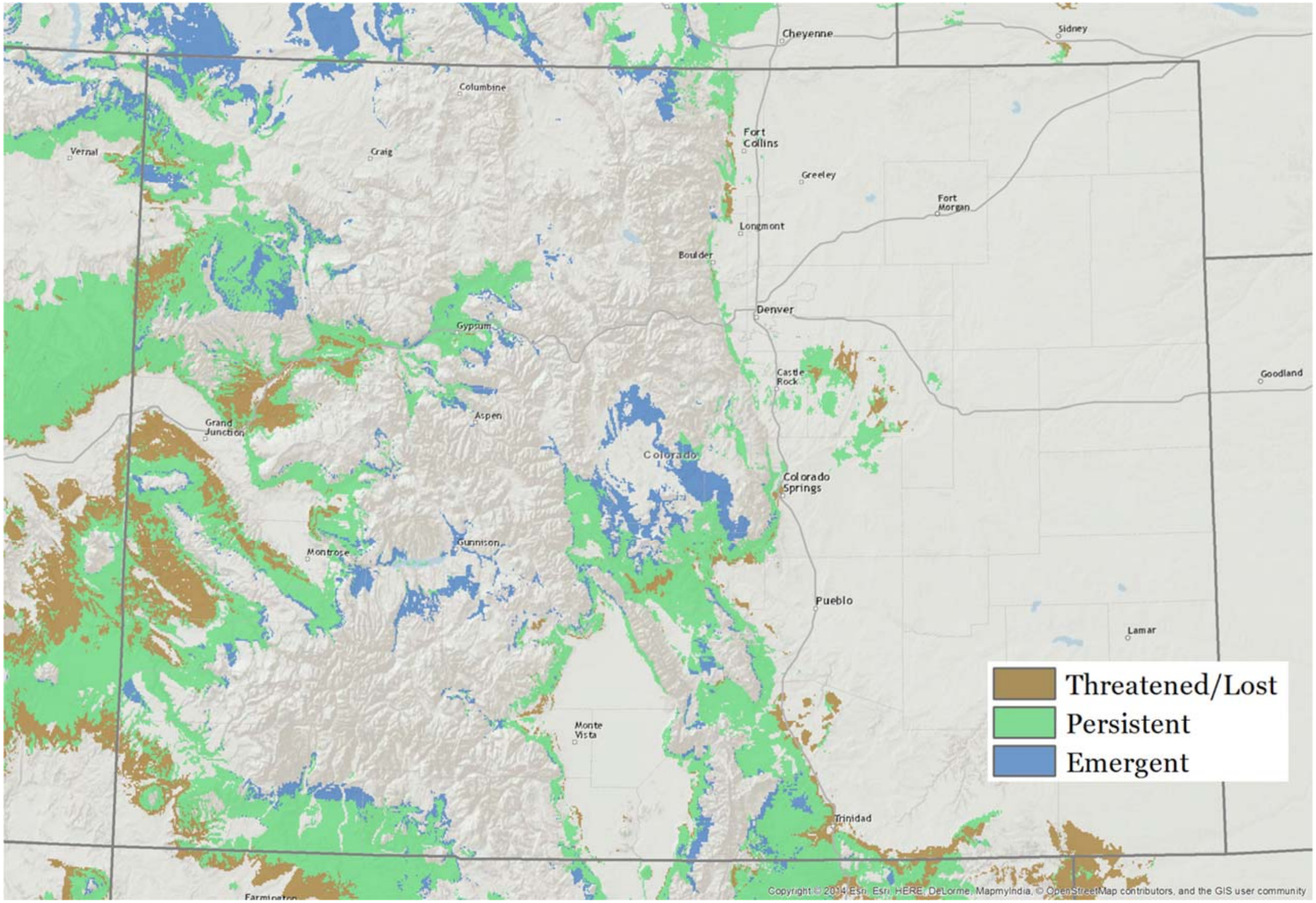


Figure 7. Modeled future suitability for pinyon pine in Colorado under the Feast & Famine climate scenario.

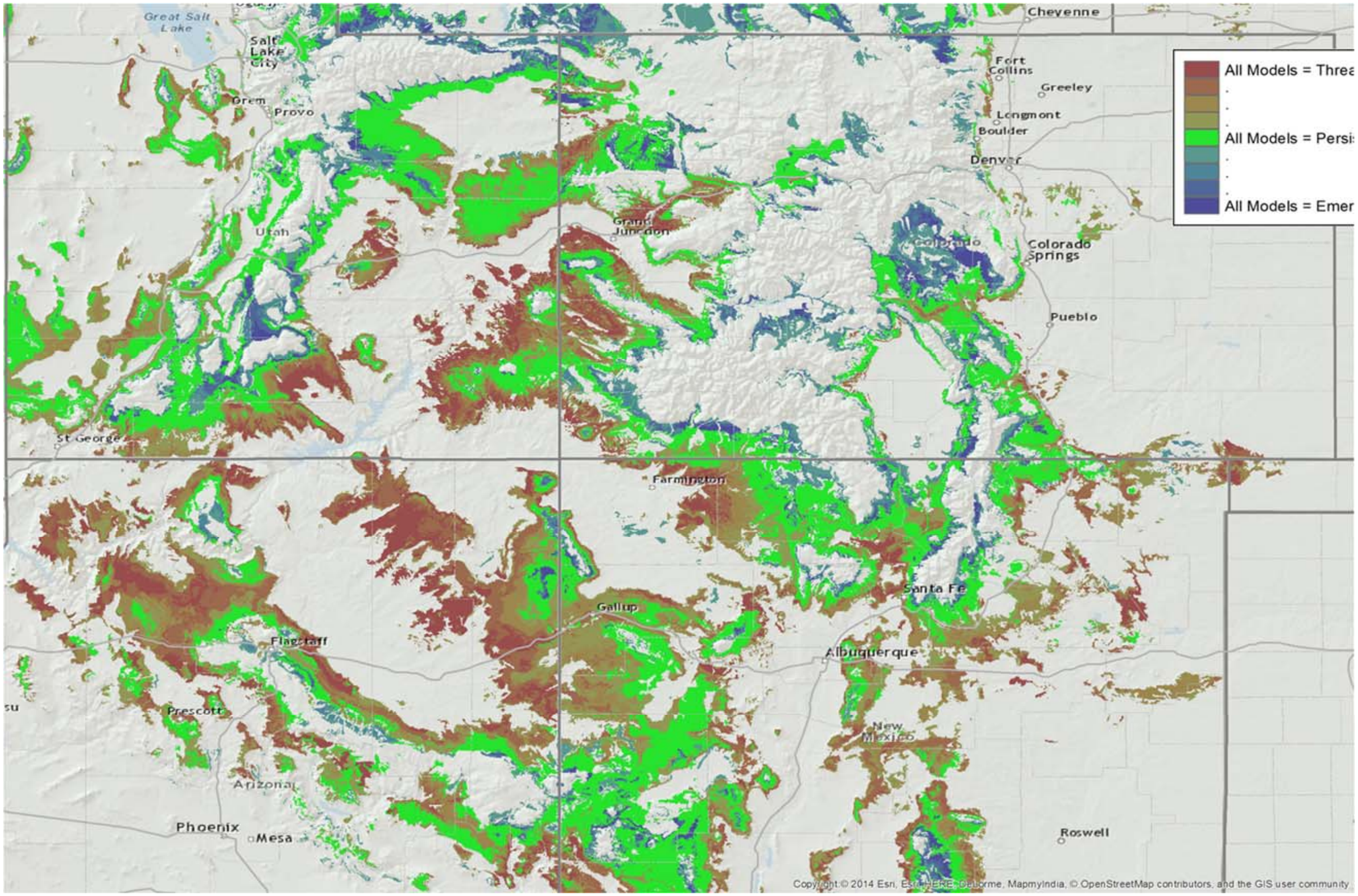


Figure 8. Modeled future suitability for pinyon pine with all climate scenarios combined, across the Four Corners distribution.

Models of potential future suitability for Utah Juniper (*Juniperus osteosperma*)

Results of the response of Utah juniper under four possible future climate scenarios are shown in Figures 9 through 13. Patterns of future Utah juniper habitat suitability are similar to those for pinyon pine. Lower elevation areas are projected to become unsuitable, especially for the two hot scenarios, at elevations similar to pinyon pine (below 6,500 ft) or slightly lower. Lost suitability is more prevalent in the southern portion of the west slope (south of Rangely); extensive areas of northwestern Colorado currently occupied by desert shrubland types are projected to increase in suitability for Utah juniper. The Hot & Wet scenario in particular shows extensive expansion of suitable habitat for the species, although the easternmost areas are often disjunct from the current species range.

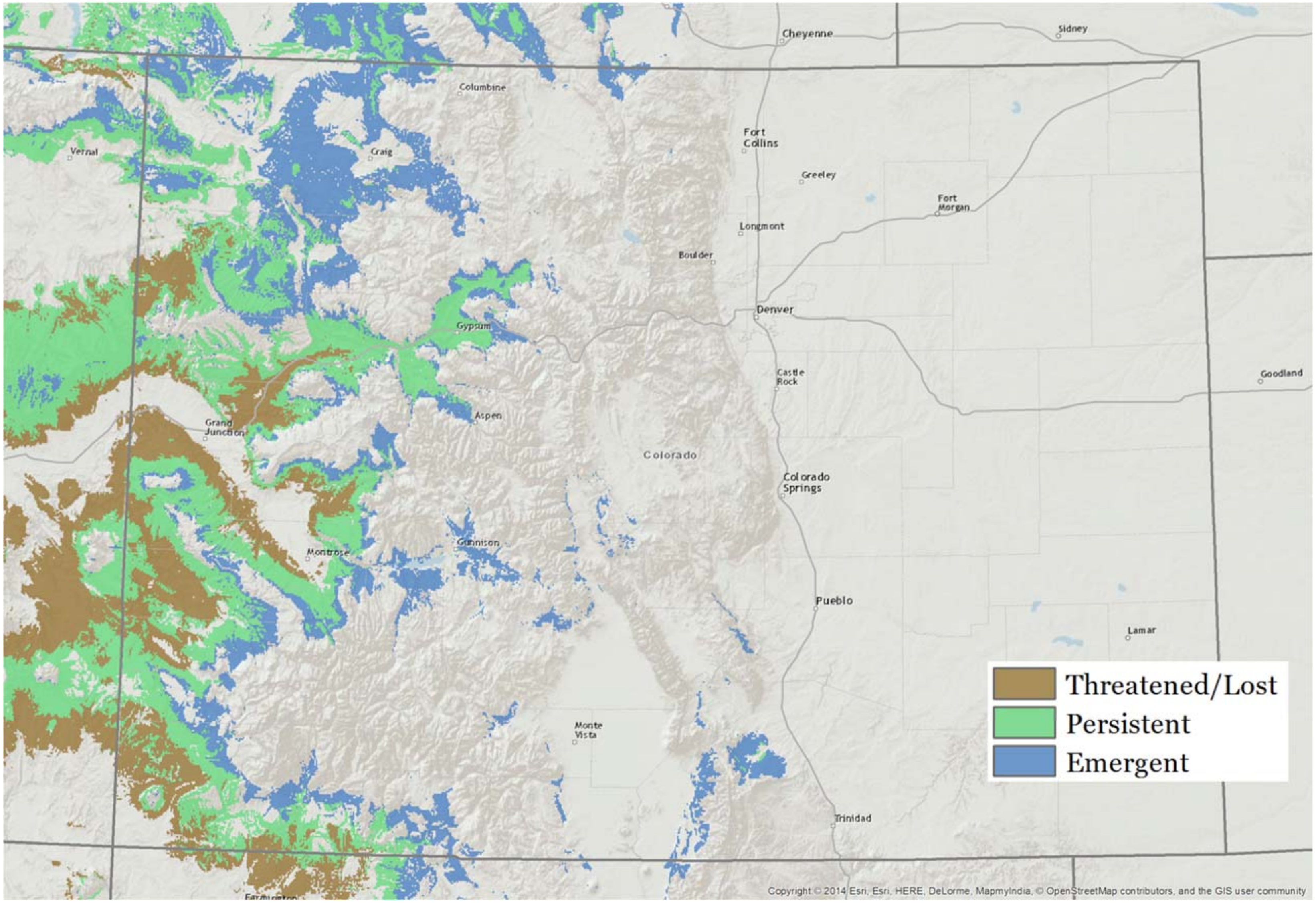


Figure 9. Modeled future suitability for Utah juniper in Colorado under the Hot & Dry climate scenario.

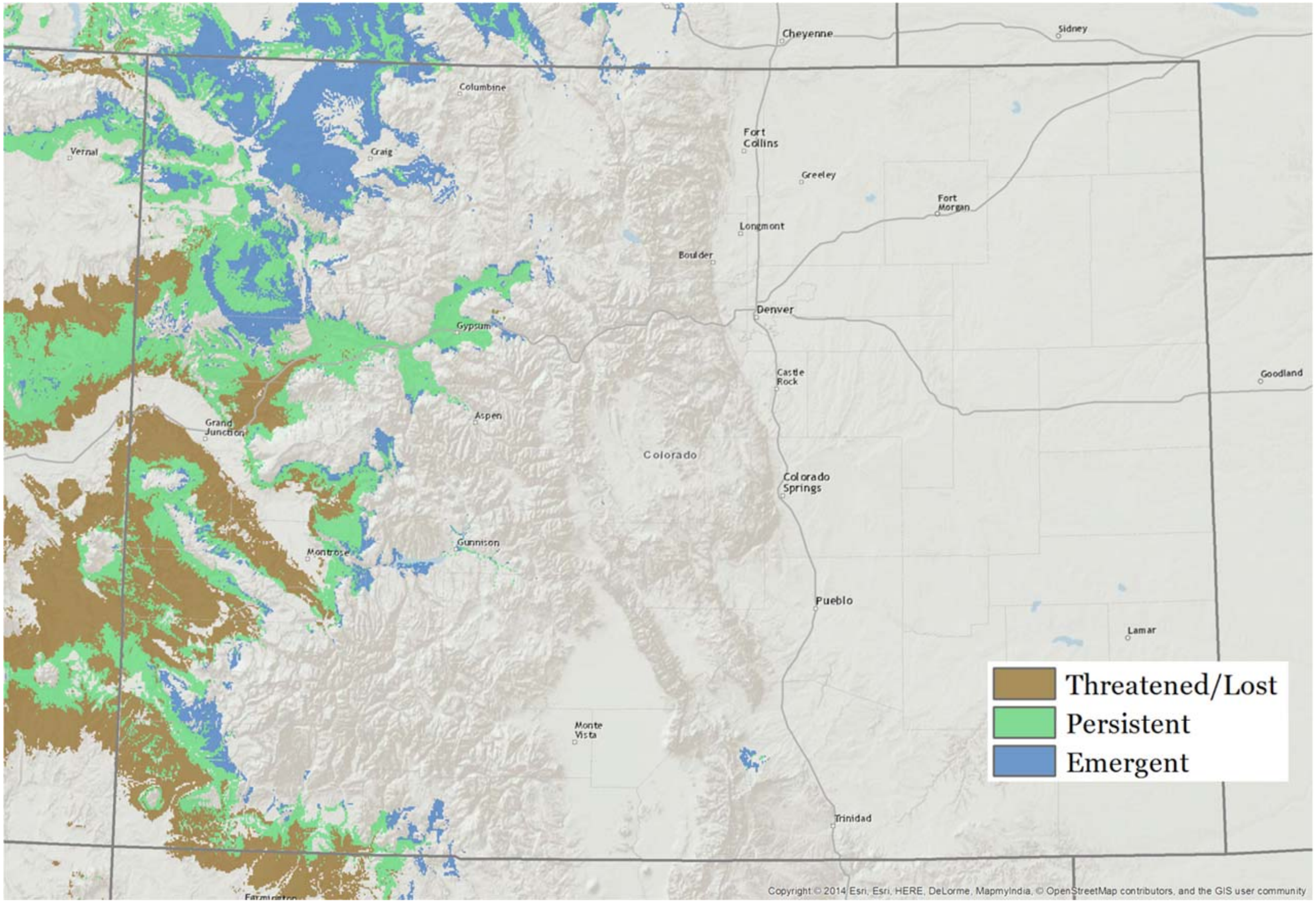


Figure 10. Modeled future suitability for Utah juniper in Colorado under the Hot & Wet climate scenario.

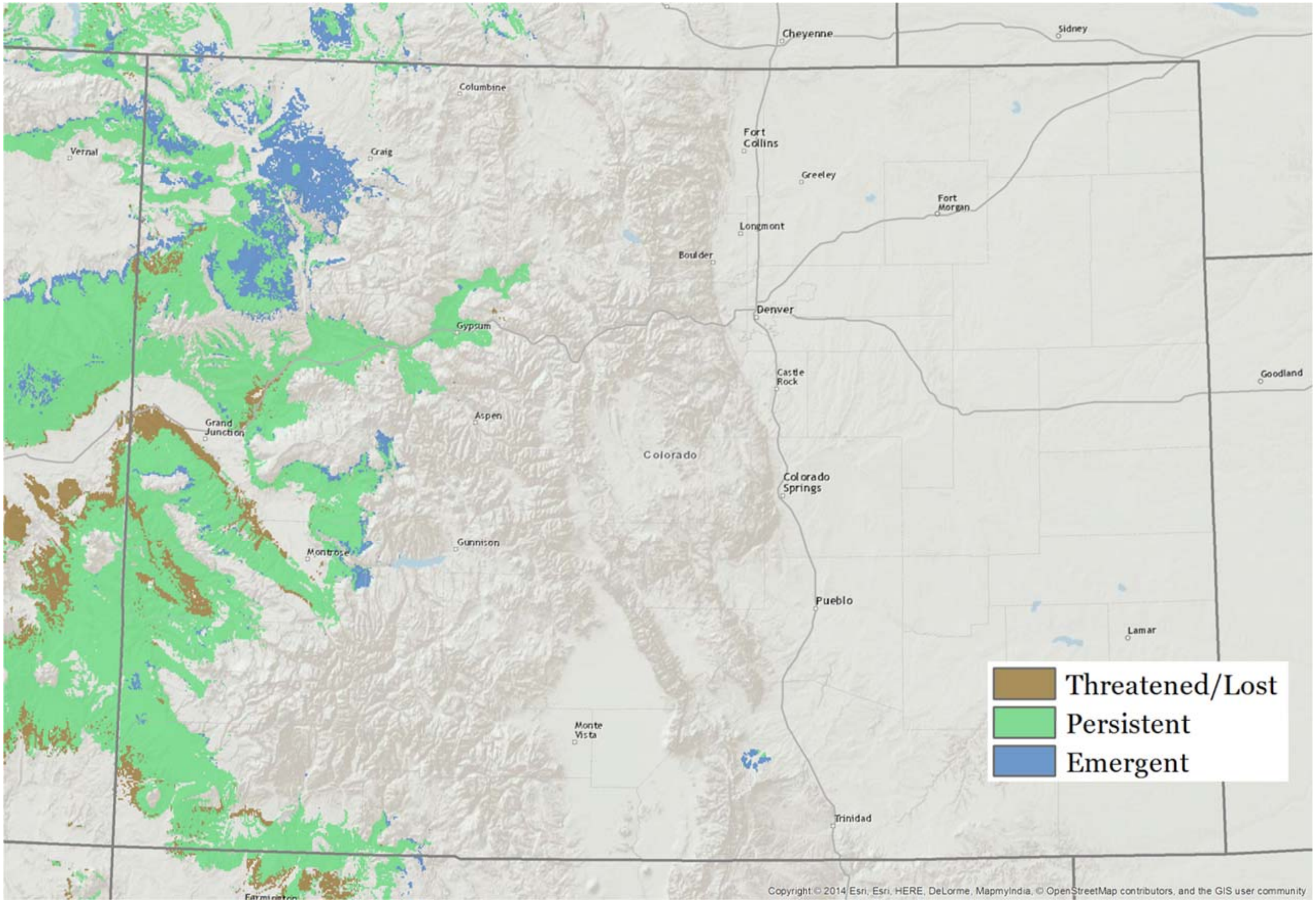


Figure 11. Modeled future suitability for Utah juniper in Colorado under the Warm & Wet climate scenario.

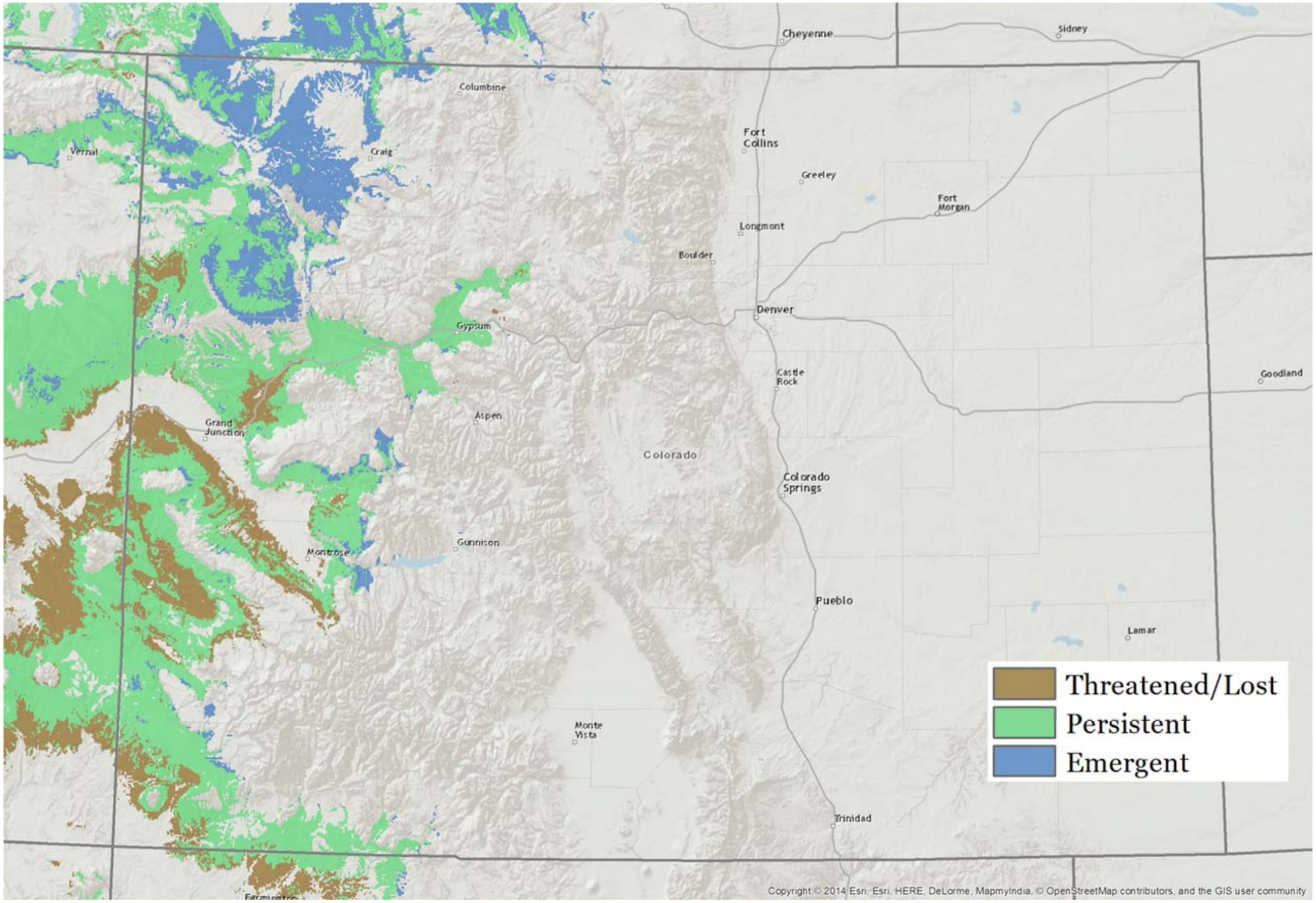


Figure 12. Modeled future suitability for Utah juniper in Colorado under the Feast & Famine climate scenario.

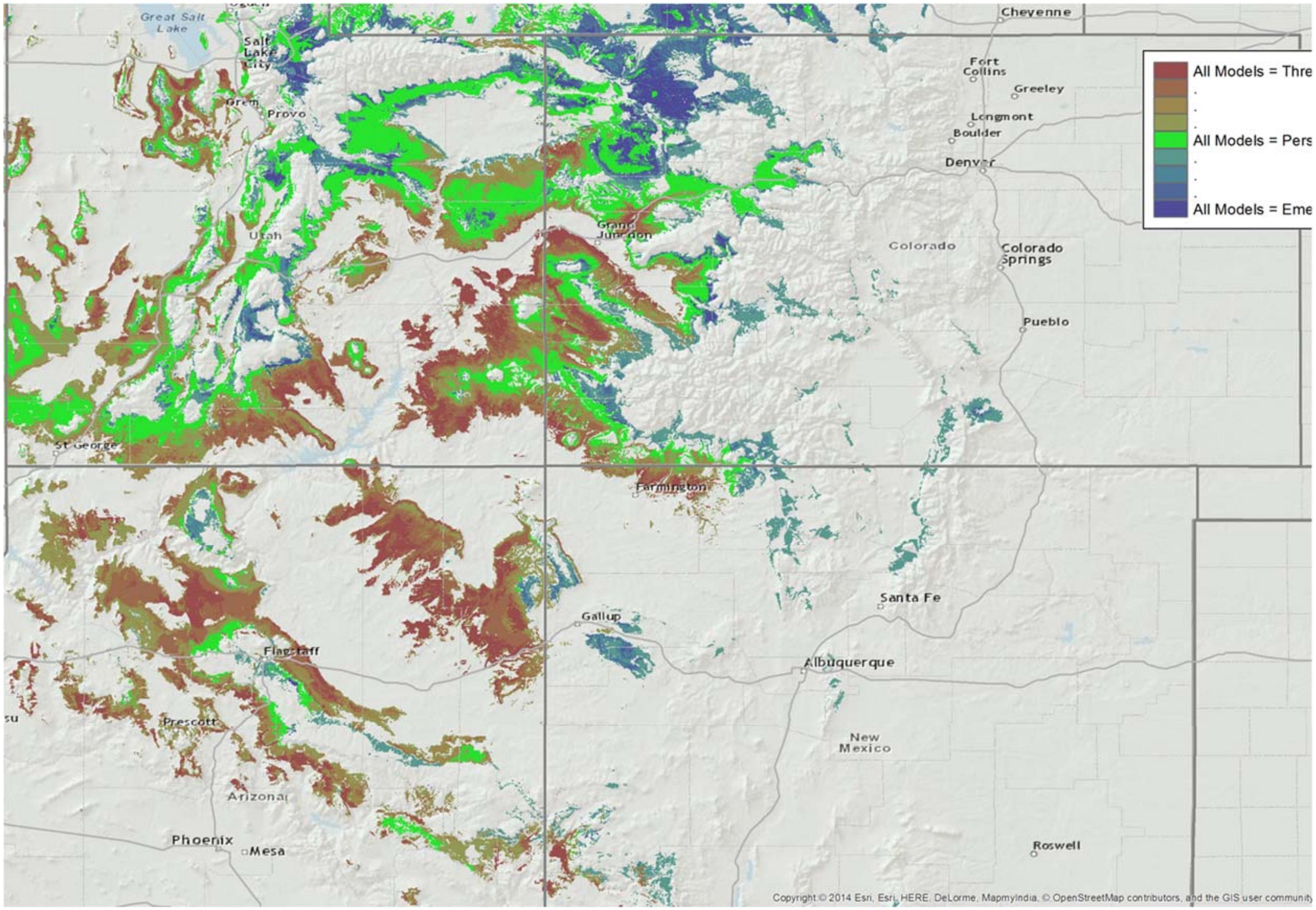


Figure 13. Modeled future suitability for Utah juniper with all climate scenarios combined, across the Four Corners distribution.

Models of potential future suitability for One-seed Juniper (*Juniperus monosperma*)

We constructed two versions of the models for one-seed juniper. The differences between the versions indicated that non-climate, anthropogenically driven factors (fire-suppression and land use history) have a substantial effect on the documented recent extent of this species. Since this eastern Colorado species is not as important for BLM lands, we did not prioritize the exploration of this effect with additional modeling work, but used the more conservative of our two model sets (shown in Figures 14-18). These models focused on the current extent of the species, rather than on areas where habitat is currently suitable but one-seed juniper is not present due to human activities. The Hot & Dry scenario is the most severe for suitable habitat loss, showing little remaining suitable habitat for the species in Colorado. Other scenarios indicate loss of suitability primarily in the driest areas of southeastern Colorado, persistent habitat at higher elevations, and a possibility of expanded suitability at higher elevations. Confidence in these conclusions is low; in the absence of extended drought or suppression by human actions, stands of one-seed juniper could otherwise be expected to persist or possibly expand in many areas.

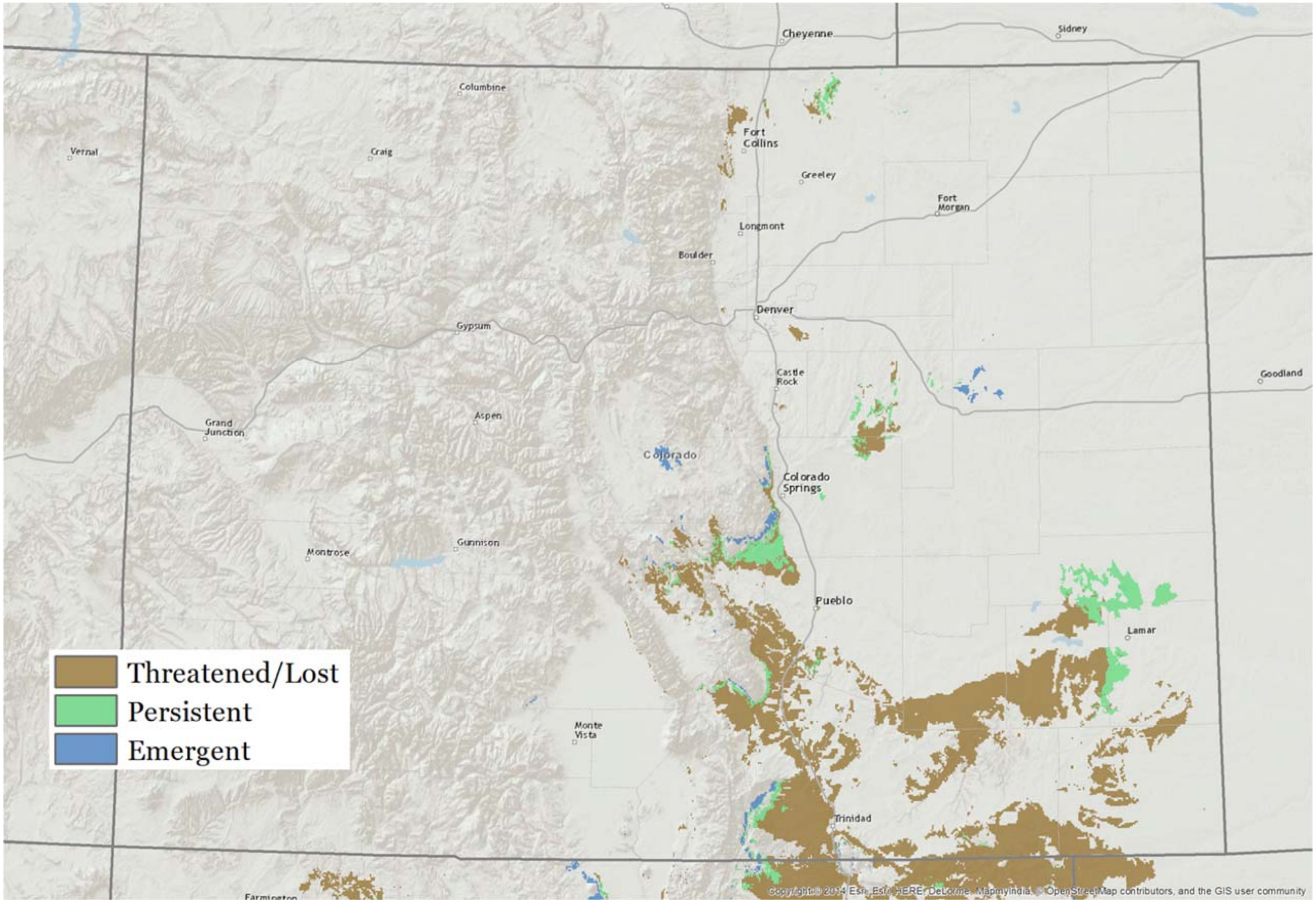


Figure 14. Modeled future suitability for one-seed juniper in Colorado under the Hot & Dry climate scenario.

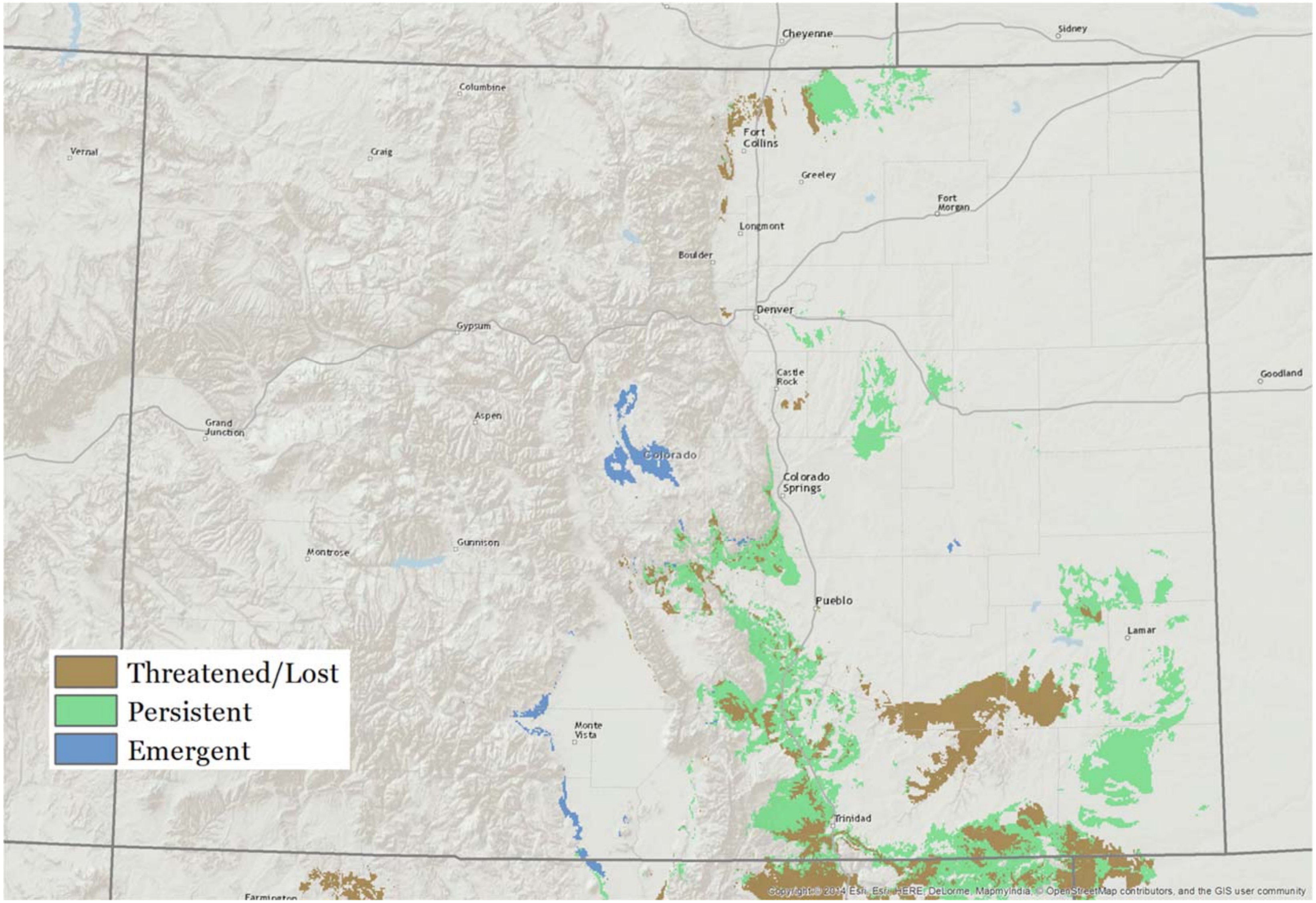


Figure 15. Modeled future suitability for one-seed juniper in Colorado under the Hot & Wet climate scenario.

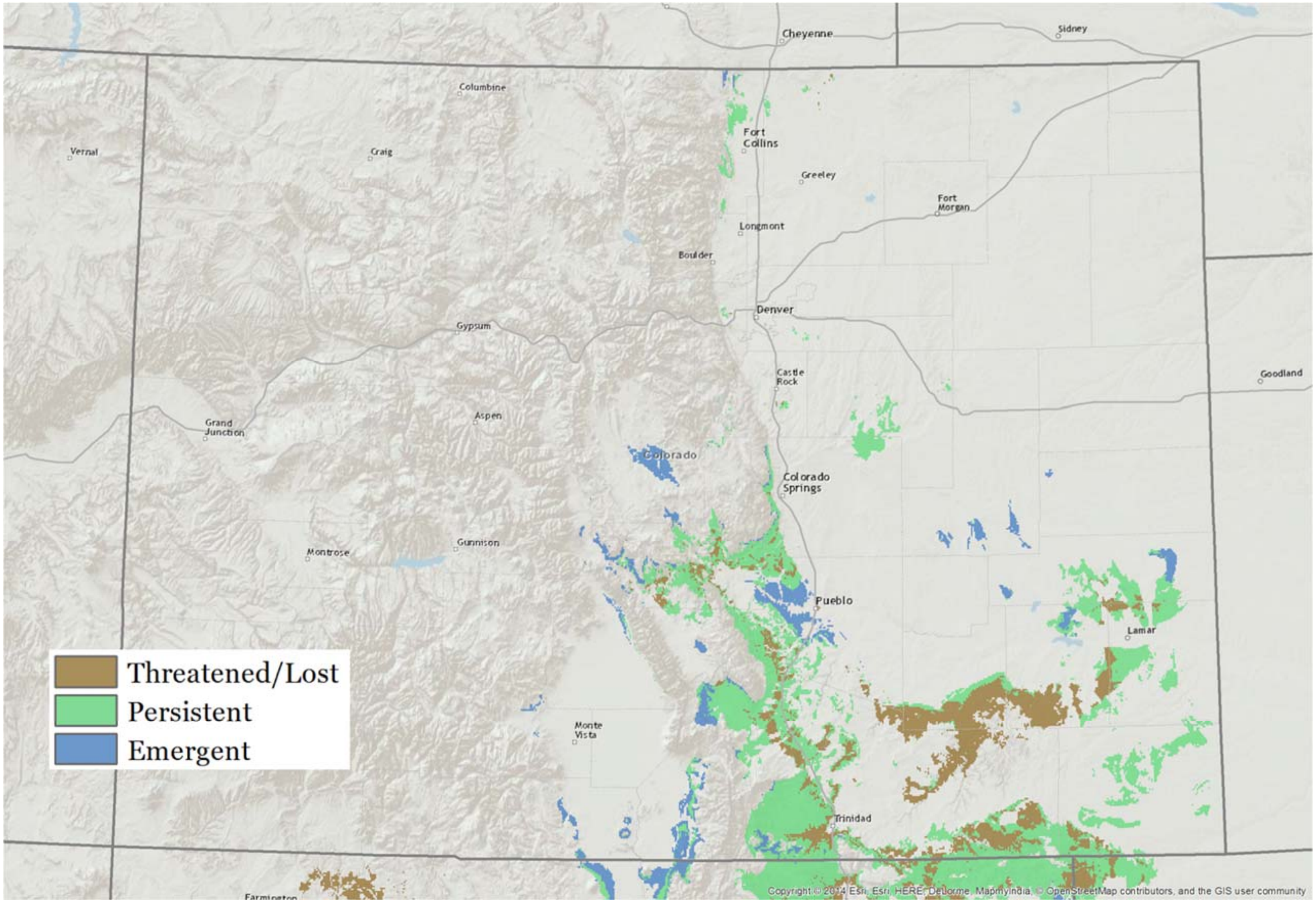


Figure 16. Modeled future suitability for one-seed juniper in Colorado under the Warm & Wet climate scenario.

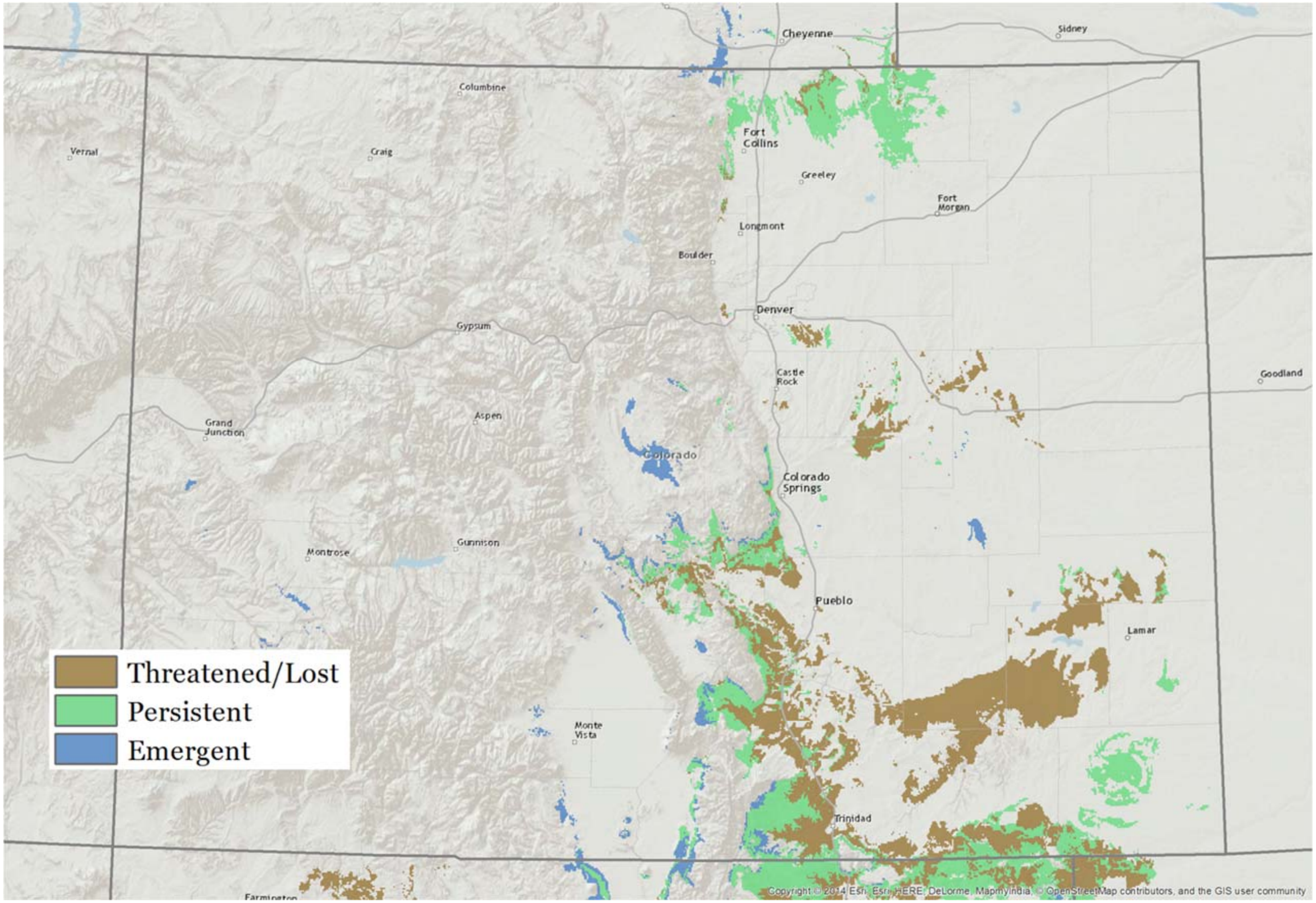


Figure 17. Modeled future suitability for one-seed juniper in Colorado under the Feast & Famine climate scenario.

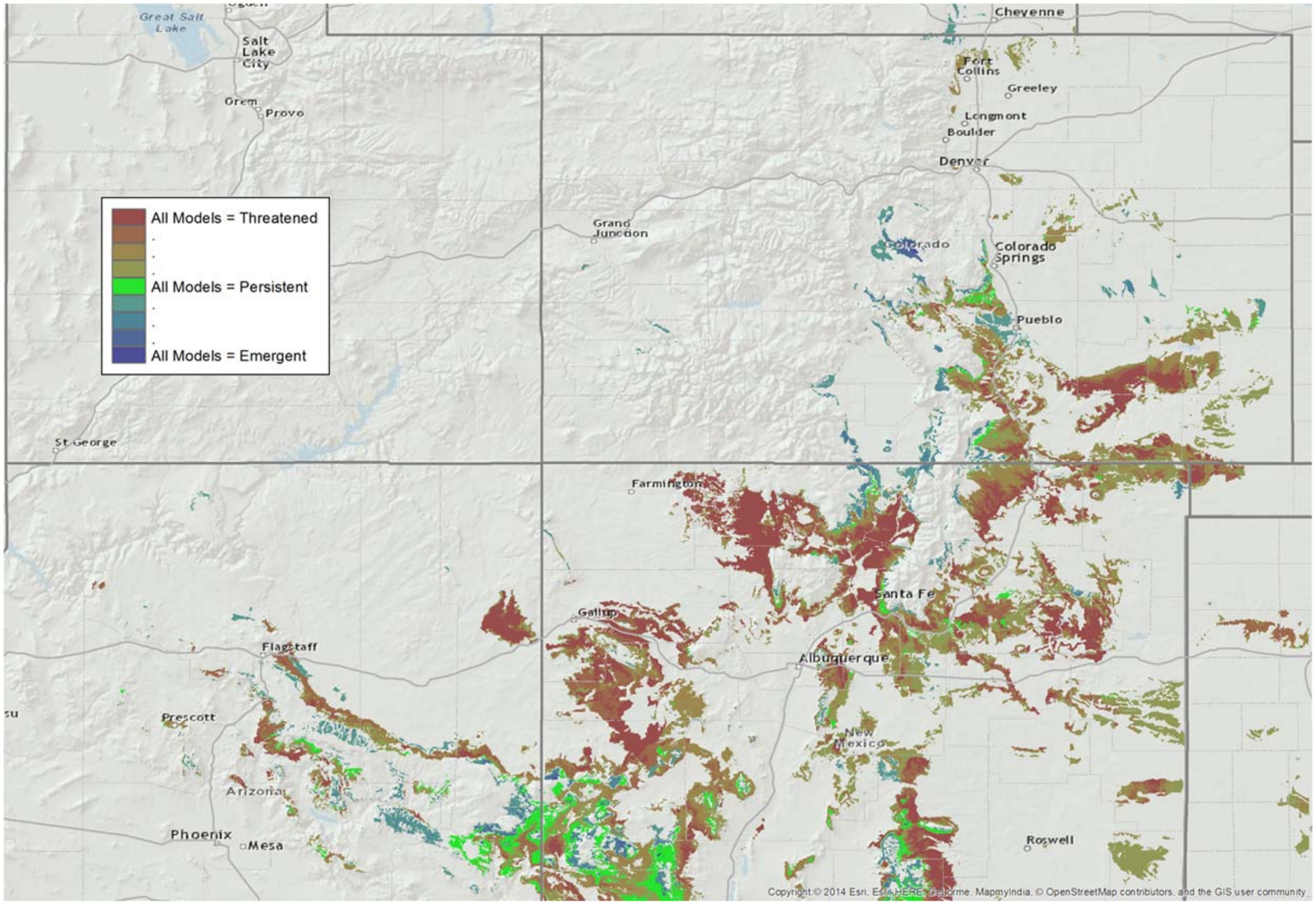


Figure 18. Modeled future suitability for one-seed juniper with all climate scenarios combined, across the Four Corners distribution.

Cold-Water Fish

In collaboration with BLM fisheries biologists, we determined that the most important climate-related information needs for fisheries management were:

1. An improved understanding of *how to evaluate* potential habitat improvement projects through a climate lens, and
2. A means to determine *where* projects would most likely be successful over the long term.

Though both cold-water and warm-water species are vulnerable to impacts from climate change, BLM fisheries managers highlighted the particular need for cold-water fisheries (including native and sport species) management decisions in the near term, so we defined target species for additional assessment as:

- Cutthroat trout (*Oncorhynchus clarkii*)
- Rainbow trout (*Oncorhynchus mykiss*)
- Brook trout (*Salvelinus fontinalis*)
- Brown trout (*Salmo trutta*)
- Bluehead sucker (*Catostomus discobolus*)
- Mountain whitefish (*Prosopium williamsoni*)

Decision Support Matrix

As management and conservation resources are limited and needs are great, it is crucial to leverage previous work whenever possible. In 2016, Nelson et al.[1] developed a decision support framework specifically for purposes compatible with our first information need: a way to evaluate management goals and strategies for fisheries within the context of climate change. Their work, which focused on native salmonids (cold-water species) in the northern Rocky Mountains, resulted in a three-step matrix that considers key vulnerabilities (habitat suitability, threats from non-native fish, and connectivity) and aligns those with options for management goals and implementation strategies.

The BLM fisheries managers agreed that Nelson et al.'s framework offered an excellent tool for assessing vulnerability and documenting decision rationale, since the basic data and assumptions behind the framework are correct and relevant to Colorado cold-water fisheries. One key disconnect, however, is the treatment of non-native sport fish. In Nelson et al.'s framework, non-native species are (correctly) treated as one of the key vulnerabilities for native salmonids, based on the considerable potential for conflict related to hybridization and competition among the species. However, a reality of multiple-use resource management is the need to find balance between conservation needs of native species, and social / economic benefits of non-native sport fisheries. Thus, we adapted the language in Nelson et al.'s framework to reflect this multiple-use

[1] http://rmpf.weebly.com/cold-water-ecosystem-management-tool.html

management need, but otherwise maintained the framework as originally developed (see Appendix B for adapted framework).

Habitat Suitability Models

Nelson et al.'s decision support framework lays out a consistent means of evaluating relative priorities for potential management actions, but does not specifically address the spatial component of decision-making. So to address our second information need—a means of determining where habitat improvement projects should be implemented—we built upon existing methods (e.g., NorWeST) to develop future habitat suitability models on a mid-Century timeframe. Key components of this effort were:

- Determine habitat suitability requirements for each species that can be represented across Colorado in present and future projected conditions.
- Apply these criteria to create habitat suitability maps for all species in current and future timeframes.

Fish Habitat Suitability Criteria

We reviewed recent literature focusing on stream flow, slope and water temperature criteria for the target fish species, with an emphasis on publications focusing on the western U.S. (especially Colorado) streams and rivers. Micro-scale habitat requirements (e.g., pools and riffles), other measures of water quality, and interactions with non-native fish could not be addressed with the available input data and so were not included as criteria. Figure 19 and Tables 4-5 summarize the criteria used.

Table 4. Temperature criteria used for each species.

	Temperature - mean summer (°C)		MWMT
Species	**Too Cold**	**Optimal**	**Too Hot**
Cutthroat Trout	< 6.4	11 - 18 [6.4 - 11]*	24
Rainbow Trout	< 9	> 11 - 18	24
Brook Trout	< 8	10 - 15	24
Brown Trout	< 8	12 - 18	24
Bluehead Sucker	< 8	19 - 21	--[†]
Mountain Whitefish	< 4.4	4.4 - 9	24

*Temperature range in brackets is the protectively cold 'climate shield' as discussed in Isaak et al. (2012).

[†]Bluehead Sucker have a maximum survival temperature of 27 °C (Smith and Friggens 2017), but this threshold was frequently exceeded in the model input data for known habitat, so this criteria was not used in the final models.

MWMT = Maximum Weekly Maximum Temperature (°C)

Table 5. Other criteria used in fish models.

	Flow-Ecology Metric		Seasonal Flows (cfs)		Slope
Species	**Not Suitable**	**Optimal**	**Not Suitable**	**Optimal**	**Optimal**
Cutthroat Trout	TFEM < 0.125	TFEM > 0.25	--	SuLF ≥ 0.6	< 20%
Rainbow Trout	TFEM ≤ 0.15	TFEM > 0.25	--	--	--
Brook Trout	TFEM ≤ 0.15	TFEM > 0.25	--	--	≤ 8%
Brown Trout	TFEM ≤ 0.15	TFEM > 0.25	--	--	< 6%
Bluehead Sucker	SFEM > 0.5	SFEM < 0.25	SuLF < 2.80	SpPF> 800	--
Mountain Whitefish	TFEM ≤ 0.15	TFEM > 0.25	--	--	--

TFEM = Trout flow-ecology metric; SFEM = Sucker flow-ecology metric; SuLF = Summer Low-Flow; SpPF = Spring Peak-Flow. See methods section for formulas.

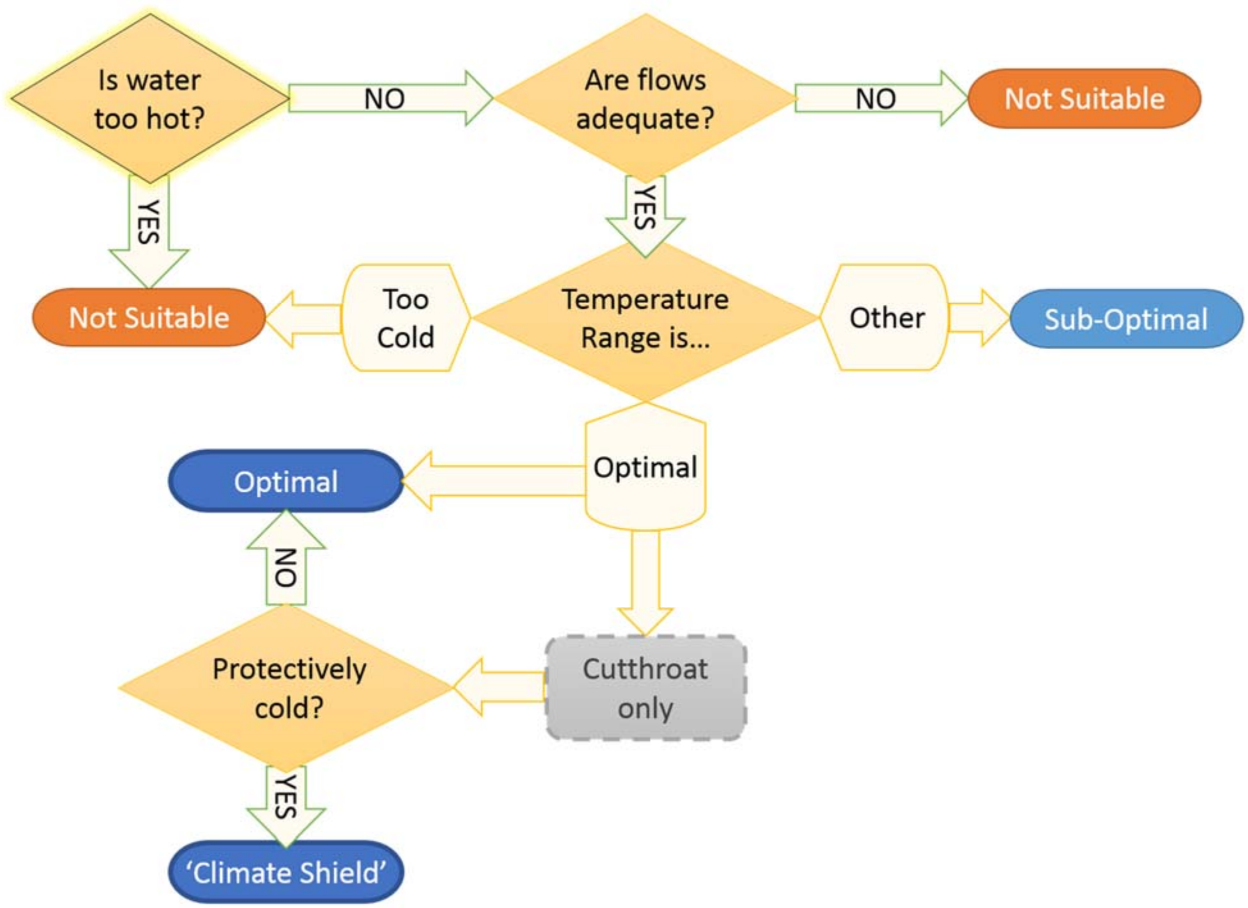


Figure 19. Decision tree (simplified) used to apply temperature and flows criteria to each species.

Cutthroat trout subspecies in Colorado have very similar temperature requirements (Smith and Friggens 2017, Roberts et al. 2013, Zeigler et al. 2013) and no evidence was found that they have different flow requirements. Therefore, all cutthroat are treated here at the species level. Cutthroat cannot survive a Maximum Weekly Maximum Temperature (MWMT) of ≥ 26 °C (Smith and Friggens 2017, Roberts et al. 2013), but there is evidence that areas with a MWMT > 24 °C are unlikely to support any of the trout species or mountain whitefish (Brinkman et al. 2013, Zeigler et al. 2013, Mohseni et al. 2003, Eaton et al. 1995). The optimal temperature range for cutthroat trout is generally recognized to be between 9-18 °C (Smith and Friggens 2017, Hunt et al. 2016, Roberts et al. 2013, Zeigler et al. 2013), although Isaak et al. (2012 and 2015) make a case for a mean summer water temperature range of 6.4-11 °C as a 'climate shield' to minimize competition and hybridization with other species of trout. A suitable slope of stream reaches for cutthroat is < 15% (Isaak et al. 2015, Wenger et al. 2011), however this was found to be too restrictive in the model, so an optimal slope of < 20% was used instead.

Rainbow and brown trout have similar upper temperature limits as cutthroat, but with a slightly warmer optimal range of 12-18 °C and a lower reproductive tolerance of 9 °C for rainbow (Isaak et al. 2014, Brinkman et al. 2013, Hunt et al. 2013, Isaak et al. 2012, Meisner et al. 1988, Eaton et al. 1995). Brown trout are the most sensitive to steep slopes, preferring ≤ 6%, while rainbow trout occurrence does not appear to be affected by slope one way or the other (Wenger et al. 2011). Brook trout have an optimal temperature range of 10-15 °C (Peterson et al. 2013, Eaton et al. 1995) and prefer less steep slopes of ≤ 8% (Peterson et al. 2013, Wenger et al. 2011). Minimum reproduction temperatures could not be found specifically for brook and brown trout, so were assumed to be 8 °C for this analysis.

Mountain whitefish have similar requirements to the trout species, but with a much colder optimal range of 5-9 °C (Brinkman et al. 2013). Minimum reproduction temperature was assumed to be 4.4 °C, and no stream slope information could be found. Bluehead sucker are regarded as more of a warm-water fish, with an optimal temperature range of 19-21 °C, a maximum survival temperature of 27 °C, and a minimum reproduction temperature of 8 °C (Smith and Friggens 2017). Bluehead have a minimum slope requirement of 0.1%, but no stated maximum (Sanderson et al. 2012).

For stream flow requirements, the trout flow-ecology metric described in Sanderson et al. (2012) was used for all trout and mountain whitefish. This metric uses mean summer (August – September) flow as a proportion of mean annual flow to describe low flow suitability for trout. The five suitability classes of the original metric were simplified to regard > 0.25 as optimal, ≤ 0.15 as unsuitable, and > 0.15 – 0.25 as suboptimal. In their review of the initial results, BLM fisheries biologists determined that the 0.15 threshold was too restrictive for cutthroat trout, so this metric was changed to 0.125 for cutthroat only. To prevent this change from selecting streams that essentially dry up during the lowest summer flows as optimal habitat, an additional criteria of summer low flow ≥ 0.6 cfs was added for cutthroat.

The sucker flow-ecology metric also described in Sanderson et al. (2012) was used as the starting point for bluehead sucker flow requirements. This metric estimates potential sucker biomass from a 30-day low flow value and then calculates the percent change in biomass under natural versus modified low flows to describe risk of losing sucker populations under modified flows. A loss of > 50% biomass is considered a very high risk, whereas a loss of < 25% biomass is considered minimal risk. For this analysis, instead of natural versus modified water flows, I used current versus future projected flows to describe future habitat suitability, with a > 50% loss in sucker biomass being unacceptable (not suitable) and a < 25% loss considered still within optimal suitability (with the range 25-50% being suboptimal). For current habitat suitability, a biomass index of 14% of potential maximum biomass, which equates to a summer low-flow of 2.8 cfs, was used as the minimum acceptable. Because of the importance of high spring flows to bluehead sucker recruitment (Sanderson et al. 2012, Anderson and Stewart 2007, Propst and Gido 2004), an approximation of spring flows ≥ 800 cfs was added as an additional optimal criterion for bluehead sucker.

Data Analysis Methods

Stream temperature and base flow index data from NorWeST Predicted Stream Temperatures (Parkes-Payne 2018, Isaak et al. 2016) and stream flow metrics from Western US Stream Flow Metric Dataset (Wenger and Luce 2016, abbreviated herein as WUS Flows) were combined into a single dataset. Because these two datasets do not use exactly the same stream flow lines or identifiers (COMID), several weeks of manual cross walking were required and not all stream segments could be successfully combined between the datasets. Additionally, both datasets had areas of no data, which were not included in the analyses. All analyses were restricted to the extent of the NorWeST data, which does not cover the Eastern plains of Colorado. The combined dataset was further restricted to likely perennial streams and rivers, using a combination of NHD classification of feature type, summer low flows (described below), and visual review to create a sub-dataset most likely to contain suitable habitat for the fish species of interest. The final combined dataset contains 63,714 line segments totaling approximately 54,000 km of stream.

The input metrics of interest are described in Tables 6 and 7. Descriptions are from the documentation of each dataset.

Table 6. Stream metrics used from NorWeST.

Fieldname	Description
BFI	Base flow index. Base flow to total flow as a percentage
S1_93_11	Historical composite scenario representing 19 year average August mean stream temperatures for 1993-2011
SLOPE	Slope (rise/run) for each NHDPlus stream reach
S30_2040D	Future scenario based on global climate model ensemble averages that represent the A1B warming trajectory for 2040s (2030-2059). Future stream deltas within a processing unit were based on similar projected changes in August air temperature and stream discharge, but also accounted for differential warming of streams by using historical temperatures to scale temperature increases so that cold streams warm less than warm streams.
S37_9311M*	Historical composite scenario representing 19 year average Maximum Weekly Maximum Temperature (MWMT or 7 DADM) for 1993 - 2011.
S39_2040DM*	Future Maximum Weekly Maximum Temperature (MWMT or 7DADM) stream scenario based on global climate model ensemble average projected changes for the A1B warming trajectory in the 2040s (2030-2059). Future stream deltas within a NorWeST unit account for differential sensitivity among streams so that cold streams warm less than warm streams.

* NorWeST only has values for the maximum temperature measures S37_9311M and S39_2040DM (MWMT) for the Colorado River basin. However, the MWMT values that are available appear to be a simple derivation from the mean August stream temperature, because these two metrics are perfectly correlated ($r = 1.0$, $p < 0.0001$). The missing MWMT data were therefore filled in using the following linear function for both the historic and 2040 periods: MWMT = 4.376 + (1.133 * [Mean August]).

Table 7. Stream metrics used from WUS Flows.

Fieldname	Description
MA_Hist	Mean annual flow rate (cfs) for the historical period (1977-2006).
MA_2040	Mean annual flow rate (cfs) for the period 2030-2059, based on the A1B emissions scenario.
MS_Hist	Mean summer flow rate (cfs) for the historical period (1977-2006). Summer is here defined as June 1 - September 30.
MS_2040	Mean summer flow rate (cfs) for the period 2030-2059, based on the A1B emissions scenario. Summer is here defined as June 1 - September 30.

The ‘mean summer’ flows metrics MS_Hist and MS_2040 include the likely timing for peak flow (June in Colorado) as well as post-runoff low flow. Both low flow and peak flow rates are necessary to calculate flow-ecology metrics for trout and bluehead sucker, so these values were estimated from the available ‘mean summer’ (MS) rates. Summer low flow was calculated to be the MS multiplied by the BFI as a percentage. Peak flow was assumed to be the remaining flow volume not covered in summer low flow, which was further assumed to take place all in June.

Summer low flow (cfs) = MS * (BFI / 100)
MS_total = MS * the number of seconds in June – September.
LowFlow_total = Summer low flow * the number of seconds in July – September.
PeakFlow_total = MS_total - LowFlow_total
PeakFlow (cfs) = PeakFlow_total / the number of seconds in June.

These estimations are not intended to be literal representations of peak and low flow rates, but within the context of the flow-ecology metrics they provide relative measures of minimum and maximum spring-summer flows. The trout flow-ecology metric is simply

Low Flow (cfs) / Mean Annual Flow (cfs)

for both historic and future time periods. The sucker flow-ecology metric described in Sanderson et al. (2012) is a measure of change, and so only applies to the future time period. For the historic period, habitat suitability was based on the first component of the metric; relative sucker biomass (RSB) for the historic period.

RSB = 0.1026 * (Summer low flow (cfs))$^{0.3021}$
sucker flow-ecology metric = (RSB_historic - RSB_future) / RSB_historic

The models for bluehead sucker and mountain whitefish were masked to the known ranges of each species, including areas where the species were introduced.

Results and Discussion

Current and future predicted habitat suitability for the six species are shown in Figures 20-32. The designations ‘Optimal’ and ‘Sub-Optimal’ – plus, for cutthroat trout, ‘Climate Shield’ – are all suitable to support fish. Likewise ‘Not Suitable’ and ‘Too Cold’ are both unsuitable. These sub-categories of habitat suitability are intended to help BLM manage areas of differing suitability accordingly, and to understand how these areas may change in the future.

For cutthroat trout, 73% of modeled stream kilometers (~40,000 km) are currently suitable to one degree or another. In 2040, that is projected to decrease to 62%. The largest area of change is in the loss of stream segments designated as ‘Climate Shield’ – protectively cold against invasion and hybridization with other trout species, such as rainbow. Approximately 4,350 km of stream currently in the ‘Climate Shield’ category will lose this classification. Most of these stream segments remain suitable, but many (~ 2,000 km) become ‘Sub-Optimal’, indicating that flows may decrease from Optimal in addition to warming temperatures. Approximately 650 km drop from ‘Climate Shield’ to ‘Not Suitable’ in 2040.

Rainbow trout has fewer suitable stream kilometers to start with (~33,000 km) and approximately 1,800 of these km become unsuitable by 2040. The reason loss of suitability is not higher is because over 4,000 km of stream that are currently too cold for rainbow trout warm up sufficiently to become suitable by 2040. Brown and brook trout current and future suitability closely follows that of cutthroat, with nearly 6,000 km of stream that are currently suitable becoming unsuitable by 2040 for the three trout species. Though of the three, brook trout fairs slightly better because of the transition of about 600 km from ‘Too Cold’ to suitable. Few areas are too cold for either cutthroat or brown trout at the start.

Approximately 16,000 km (42% of all modeled stream kilometers) for bluehead sucker are currently suitable, with ‘Optimal’ habitat restricted to the larger river channels. Areas that are currently too cold are unlikely to become suitable in the future because of lower flows. No stream is currently too cold for mountain whitefish, and 76% (~12,000 km) of the area modeled for this species is currently suitable. This goes down to 63% (~10,000 km) by 2040 with proportionally the greatest loss in the ‘Optimal’ category.

Model Accuracy and Limitations

A measure of model accuracy was made by comparing modeled current suitability against Colorado Parks and Wildlife (CPW) known fish streams for cutthroat trout and bluehead sucker, the only two species in this study for which CPW data were available (CDOW 2012). This method can only realistically test for true positives (both the model and CPW data agree on likely species presence) and false negatives (areas that CPW has identified as being currently occupied by a particular species that the model shows as unsuitable). This allows for the calculation of model *sensitivity*, or the probability of true presence, but not *specificity*, the probability of true absence. There is also the issue that CPW stream lines are not identical to the stream lines used in the models, so that queries of the two data sources do not always match up. With those caveats in mind, the cutthroat trout model shows a sensitivity of 83%, whereas the bluehead sucker model has a sensitivity of 79%.

These models have a number of limitations which should be noted. Foremost among them are the limitations of the input temperature and flows data. The inputs are themselves models based on actual gauge data, but there are a limited number of gauges in the state, and their locations are not evenly distributed among the stream network. The modeled interpolations are likely wrong in areas of few or no gauges. For instance, the Dolores River and its tributaries are represented as too hot and dry, yet are known to support cutthroat trout.

These data only represent streams—water bodies were not included in the original input data, and thus are not represented in the models. The future projected input values were based on a single climate projection scenario with no measure of uncertainty. While all climate projections agree on the temperature warming, they do not agree on the magnitude of warming, and projections of precipitation are highly variable in both direction and magnitude. The particular climate scenario used for both NorWeST and WUS Flows shows most areas becoming drier, whereas other models show some areas becoming wetter in the future.

The MWMT values that are available from NorWeST (Colorado River basin only) do not appear to be based on actual gauge data, and the equation used to fill in the missing MWMT values for the other basins was not based on gauge data either. A great many assumptions were also required in order to derive estimates of summer low flow and spring peak flow from the single 'mean summer' flow values. These were vetted by BLM fisheries biologists, but are still assumptions.

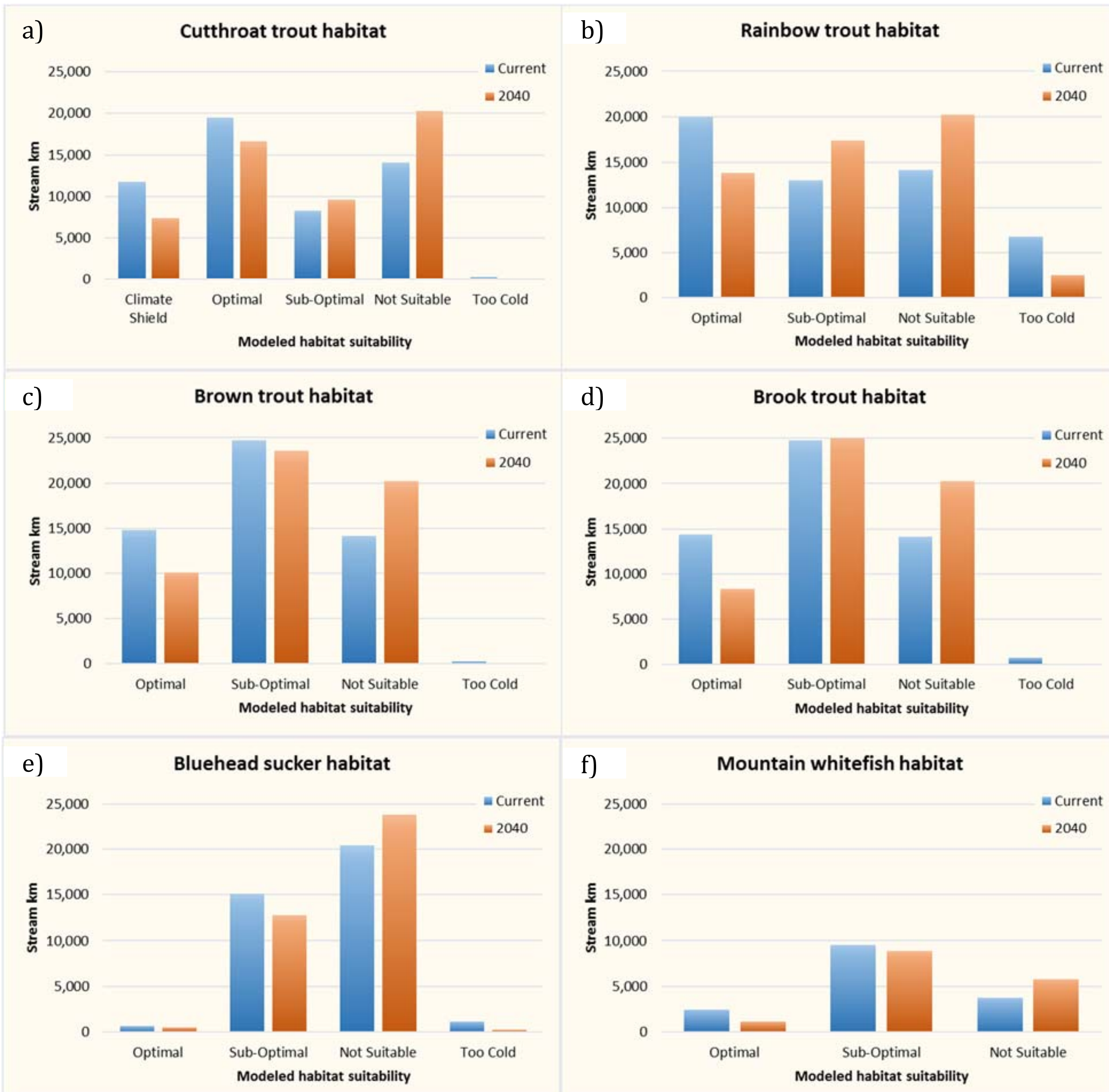


Figure 20. Change in each habitat suitability category for each species model from current to future projected (2040).

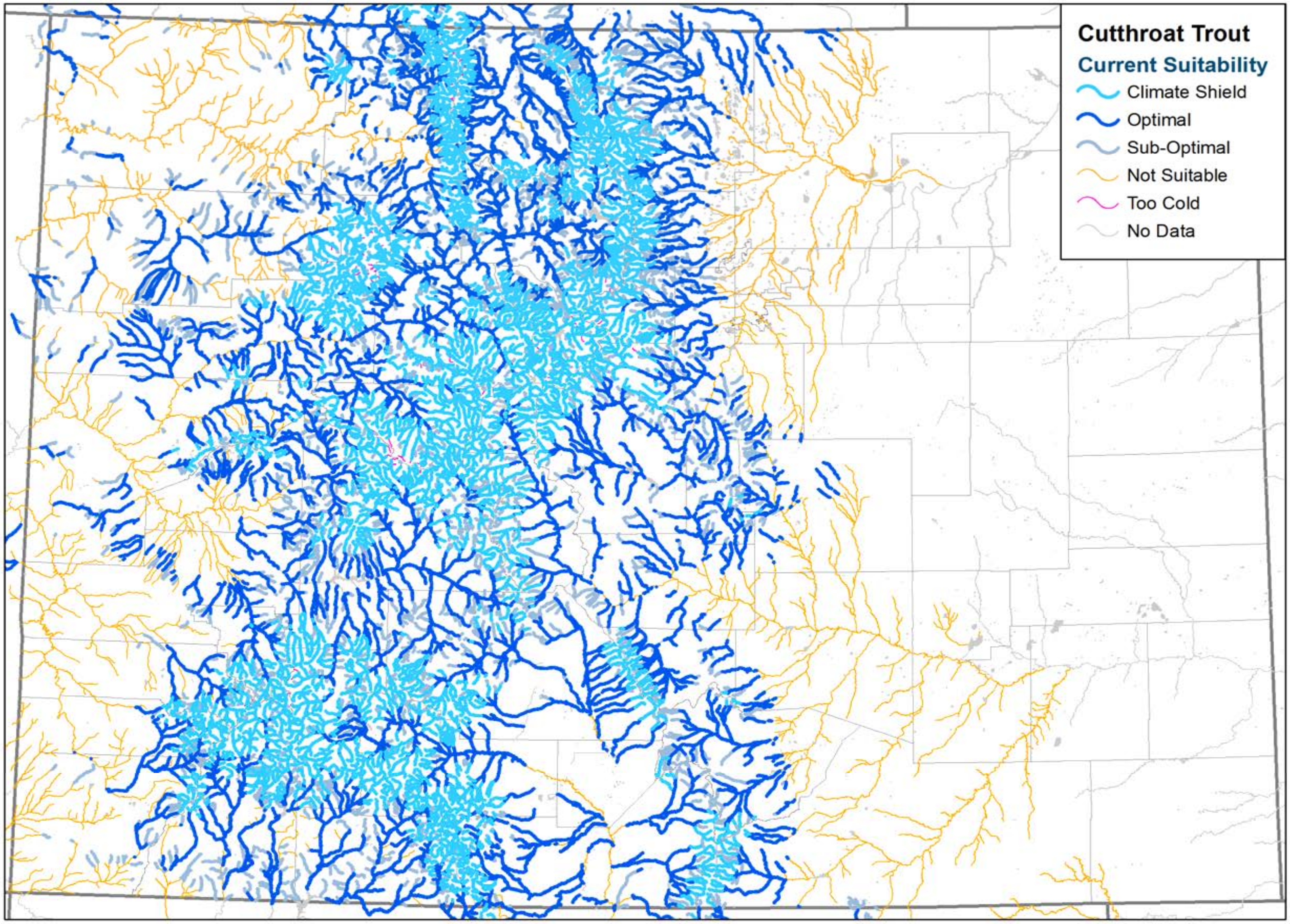


Figure 21. Current habitat suitability model for cutthroat trout. Source for Climate Shield: Isaak et al. 2012.

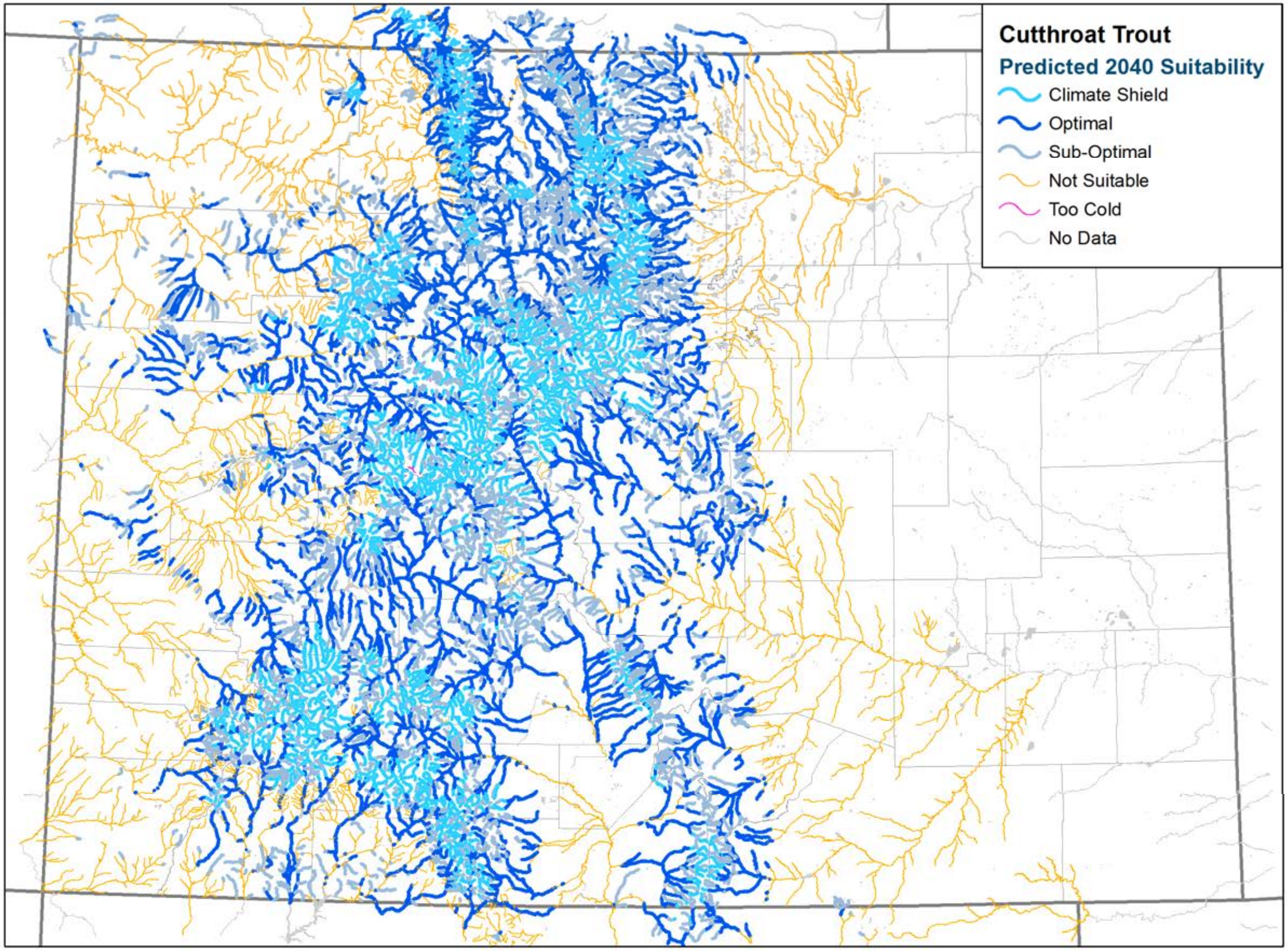


Figure 22. Predicted habitat suitability at mid-Century for cutthroat trout. Source for Climate Shield: Isaak et al. 2012.

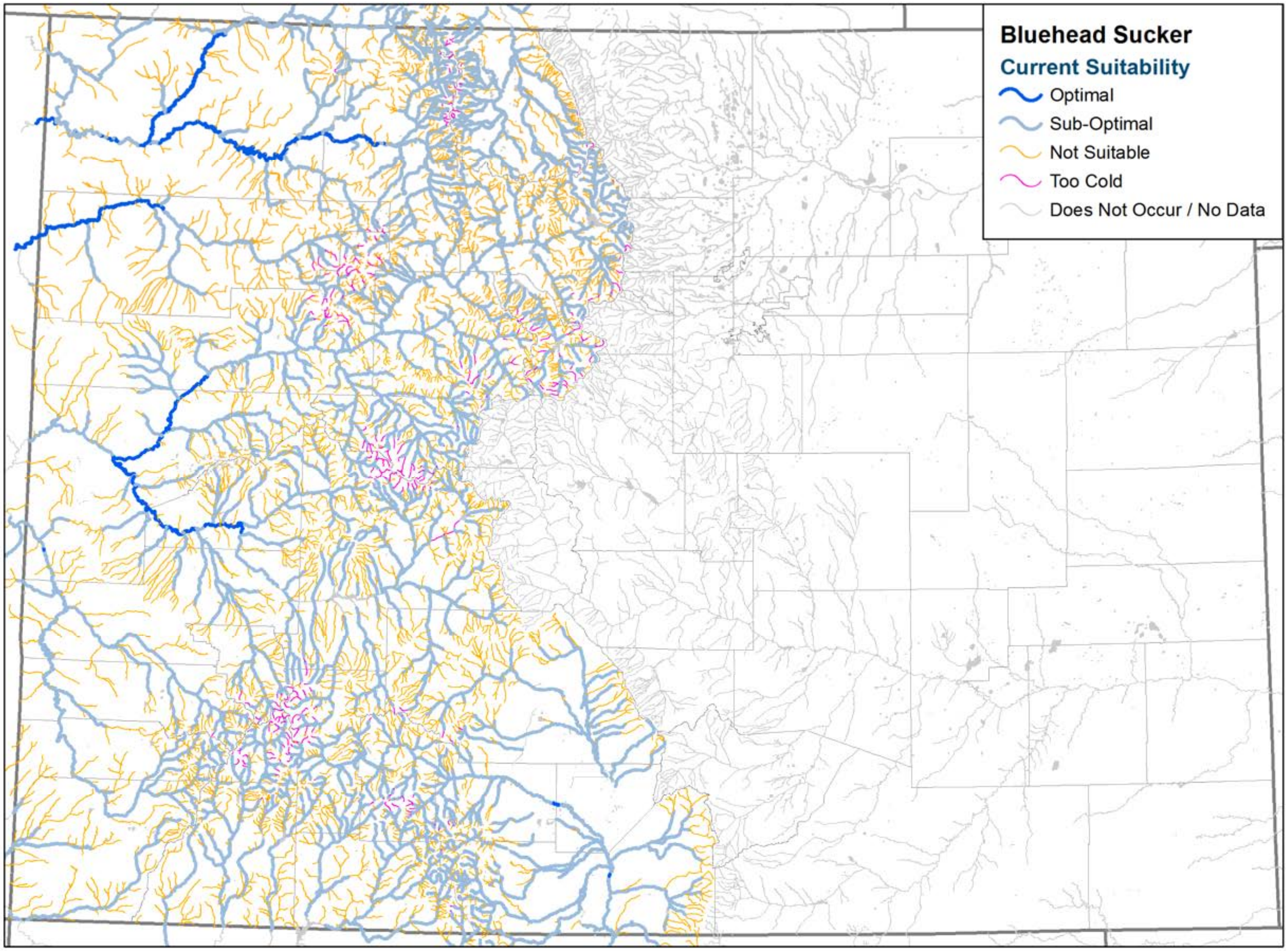


Figure 23. Current habitat suitability model for bluehead sucker.

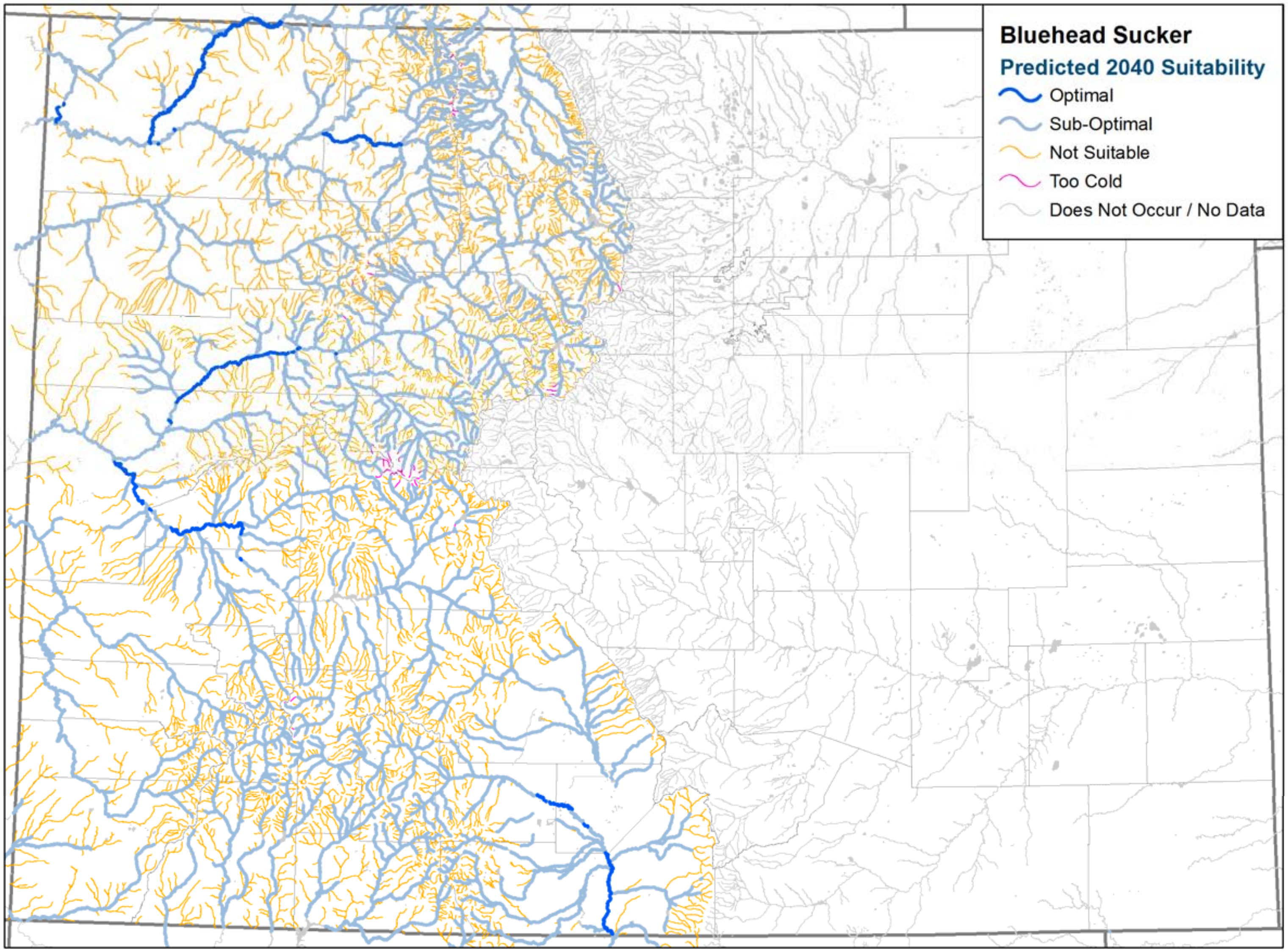


Figure 24. Predicted habitat suitability at mid-Century for bluehead sucker.

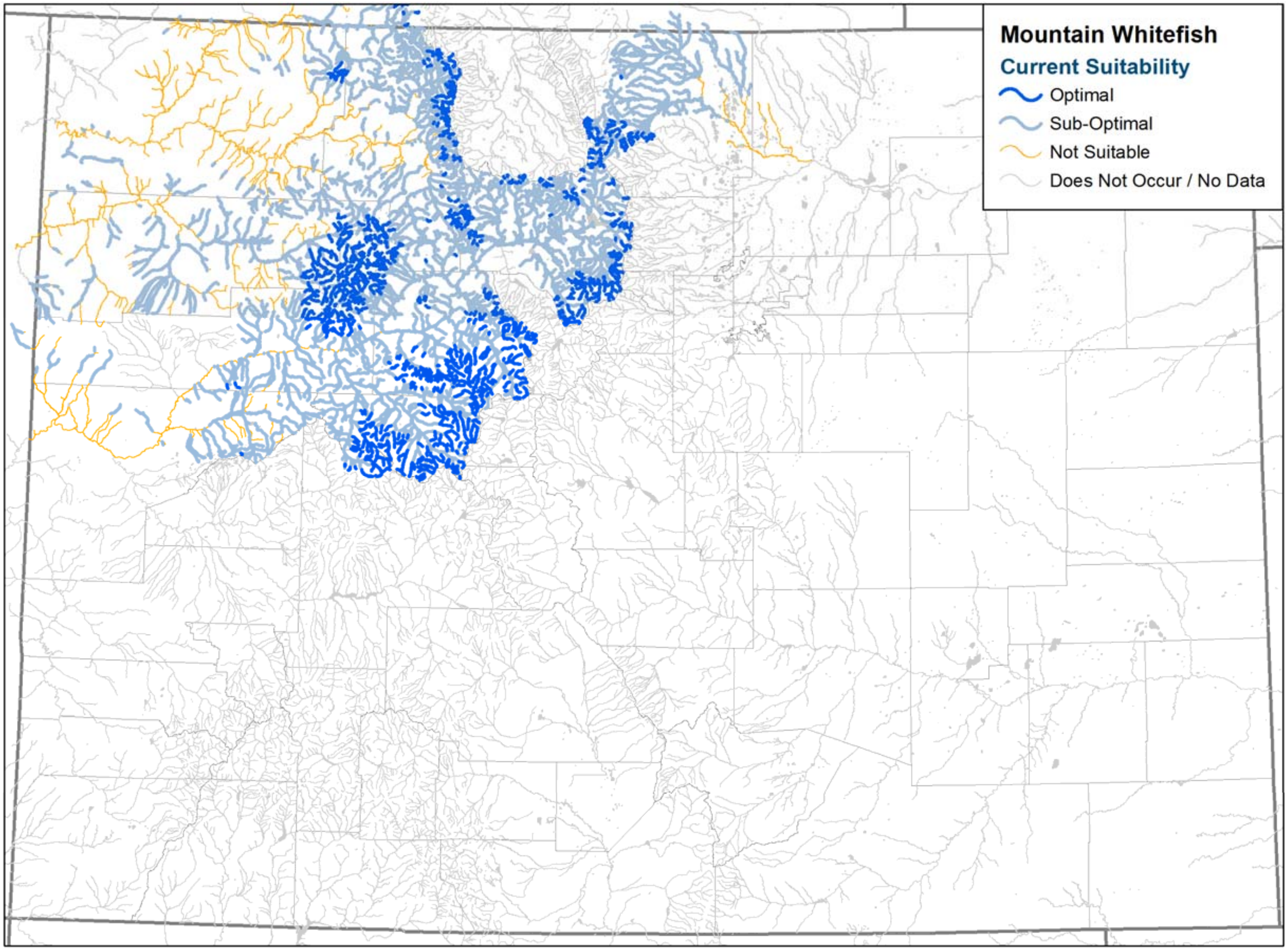


Figure 25. Current habitat suitability model for mountain whitefish.

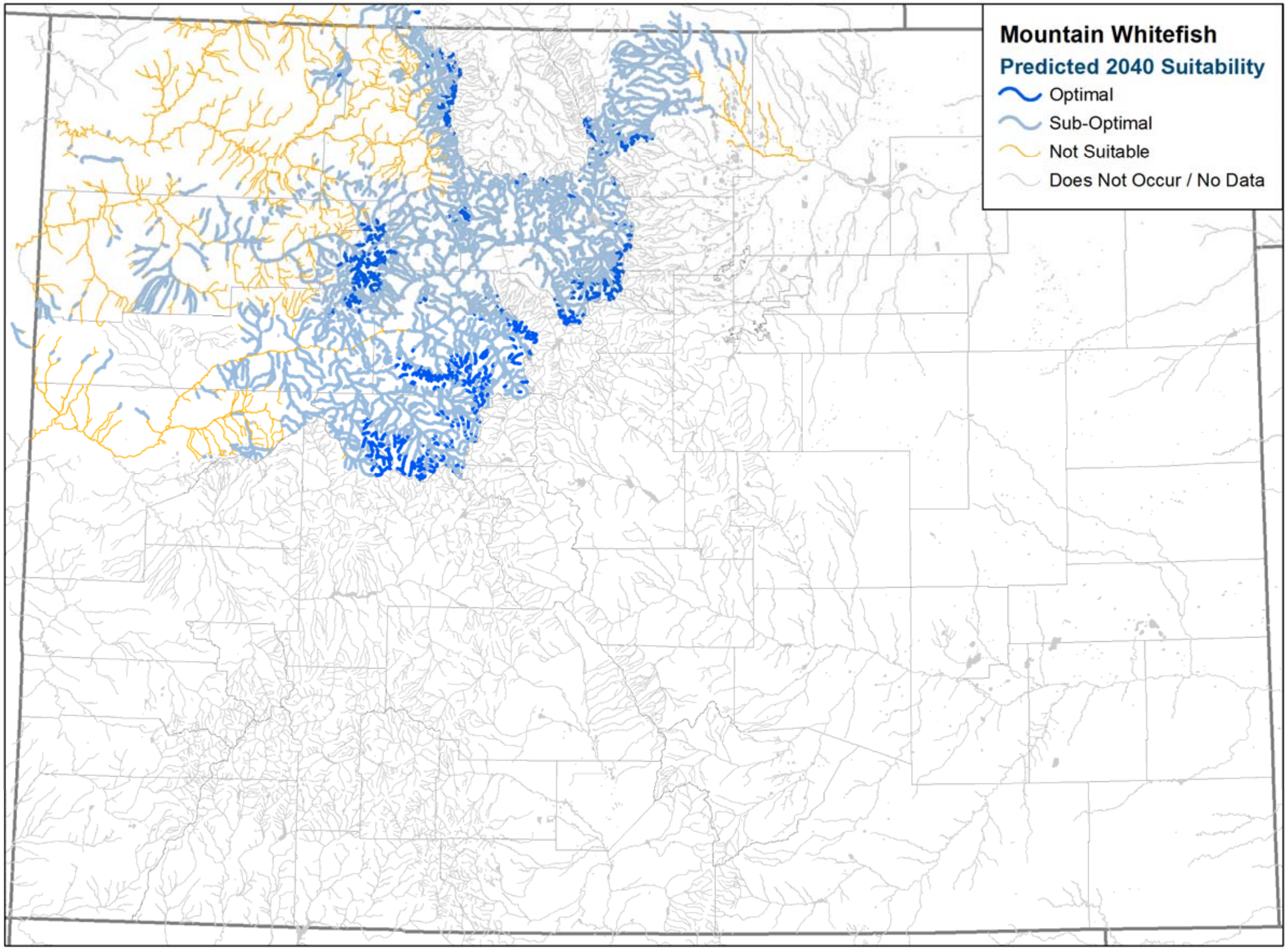


Figure 26. Predicted habitat suitability at mid-Century for mountain whitefish.

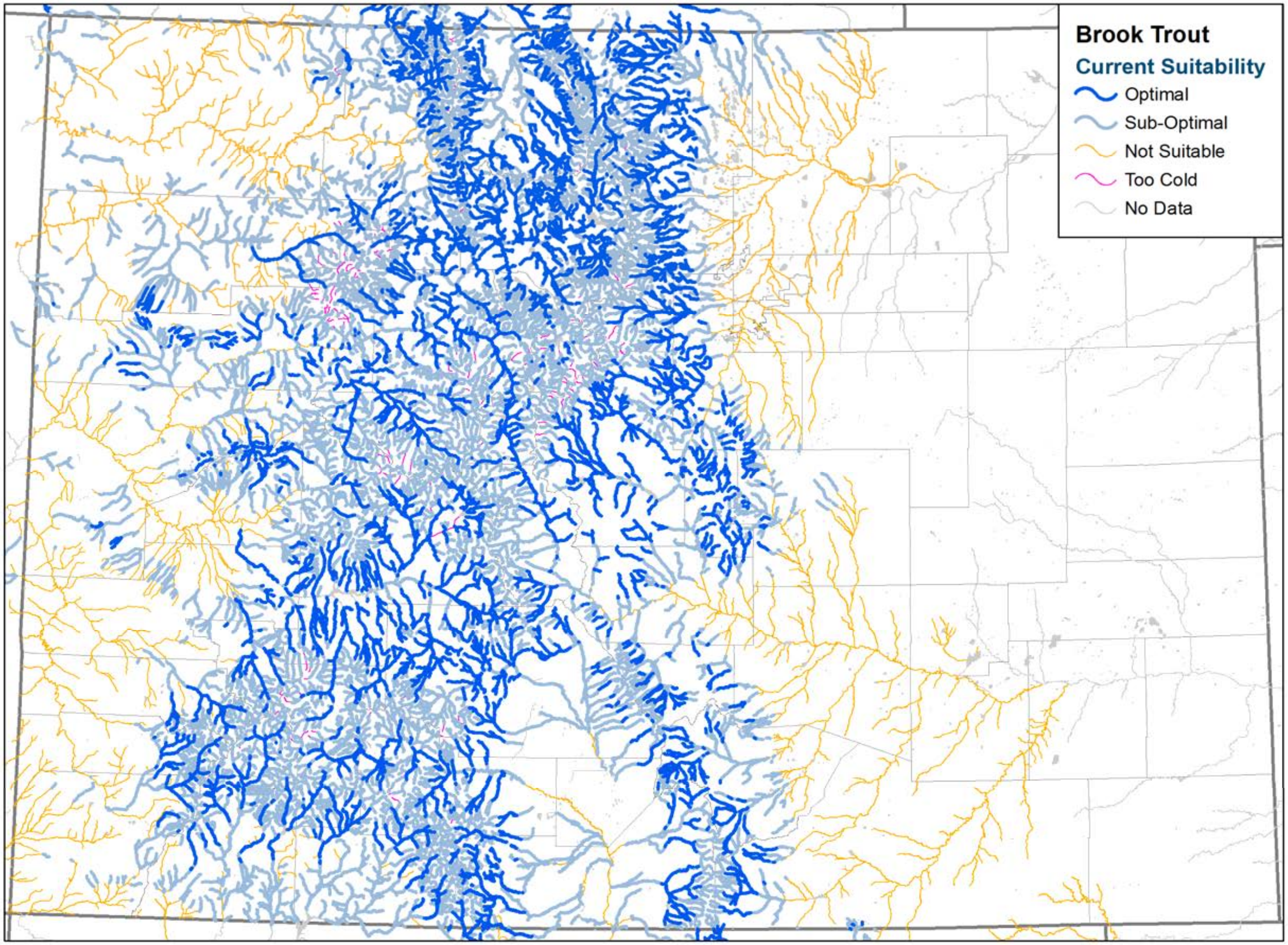


Figure 27. Current habitat suitability model for brook trout.

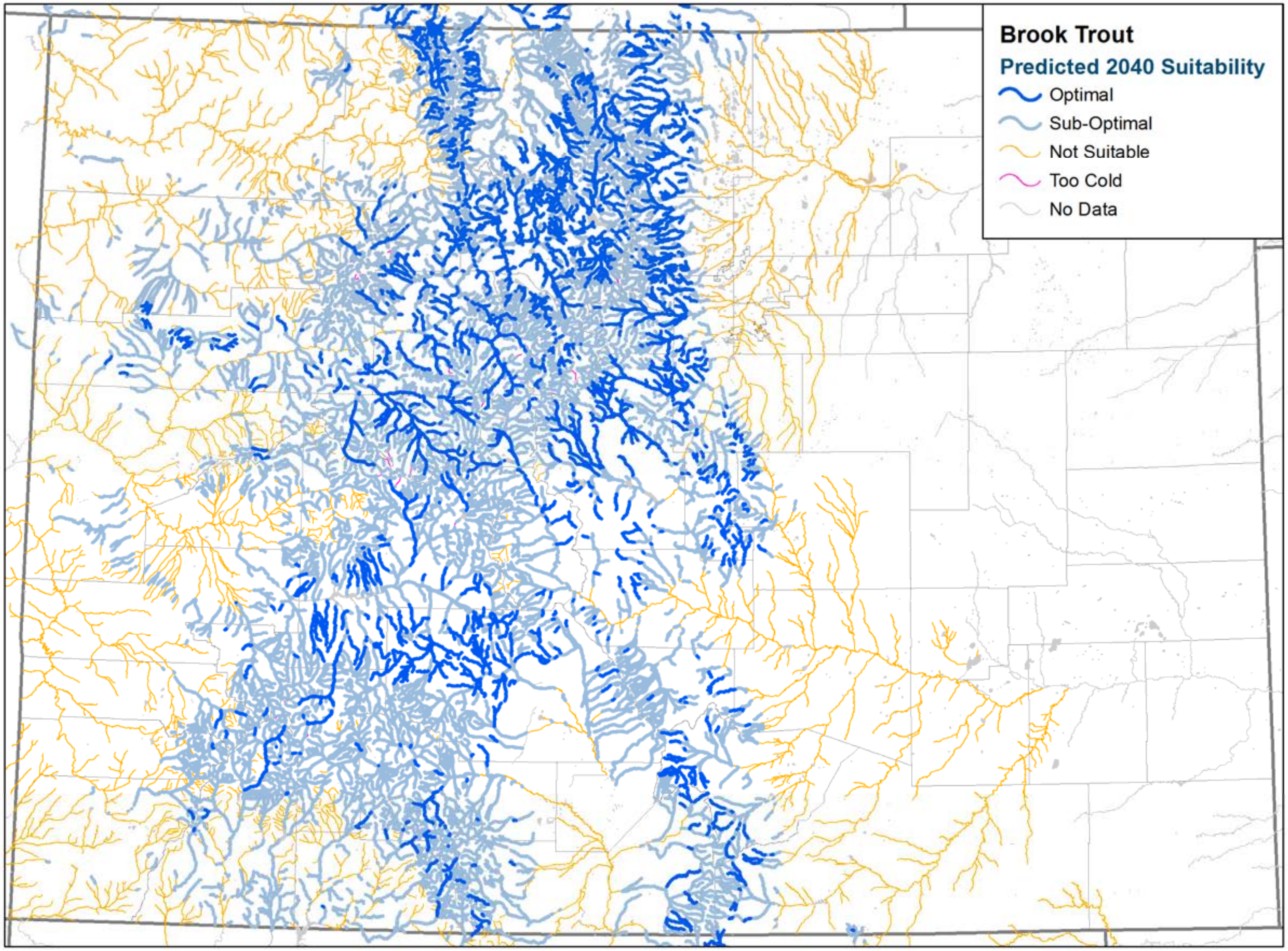


Figure 28. Predicted habitat suitability at mid-Century for brook trout.

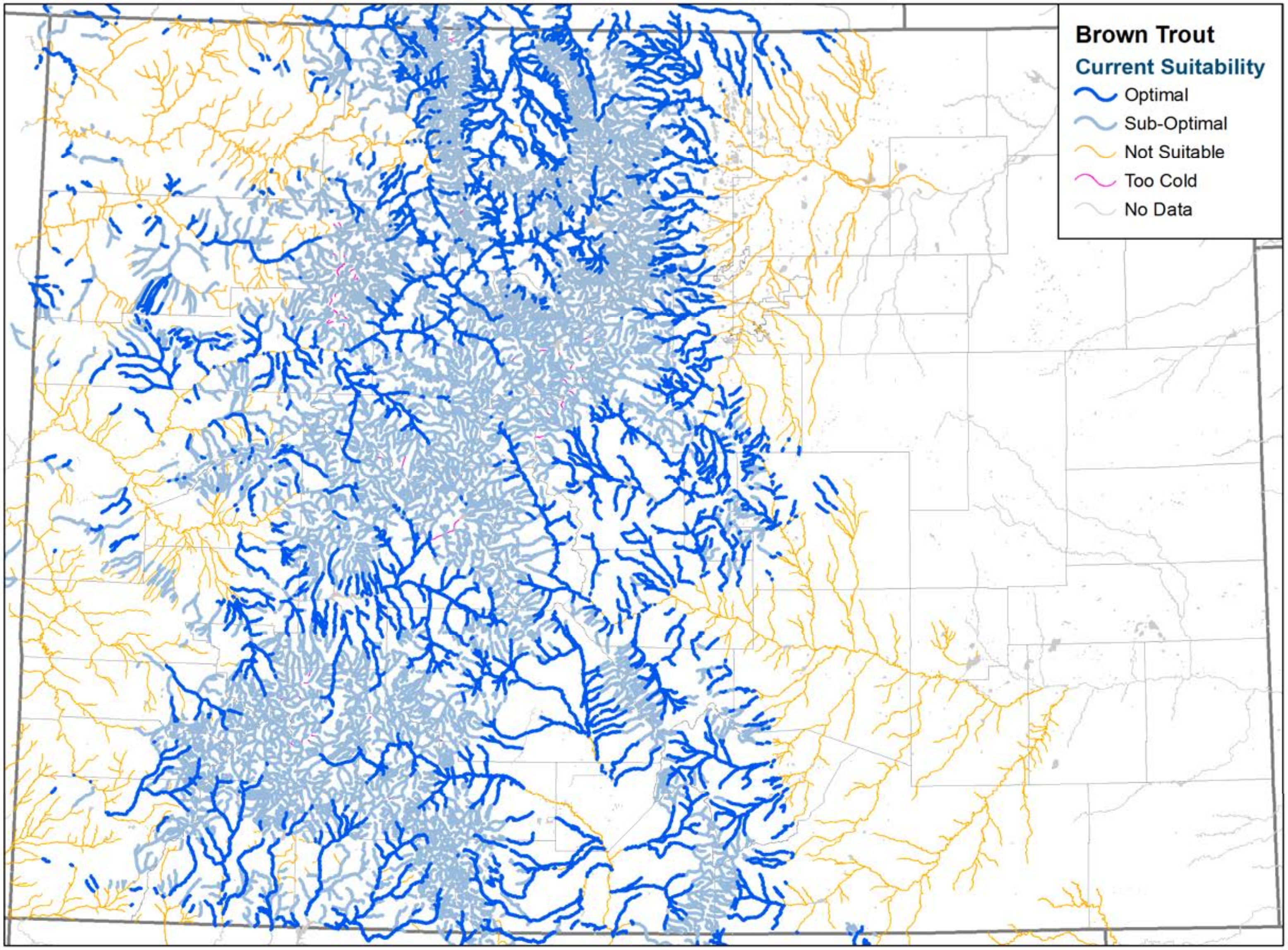


Figure 29. Current habitat suitability model for brown trout.

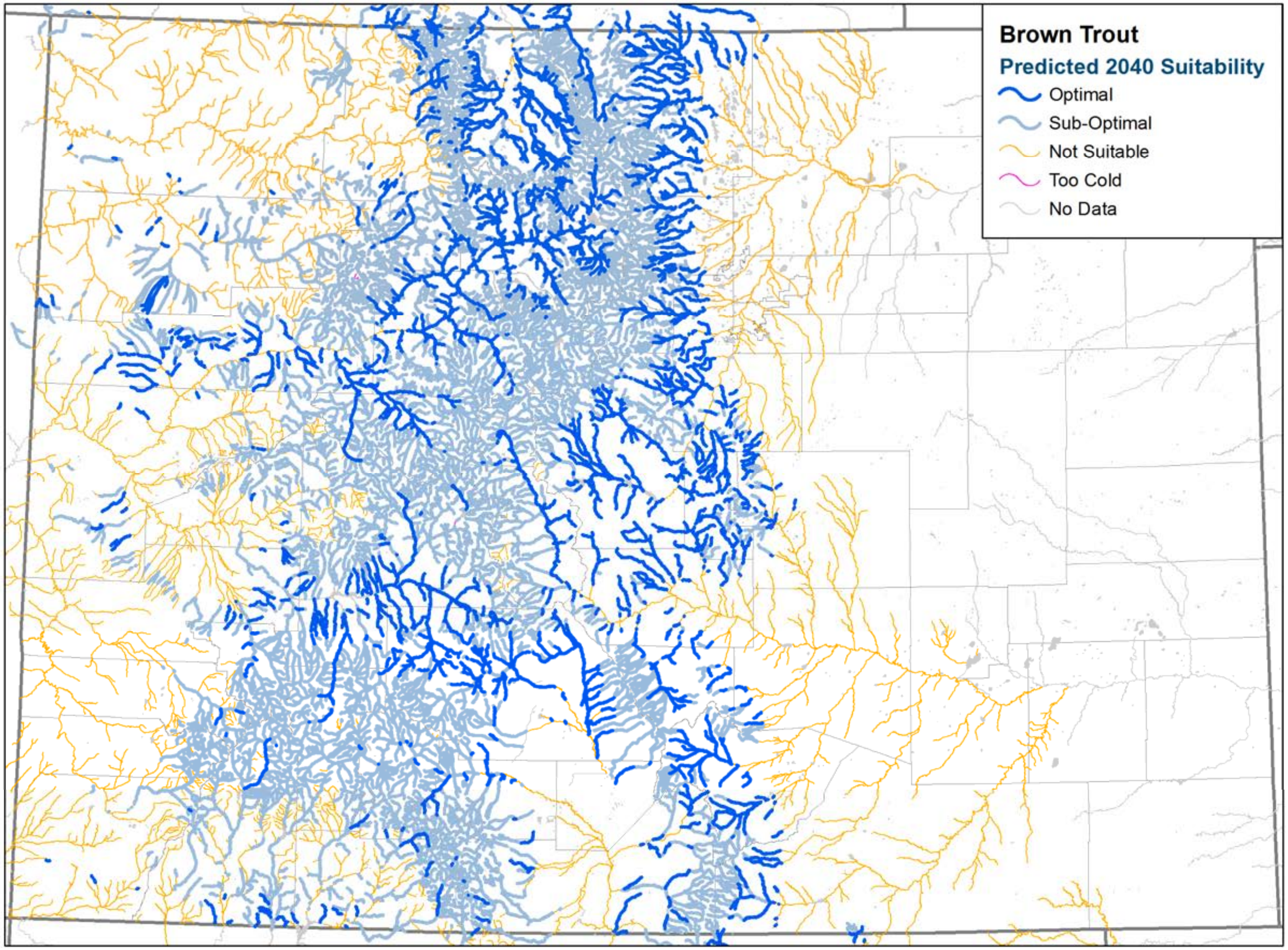


Figure 30. Predicted habitat suitability at mid-Century for brown trout.

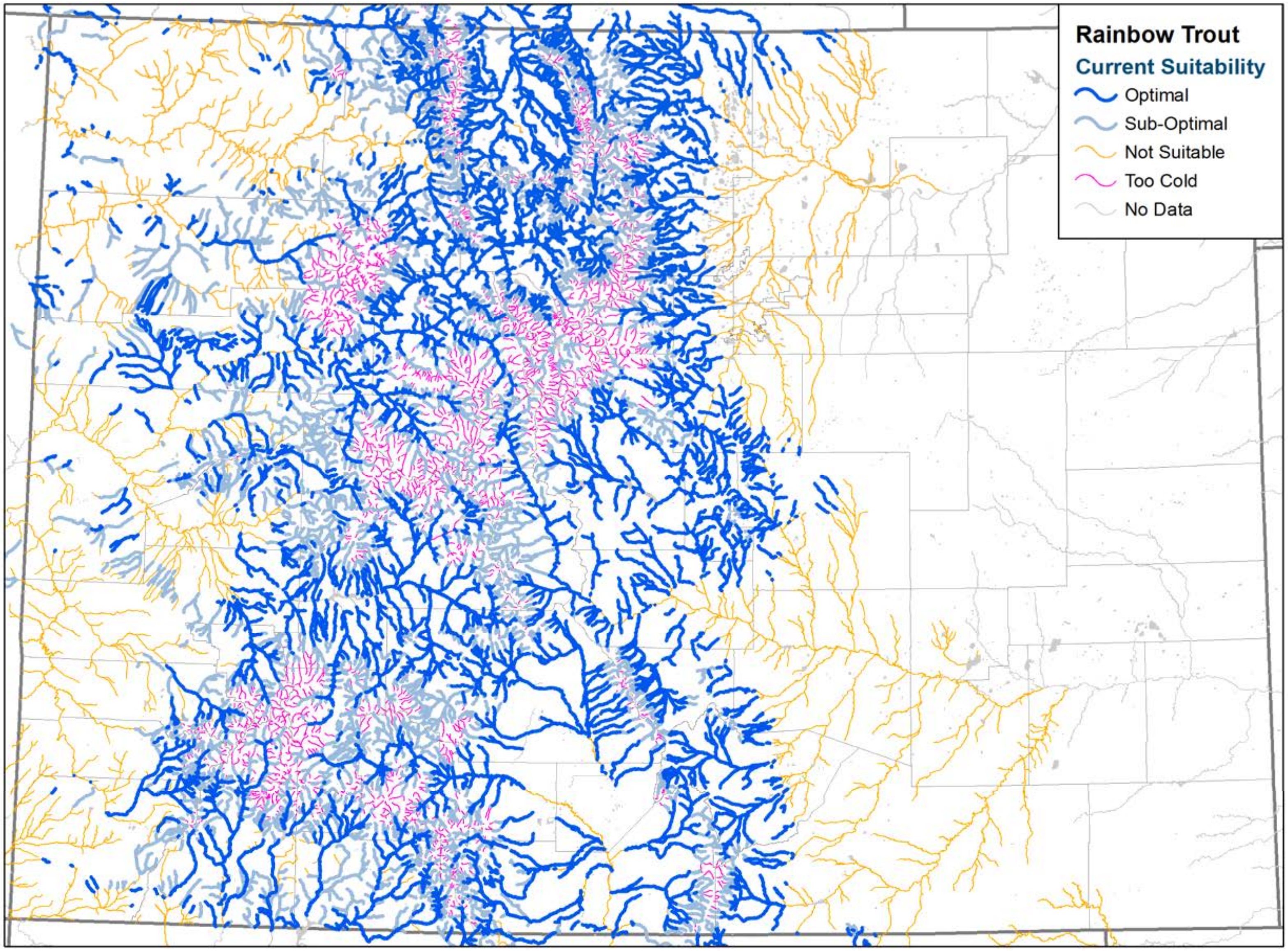


Figure 31. Current habitat suitability model for rainbow trout.

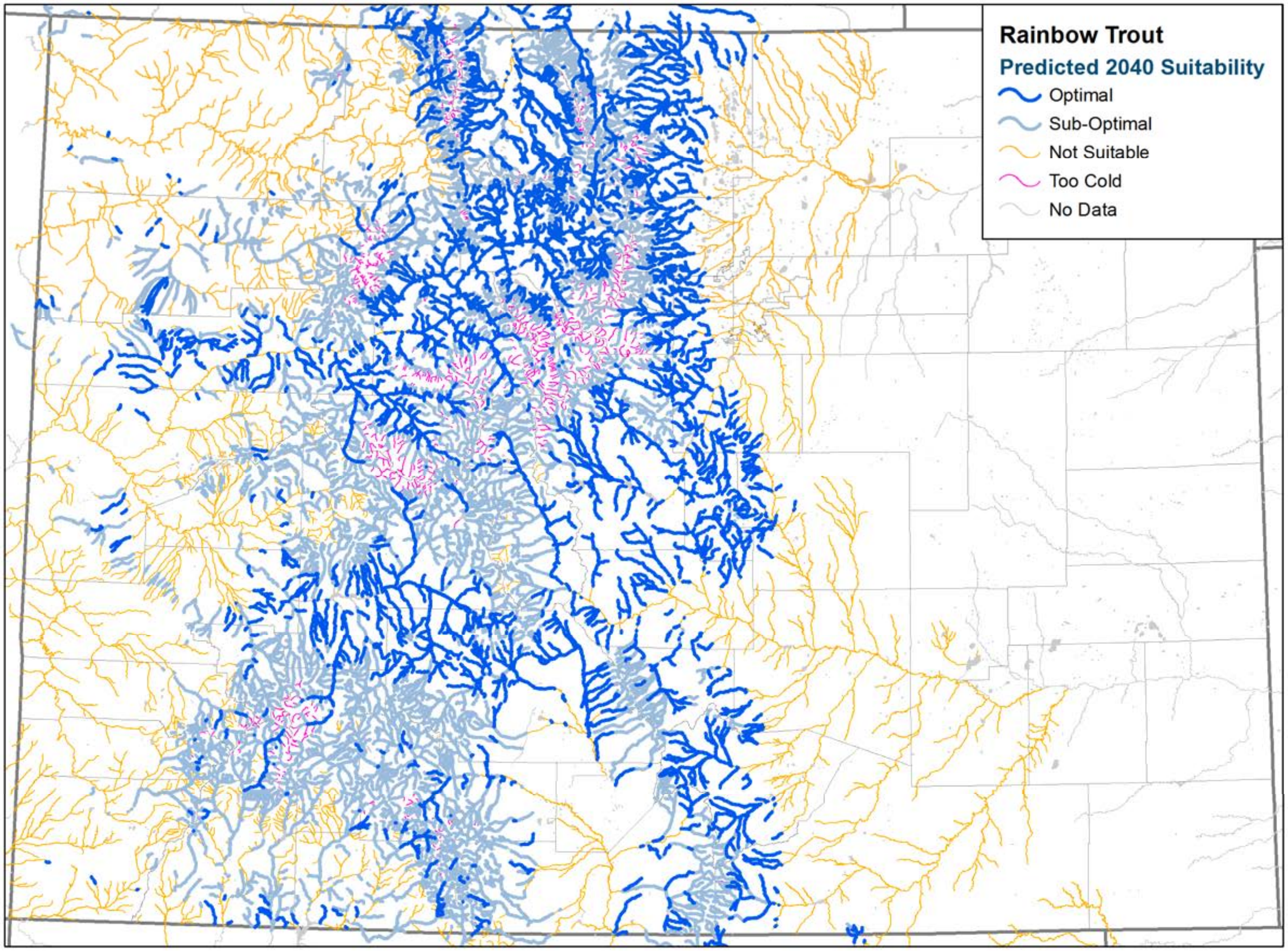


Figure 32. Predicted habitat suitability at mid-Century for rainbow trout.

Bibliography for Cold-water Fish

Anderson, R.M. and G. Stewart. 2007. Impacts of stream flow alterations on the native fish assemblage and their habitat availability as determined by 2D modeling and the use of fish population data to support instream flow recommendations for the sections of the Yampa, Colorado, Gunnison and Dolores rivers in Colorado. Colorado Division of Wildlife Aquatic Wildlife Research. Special Report Number 80. SRP15277.

Brinkman, S.F., H.J. Crockett, and K.B. Rogers. 2013. Upper thermal tolerance of mountain whitefish eggs and fry. Transactions of the American Fisheries Society 142(3):824–831. https://afspubs.onlinelibrary.wiley.com/doi/full/10.1080/00028487.2013.765503.

Colorado Division of Wildlife (now Colorado Parks and Wildlife). 2012. Fish streams and lakes. Vector digital data.

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. O'Brien, H.G. Stefany, M. Hondzo, and R.M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20(4):10–18. https://afspubs.onlinelibrary.wiley.com/doi/abs/10.1577/1548-8446%281995%29020%3C0010%3AAFISFE%3E2.0.CO%3B2.

Hunt, L.M., E.P. Fenichel, D.C. Fulton, R. Mendelsohn, J.W. Smith, T.D. Tunney, A.J. Lynch, C.P. Paukert, and J.E. Whitney. 2016. Identifying alternate pathways for climate change to impact inland recreational fishers. Pp. 362–373 *in* Climate Change and North American Inland Fishes. Fisheries, Special Issue. 2016. 41(7):325–428. http://dx.doi.org/10.1080/03632415.2016.1205860.

Isaak, D.J., C.C. Muhlfeld, A.S. Todd, R. Al-Chokhachy, J. Roberts, J.L. Kershner, K.D. Fausch, and S.W. Hostetler. 2012. The past as prelude to the future for understanding 21st-Century climate effects on Rocky Mountain trout. Fisheries 37(12):542–556.

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181–9205. https://doi.org/10.1002/2017WR020969.

Isaak, D.J., M.K. Young, D. Nagel, and D. Horan. 2014. Coldwater as a climate shield to preserve native trout through the 21st Century. Proceedings of the Wild Trout Symposium XI, Sept. 22–25, 2014, West Yellowstone, MT. https://www.wildtroutsymposium.com/proceedings-11.pdf

Isaak, D., M. Young, D. Nagel, D. Horan, M. Groce, and S. Parkes. 2015. Climate Shield bull trout and cutthroat trout population occurrence scenarios for the western U.S. Rocky Mountain Research Station, U.S. Forest Service Data Archive, Fort Collins, CO.

Meisner, J.D., J.S. Rosenfeld, and H.A. Regier. 1988. The role of groundwater in the impact of climate warming on stream salmonines. Fisheries 13(3):2–8.

https://www.tandfonline.com/doi/abs/10.1577/1548-8446%281988%29013%3C0002%3ATROGIT%3E2.0.CO%3B2

Mohseni, O., H.G. Stefan, and J.G. Eaton. 2003. Global warming and potential changes in fish habitat in U.S. streams. Climatic Change 59:389–409.

Nelson, R., Cross, M., Hansen, L., and G. Tabor. 2016. A three-step decision support framework for climate adaptation: Selecting climate-informed conservation goals and strategies for native salmonids in the northern U.S. Rockies. Wildlife Conservation Society, EcoAdapt, Center for Large Landscape Conservation. Bozeman, MT, USA. http://rmpf.weebly.com/cold-water-ecosystem-management-tool.html.

Parkes-Payne, S. 2018. June 2018 update to the NorWeST Modeled Stream Temperature Stream Lines for the "Upper Green-North Platte" Processing Unit: Upper Green, North Platte, Yampa, and South Platte Watersheds. Vector digital data. Available at: www.fs.fed.us/rm/boise/AWAE/projects/

NorWeST. 2019. Regional database and modeled stream temperatures. https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml. Accessed 01/07/2019.

Peterson, D.P., S.J. Wenger, B.E. Rieman, and D.J. Isaak. 2013. Linking climate change and fish conservation efforts using spatially explicit decision support tools. Fisheries 38(3):112–127.

Propst, D.L. and K.B. Gido. 2004. Responses of native and nonnative fishes to natural flow regime mimicry in the San Juan River. Transactions of the American Fisheries Society 133(4):922–931. https://afspubs.onlinelibrary.wiley.com/doi/full/10.1577/T03-057.1.

Roberts, J.J., K.D. Fausch, D.P. Peterson, and M.B. Hooten. 2013. Fragmentation and thermal risks from climate change interact to affect persistence of native trout in the Colorado River basin. Global Change Biology 19(5):1383–1398. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12136.

Sanderson, J., B. Bledsoe, N.L. Poff, T. Wildling, and N. Fey. 2012. Yampa-White Basin Roundtable watershed flow evaluation tool study. Report prepared for The Nature Conservancy, Boulder, CO.

Smith, D.M. and M.M. Friggens. 2017. A spatially explicit and quantitative vulnerability assessment of coldwater fish habitat and riparian corridors in the Intermountain West. U.S. Forest Service Rocky Mountain Research Station, Albuquerque, NM.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences 108(34):14175–14180.

Wenger, S.J. and C.H. Luce. 2016. Western U.S. stream flow metrics: a dataset of modeled flow metrics for streams in major river basins of the Western US for historical and future climate change scenarios. Data last updated 03/01/2016. https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml.

Zeigler, M.P., S.F. Brinkman, C.A. Caldwell, A.S. Todd, M.S. Recsetar, and S.A. Bonar. 2013. Upper Thermal Tolerances of Rio Grande Cutthroat Trout under Constant and Fluctuating Temperatures, Transactions of the American Fisheries Society, 142(5):1395–1405. https://afspubs.onlinelibrary.wiley.com/doi/full/10.1080/00028487.2013.811104.

Woodin, H.E. and A.A. Lindsey. 1954. Juniper-pinyon east of the Continental Divide, as analyzed by the pine-strip method. Ecology 35:473–489.

San Luis Valley Field Office

The overall objective of conducting the vulnerability assessment and the subsequent expanded analyses reported herein was to assist BLM with improved planning and decision-making. As a pilot effort to work out how we might best offer support, we collaborated with resource scientists, planners, and managers in the San Luis Valley Field Office (SLVFO) to understand their planning process and highest priority information needs for their current planning efforts. In collaboration with social scientists at the Natural Resource Ecology Laboratory at CSU, we participated in a series of calls and meetings with planning and resource staff at SLVFO, to identify important social-ecological systems and to translate climate vulnerability and impact information for those systems into a format that can be readily inserted into the SLVFO's planning. We identified the following as the most significant issues (not in prioritized order):

- Pinyon-juniper forests and woodlands
- Sagebrush
- Montane grasslands
- Winterfat shrub-grasslands
- Streams and riparian
- Wetlands, seeps, springs, and irrigated meadows
- Ranching and big game hunting livelihoods

CNHP focused our efforts on the biological resources from this list. For the biological resources, we adapted previously completed analyses at the statewide scale to the San Luis Valley scale, according to the process described below. See Appendix C for the climate change primer presentation prepared for the SLVFO. Additional information on the livelihoods assessment (McNeely et al. in prep) will be available soon from the Natural Resources Ecology Lab, and will be accessible from https://cnhp.colostate.edu/projects/climate-change/#COBLM.

Climate Impact Scoring

Building on methods developed with other partners (Rondeau et al. 2017, TNC 2018), we evaluated climate impacts to the conservation targets listed above. The same four climate scenarios (Hot & Dry, Hot & Wet, Feast & Famine, and Warm & Wet) used to evaluate pinyon and juniper future suitability were used to link potential future climate conditions to possible impacts. Scores (Table 8) are based on the severity and extent (scope) of the impact; values less than zero indicate a negative impact, zero indicates no impact, and values greater than zero indicate a positive effect of the change.

We also developed a summary of potential change in climate factors for each scenario (Table 9), using averaged data for Conejos and Saguache counties as the quickest means of estimating the effect for the San Luis Valley study area. Monthly summary data (1950-2099) were obtained from the National Climate Change Viewer (now known as the Regional Climate Change Viewer http://regclim.coas.oregonstate.edu/visualization/rccv/).

Where spatial (GIS) data were available, impact scores were developed by examining the data in GIS and making an approximate determination of the category that best fit the pattern across the San Luis Valley, with a focus on lower elevations. GIS datasets included:

- Annual and seasonal change for precipitation (% change) and temperature (degrees C)
- Extreme event frequency for Climate Water Deficit (MAM, JJA, and Apr-Sep growing season)
- Bioclimatic niche models developed by CNHP for *Pinus edulis*, *Juniperus monosperma*, *Artemisia tridentata vaseyana*, and *A. tridentata wyomingensis*, indicating future habitat suitability (lost/threatened, persistent, or emergent)

Table 8. Definitions of impact scoring levels used to assess climate impacts.

Impact Score	Definition
-3	The severity of the impact is high and the scope is widespread (>75% of the area)
-2	The scope of the impact is not widespread, but if the impact occurs it is severe; or the severity is low-mild but widespread
-1	Impact is low or severe, however if severe, the scope is small
0	no impact
1	Slight positive impact for much of the target
2	Positive impact for much of the target
3	Widespread positive impact, with expected significant increases

For each conservation target, we completed the following categories (Table 10). Overall vulnerability levels for each ecological-social conservation target are shown in Table 11, and a more detailed synopsis for each target follows.

- **Ecological-Social System - Nested Target:** broad categories of values and specific types of associated habitat, species, or livelihood chosen by stakeholders that include both natural ecosystems and the people who interact with them.
- **Key Attribute:** characteristic feature or process crucial to the health of the target that is assessed for vulnerability.
- **Measurable Climate Indicator**: trait or environmental influence that is affected by temperature or precipitation, and can be scored for degree of positive or negative effect.
- **Impact Assessment Factor:** quantifiable climate-derived dataset used to assess the amount and direction (+ or -) of impact to the key attribute under future climate scenarios.
- **Metric:** threshold or data values that determine positive or negative outcome under different climate scenarios.
- **Confidence Categories:** Confidence categories reflect 1) how much is known about the influence of climate on the target, and 2) the extent to which available data allows us to assign impact ranks.

Table 9. Summary of potential change in climate-related metrics for four future climate scenarios.

Changes are based on comparison between recent past (1985-2015) and mid-Century (2020-2050) using average of monthly data for Saguache and Conejos counties. In general, the southern portion of the valley (Conejos) is slightly warmer and drier than the northern portion (Saguache). For shaded cells, green=wetter; yellow=drier; white=no significant change.

Climate Metric	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Annual temperature increase °F (°C)	3.6 (2.0)	3.2 (1.8)	2.6 (1.4)	1.8 (1.0)
Winter temperature increase °F (°C)	3.0 (1.7)	3.6 (2.0)	3.0 (1.6)	2.4 (1.3)
Spring temperature increase °F (°C)	3.0 (1.7)	3.4 (1.9)	2.1 (1.1)	1.5 (0.8)
Summer temperature increase °F (°C)	4.5 (2.5)	2.2 (1.2)	2.7 (1.5)	2.0 (1.1)
Fall temperature increase °F (°C)	4.0 (2.2)	3.5 (1.9)	2.6 (1.4)	1.2 (0.7)
Summer like 2002	four of five years	one in five years	two in five years	one in 15 years
Snowline/ Freezing Level[2]	shifts up by 1,100 ft.	shifts up by 1,000 ft.	shifts up by 780 ft.	shifts up by 540 ft.
Annual precipitation change (%)	1%	13%	1%	10%
Winter precipitation change (%)	27%	19%	4%	7%
Spring precipitation change (%)	-4%	26%	3%	8%
Summer precipitation change (%)	-13%	-2%	3%	12%
Fall precipitation change (%)	-2%	15%	-6%	12%
Summer monsoon (Jul-Aug precipitation)	decrease by 11%	decrease by 4%	no change but large year to year fluctuation	increase by 17%
April 1 SWE change (monthly SWE average for March)	0%	-31%	-19%	-6%
Total runoff	-11%	15%	-13%	6%
Apr-Sep Soil water storage change	-23%	-14%	-14%	-6%

[2] Based on the rule-of-thumb: 300ft increase in freezing level for every degree F warming

Climate Metric	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Apr-Sep Evaporative deficit change (approximates drought intensity)	39%	19%	21%	4%
Severe drought years (like 2002) frequency	every 5-10 years	about once in 10 years - more often for center of SLV	every 5-10 years in southern portion	<1 per decade
Severe drought duration	1-2 years	1-2 years	1-3 years lower elevations worst	1 year
Fire frequency (tied to dryness of summer months)	greater fire frequency, especially in high elevation	some increase in fire frequency	fire risk during dry years is very high due to high fuel load from wet years	same as current
Fire season length (associated with growing season length)	noticeably longer	longer	somewhat longer and large year to year fluctuations	same as current

Table 10. Potential impacts from four future climate scenarios on social-ecological targets in the San Luis Valley. Assessment timeframe: 2020-2050.

Key Attribute	Measurable Climate Indicator	Impact Assessment Factor	Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Confidence Level
PINYON-JUNIPER WORKING LANDSCAPE – PINYON JUNIPER WOODLANDS								
Forest Regeneration	Pinyon and juniper regeneration	Winter moisture	Percent departure	2	2	0	1	Moderate
Forest Mortality	Pinyon and juniper mortality	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
Fire Regime	Increased fire risk	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
Species Composition	Loss of persistent PJ stands	Change in environmental suitability	Bioclimatic niche models (*Pinus edulis*, *Juniperus monosperma*)	-1	-1	-1	-1	Moderate
	Loss of PJ obligate birds, (e.g., Pinyon Jay, Gray Vireo, Juniper Titmouse)	Change in environmental suitability	Bioclimatic niche models (*Pinus edulis*, *Juniperus monosperma*)	-1	-1	-1	-1	Moderate
SHRUB-STEPPE WORKING LANDSCAPE: WINTERFAT SHRUB-GRASSLAND								
Plant Production	Shallow-rooted shrub, grass, forb production	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
	Blue grama abundance	Spring (Apr-Jun) Minimum Temperature (Mar-May average temp as a surrogate)	1 C increase leads to a 1/3 loss of blue grama growth	-3	-3	-2	-2	High
	Blue grama mortality	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	High

Key Attribute	Measurable Climate Indicator	Impact Assessment Factor	Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Confidence Level
Shrub Regeneration	Winterfat seed production	Growing season moisture (Jun-Aug)	Percent departure	-2	0	0	2	Low-moderate
	Winterfat flowering & seedling recruitment	Winter moisture	Percent departure	2	2	0	1	Low-moderate
Invasive Species	Cheatgrass abundance	Spring and fall moisture enhances cheatgrass germination	> 5% Change in average spring or fall precipitation	-1	-3	0	-3	High
SHRUB-STEPPE WORKING LANDSCAPE: MONTANE GRASSLAND								
Plant Production	Grass production	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Low-moderate
Species composition	Proportion of warm or cool season grasses	Summer temperature and soil moisture	Jun-Aug temperature and Climate Water Deficit change	-3	-2	-2	-1	Low
Invasive Species	Cheatgrass abundance	Spring and fall moisture enhances cheatgrass germination	> 5% Change in average spring or fall precipitation	1	-2	0	-2	Low-moderate
SHRUB-STEPPE WORKING LANDSCAPE: RANCHING LIVELIHOOD								
Cattle production	Cattle production	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
Plant Production	Grass production	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
SAGEBRUSH WORKING LANDSCAPE: SAGEBRUSH								
Plant Production	Sagebrush, grasses, forbs	Frequency of severe summer drought	Extreme event frequency (Climate Water Deficit Jun-Aug)	-3	-1	-2	0	Moderate

Key Attribute	Measurable Climate Indicator	Impact Assessment Factor	Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Confidence Level
Sagebrush mortality	Drought	Winter precipitation	> 5% Change in average winter precipitation	2	2	0	1	Low-moderate
Invasive Species	Cheatgrass abundance	Spring and fall moisture enhances cheatgrass germination	> 5% Change in average spring or fall precipitation	1	-2	0	-2	Low-moderate
Species Composition	Sagebrush persistence	Change in environmental suitability	*Artemisia tridentata* bioclimatic niche models	-2	n/a	-3	-1	Low-moderate
	Juniper expansion into sagebrush	Change in environmental suitability	*Juniperus monosperma* bioclimatic niche models	1	0	0	-3	Moderate
WILDLIFE: GUIDED HUNTING FOR BIG GAME								
Mule deer, Elk, Pronghorn population numbers	Winter survival	Severe winter	Combination Snow Water Equivalent & winter mean temp as surrogate for Accumulated Winter Season Index	0	0	-1	-1	Low
	Survival & Recruitment	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0	Moderate
WETLAND & RIPARIAN: SEEPS, SPRINGS, WETLANDS								
Wetland condition	Wetland area (by snowmelt timing and water availability)	Winter snowpack; summer evapo-transpiration	Combined percent departure	-3	-3	-3	-1	Low-moderate
Wetland condition	Wetland extent (by hydrologic regime/type)	Growing season precipitation and evapo-transpiration	Combined percent departure	-3	-2	-2	0	Low-moderate

Key Attribute	Measurable Climate Indicator	Impact Assessment Factor	Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Confidence Level
Groundwater recharge	Groundwater recharge (affects extent and wetness of seeps, springs, and other groundwater dependent ecosystems)	Snow Water Equivalent change (Snow vs. rain & reduced spring snowpack); Total runoff (snowmelt and peak runoff timing); extreme drought frequency; Apr-Sep evapo-transpiration change	Combined departure and drought frequency	-3	-2	-3	-1	Low
WETLAND & RIPARIAN: WATER FOR HAY MEADOWS AND GREATER SANDHILL CRANE FORAGING AREAS								
Water availability and drought groundwater recharge	Winter snowpack and snowmelt timing (water available to irrigate fields) Spring water deficit (extent of hay meadow irrigation)	April 1 Snow Water Equivalent; Total runoff; Drought (year-round and growing season);	Combined departure and drought frequency	-2	-2	-3	0	Moderate
WETLAND & RIPARIAN: RIPARIAN FOREST, ADJACENT SHRUBLANDS, SOUTHWESTERN WILLOW FLYCATCHER HABITAT								
Riparian area condition	Winter snowmelt and melt timing; Riparian forest area and species composition; Cottonwood cover (vs. willow/ herbaceous/ drought-tolerant/late-successional species)	April 1 Snow Water Equivalent; Total runoff; Drought (year-round and growing season)	Combined departure and drought frequency	-2	-2	-3	0	Moderate
WETLAND & RIPARIAN: AQUATIC SYSTEM, NATIVE AND SPORT FISH								
Stream flow	Number and extent of cold water native fish; trout base flows (average August, September monthly flows)	April 1 Snow Water Equivalent; summer/fall runoff; summer temperature	Combined departure	-3	-3	-2	-1	Low

Key Attribute	Measurable Climate Indicator	Impact Assessment Factor	Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Confidence Level
Stream temperature	Number and extent of cold water native fish - water temperatures above optimal thresholds for trout (10-18° C)	Warm to cold water transition line model	Change in elevation of transition zone	-3	-3	-3	-2	Low-moderate

Table 11. Summary of roll-up vulnerability scores for social-ecological systems by climate scenario.

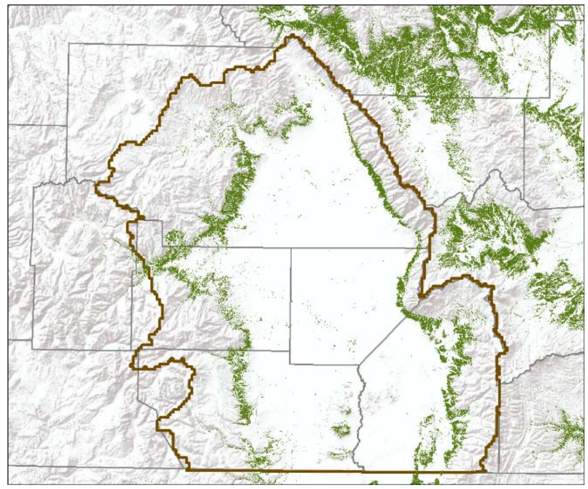
Ecological-Social System	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Vulnerability
Pinyon-Juniper	-1	0	-2	0	Low
Shrub-steppe winterfat	-2	-1	-1	0	Moderate
Montane grassland	-2	-1	-1	-1	Moderate
Sagebrush	0	0	-1	-1	Low
SLV wildlife	-2	-1	-2	-1	Moderate
Wetland	-3	-2	-3	-1	High
Riparian & Streams	-3	-3	-3	-1	High
Ranching	-3	-1	-3	0	Moderate
Big game hunting	-2	-1	-2	-1	Moderate

The SLVFO expressed interest in understanding how the vulnerability of their priority ecosystems at the SLV regional scale compares to the vulnerability of those systems at the statewide scale (as assessed in CNHP 2015). A direct comparison is difficult because of differences in the methods used and the way ecosystems were defined (i.e., lumped or split), in the two assessments. However, in both vulnerability assessments, scores indicate *relative* vulnerability rather than absolute vulnerability. Table X shows how the results of the two assessments compare, along with comments to aid in interpretation of differences.

Table 12. Comparison of vulnerability scores between statewide assessment (CNHP 2015) and San Luis Valley assessment (Fink et al. 2019).

Ecosystem Target	**Statewide vulnerability score**		**SLV vulnerability score**	**Comments**
Pinyon-Juniper woodlands	**High**		Low	Statewide analysis considered Colorado Plateau pinyon-juniper (Utah juniper) and Southern Rocky Mountain pinyon-juniper (one-seed juniper) as a single system. SLV contains So. Rocky Mountain pinyon-juniper, which is generally a higher elevation, less vulnerable type than the CO Plateau type.
Desert shrublands / Winterfat	Moderate		Moderate	Statewide analysis scored desert shrubland system, which included winterfat as a large patch system along with other shrubs (e.g., mat saltbush). SLV analysis considered winterfat as a matrix system characterized primarily by winterfat. In Colorado, SLV is <u>the</u> most important place for winterfat shrub-steppe.
Sagebrush shrublands	Low		Low	In SLV, as in most of Colorado, sagebrush shrublands are considered less vulnerable than sagebrush areas to the west and north of the state. Stands that are in poor condition are likely to be more vulnerable.
Montane grasslands	Moderate		Moderate	Characteristics and vulnerability of montane grasslands are comparable between SLV and statewide scales.
Riparian woodlands and shrublands	Mountain: Low	**West Slope: Very High**	**High**	Statewide analysis considered riparian systems separately for eastern plains, mountains, and West Slope. The SLV has some riparian systems that are comparable to Colorado's mountain riparian systems, and others that are more comparable to West Slope systems, but these were not distinguished in the SLV analysis.
Wetlands	Mountain: Moderate	West Slope: Moderate	**High**	Statewide analysis considered wetland systems separately for eastern plains, mountains, and West Slope. The SLV has some wetlands that are comparable to Colorado's mountain wetlands, and others that are more comparable to West Slope wetlands, but these were not distinguished in the SLV analysis.

PINYON-JUNIPER WOODLANDS



Climate Vulnerability Score: Low Vulnerability

Pinyon-juniper woodlands in the San Luis Valley are distributed on the foothills around the perimeter of the valley floor, generally at elevations of 7,950 to 8,950 ft, with additional stands at similar elevations on hills and mesas in the southern portion of the valley.

Pinyon-juniper woodlands are influenced by climate, fires, insect-pathogen outbreaks, and livestock grazing (West 1999, Eager 1999). Although it is clear that the structure and condition of many pinyon-juniper woodlands has been significantly altered since European settlement (Tausch 1999), in recent years there has been an emerging recognition that not all of these woodlands are dramatically changed by anthropogenic influence. Increasing density of pinyon juniper woodlands and expansion into adjacent grassland or shrubland are well documented in some areas, but is not a universal phenomenon in the western U.S. (Romme et al. 2009).

Both pinyon pine and juniper are fairly slow growing, and can live for hundreds of years, a life cycle that is well adapted to xeric habitats, but is less suitable for quickly changing conditions. Although individuals of both species become reproductive after a few decades, most seed production is due to mature trees of 75 years of age or older (Gottfried 1992). Both species reproduce only from seeds, and do not resprout after fire. Cone production of mature pinyon pine takes three growing seasons, and the large seeds have a fairly short life span of 1-2 years (Ronco 1990). Juniper cones (often called berries) may require 1-2 years of ripening before they can germinate (Gottfried 1992). The smaller seeds of juniper are generally long-lived, surviving as long as 45 years. Birds are important dispersers of both pinyon pine and juniper seed (Gottfried 1992).

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

Forest regeneration: Winter moisture

Winter precipitation is crucial for the persistence of pinyon-juniper woodlands because it replenishes the deep soil moisture that enables tree growth and survival. We used departure from 1985-2015 average winter precipitation as our impact assessment metric. In the San Luis Valley, our four scenarios predict increased winter moisture or, in the case of the Feast & Famine scenario, essentially no change from current levels. However, as winter temperatures increase, some of this additional winter moisture is likely to fall as rain instead of snow. Furthermore, warmer winters and a longer growing season may increase the duration of active photosynthesis for trees, and deplete soil moisture earlier than current timing.

Forest mortality and fire regime: Severe growing season drought

Although the San Luis Valley is already Colorado's driest region, it is still vulnerable to drought. Pinyon and juniper are both adapted to arid climatic conditions, but pinyon trees are more vulnerable to severe or prolonged water stress (Breshears et al. 2008). Growing season drought also increases fire risk as well as insect and disease events, which increases tree mortality. We used projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. In the San Luis Valley, the Hot & Dry and the Feast & Famine scenarios predict increased frequency (every 5-10 years) of severe growing season drought for most of the region. The Hot & Wet scenario predicts increased frequency (every 3-5 years) only in the center of the valley floor (below the pinyon-juniper zone), while the Warm & Wet scenario shows no change from the historic frequency of severe drought.

Species composition: Change in environmental suitability

The current composition of pinyon-juniper woodlands with their suite of associated species is closely tied to regional climatic conditions (i.e., seasonal patterns of precipitation and temperature variation). As temperatures warm and precipitation patterns shift, the persistence and relative abundance of pinyon and juniper trees is likely to change. Junipers are more drought tolerant, and may expand, while pinyon trees could experience greater mortality. Invasive plant species may increase and move into new habitat. Moreover, populations of characteristic and obligate bird species (e.g., Pinyon jay, Gray vireo, Juniper titmouse) in these woodlands are likely to decline with loss of habitat suitability. We used predicted bioclimatic niche models for two-needle pinyon (*Pinus edulis*) and one-seed juniper (*Juniperus monosperma*) to evaluate the impacts of environmental change under future climate conditions. All four scenarios predict a contraction of pinyon habitat on the western edge of the San Luis Valley, but a potential for increasing suitability at higher elevations adjacent to the current distribution. Suitability for juniper is predicted to be stable or increasing except for in the southeastern portion of the region. Because pinyon pine in particular may be slow to colonize newly suitable areas, we considered the loss of suitable habitat as more important in the short-term (up to mid-century), especially for obligate bird species.

Summary

Drought and warming temperatures are the primary climate factors contributing to the vulnerability of pinyon-juniper woodlands, since these conditions increase the likelihood of tree mortality both directly, and from increased fire or insect outbreaks.

Suggested Strategies

Identify and Protect Climate Refugia: Maintaining persistent mature stands that support the imperiled Pinyon jay and other pinyon pine obligate birds can help identify important stands. Thinning of persistent pinyon-juniper stands is best applied when human infrastructure is at risk, but otherwise, this treatment should be used sparingly as thinning has impacts on birds.

Identifying and protecting areas where recent recruitment is evident is another sign that the area may be within a climate refugia.

Allow Transformation: Catastrophic wildfires may kill the majority of the trees and transform the site into a grassland. Revegetation-seeding of a burned site should use a climate-smart seed mix that benefits the transformation.

Sites where suitable habitat is likely to emerge may benefit from allowing pinyon pines to move into the area.

Bibliography for Pinyon-Juniper

Adams, H.D., M. Guardiola-Claramonte, G.A. Barron-Gafford, J. Camilo Villegas, D.D. Breshears, C.B. Zou, P.A. Troch, T.E. Huxman, and H.A. Mooney. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. PNAS 106:7063–7066.

Adams, H.D., G.A. Barron-Gafford, R.L. Minor, A.A. Gardea, L.P. Bentley, D.J. Law, D.D. Breshears, N.G. McDowell, and T.E. Huxman. 2017. Temperature response surfaces for mortality risk of tree species with future drought. Environmental Research Letters 11:115014.

Barger, N.N., H.D. Adams; C. Woodhouse, J.C. Neff, and G.P. Asner. 2009. Influence of livestock grazing and climate on piñon pine (*Pinus edulis*) dynamics. Rangeland Ecology and Management 62:531–539.

Betancourt, J.L., E.A. Pierson, K. Aasen-Rylander, J.A. Fairchild-Parks, and J.S. Dean. 1993. Influence of history and climate on New Mexico pinyon-juniper woodlands. Pp. 42–62 *in*: E.F. Aldron and D.W. Shaw, eds. Managing pinyon-juniper ecosystems for sustainability and social needs: proceedings of the symposium; 26–30 April 1993; Santa Fe, NM. U.S. Department of Agriculture, Forest Service, General Technical Report RM-236.

Bradley, A.F., N.V. Noste and W.C. Fischer. 1992. Fire ecology of forests and woodlands in Utah. USDA Forest Service General Technical Report INT-287. Intermountain Research Station. Ogden, UT. 128 pp.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and C.W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences 102:15144–15148.

Breshears, D.D., O.B. Myers, C.W. Meyer, F.J. Barnes, C.B. Zou, C.D. Allen, N.G. McDowell, and W.T. Pockman. 2008. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment 7:185–189.

Brown, D.E. 1994. Great Basin Conifer Woodland. *In*: Brown, D.E., ed. Biotic communities: southwestern United States and northwestern Mexico. University of Utah Press, Salt Lake City, UT.

Chambers, J.C., S.B. Vander Wall, and E.W. Schupp. 1999. Seed and seedling ecology of piñon and juniper species in the pygmy woodlands of western North America. The Botanical Review 65:1–38.

Clifford, M.J., P.D. Royer, N.S. Cobb, D.D. Breshears, and P.L. Ford. 2013. Precipitation thresholds and drought-induced tree die-off: insights from patterns of *Pinus edulis* mortality along an environmental stress gradient. New Phytologist 200:413–421.

Comer, P., S. Menard, M. Tuffly, K. Kindscher, R. Rondeau, G. Jones, G. Steinuaer, and D. Ode. 2003. Upland and wetland ecological systems in Colorado, Wyoming, South Dakota, Nebraska, and Kansas. Report and map (10 hectare minimum map unit) to the National Gap Analysis Program, U.S. Dept. of Interior USGS. NatureServe, Arlington, VA.

Eager, T.J. 1999. Factors affecting the health of pinyon pine trees (*Pinus edulis*) in the pinyon-juniper woodlands of western Colorado. Page 397 *in* S. B. Monsen and R. Stevens, eds. Proceedings: ecology and management of pinyon-juniper communities within the Interior West. U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, Proc. RMRS-P-9 Ogden, UT.

Eisenhart, K.S., 2004. Historic range of variability of piñon-juniper woodlands on the Uncompahgre Plateau, western Colorado. Ph.D. Dissertation, University of Colorado, Boulder, CO.

Flatley, W.T. and P.Z. Fulé. 2016. Are historical fire regimes compatible with future climate? Implications for forest restoration. Ecosphere 7:e01471.

Floyd, M.L., W.H. Romme, and D.D. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. Ecological Applications 10:1666–1680.

Floyd, M.L., W.H. Romme, M.E. Rocca, D.P. Hanna, and D.D. Hanna. 2015. Structural and regenerative changes in old-growth piñon-juniper woodlands following drought-induced mortality. Forest Ecology and Management 341:18–29.

Gottfried, G.J. 1992. Ecology and management of the southwestern pinyon-juniper woodlands. Pp 78-86 *In*: Ffolliott, P.F., G.J Gottfried, D.A Bennett [and others], technical coordinators. Ecology and management of oaks and associated woodlands: perspectives in the SW United States and Mexico: Proceedings; 1992 April 27-30; Sierra Vista, AZ. Gen. Tech. Rep. RM-218. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Heil, K.D., J.M. Porter, R. Fleming, and W.H. Romme. 1993. Vascular flora and vegetation of Capitol Reef National Park, Utah. National Park Service Technical Report NPS/NAUCARE/NRTR-93/01.

Kearns, H.S.J. and W.R. Jacobi. 2005. Impacts of black stain root disease in recently formed mortality centers in the piñon-juniper woodlands of southwestern Colorado. Can. J. For. Res. 35:461–471.

Kennard, D.K. and A.J. Moore. 2013. Fire history, woodland structure, and mortality in a piñon-juniper woodland in the Colorado National Monument. Natural Areas Journal 33:296–306.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. Ecological Applications 19:1003–1021.

Peet, R.K. 2000. Forests and meadows of the Rocky Mountains. Chapter 3 *in* Barbour, M.G. and W.D. Billings, eds. North American Terrestrial Vegetation, second edition. Cambridge University Press.

Redmond, M.D., F. Forcella, and N.N. Barger. 2012. Declines in pinyon pine cone production associated with regional warming. Ecosphere 3:120. http://dx.doi.org/10.1890/ES12-00306.1

Redmond, M.D. and N.N. Barger. 2013. Tree regeneration following drought- and insect-induced mortality in piñon-juniper woodlands. New Phytologist 200:402–412.

Redmond, M.D., N.S. Cobb, M.J. Clifford, and N.N. Barger. 2015. Woodland recovery following drought-induced tree mortality across an environmental stress gradient. Global Change Biology 21:3685–3695.

Reid, M.S., K.A. Schulz, P.J. Comer, M.H. Schindel, D.R. Culver, D.A. Sarr, and M.C. Damm. 1999. An alliance level classification of vegetation of the coterminous western United States. A report to the University of Idaho Cooperative Fish and Wildlife Research Unit and National Gap Analysis Program in fulfillment of cooperative agreement 1434-HQ-97-AG-01779. The Nature Conservancy, Western Conservation Science Department, Boulder CO.

Romme, W.H., C.D. Allen, J.D. Bailey, W.L. Baker, B.T. Bestelmeyer, P.M. Brown, K.S. Eisenhart, M.L. Floyd, D.W. Huffman, B.F. Jacobs, R.F. Miller, E.H. Muldavin, T.W. Swetnam, R.J. Tausch, and P.J. Weisberg. 2009. Historical and modern disturbance regimes, stand structures, and landscape dynamics in piñon-juniper vegetation of the western United States. Rangeland Ecology and Management 62:203–222.

Ronco, F.P., Jr. 1990. *Pinus edulis* Engelm. pinyon. *In*: Burns, R.M. and B.H. Honkala, technical coordinators. Silvics of North America. Volume 1. Conifers. Agric. Handb. 654: 327–337. U.S. Department of Agriculture, Forest Service, Washington, D.C.

Shaw, J.D., B.E. Steed, and L.T. Deblander. 2005. Forest inventory and analysis (FIA) annual inventory answers the question: what is happening to pinyon juniper woodlands? Journal of Forestry 103(6):280–285.

Springfield, H.W. 1976. Characteristics and management of southwestern pinyon-juniper. Colorado State University, Fort Collins, CO. 181 pp.

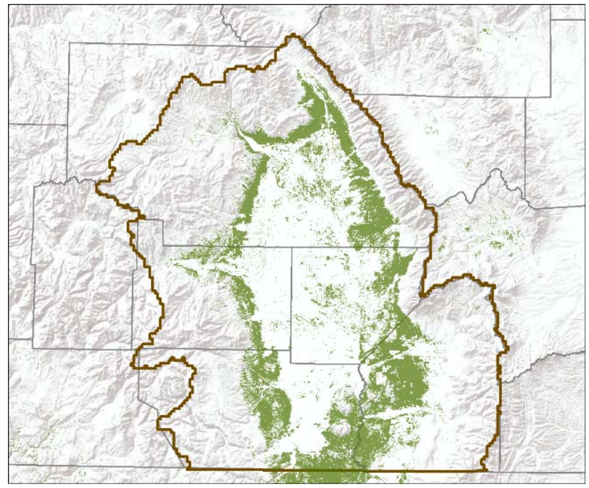
Tausch R.J. 1999. Historic pinyon and juniper woodland development. Pp. 12–19 *in*: S.B. Monsen and R. Stevens, eds. Proceedings of the Conference on Ecology and Management of Pinyon-Juniper Communities within the Interior West. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

West, N.E. 1999. Distribution, composition, and classification of current Juniper-Pinyon woodlands and savannas across western North America. Pp. 20–23 *in* S.B. Monsen and R. Stevens, eds. Proceedings: ecology and management of pinyon-juniper communities within the Interior West. Proc. RMRS-P-9. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Woodin, H.E., and A.A. Lindsey. 1954. Juniper-pinyon east of the Continental Divide, as analyzed by the pine-strip method. Ecology 35:473–489.

WINTERFAT SHRUB-GRASSLAND

R. Rondeau



Climate Vulnerability Score: Moderate Vulnerability

Winterfat shrub-grasslands in the San Luis Valley are distributed on lower foothills and valley floor below or intermingled with the zone of pinyon-juniper woodlands. In combination with climatic variability, grazing disturbances act to change floristic composition of desert shrublands over time. Historically, winterfat (*Krascheninnikovia lanata*) was dominant in this dwarf-shrub ecosystem. This shrub, together with the grasses needle-and-thread (*Hesperostipa comata*) and Indian ricegrass (*Achnatherum hymenoides*), are preferred by livestock and have a tendency to decrease in density and cover if grazing pressure is high. As a consequence of anthropogenically induced changes in grazing, the species composition has shifted, with rabbitbrush replacing winterfat, and warm season grasses, especially blue grama, expanding into the areas that previously had cool season grasses (e.g., needle-and-thread and Indian ricegrass). While blue grama is a highly productive and palatable grass, the loss of cool season grasses and winterfat means lower species diversity, which leads to reduced grazing potential.

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

Plant production: Severe growing season drought

Plant growth and reproduction depends on sufficient soil moisture during the growing season (generally April through September). Depletion of soil moisture during very dry growing seasons also reduces the infiltration depth of winter precipitation, decreasing the soil moisture available in both shallow and deeper soil layers. Shallow-rooted shrubs, grasses, and forbs will be the first species affected by extreme drought, which can reduce the growth and survival of these species. Repeated or long-term drought eventually reduces cover of blue grama, an important understory grass in winterfat shrubland. Increasing frequency of severe drought events can eventually lead to critical changes in community composition. We used projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. In the San Luis Valley, the Hot & Dry and the Feast & Famine scenarios predict increased frequency (every 5-10 years) of severe growing season drought for most of the region. The Hot & Wet scenario predicts increased frequency (every 3-5 years) only in the center of the valley floor, which is largely outside of the shrub-steppe zone, and the Warm & Wet scenario shows no change from the historic frequency of severe drought.

Plant production: Spring minimum temperature

Warmer spring night-time temperatures decrease the growth of blue grama. We used spring (March-May) average temperature as a surrogate for minimum spring temperature, with a 1° C increase as a baseline threshold for decreased blue grama growth. With the exception of the Warm & Wet scenario, predicted average spring temperature increases are greater than 1° C, with 1.1° C for Feast & Famine, and more than 1.5°C for the two hot scenarios. Because minimum temperatures are likely to show similar increases, we expect blue grama production to be negatively affected under most predicted future conditions.

Shrub regeneration: Growing season moisture

Winterfat seed production relies on sufficient summer moisture for a typical seed crop. We used departure from 1985-2015 average summer (June-August) precipitation as our impact assessment metric. In the San Luis Valley, the Hot & Dry scenario predicts decreased summer moisture, and the Hot & Wet scenario predicts increased summer moisture. The other scenarios predict essentially no change from historic levels, which have presumably been adequate for winterfat seed production.

Shrub regeneration: Winter moisture

The growth and flowering rate of winterfat during spring and early summer is linked to winter precipitation levels, which replenish soil moisture. Winterfat is generally able to use deeper soil moisture than more shallow-rooted grasses and forbs, but low levels of winter precipitation may result in reduced infiltration depth of this moisture when plant growth during the previous growth year has depleted shallow soil moisture. We used departure from 1985-2015 average winter precipitation as our impact assessment metric. In the San Luis Valley, our four scenarios predict increased winter moisture or, in the case of the Feast & Famine scenario, essentially no change from current levels. However, as winter temperatures increase, some of this additional winter moisture is likely to fall as rain instead of snow, which could change infiltration patterns.

Invasive species: Spring and fall precipitation

Changes in either fall precipitation or winter/spring precipitation could affect germination and establishment of cheatgrass. This annual grass can germinate in either spring or fall if precipitation is adequate, and is able to establish and spread if not constrained by frequent drought. We used percent departure from 1985-2015 average spring or fall precipitation, with a 5% change threshold, as our impact assessment metric. In the San Luis Valley, the two wet scenarios both predict increased spring and fall precipitation, which may provide enhanced establishment conditions for cheatgrass. Although the Hot & Dry scenario predicts increased winter precipitation that could provide some snowmelt spring moisture, both this and the Feast & Famine scenario predict drier conditions for fall.

Summary

Although these shrublands are predicted to experience adequate or increased winter moisture, summer growing season conditions may act to overcome any potential benefit. If conditions are not exacerbated by increased disturbance and invasion by exotic species, these shrublands are likely to be able to persist in their current condition.

Bibliography for Winterfat Shrub-Grassland

Carey, J.H. 1995. *Krascheninnikovia lanata*. *In*: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. https://www.fs.fed.us/database/feis/plants/shrub/kralan/all.html

Hironaka, M., M.A. Fosberg, and A.H. Winward. 1983. Sagebrush-grass habitat types of southern Idaho. Forestry, Wildlife, and Range Experiment Station Bulletin No. 15, University of Idaho, Moscow, ID. 44 pp.

Johnston B.C. 1997. Ecological types of the Upper Gunnison Basin. Review draft. U.S. Department of Agriculture, Forest Service, Gunnison, CO. 539 pp.

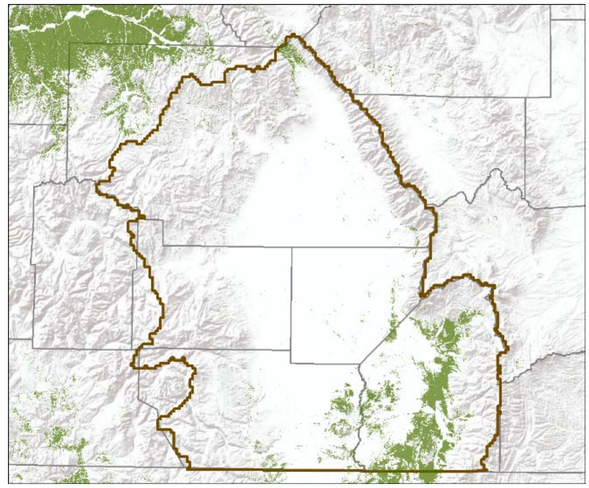
Schwinning, S., B.I. Starr, and J.R. Ehleringer. 2005a. Summer and winter drought in a cold desert ecosystem (Colorado Plateau) Part I: effects on soil water and plant water uptake. Journal of Arid Environments 60:547–566.

Schwinning, S., B.I. Starr, and J.R. Ehleringer. 2005b. Summer and winter drought in a cold desert ecosystem (Colorado Plateau) Part II: effects on plant carbon assimilation and growth. Journal of Arid Environments 61:61–78.

West, N.E. 1983. Overview of North American temperate deserts and semi-deserts. Pp. 321–330 *in* N.E. West, ed. Temperate deserts and semi-deserts. Ecosystems of the world, Volume 5. Elsevier Publishing Company. Amsterdam.

Woodmansee, R.G. and L.D. Potter. 1971. Natural reproduction of winterfat (*Eurotia lanata*) in New Mexico. Journal of Range Management 24:24–30.

Sagebrush Shrublands



Climate Vulnerability Score: Low Vulnerability

Sagebrush shrublands are comparatively uncommon in the San Luis Valley, restricted primarily to the southeastern portion of the area. These shrublands are found at elevations of 7,500 to 8,400 feet, generally below the adjacent pinyon-juniper woodland stands, and intermingled with shrub-steppe.

Although sagebrush tolerates dry conditions and fairly cool temperatures it is not fire adapted, and is likely to be severely impacted by intense fires that enhance wind erosion and eliminate the seed bank (Schlaepfer et al. 2014). Increased fire frequency and severity in these shrublands could result in increasing area dominated by exotic grasses, especially cheatgrass (*Bromus tectorum*) (D'Antonio and Vitousek 1992; Shinneman and Baker 2009). Warmer, drier sites (typically found at lower elevations) are more easily invaded by cheatgrass (Chambers et al. 2007). There is a moderate potential for invasion by knapweed species, oxeye daisy, leafy spurge, and yellow toadflax under changing climatic conditions, and a potential for changing fire dynamics to affect the ecosystem. Grazing by large ungulates (both wildlife and domestic livestock) can change the structure and nutrient cycling of sagebrush shrublands (Manier and Hobbs 2007), but the interaction of grazing with other disturbances such as fire and invasive species under changing climatic conditions is complex (e.g., Davies et al. 2009) and not well studied in Colorado.

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

Plant production: Severe growing season drought

Sagebrush shrubland species in the San Luis Valley are adapted to arid climatic conditions, but still vulnerable to severe or prolonged water stress. Because these shrublands are apparently able to dominate a zone of precipitation between drier winterfat shrublands and higher, somewhat more mesic pinyon-juniper woodland, the distribution of sagebrush shrublands is likely to be affected by changes in precipitation patterns (Bradley 2010). We used projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. In the southeastern San Luis Valley, the Feast & Famine scenario predicts increased frequency (every 5-10 years) of severe growing season drought for areas supporting sagebrush shrublands. The Hot & Dry and Hot & Wet scenarios predict somewhat increased frequency (every 10-15 years) while the Warm & Wet scenario shows no change from the historic frequency of severe drought.

Sagebrush mortality: Winter precipitation

Seasonal timing of precipitation is important for sagebrush growth; summer moisture stress may limit growth if winter precipitation is low (Germino and Reinhardt 2014). Winter snowpack is critical for sagebrush growth; lower elevations are probably more at risk from temperature impacts in comparison to upper elevations due to less snow, and consequently greater water stress. We used percent departure from 1985-2015 average winter precipitation, with a 5% change threshold, as our impact assessment metric. In the San Luis Valley, our four scenarios predict increased winter moisture or, in the case of the Feast & Famine scenario, essentially no change from current levels. However, as winter temperatures increase, some of this additional winter moisture is likely to fall as rain instead of snow. Winter precipitation falling as snow is important for replenishing deep soil moisture with gradual snowpack melting.

Invasive species: Spring and fall precipitation

Changes in either fall precipitation or winter/spring precipitation could affect germination and establishment of cheatgrass. This annual grass can germinate in either spring or fall if precipitation is adequate, and is able to establish and spread if not constrained by frequent drought. Fall germination can give cheatgrass a head start in competition against native species for spring moisture. We used percent departure from 1985-2015 average spring or fall precipitation, with a 5% change threshold, as our impact assessment metric. In the San Luis Valley, the two wet scenarios both predict increased spring and fall precipitation, which may provide enhanced establishment conditions for cheatgrass. Although the Hot & Dry scenario predicts increased winter precipitation that could provide some snowmelt spring moisture, both this and the Feast & Famine scenario predict drier conditions for fall, which would constrain cheatgrass germination in that season.

Species composition: Change in environmental suitability

The distribution and distinguishing environmental requirements of the three subspecies of big sagebrush (*Artemisia tridentata*) in Colorado are not well defined. All three subspecies have been recorded as present in the southeastern San Luis Valley, and subspecies *wyomingensis* appears to be most common. There is a possibility that one subspecies will be better able to tolerate future climate conditions in comparison with the others. We used predicted bioclimatic niche models for big sagebrush subspecies (*wyomingensis, vaseyana*, and *tridentata*) to evaluate the impacts of environmental change under future climate conditions for three of the four scenarios (models for Hot & Wet were not available). We also used one-seed juniper (*Juniperus monosperma*) niche models for all four scenarios to examine the potential for juniper expansion into sagebrush shrublands. Suitability for subspecies *wyomingensis* decreased in all scenarios, but with some indication of persistence at higher elevations under Warm & Wet conditions. Suitability for subspecies *vaseyana* was found only at elevations far above its current distribution under the Hot & Dry scenario; the other two scenarios predicted a complete loss of suitable habitat for this subspecies. Subspecies *tridentata* was predicted to experience increased suitability under all three scenarios. Predicted expansion of juniper into sagebrush shrubland was negligible except under the Warm & Wet scenario, which shows a potential for increased expansion of juniper into lower elevations of the sagebrush zone. Overall, sagebrush shrublands as currently constituted in the San Luis Valley are likely to decrease somewhat in extent unless one subspecies is able to quickly move into newly suitable, higher elevation habitat.

Summary

Due to the limited extent of these shrublands in the San Luis Valley, and the comparatively low projected exposure to warmer and drier conditions, we anticipate low vulnerability to climate change for sagebrush in the region.

Bibliography for Sagebrush

Bentz, B., D. Alston, and T. Evans. 2008. Great Basin insect outbreaks. Pp. 45-48 *in*: Chambers, J.C., N. Devoe, and A. Evenden, eds. Collaborative management and research in the Great Basin—examining the issues and developing a framework for action. Gen. Tech. Rep. RMRS-GTR-204. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Bradley, B.A. 2010. Assessing ecosystem threats from global and regional change: hierarchical modeling of risk to sagebrush ecosystems from climate change, land use and invasive species in Nevada, USA. Ecography 33:198–208.

Chambers, J.C., B.A. Roundy, R.R. Blank, S.E. Meyer, and A. Whittaker. 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? Ecological Monographs 77:117–145.

D'Antonio, C.M. and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:63–87.

Davies, K.E., T.J. Sevjcar, and J.D. Bates. 2009. Interaction of historical and nonhistorical disturbances maintains native plant communities. Ecological Applications 19:1536–1545.

Germino, M.J. and K. Reinhardt. 2014. Desert shrub responses to experimental modification of precipitation seasonality and soil depth: relationship to the two-layer hypothesis and ecohydrological niche. Journal of Ecology 102:989–997.

Howard, J.L. 1999. *Artemisia tridentata* subsp. *wyomingensis*. *In*: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/

Johnson, K.A. 2000. *Artemisia tridentata* subsp. *vaseyana*. *In*: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/

Lambrecht, S.C., A.K. Shattuck, and M.E. Loik. 2007. Combined drought and episodic freezing on seedlings of low- and high-elevation subspecies of sagebrush (*Artemisia tridentata*). Physiologia Plantarum 130:207–217.

Manier, D.J. and N.T. Hobbs. 2007. Large herbivores in sagebrush steppe ecosystems: livestock and wild ungulates influence structure and function. Oecologia 152:739–750.

Perfors, T., J. Harte, and S.E. Alter. 2003. Enhanced growth of sagebrush (*Artemisia tridentata*) in response to manipulated ecosystem warming. Global Change Biology 9:736–742.

Pocewicz, A., H.E. Copeland, M.B. Grenier, D.A. Keinath, and L.M. Washkoviak. 2014. Assessing the future vulnerability of Wyoming's terrestrial wildlife species and habitats. Report prepared by The Nature Conservancy, Wyoming Game and Fish Department and Wyoming Natural Diversity Database, Laramie, WY.

Poore, R.E., C.A. Lamanna, J.J. Ebersole, and B.J. Enquist. 2009. Controls on radial growth of mountain big sagebrush and implications for climate change. Western North American Naturalist 69:556–562.

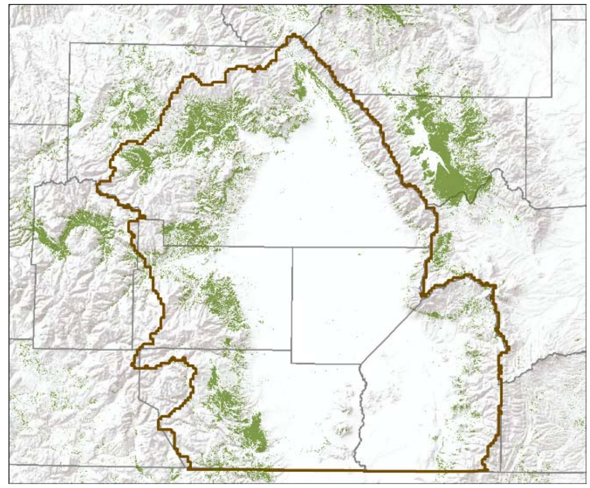
Schlaepfer, D.R., W.K. Lauenroth, and J.B. Bradford. 2012. Effects of ecohydrological variables on current and future ranges, local suitability patterns, and model accuracy in big sagebrush. Ecography 35:374–384.

Shinneman, D.J. and W.L. Baker. 2009. Environmental and climatic variables as potential drivers of post-fire cover of cheatgrass (*Bromus tectorum*) in seeded and unseeded semiarid ecosystems. International Journal of Wildland Fire 18:191–202.

Tirmenstein, D. 1999. *Artemisia tridentata* spp. *tridentata*. *In*: Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. http://www.fs.fed.us/database/feis/

Young, J.A. and R.A. Evans. 1989. Dispersal and germination of big sagebrush (*Artemisia tridentata*) seeds. Weed Science 37:201–206.

MONTANE GRASSLANDS



R. Rondeau

Climate Vulnerability Score: Moderately Vulnerable

The largest tracts of montane grassland in the San Luis Valley are concentrated on the western edge of the valley, where they are found above the zone of pinyon-juniper at elevations from 8,500 to 10,400 ft. These grasslands are intermingled with wooded areas, including pinyon-juniper at lower elevations, and ponderosa, mixed-conifer, and bristlecone pine at higher elevations. Locally abundant warm-season grasses include blue grama, galleta, and several muhly species, while cool-season types are typically fescue, needle-and-thread, western wheatgrass and junegrass.

A variety of factors, including fire, wind, cold-air drainage, climatic variation, soil properties, competition, and grazing have been proposed as mechanisms that maintain open grasslands and parks in wooded surroundings (Anderson and Baker 2005; Zier and Baker 2006; Coop and Givnish 2007). Historically, soil disturbance was largely the result of occasional concentrations of large native herbivores, or the digging action of fossorial mammals. Domestic livestock ranching has changed the timing and intensity of grazing disturbance from that of native herbivores, with the potential to alter species composition, soil compaction, nutrient levels, and vegetation structure (Smith 1967; Turner and Paulsen 1976; Brown 1994). In combination with grazing of domestic livestock, various range improvement activities (e.g., seeding, rodent control, herbicide application) have the potential to alter natural ecosystem processes and species composition. Grazing by domestic livestock may act to override or mask whatever natural mechanism is responsible for maintaining an occurrence. This interaction of multiple factors indicates that management for the maintenance of these montane and subalpine grasslands may be complex.

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

Plant production: Severe growing season drought

Grass production depends on sufficient soil moisture during the growing season (generally April through September). Depletion of soil moisture during very dry growing seasons also reduces the infiltration depth of winter precipitation, decreasing the soil moisture available in both shallow and deeper soil layers. Grasses and forbs will be affected by extreme drought, which can reduce the growth and survival of these species. Repeated or long-term drought eventually reduces cover of blue grama, an important understory grass in lower elevation grasslands in the San Luis Valley. Increasing frequency of severe drought events can eventually lead to critical changes in community composition. We used projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. In the San Luis Valley, the Hot & Dry and the Feast & Famine scenarios predict increased frequency (every 5-10 years) of severe growing season drought for most of the region. The Hot & Wet scenario predicts increased frequency (every 3-5 years) only in the center of the valley floor, and the Warm & Wet scenario shows no change from the historic frequency of severe drought.

Proportion of warm or cool season grasses: Summer temperature and soil moisture

The proportion of warm-season (C-4) vs cool-season (C-3) grasses in these montane grasslands is tied to long-term trends in temperature and precipitation, especially patterns of summer growing season temperature and soil moisture availability. Cool-season grasses expand during periods of cooler, drier summer climate, and warm-season grasses are favored when summers are warmer and wetter. We used a combination of summer (June-August) mean temperature and climate water deficit (a measure of evaporative demand that exceeds available soil moisture) as our impact assessment metric. All scenarios predict at least a 1.1°C increase in summer average temperatures, and the Hot & Dry scenario has the highest predicted increase of 2.5°C. Changes in growing season evaporative deficit are large (19-39%) for all scenarios except the Warm & Wet. Most scenarios predict warm and dry future climatic conditions, neither of which favors warm- or cool-season grasses. When considered together with an increase in atmospheric CO2, outcomes for species composition in these grasslands are difficult to predict. Although a shift toward warm season grasses is more likely, novel species combinations are also potential outcomes.

Invasive species: Spring and fall precipitation

Changes in either fall precipitation or winter/spring precipitation could affect germination and establishment of cheatgrass. This annual grass can germinate in either spring or fall if precipitation is adequate, and is able to establish and spread if not constrained by frequent drought. Fall germination can give cheatgrass a head start in competition against native species for spring moisture. We used percent departure from 1985-2015 average spring or fall precipitation, with a 5% change threshold, as our impact assessment metric. In the San Luis Valley, the two wet scenarios both predict increased spring and fall precipitation, which may provide enhanced establishment conditions for cheatgrass. Although the Hot & Dry scenario predicts increased winter precipitation that could provide some snowmelt spring moisture, both this and the Feast & Famine scenario predict drier conditions for fall, which would constrain cheatgrass germination in that season.

Summary

Warmer, drier conditions are likely to facilitate the spread of invasive species, and could allow woody species to establish in grasslands. However, an increase in forest fire activity under future conditions may allow some grasslands to expand into adjacent burned areas.

Bibliography for Montane Grasslands

Anderson, M.D. and W.L. Baker. 2005. Reconstructing landscape-scale tree invasion using survey notes in the Medicine Bow Mountains, Wyoming, USA. Landscape Ecology 21:243–258.

Brown, D.E. 1994. Grasslands. Part 4 *in* Brown, D.E., ed. Biotic communities: southwestern United States and northwestern Mexico. University of Utah Press, Salt Lake City, UT.

Brown, D.E. and E. Makings. 2014. A guide to North American grasslands. Desert plants Vol. 29, No. 2. University of Arizona, Boyce Thompson Arboretum, Superior, AZ.

Cantor, L.F. and T.J. Whitham. 1989. Importance of belowground herbivory: pocket gophers may limit aspen to rock outcrop refugia. Ecology 70(4):962–970.

Coop, J.D. and T.J. Givnish. 2007. Spatial and temporal patterns of recent forest encroachment in montane grasslands of the Valles Caldera, New Mexico, USA. Journal of Biogeography 34:914–927.

Daubenmire, R.F. 1943. Vegetational zonation in the Rocky Mountains. Botanical Review 9:325–393.

Ellison, L. 1946. The pocket gopher in relation to soil erosion on moutain range. *Ecology* 27(2):101–114.

Jamieson, D.W., W.H. Romme, and P. Somers. 1996. Biotic communities of the cool mountains. Chapter 12 *in* Blair, R. ed. The western San Juan Mountains: their geology, ecology, and human history. University Press of Colorado, Niwot, CO.

Knight, D.H. 994. Mountains and Plains: the Ecology of Wyoming Landscapes. Yale University Press, New Haven, CT. 338 pp.

Paulsen, H.A., Jr. 1969. Forage values on a mountain grassland-aspen range in western Colorado. Journal of Range Management 22:102–107.

Paulsen, H.A., Jr. 1975. Range management in the central and southern Rocky Mountains: a summary of the status of our knowledge by range ecosystems. USDA Forest Service Research Paper RM-154. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Peet, R.K. 1981. Forest vegetation of the Colorado Front Range: composition and dynamics. Vegetatio 45:3–75.

Peet, R.K. 2000. Forests and meadows of the Rocky Mountains. Chapter 3 *in* Barbour, M.G. and W.D. Billings, eds. North American terrestrial vegetation, second edition. Cambridge University Press, New York, NY.

Schauer, A.J., B.K. Wade, and J.B. Sowell. 1998. Persistence of subalpine forest-meadow ecotones in the Gunnison Basin, Colorado. Great Basin Naturalist 58(3):273–281.

Sims, P.L., and P.G. Risser. 2000. Grasslands. Pp.323–35 *in*: Barbour, M.G. and W.D. Billings, eds., North American terrestrial vegetation, second edition. Cambridge University Press, New York, NY.

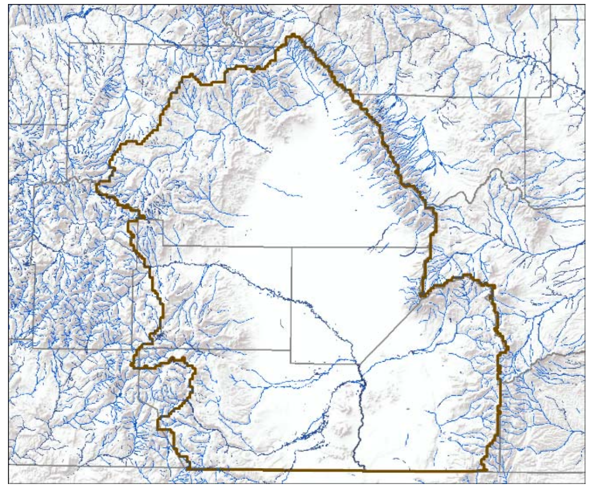
Smith, D.R. 1967. Effects of cattle grazing on a ponderosa pine-bunchgrass range in Colorado. USDA Forest Service Technical Bulletin No. 1371. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Stohlgren, T.J., L.D. Schell, and B. Vanden Huevel. 1999. How grazing and soil quality affect native and exotic plant diversity in rocky mountain grasslands. Ecological Applications 9:45–64

Turner, G.T. and H.A. Paulsen, Jr. 1976. Management of mountain grasslands in the Central Rockies: the status of our knowledge. USDA Forest Service Research Paper RM-161. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Zier, J.L. and W.L. Baker. 2006. A century of vegetation change in the San Juan Mountains, Colorado: an analysis using repeat photography. Forest Ecology and Management 228:251–262.

STREAMS AND RIPARIAN AREAS



R. Rondeau

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Climate Vulnerability Score: Highly Vulnerable

Streams and their adjacent riparian vegetation are important habitat both for aquatic organisms including both native and introduced fish, and for birds and other terrestrial animals that use the riparian forest and shrubland.

Riparian woodlands and shrublands occur primarily at elevations above the valley floor in the San Luis Valley. Montane to subalpine riparian woodlands are seasonally flooded forests and woodlands. Riparian shrublands may occur as narrow bands of shrubs lining streambanks and alluvial terraces, or as extensive willow carrs in broader subalpine valleys. At lower elevations riparian woodlands and shrublands are found within the flood zone of rivers, on islands, sand or cobble bars, and immediate streambanks. Native fish in the region include the Rio Grande cutthroat trout (*Salmo clarki virginalis*), the Rio Grande sucker (*Castostomus plebeius*), and the Rio Grande chub (*Gila pandora*). Introduced cold water sport fish (rainbow, brown, and brook trout) are also present in perennial streams in the area.

Baron and Poff (2004) identified five dynamic factors that shape the structure and function of freshwater ecosystems: the flow pattern of water through the system, inputs of sediment and organic matter, nutrient and chemical conditions, temperature and light levels, and plant and animal assemblages. Changing climate conditions can affect all these factors, but directly act through temperature and flow. Moreover, riverine systems act to integrate and collect the effects of disturbances within the catchment, including those due to flow modification (Naiman et al. 2002).

Flow patterns describe the way water passes into and out of streams, rivers, lakes and associated wetlands. Important characteristics include base flow levels, the periodicity and magnitude of both annual or frequent floods and rare and extreme flood events, seasonality of flows, and annual variability (Baron and Poff 2004). Cottonwoods require periodic flood events for dispersal and seed establishment. Aquatic organisms evolved with and are adapted to the characteristic natural flow regime of their habitat. Changes in flow regime (e.g., increased flood events, or extreme low water conditions) can cause serious disruption to the reproduction and survival of many aquatic species, leading to an eventual loss of biodiversity (Bunn and Arthington 2002). Water temperature is a key influence on oxygen concentration and on the survival or reproductive success of fish and other aquatic organisms.

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

Riparian area condition: Winter snowpack and snowmelt timing; year-round flow regime
Riparian forests are closely tied to the stream flow regime, as well as groundwater discharge from upslope areas (including irrigation return flows in some areas). Riparian plant communities reflect the overall hydrologic (and disturbance) regime of the floodplain where they occur. Spring high flows due to melting winter snowpack are critical to spring runoff and provide the deep soil moisture needed for vegetation to withstand hot, dry summers. We used a combination of departure from 1985-2015 average for April 1 SWE (snow water equivalent) and total annual runoff, together with projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. The Feast & Famine scenario has the greatest predicted combination of negative effects in all sub-metrics. The Warm & Wet scenario is little changed from recent historic conditions, while the other scenarios have negative effects but to a somewhat lesser extent than the Feast & Famine scenario.

Aquatic system with native and sport fish: Late summer and fall instream base flows
Changes to the natural flow regime of streams occupied by cold water native fish will influence the elevation limit/extent of available native fish habitat. Warming water temperatures are expected to lead to lower summer flows. Warmer temperatures will generally result in earlier snowmelt and runoff for mountain streams and rivers. Natural flow regimes are largely driven by runoff from winter snowpack. Late summer low flows are a critical "pinch point" for trout. We used a combination of departure from 1985-2015 average for April 1 SWE and summer/fall annual runoff, together with projected changes in summer temperatures. Predicted SWE shows a large decrease for the Hot & Wet and the Feast & Famine scenarios, and little change for the others. Summer/fall runoff decreases for all scenarios, especially for the Hot & Dry and the Hot & Wet. Summer temperatures increase under all scenarios, with the greatest increase for the Hot & Dry scenario. The change to lower flows in late summer, and warmer water temperatures are likely to have negative impacts on fish.

Aquatic system with native and sport fish: Cold water temperatures

Warming water temperatures are expected to lead to loss of cool-water reaches in both rivers and streams in the San Luis Valley. An overall retreat of cold water conditions to higher elevations is predicted. Cold-water fish species are likely to experience restricted habitat, and if they are not able to migrate as temperatures change, may be eliminated from many stream reaches. We used a predicted cold-to-warm water transition zone model (CNHP 2015) to evaluate the change in available cold water habitat. Individual models for the four scenarios were not available, but the mean lower-emissions model (corresponding to the Warm & Wet scenario) indicated an elevation change of 1,000 ft. higher for the transition zone compared to the present, and the mean higher-emissions model (corresponding to the other scenarios) added approximately another 500 ft. in elevation gain for the transition zone.

Summary

Streams and associated riparian areas are the most highly vulnerable ecosystems in the San Luis Valley, especially as habitat for wildlife and aquatic organisms. Warming temperatures are expected to increase stress in these systems during the late summer and fall, even under conditions of increased annual or winter precipitation. Diversions mandated under the Rio Grande Compact and Rio Grande Convention are likely to increase these effects.

Bibliography for Streams and Riparian Areas

Auble, G.T., J.M. Friedman, and M.L. Scott. 1994. Relating riparian vegetation to present and future streamflows. Ecological Applications 4:544–554.

Baker, D.W., B.P. Bledsoe, C.M. Albano, and N.L. Poff. 2011. Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain Streams. River Research and Applications 27:388–401.

Baron, J.S. and N.L. Poff. 2004. Sustaining healthy freshwater ecosystems. Universities Council on Water Resources, Water Resources Update 127:52–58.

Bunn, S.E. and A.H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environmental Management 30:492–507.

Capon, S.J., L.E. Chambers, R. MacNally, R.J. Naiman, P. Davies, N. Marshall, J. Pittock, M. Reid, T. Capon, M. Douglas, J. Catford, D.S. Baldwin, M. Stewardson, J. Roberts, M. parsons, and S.E. Williams. 2013. Riparian ecosystems in the 21st century: hotspots for climate change adaptation? Ecosystems 16:359–381.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559–568.

Charron, I. and E.A. Johnson. 2006. The importance of fires and floods on tree ages along mountainous gravel-bed streams. Ecological Applications 16:1757–1770.

Colorado Natural Heritage Program [CNHP]. 2015. Climate change vulnerability assessment for Colorado Bureau of Land Management. K. Decker, L. Grunau, J. Handwerk, and J. Siemers, ed. Colorado Natural Heritage Program, Colorado State University, Fort Collins, CO.

Dodds, W.K. 1997. Distribution of runoff and rivers related to vegetative characteristics, latitude, and slope: a global perspective. Journal of the North American Benthological Society 16:162–168.

Holsinger, L., R.E. Keane, D.J. Isaak, L. Eby, and M.K. Young. 2014. Relative effects of climate change and wildfires on stream temperatures: a simulation modeling approach in a rocky Mountain watershed. Climatic Change 124:191–206.

Isaak, D.J., C.C. Huhlfeld, A.S. Todd. R. Al-Chokhachy, J. Roberts, J.L. Kershner, K.D. Fausch, and S.W. Hostetler. 2012. The past as prelude to the future for understanding 21st-century climate effects on Rocky Mountain trout. Fisheries 37:542–556.

Khamis, K., D.M. Hannah, M. Hill Clarvis, L.E. Brown, E. Castella, and A.M. Milner. Alpine aquatic ecosystem conservation policy in a changing climate. Environmental Science & Policy 43:39–55.

Lukas, J., J. Barsugli, N. Doesken, I. Rangwala, and K. Wolter. 2014. Climate change in Colorado: a synthesis to support water resources management and adaptation. Second edition. Report for the Colorado Water Conservation Board. Western Water Assessment, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO.

Perry, L.G., D.C. Andersen, L.V. Reynolds, S.M. Nelson, and P.B. Shafroth. 2012. Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. Global Change Biology 18:8221–842.

Poff, N.L., M.M. Brinson, and J.W. Day. 2002. Aquatic ecosystems and global climate change: potential impacts on inland freshwater and coastal wetland ecosystems in the United States. Prepared for the Pew Center on Global Climate Change. http://www.c2es.org/publications/aquatic-ecosystems-and-climate-change

Rood, S.B., J. Pan, K.M. Gill, C.G. Franks, G.M. Samuelson, and A. Shepherd. 2008. Declining summer flows of Rocky Mountain rivers: changing seasonal hydrology and probable impacts on floodplain forests. Journal of Hydrology 349:397–410.

Stromberg, J.C. and T.J. Rychener. 2010. Effects of fire on riparian forests along a free-flowing dryland river. Wetlands 30:75–86.

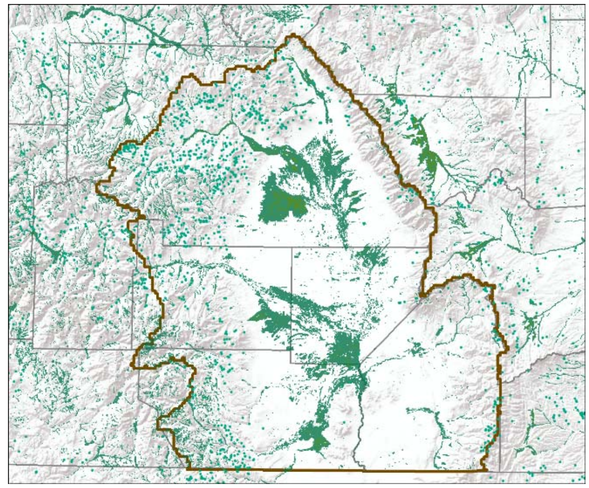
Naiman, R.J., S.E. Bunn, C. Nilsson, G.E. Petts, G. Pinay, L.C. Thompson. 2002. Legitimizing fluvial ecosystems as users of water: an overview. Environmental Management 30:455–467

The Nature Conservancy [TNC]. 2012. Freshwater measures of condition for Colorado. Geodatabase. The Nature Conservancy of Colorado, Boulder, CO.

Wohl, E. 2006. Human impacts to mountain streams. Geomorphology 79:217–248.

WETLANDS, SEEPS/SPRINGS, AND IRRIGATED MEADOWS

R. Rondeau



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Climate Vulnerability Score: Highly Vulnerable

Wetlands of the San Luis Valley are found at all elevations, and are usually dominated by herbaceous vegetation, but can include shrubs or taller woody vegetation. These small patch ecosystems account for about 6% of the total acreage of the area. Herbaceous wetlands of the region are primarily freshwater emergent types.

Seeps and springs include small wetlands that are hydrologically supported by groundwater discharge. In the San Luis Valley they are more often found at elevations above the valley floor, and are more concentrated on the western side of the valley.

Irrigated meadows are concentrated in the valley bottoms of the major perennial streams in the area. Together with the intermingled wetlands, they provide habitat for both migrating and breeding waterfowl and are a major stopover for migrating Sandhill cranes.

The extent, attributes, and persistence of wetland ecosystems are determined by how water functions within the landscape. These hydrologic patterns are the primary determinant of the development and maintenance of wetland ecosystems, and variations in timing and duration of inundation largely determine the type of wetland. The water budget or hydroperiod of a wetland includes precipitation, evapotranspiration, and both surface flow and groundwater.

Vulnerability Assessment Scoring Across Four Climate Scenarios, 2035

The effects of climate change on wetlands are likely to occur via changes in hydrology, as well as by the direct and indirect effects of temperature change and the character of the surrounding landscape. Changes in precipitation patterns together with warming temperatures are predicted to result in decreased late-summer base flows and altered hydroperiods, with peak run-off expected to occur much earlier than has historically been the case. Frequency of seasonal or extended severe drought is expected to increase. Both surface and ground water depths are likely to be affected, leading to altered chemical properties and nutrient levels in wetlands. Such changes will also affect the flora and fauna that use wetlands. Altered precipitation patterns could result in increased frequency of extreme flooding events, with consequent erosion and sediment deposition, especially in areas that experience increased severity of wildfire in adjacent uplands. Wetlands are especially vulnerable to changing climate conditions because they accumulate impacts from the surrounding landscape.

Wetland condition: Winter snowpack and summer evapotranspiration

Natural wetlands depend on runoff and sufficient water during the growing season to maintain stability and provide useable habitat for birds. We used a combination of departure from 1985-2015 average April 1 snow-water equivalent (SWE) and growing season (April-September) evaporative deficit as our impact assessment metric. Predicted SWE shows a large decrease for the Hot & Wet and the Feast & Famine scenarios, and little change for the others. Evaporative deficit during the growing season is severe for most predicted scenarios with the exception of the Warm & Wet scenario.

Wetland condition: Growing season precipitation and evapotranspiration

Changes in precipitation, temperature, evapotranspiration, and groundwater recharge will alter the extent and type (vegetation and hydrology) of wetlands, seeps, and springs. We used a combination of departure from 1985-2015 average summer (June-August) precipitation and growing season (April-September) evaporative deficit as our impact assessment metric. With the exception of the Hot & Dry scenario, predicted summer average precipitation shows little change from the recent historic period. Evaporative deficit during the growing season is severe for most predicted scenarios with the exception of the Warm & Wet scenario.

Groundwater recharge: Winter snowpack, total runoff, drought

Lowland groundwater recharge may be tied to both local (influenced by evapotranspiration, land cover, and groundwater and surface water withdrawals) and regional (influenced by snowpack and snowmelt timing) groundwater systems, and many of these factors are not well-accounted for in hydrologic models used to evaluate the impacts of climate change. Groundwater recharge is primarily driven by snowpack and snowmelt in our region. We used a combination of departure from 1985-2015 average for April 1 SWE, total annual runoff, and growing season (April-September) evaporative deficit, together with projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. The Hot & Dry scenario and the Feast & Famine scenario have the greatest predicted negative effects for all sub-metrics. The Hot & Wet scenario and Warm & Wet scenario are also predicted to have negative effects, but to a lesser degree.

Water available to irrigate fields: Winter snowpack and snowmelt timing

Alteration in the amount and timing of delivery for water to irrigate bird aggregation areas influences the availability of suitable habitat and food resources. Groundwater depletion in the San Luis Valley continues to be problematic, and could be exacerbated by a reduction in snowpack/surface water. Trends are for less irrigation due to lower water availability. We used a combination of departure from 1985-2015 average for April 1 SWE and total annual runoff, together with projected frequency of growing season climate water deficit extreme events (e.g., comparable to the droughts of 2002 and 2012) as our impact assessment metric. The Feast & Famine scenario has the greatest predicted combination of negative effects in all sub-metrics. The Warm & Wet scenario is little changed from recent historic conditions, while the other scenarios have negative effects but to a somewhat lesser extent than the Feast & Famine scenario.

Summary

Warmer and drier conditions for lower elevation wetlands are likely to result in reduced water inputs to these habitats, and lower groundwater levels in general that may reduce the extent and degrade the condition of wetlands. In higher elevations warmer temperatures and consequent earlier snowmelt may influence the species composition of wetland habitats. Ground-water dependent wetlands at higher elevations are expected to be somewhat buffered from hydrologic change.

Bibliography for Wetlands, Seeps/Springs, and Irrigated Meadows

Burns, E.R., Y. Zhu, H. Zhan, M. Manga, C.F. Williams, S.E. Ingebritsen, and J.B. Dunham. 2017. Thermal effect of climate change on groundwater-fed ecosystems. Water Resources Research 53:3341–3351.

Elias, E.H., A. Rango, C.M. Steele, J.F. Mejia, and R. Smith. 2015. Assessing climate change impacts on water availability of snowmelt-dominated basins of the Upper Rio Grande basin. Journal of Hydrology Regional Studies 3:525–546.

Meixner, T., A.H. Manning, D.A. Stonestrom, D.M. Allen, H. Ajami, K.W. Blasch, A.E. Brookfield, C.L. Castro, J.F. Clark, D.J. Gochis, A.L. Flint, K.L. Neff, R. Niraula, M. Rodell, B.R. Scanlon, K. Singha, and M.A. Walvoord. 2016. Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology 534:124–138.

Niraula, R., T. Meixner, F. Domingues, N. Bhattarai, M. Rodell, H. Ajami, D. Gochis, and C. Castro. 2017. How might recharge change under projected climate change in the western U.S.? Geophysical Research Letters 44:10407–10418. https://doi.org/10.1002/2017GL075421

Smith, D.M. and M.M. Friggens. 2017. A spatially explicit and quantitative vulnerability assessment of coldwater fish habitat and riparian corridors in the Intermountain West. U.S. Forest Service Rocky Mountain Research Station, Albuquerque, NM.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. PNAS Early Edition 1–6. www.pnas.org/cgi/doi/10.1073/pnas.1103097108

LITERATURE CITED

Adams, H.D., M. Guardiola-Claramonte, G.A. Barron-Gafford, J. Camilo Villegas, D.D. Breshears, C.B. Zou, P.A. Troch, T.E. Huxman, and H.A. Mooney. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. PNAS 106:7063–7066.

Adams, H.D., G.A. Barron-Gafford, R.L. Minor, A.A. Gardea, L.P. Bentley, D.J. Law, D.D. Breshears, N.G. McDowell, and T.E. Huxman. 2017. Temperature response surfaces for mortality risk of tree species with future drought. Environmental Research Letters 11:115014.

Anderson, R.M. and G. Stewart. 2007. Impacts of stream flow alterations on the native fish assemblage and their habitat availability as determined by 2D modeling and the use of fish population data to support instream flow recommendations for the sections of the Yampa, Colorado, Gunnison and Dolores rivers in Colorado. Colorado Division of Wildlife Aquatic Wildlife Research. Special Report Number 80. SRP15277.

Barger, N.N., H.D. Adams; C. Woodhouse, J.C. Neff, and G.P. Asner. 2009. Influence of livestock grazing and climate on piñon pine (*Pinus edulis*) dynamics. Rangeland Ecology and Management 62:531–539.

Breshears, D.D., O.B. Myers, C.W. Meyer, F.J. Barnes, C.B. Zou, C.D. Allen, N.G. McDowell, and W.T. Pockman. 2008. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment 7:185–189.

Brinkman, S.F., H.J. Crockett, and K.B. Rogers. 2013. Upper thermal tolerance of mountain whitefish eggs and fry. Transactions of the American Fisheries Society 142(3):824–831. https://afspubs.onlinelibrary.wiley.com/doi/full/10.1080/00028487.2013.765503.

Clifford, M.J., P.D. Royer, N.S. Cobb, D.D. Breshears, and P.L. Ford. 2013. Precipitation thresholds and drought-induced tree die-off: insights from patterns of *Pinus edulis* mortality along an environmental stress gradient. New Phytologist 200:413–421.

Cole, K.L., J. Fisher, S.T. Arundel, J. Cannella, and S. Swift. 2008. Geographical and climatic limits of needle types of one- and two-needled pinyon pines. Journal of Biogeography 335:257–269.

Colorado Natural Heritage Program [CNHP]. 2015. Climate change vulnerability assessment for Colorado Bureau of Land Management. Colorado Natural Heritage Program, Colorado State University, Fort Collins, CO. https://cnhp.colostate.edu/download/documents/2015/CCVA_for_Colorado_BLM_final.pdf

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. O'Brien, H.G. Stefany, M. Hondzo, and R.M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries

20(4):10–18. https://afspubs.onlinelibrary.wiley.com/doi/abs/10.1577/1548-8446%281995%29020%3C0010%3AAFISFE%3E2.0.CO%3B2.

Gottfried, G.J. 1992. Ecology and management of the southwestern pinyon-juniper woodlands. Pp 78–86 *In*: Ffolliott, P.F., G.J Gottfried, D.A Bennett [and others], technical coordinators. Ecology and management of oaks and associated woodlands: perspectives in the SW United States and Mexico: Proceedings; 1992 April 27–30; Sierra Vista, AZ. Gen. Tech. Rep. RM-218. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Gunderson, L.H. 2000. Ecological resilience–In theory and application. Annual Review of Ecology and Systematics 31:425–439.

Heil, K.D., Porter, J.M., Fleming, R., and Romme, W.H. 1993. Vascular flora and vegetation of Capitol Reef National Park, Utah. National Park Service Technical Report NPS/NAUCARE/NRTR-93/01.

Hunt, L.M., E.P. Fenichel, D.C. Fulton, R. Mendelsohn, J.W. Smith, T.D. Tunney, A.J. Lynch, C.P. Paukert, and J.E. Whitney. 2016. Identifying alternate pathways for climate change to impact inland recreational fishers. Pp. 362–373 *in* Climate Change and North American Inland Fishes. Fisheries, Special Issue. 2016. 41(7):325–428. http://dx.doi.org/10.1080/03632415.2016.1205860.

Isaak, D.J., C.C. Muhlfeld, A.S. Todd, R. Al-Chokhachy, J. Roberts, J.L. Kershner, K.D. Fausch, and S.W. Hostetler. 2012. The past as prelude to the future for understanding 21st-Century climate effects on Rocky Mountain trout. Fisheries 37(12):542–556.

Isaak, D., S. Wenger, E. Peterson, J. Ver Hoef, D. Nagel, C. Luce, S. Hostetler, J. Dunham, B. Roper, S. Wollrab, G. Chandler, D. Horan, and S. Parkes-Payne. 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181–9205. https://doi.org/10.1002/2017WR020969.

Isaak, D.J., M.K. Young, D. Nagel, and D. Horan. 2014. Coldwater as a Climate Shield to Preserve Native Trout Through the 21st Century. Proceedings of the Wild Trout Symposium XI, Sept. 22–25, 2014, West Yellowstone, MT. https://www.wildtroutsymposium.com/proceedings-11.pdf

Isaak, D., M. Young, D. Nagel, D. Horan, M. Groce, and S. Parkes. 2015. Climate Shield bull trout and cutthroat trout population occurrence scenarios for the western U.S. Rocky Mountain Research Station, U.S. Forest Service Data Archive, Fort Collins, CO.

Meisner, J.D., J.S. Rosenfeld, and H.A. Regier. 1988. The role of groundwater in the impact of climate warming on stream salmonines. Fisheries 13(3):2–8. https://www.tandfonline.com/doi/abs/10.1577/1548-8446%281988%29013%3C0002%3ATROGIT%3E2.0.CO%3B2

Mohseni, O., H.G. Stefan, and J.G. Eaton. 2003. Global warming and potential changes in fish habitat in U.S. streams. Climatic Change 59:389–409.

Nelson, R., Cross, M., Hansen, L., and G. Tabor. 2016. A three-step decision support framework for climate adaptation: Selecting climate-informed conservation goals and strategies for native salmonids in the northern U.S. Rockies. Wildlife Conservation Society, EcoAdapt, Center for Large Landscape Conservation. Bozeman, MT, USA. http://rmpf.weebly.com/cold-water-ecosystem-management-tool.html.

Peterson, D.P., S.J. Wenger, B.E. Rieman, and D.J. Isaak. 2013. Linking climate change and fish conservation efforts using spatially explicit decision support tools. Fisheries 38(3):112–127.

Propst, D.L. and K.B. Gido. 2004. Responses of native and nonnative fishes to natural flow regime mimicry in the San Juan River. Transactions of the American Fisheries Society 133(4):922–931. https://afspubs.onlinelibrary.wiley.com/doi/full/10.1577/T03-057.1.

Redmond, M.D., F. Forcella, and N.N. Barger. 2012. Declines in pinyon pine cone production associated with regional warming. Ecosphere 3:120. http://dx.doi.org/10.1890/ES12-00306.1

Redmond, M.D., N.S. Cobb, M.J. Clifford, and N.N. Barger. 2015. Woodland recovery following drought-induced tree mortality across an environmental stress gradient. Global Change Biology 21:3685–3695.

Roberts, J.J., K.D. Fausch, D.P. Peterson, and M.B. Hooten. 2013. Fragmentation and thermal risks from climate change interact to affect persistence of native trout in the Colorado River basin. Global Change Biology 19(5):1383–1398. https://onlinelibrary.wiley.com/doi/full/10.1111/gcb.12136.

Ronco, F.P., Jr. 1990. *Pinus edulis* Engelm. pinyon. Pp. 327–337 *In*: Burns, R.M. and B.H. Honkala, technical coordinators. Silvics of North America. Volume 1. Conifers. Agric. Handb. 654. U.S. Department of Agriculture, Forest Service, Washington, DC.

Rondeau, R., M. Bidwell, B. Neely, I. Rangwala, L. Yung, and C. Wyborn. 2017. Pinyon-juniper landscape: San Juan Basin, Colorado social-ecological climate resilience project. North Central Climate Science Center, Ft. Collins, CO. https://cnhp.colostate.edu/download/documents/2017/SECR_PJ_Landscape_Report_21FEB_Final.pdf

Sanderson, J., B. Bledsoe, N.L. Poff, T. Wildling, and N. Fey. 2012. Yampa-White Basin Roundtable watershed flow evaluation tool study. Report prepared for The Nature Conservancy, Boulder, CO.

Smith, D.M. and M.M. Friggens. 2017. A spatially explicit and quantitative vulnerability assessment of coldwater fish habitat and riparian corridors in the Intermountain West. U.S. Forest Service Rocky Mountain Research Station, Albuquerque, NM.

The Nature Conservancy [TNC]. 2018. Colorado Climate Impacts and Opportunities Project Final Report. The Nature Conservancy in collaboration with Colorado Natural Heritage Program and Western Water Assessment/University of Colorado.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences 108(34):14175–14180.

Wenger, S.J. and C.H. Luce. 2016. Western U.S. stream flow metrics: a dataset of modeled flow metrics for streams in major river basins of the Western US for historical and future climate change scenarios. Data last updated 03/01/2016. https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml.

Woodin, H.E. and A.A. Lindsey. 1954. Juniper-pinyon east of the Continental Divide, as analyzed by the pine-strip method. Ecology 35:473–489.

APPENDIX A: ECOLOGICAL RESPONSE MODELS FOR PINYON AND JUNIPER – TECHNICAL METHODS

Bioclimatic Models

The analysis area was the four-corner states of Utah, Colorado, New Mexico, and Arizona, representing the species distribution of *Pinus edulis*. Species modeled were *Pinus edulis* (PIED), *Juniperus osteosperma* (JUOS), and *Juniperus monosperma* (JUMO). Point locations used for presence and pseudo-absence inputs were compiled from Vegbank (Peet et al. 2013), the Rocky Mountain Herbarium (2015), GBIF (2015), CNHP (2016), and CNAP (2001).

Pseudo-absence points were taken from other ecological systems with similar environmental niches within the study area, such as sagebrush, that were at least 5 km away from a presence point. For PIED, pseudo-absence points were further limited by removing those that fell within areas of currently mapped pinyon-juniper. For the two junipers, presence points from one species (also at least 5 km away) were additionally used as pseudo-absence for the other. In total the PIED models used 3,855 presence and 2,517 pseudo-absence points, the JUOS models had, 2,540 presence and 1,745 pseudo-absence points and for JUMO, 1,479 presence and 1,893 pseudo-absence points were used.

Environmental inputs included climate, soils, and degrees slope (Table A-1). Climate data were derived from NASA Earth Exchange downscaled climate models (Thrasher et al. 2013). Seasonal and annual temperature and precipitation metrics were calculated and averaged over 1970-2000 to represent current conditions, and over 2035-2065 to represent future projected conditions at mid-century. Soils metrics included soil pH, percent organic matter, percent sand, percent silt, percent clay, soil depth, and available water supply down to 150cm in depth (AWS). Soils data were derived from STATSGO2 (USDA-NRCS 2006), calculated as a weighted mean across all soil components and all soil depth layers per unit using the NRCS Soil Data Viewer (v6.2 rev.1046). Areas of No Data were then interpolated using an annulus focal mean. Slope was calculated from GTOPO (USGS-EROS 1996) which, while an older dataset, natively matched the resolution of the climate data (30 arc-second).

The R package randomforest (version 4.6-10; Liaw and Wiener, 2002) was used within the SAHM (Morisette et al. 2013) package in VisTrails (NYU-Poly and Univ. of UT 2014) to create current condition bioclimatic models for the 3 species for each of the 4 climate scenarios. Models were run iteratively to achieve robust results with the available inputs.

Table A-1. All model input data considered for bioclimatic models.

Metric	Data Source
Total winter precipitation (mm) Maximum winter temperature (°C) Mean winter temperature (°C) Minimum winter temperature (°C) Total spring precipitation (mm) Maximum spring temperature (°C) Mean spring temperature (°C) Minimum spring temperature (°C) Total summer precipitation (mm) Maximum summer temperature (°C) Mean summer temperature (°C) Minimum summer temperature (°C) Total autumn precipitation (mm) Maximum autumn temperature (°C) Mean autumn temperature (°C) Minimum autumn temperature (°C) Total annual precipitation (mm) Mean annual temperature (°C)	NASA NEX dcp30 30-yr averages of seasonal and annual temperature and precipitation metrics. "Current" time period 1970-2000 ('1985') "Future" period 2035-2065 ('2050'). Where: winter = December, January, February | spring = March, April, May | summer = June, July, August | autumn = September, October, November GCM.RCP combinations used Hot & Dry: hadgem2-es.rcp85 Hot & Wet: miroc-esm.rcp85 Feast & Famine: cesm1-bgc.rcp85 Warm & Wet: cnrm-cm5.rcp45
Soil pH Percent Organic matter Percent Sand, Silt, and Clay Soil Depth (cm) Available Water Supply down to 150 cm depth	STATSGO2 soils metrics
Slope Aspect as northness Aspect as eastness	GTOPO30. 30 arc-second DEM of North America

Models were evaluated on both calculated performance metrics (Table A-2) and visual evaluation of results by CNHP ecologists. Tweaks to improve model performance included selecting different final inputs to minimize degree of covariate correlation while maximizing percent deviance explained, and removing outlier presence or pseudo-absence points that confounded results. Once current condition models were complete for each species for each climate scenario, they were applied to projected future conditions to create projected future suitable habitat distribution models.

Table A-2. Performance metric results for models.

Averages over the 4 climate scenarios:				
Species	**AUC**	**% CC**	**% DE**	**TSS**
PIED	0.922	85.2%	48.7%	0.676
JUOS	0.956	89.0%	60.8%	0.779
JUMO	0.964	90.9%	65.5%	0.818

AUC = Area Under the Curve, % CC = Percent Correctly Classified, % DE = Percent Deviance Explained, TSS = True Skill Statistic.

Model Processing for Change Categories

The modeled current suitable habitat and modeled future suitable habitat were combined to show change, using various thresholds to distinguish categories, as well as current mapped occupied area. Sources of current vegetation cover (LandFire existing vegetation, USGS-WFS 2016 and Regional GAP landcover, USGS-GAP 2016) treat pinyon-juniper woodland as a single type, even though the range varies greatly in the proportion of pinyon pine as well as the species of juniper. Therefore, several filtering steps were necessary to make sure that the current and future models realistically represent current occupied and projected change in distribution of the individual species.

The initial threshold ("low cutoff") was used to discard areas of the models where the probability of occurrence (i.e., the random forest probability output) below which the species is assumed unlikely to occur. These values were calculated as a part of the modeling process. The threshold value used for the two juniper species is the value at which the model sensitivity (the probability of a true positive) equals model specificity (the probability of a true negative). This is a standard threshold used to display continuous probability models. Because the pinyon pine model is not as robust as the juniper models (lower model evaluation metrics), a lower threshold that maximizes the percent correctly classified was used instead, to prevent removing too much data from consideration at the start.

These initial thresholds, while commonly used to present suitable bioclimatic envelopes, are less practical for representing current occupied range of a species. Occupied range is frequently more restricted due to inter-species competition and stochastic historical events, requiring a higher threshold. This second threshold ("high cutoff") was calculated using the values remaining after the low cutoff was applied, summarized over current mapped pinyon-juniper (Table A-3). Several methods were tried, and the following selected based on expert evaluation as to the accuracy of the results for current distribution. For *P. edulis* and *J. osteosperma*, the 80^{th} percentile of current model values occurring over pinyon-juniper as mapped by GAP landcover was averaged over the four climate scenarios. For *J. monosperma*, the mean current model value occurring over pinyon-juniper as mapped by Landfire was averaged over the four scenarios.

Table A-3. Cutoff values used for models.

Species	Low cutoff values	High cutoff values
PIED	0.49	0.72
JUOS	0.63	0.76
JUMO	0.55	0.84

For each climate scenario, all areas where values from *both* the current and future projected models were less than the high cutoff were removed from further consideration. For the remaining areas, the future projected values were then subtracted from the current values to derive a measure of change. This results in values that can (theoretically) range from -1 (completely lost habitat suitability) to 0 (no change) to +1 (completely emergent habitat suitability). These change values were then classified into change categories (Table A-4), and model rasters were reclassified for display in these categories.

Table A-4. Criteria used to assign change categories.

Change Category	Change value range
Threatened/Lost	< hc - 1
Persistent	between hc - 1 and 1 - hc
Emergent	> 1 - hc

Where hc = high cutoff value

For display purposes, the change category rasters for the four climate scenarios of each of the three species were then combined to highlight areas where all projected futures agree. The stacked rasters were added to show the number of models agreeing on each category.

References

Colorado Natural Areas Program and others (ca. 2001). Plot data compiled from various sources as part of a revision of Galatowitsch, S. (1998). Colorado's Natural Vegetation, unpublished draft prepared for the Colorado Natural Areas Program, Colorado Department of Natural Resources, Denver, CO.

Colorado Natural Heritage Program (CNHP). 2016. Biodiversity Tracking and Conservation System (BIOTICS). Colorado Natural Heritage Program, Colorado State University, Fort Collins, CO.

Global Biodiversity Information Facility. 2015. GBIF.org GBIF Occurrence Download http://doi.org/10.15468/dl.mq9gb2. Accessed 13th October 2015.

Liaw, A. and M. Wiener. 2002. Classification and Regression by randomForest. R News 2(3), 18-22.

Morisette, J.T., C.S. Jarnevich, T.R. Holcombe, C.B. Talbert, D. Ignizio, M.K. Talbert, C. Silva, D. Koop, A. Swanson, and N.E. Young. 2013. VisTrails SAHM: visualization and workflow management for species habitat modeling. Ecography 36: 129-135 (ver. 2.0.0). Available at https://my.usgs.gov/catalog/RAM/SAHM/

NYU-Poly and Univ. of UT. 2014. VisTrails software, version 2.2.2 Available online at http://www.vistrails.org.

Peet, R.K., M.T. Lee, M.D. Jennings, D. Faber-Langendoen (eds). 2013. VegBank: The vegetation plot archive of the Ecological Society of America. http://vegbank.org; searched on 13, October, 2015.

Rocky Mountain Herbarium (RMH). 2015. University of Wyoming, Department of Botany (http://www.rmh.uwyo.edu/). Accessed October 2015.

Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321.

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). 2006. Digital General Soil Map of U.S. U.S. Department of Agriculture, Natural Resources Conservation Service, Fort Worth, Texas. Available online http://websoilsurvey.nrcs.usda.gov.

U.S. Geological Survey, Center for Earth Resources Observation and Science (USGS-EROS). 1996. GTOPO30: 30 arc-second DEM of North America. U.S. Geological Survey's Center for Earth Resources Observation and Science.

U.S. Geological Survey, Gap Analysis Program (USGS-GAP). 2016. Land Cover Data v2.2. U.S. Geological Survey, Gap Analysis Program.

U.S. Geological Survey, Earth Resources Observation and Science Center, Wildland Fire Science (USGS-WFS). 2016. LANDFIRE Existing Vegetation Type. U.S. Geological Survey's Center for Earth Resources Observation and Science. http://landfire.cr.usgs.gov

Appendix B: Decision Support Framework for Climate Adaptation in Cold-Water Fisheries

Adapted from Nelson et al. (2016) for Colorado BLM management of both native and non-native cold-water fish species

For the original framework, as well as details on background and methods, see:

Nelson, R., Cross, M., Hansen, L., and G. Tabor. 2016. A three-step decision support framework for climate adaptation: Selecting climate informed conservation goals and strategies for native salmonids in the northern U.S. Rockies. Wildlife Conservation Society, EcoAdapt, Center for Large Landscape Conservation. Bozeman, MT, USA. http://rmpf.weebly.com/cold-water-ecosystem-management-tool.html.

The framework consists of three steps, beginning with Table B-1 and then proceeding through Tables B-2 and B-3. Models in Figures 21-32 can be used to estimate habitat suitability and connectivity generally, but will not substitute for site-specific evaluation at project scales.

Strategies in Table B3 were derived from the following sources, as cited in Nelson et al. (2016).

CAP (Crown Adaptation Partnership). 2014. Workshop report—Taking action on climate change adaptation: piloting adaptation strategies to reduce vulnerability and increase resilience for native salmonids in the Crown of the Continent Ecosystem. Crown Managers Partnership, The Wilderness Society, Crown Conservation Initiative, U.S. Department of Agriculture, Forest Service. https://www.crownmanagers.org/

Cross, M., N. Chambers, L. Hansen, and G. Tabor. 2013. Workshop summary report: Great Northern Landscape Conservation Cooperative Rocky Mountain Partner Forum Climate Change and Cold Water Systems. Wildlife Conservation Society, Center for Large Landscape Conservation, EcoAdapt and the Great Northern Landscape Conservation Cooperative. http://ecoadapt.org/data/documents/RMPF_climate_workshopreport_FINAL_small.pdf

Halofsky, J.E., D.L. Peterson, S.K. Dante-Wood, L. Hoang, J.J. Ho, and L.A. Joyce, eds. 2018. Climate change vulnerability and adaptation in the Northern Rocky Mountains Part 1. Gen. Tech. Rep. RMRS-GTR-374. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Miller, S., M. Cross, and A. Schrag. 2009. Anticipating climate change in Montana: a report on a workshop with Montana Department of Fish, Wildlife and Parks focused on the Sagebrush-Steppe and Yellowstone River systems. Montana Fish Wildlife and Parks, National Wildlife Federation, Wildlife Conservation Society, World Wildlife Fund.

Nelson, R. 2014. A climate change adaptation gap analysis for the Crown of the Continent. Commissioned and published by the Crown Conservation Initiative. http://static1.1.sqspcdn.com/static/f/808688/25678703/1416253186333/CC_Gap_Analysis_Report_Public_FINAL_v2+copy.pdf?token=0OlV723%2BbCGnaxlPat4OZwr9mDE%3D

Rieman, B., and D. Isaak. 2010. Climate change, aquatic ecosystems and fishes in the Rocky Mountain West: implications and alternatives for management. General Technical Report GTR-RMRS-250. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. https://www.researchgate.net/profile/Daniel_Isaak/publication/257875934_Climate_change_aquatic_ecosystems_and_fishes_in_the_Rocky_Mountain_West_implications_and_alternatives_for_management/links/0c960526048b822109000000/Climate-change-aquatic-ecosystems-and-fishes-in-the-Rocky-Mountain-West-implications-and-alternatives-for-management.pdf

Table B- 1. STEP ONE in Climate Adaptation Decision Support Framework, modified from Nelson et al. 2016.

Key Factor of Vulnerability	HABITAT SUITABILITY To what extent will climate change alter habitat suitability for the population?	THREATS FROM UNDESIRABLE FISH To what extent will climate change increase the threat that undesirable fish present to the population?	CONNECTIVITY To what extent will climate change alter the degree of connectivity of the population to a larger network of populations and suitable habitat?
Climate-related Questions to Consider	• Are stream temperatures expected to remain (or become) suitable? • Are other key habitat conditions (e.g., streamflow quantity and timing, sediments, patch size, etc.) expected to remain or become suitable as climate changes? • Are climate-driven changes likely to interfere with life-history requirements of focal species (e.g., changes in winter flooding might influence spawning success)? • Is the population in an area naturally more resilient to changing climate conditions (i.e., because of the elevation, size of the habitat patch, connection to lakes that provide vertical temperature stratification, or the presence of features that could buffer warming such as groundwater upwelling or cold-air drainages)? • Could climate-driven changes in human water use and management affect stream flow quantity, quality and timing?	• Are undesirable fish currently present? • If undesirable fish are currently present, might climate change alter the influence of undesirable fish on desirable fish (e.g., via hybridization, competition, predation)? • If undesirable fish are currently absent, could climate change potentially increase the invasion threat (i.e., by altering habitat conditions or disturbance events that might facilitate invasion)?	• Is the population currently isolated, or is it connected to a larger network of populations and habitat? • If currently connected to a larger network, do you expect this connectivity to remain given changing climate conditions (e.g. is the existing habitat vulnerable to fragmentation by changing stream flows and temperatures)? • Are features present (e.g. culverts, low water crossings) that could become barriers to fish movement under changing stream flows? • If currently isolated, is the population like to persist given changing climate conditions and associated extreme events (e.g., wildfire, floods, erosion)?
Assess Vulnerabilities	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on habitat suitability: A -Habitat likely to remain or become suitable B - Habitat likely to become marginal (i.e., at or near thresholds for focal species) C - Habitat likely to become unsuitable	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on undesirable fish: D - Threats from undesirable fish likely to be low E - Threats from undesirable fish likely to be high (because already present or likely to increase)	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on connectivity: F - Population likely to be connected to a larger network G - Population likely to remain or become isolated

If you answered:	Go to Box:	If you answered:	Go to Box:	If you answered:	Go to Box:
A D F	1	B D F	2	C D F	3
A E F	4	B E F	5	C E F	6
A D G	7	B D G	8	C D G	9
A E G	10	B E G	11	C E G	12

Table B- 2. STEP TWO in Climate Adaptation Decision Support Framework, modified from Nelson et al. 2016.

		HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION IS CONNECTED TO A LARGER NETWORK	LOW THREAT FROM UNDESIRABLE FISH	BOX 1 *Relative vulnerability to climate change:* ***Low*** *Relative value for conservation of desirable fish species*: High value in both the short and long term Potential Goal: Protect and maintain (or improve if warranted) this habitat network for long-term conservation of desirable fish species. *Strategies*: • Protect climate refugia; • Protect existing networks; • Expand/refound populations; • Prevent invasion by undesirable fish	BOX 2 *Relative vulnerability to climate change:* ***Medium*** *Relative value for conservation of desirable fish species*: Potential value over the long term, but will likely require investment to moderate climate impacts *Potential Goal*: Improve the suitability of this habitat network for long-term conservation of desirable fish species. *Strategies*: • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of desirable fish species; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Protect existing networks; • Reduce uncertainty through research and monitoring; • Prevent invasion by undesirable fish	BOX 3 *Relative vulnerability to climate change:* ***Medium-High*** *Relative value for conservation of desirable fish species*: Potential value in the short term to help with population recovery, maintenance of genetic diversity and/or local adaptations; Longer term value is lower due to decreasing habitat suitability *Potential Goal*: Maintain population in the short-term; In the longer-term, consider facilitating the movement of current population to other locations with more suitable conditions, facilitating the transition of the location to a new state, and/or managing the location for other targets (e.g., non-fish targets) *Strategies*: • Reduce uncertainty through research and monitoring; • Increase adaptive capacity of desirable fish; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state

	HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION IS CONNECTED TO A LARGER NETWORK HIGH THREAT FROM UNDESIRABLE FISH	BOX 4 *Relative vulnerability to climate change:* ***Medium-Low*** *Relative value for conservation of desirable fish species*: High value in both the short and long term, but may require investment to prevent/remove/suppress undesirable fish *Potential Goal*: Prevent invasion of undesirable fish (or remove/suppress if already present), and protect and maintain (or improve if warranted) this habitat network for long-term conservation of desirable fish species. *Strategies*: • Remove/suppress undesirable fish; • Prevent invasion by undesirable fish; • Expand/refound populations; • Protect existing networks; • Protect climate refugia.	BOX 5 *Relative vulnerability to climate change:* ***Medium-High*** *Relative value for conservation of desirable fish species*: Potential value over the long term, but will require a high-level of investment to both moderate climate impacts and prevent/remove/suppress undesirable fish *Potential Goal*: Prevent invasion of undesirable fish (or remove/suppress if already present), and improve the suitability of this habitat network for long-term conservation of desirable fish species. *Strategies*: • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of desirable fish; • Remove/suppress undesirable fish; • Prevent invasion by undesirable fish; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Protect existing networks; • Reduce uncertainty through research and monitoring.	BOX 6 *Relative vulnerability to climate change:* ***High*** *Relative value for conservation of desirable fish species*: Potential value in the short term to help with population recovery, maintenance of genetic diversity and/or local adaptations, but will require investment to prevent/remove/suppress undesirable fish; Longer-term value is lower due to decreasing habitat suitability *Potential Goal*: Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., non-fish targets) *Strategies*: • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s).

	HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION REMAINS OR BECOMES ISOLATED LOW THREAT FROM UNDESIRABLE FISH	BOX 7 *Relative vulnerability to climate change: **Medium-Low*** *Relative value for conservation of desirable fish species*: Potential value for providing genetic diversity and/or local adaptations in both the short and long term, but will likely require investment to address fragmentation *Potential Goal*: Evaluate representativeness of this population across the landscape, and determine what level of protection/reconnection to other habitats is warranted *Strategies*: • Reconnect fragmented networks; • Protect climate refugia; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Expand population; • Prevent invasion by undesirable fish	BOX 8 *Relative vulnerability to climate change: **Medium*** *Relative value for desirable fish conservation*: Potential value for providing genetic diversity and/or local adaptations, but will likely require investment to moderate climate impacts and address fragmentation *Potential Goal*: Evaluate representativeness of this population across the landscape, and determine what level of protection/restoration/active management is warranted *Strategies*: • Reconnect fragmented networks; • Moderate stream temperature increases; • Moderate base flow decreases; • Moderate peak flow increases; • Increase adaptive capacity of desirable fish; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Reduce uncertainty through research and monitoring; • Prevent invasion by undesirable fish	BOX 9 *Relative vulnerability to climate change: **Medium-High*** *Relative value for conservation of desirable fish species*: Potential value in short-term for providing genetic diversity and/or local adaptations, but will likely require investment to address fragmentation; Longer-term value is lower due to decreasing habitat suitability *Potential Goal*: Maintain population in the short-term; In the longer-term, consider facilitating the movement of current population to other locations with more suitable conditions, facilitating the transition of the location to a new state, and/or managing the location for other targets (e.g., non-fish targets) *Strategies*: • Reduce uncertainty through research and monitoring; • Increase adaptive capacity of desirable fish; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state

		HABITAT REMAINS OR BECOMES SUITABLE	HABITAT BECOMES MARGINAL	HABITAT BECOMES UNSUITABLE
POPULATION REMAINS OR BECOMES ISOLATED	HIGH THREAT FROM UNDESIRABLE FISH	**BOX 10** *Relative vulnerability to climate change:* ***Medium*** *Relative value for conservation of desirable fish species*: Potential value, but may will likely require investment to prevent/remove/suppress undesirable fish and address fragmentation *Potential Goal*: Evaluate representativeness of this population across the landscape, and determine what level of protection, reconnection to other habitats, and management on undesirable fish is warranted *Strategies*: • Reconnect fragmented networks; • Protect climate refugia; • Minimize adverse impacts in the event of potential increased wildland fire disturbance; • Expand population; • Prevent invasion by undesirable fish	**BOX 11** *Relative vulnerability to climate change:* ***Medium-High*** *Relative value for conservation of desirable fish species*: Lower value, and will likely require a high-level of investment to moderate climate impacts, prevent/remove/suppress undesirable fish, and address fragmentation *Potential Goal*: Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., game fish or non-fish targets) *Strategies*: • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s)	**BOX 12** *Relative vulnerability to climate change:* ***High*** *Relative value for conservation of desirable fish species*: Low value *Potential Goal*: Facilitate the movement of current population to other locations with more suitable conditions; Facilitate the transition of the location to a new state; Consider managing the location for other targets (e.g., non-fish targets) *Strategies*: • Reduce uncertainty through research and monitoring; • Relocate individuals to areas likely to remain or become suitable; • Facilitate transition to a new state; • Determine additional strategies after clarifying management goal(s)

Table B- 3. STEP THREE in Climate Adaptation Decision Support Framework, modified from Nelson et al. 2016.

Strategy	Objective	Example Actions
Expand/refound populations	Increase population size and number of populations to recover large, interconnected populations	• Expand populations at or below minimum viable population size • Refound new populations in areas expected to be climatically suitable
Facilitate transition to a new state	Allow colonization by new species that may be better suited to new environments and still provide some ecological function and value	• Remove barriers to invasion • Introduce new species
Increase adaptive capacity of desirable fish	Increase resilience of desirable fish populations to warming stream temperatures and flow changes	• Identify and restore "warm-adapted" populations of desirable species • Consider limiting angler pressure on desirable fish in streams that are at or near temperature thresholds • Replicate and supplement desirable fish populations • Remove undesirable fish
	Increase desirable fish health	• Increase public education to eliminate disease vectors • Treat or remove infected/diseased fish • Eliminate or control pollutants or contaminants
	Conserve genotypic/phenotypic diversity	• Conserve or restore a diverse representation of habitats across river basins • Maintain large population sizes to minimize loss of genetic variability and adaptive potential
Minimize adverse impacts in the event of potential increased wildland fire disturbance	Identify and minimize negative effects to areas most vulnerable to fire impacts	• Develop a geospatial layer of debris flow potential for pre-fire planning • Manage natural fuel conditions and unplanned wildfire effects through fuel management actions and/or use of unplanned wildfire ignitions to minimize negative effects (severity and extent) of fire
	Restore areas adversely affected by fire	• Inventory disturbed areas for candidate sites for riparian and upland vegetation restoration
Moderate base flow decreases	Restore or replicate stream flows	• Remove or breach dams • Increase storage of water in floodplains by encouraging natural flooding and groundwater infiltration • On regulated streams, pulse flows during critical times, sourcing from lower in the thermocline

Strategy	Objective	Example Actions
	Reduce water withdrawals and/or water diversions	• Increase efficiency of irrigation techniques • Explore potential to combine sprinkler and flood irrigation to capture increasing spring floods (and recharge groundwater supplies) and then switch to more efficient sprinkler irrigation when stream flows are lower • Consider alternative water supplies for public land operations to retain in-stream flows Legally secure water rights / agreements for in-stream flows • Reform water laws to enable increased acquisition of in-stream flow rights • Explore the use of water trusts / funds to increase investments in the protection of watershed health and function • Use water pricing to encourage water conservation • Where water diversions exist, ensure fish ladders avoid entrainment of desirable species
	Restore riparian vegetation	• Establish desirable riparian vegetation • Remove undesirable riparian vegetation
	Increase natural water storage in groundwater aquifers	• Reintroduce beaver and/or install artificial beaver-mimic dams where compatible with fish conservation goals • Increase off-channel habitat and protect refugia in side channels • Protect wetland-fed streams which maintain higher summer flows • Maintain / restore forest and wetland vegetation cover • Reduce road density
Moderate peak flow increases	Restore floodplain connections	• Remove infrastructure (e.g., roads, levees, rip rap, etc.) from floodplains • Reconnect floodplain features (e.g., channels, ponds) • Create new or restore degraded floodplain habitats
	Restore incised (scoured) channels	• Reintroduce beaver to encourage dam-building that increases sediment storage and deposition
	Restore riparian vegetation	• Establish riparian vegetation; remove undesirable vegetation • Remove stressors that cause riparian damage (illegal or degraded trails, cattle, etc.)

Strategy	Objective	Example Actions
	Restore stream flow regimes	• Disconnect road drainage from streams • Remove or retrofit undersized culverts Restore natural drainage systems, create retention ponds
	Reduce rain-on-snow flooding	• Maintain/restore forest, wetland and riparian vegetation cover
Moderate stream temperature increases	Connect populations to cold-water stream networks	• Remove dams or culverts that act as barriers and limit fish access to cold-water streams • Restore / provide in-stream flows • Resolve thermal barriers
	Reconnect floodplains	• Reconnect floodplain features (e.g. side channels, ponds) • Designate and restore natural floodplain boundaries • Remove infrastructure (e.g., roads, levees, rip rap, etc.) from floodplains
	Restore incised (scoured) channels	• Reintroduce beaver or build beaver dam analogs to increase sediment storage • Restore riparian vegetation • Remove stressors that cause riparian damage (illegal or degraded trails, cattle, etc.)
	Restore stream flows	• Work to restore natural flow regimes • Reduce water withdrawals, restore summer baseflow • On regulated streams, pulse flows during critical times, sourcing from lower in the thermocline
	Maintain/enhance riparian vegetation to shade streams	• Reduce grazing pressure (e.g. reduce stocking rates, use rest-rotation systems, fence riparian areas, provide off-stream water sources, retire vacant allotments in priority fish areas, increase monitoring in priority areas to ensure good practices) • Restore riparian vegetation in degraded areas • Adjust riparian vegetation to favor species that are better suited for future climate conditions
Prevent invasion of undesirable fish	Prevent undesirable fish invasion	• Strategically use physical or electrical barriers to prevent further spread of undesirable fish • Model future changes in stream flow and habitat to anticipate future invasion hotspots
	Restore habitats that convey an advantage for desirable fish over undesirable fish	• Restore spawning habitats for desirable fish • Connect current desirable populations with streams that are too cold for undesirable fish
	Expand existing desirable fish populations to increase chances of resisting invasion	• Expand desirable fish populations in areas where trying to prevent invasion of undesirable fish

Strategy	Objective	Example Actions
Protect climate refugia	Identify and protect areas likely to remain climatically suitable over the long-term	• Establish large-scale reserves for long-term desirable cold-water fish conservation • Connect current populations with streams that are currently too cold (and may warm to suitable levels in the future) • Look for opportunities for reintroductions in habitats likely to remain suitable over the long-term • Understand and map where groundwater inputs may buffer projected stream temperature increases
	Protect and restore critical or unique habitats that buffer survival during vulnerable periods (i.e., seasonally or at particular life history stages)	• Protect/restore off-channel habitats, spring brooks, and seeps important as early rearing environments • Protect/restore flood or thermal refugia and stream segments that are important as connections
Protect existing networks	Identify existing networks and potential threats to them (e.g. undesirable invasion, stream temp fragmentation)	• Establish large-scale reserves for long-term desirable cold-water fish conservation • Address threats to the network
Reconnect fragmented networks	Identify opportunities for reconnecting fragmented networks	• Remove instream barriers • Replace or retrofit culverts that will not function well during future low base flows • Maintain or reconnect large networks of habitat
Reduce uncertainty through research and monitoring	Improve systematic data collection and access across management and political boundaries	• Initiate and/or expand collaborative data collection and sharing that spans agencies and geographical boundaries, to ensure climate-fish research occurs at appropriate scales • Ensure published data are accessible in appropriate data repositories • Create, maintain, and use cross-boundary databases for monitoring data • Strategically improve and standardize monitoring efforts • Conduct strategic sampling that targets locations of higher biological or climatic interest (e.g., areas with the highest rates of climate change)

Strategy	Objective	Example Actions
	Transition research and monitoring toward population dynamics and sensitivity analyses	• Examine/study how climatic variation influences population dynamics (not just demography/ growth/phenology) in light of ecological context • Determine how climate change indirectly affects desirable populations (e.g., through exacerbating interactions between desirable and undesirable species; through influencing disease dynamics, etc.)
	Monitor changes in aquatic food web dynamics	• Assess food webs for baseline data; monitor food web dynamics in space and time
Relocate individuals to areas likely to remain or become suitable	Maintain gene flow, establish self- sustaining populations, and buffer potential for catastrophic losses	• Transport individuals to existing but otherwise inaccessible habitats likely to remain or become suitable as climate changes
Remove/suppress undesirable fish	Remove or suppress undesirable fish	• Remove or control undesirable fish (via electrofishing, chemical removal, genetic swamping) • Encourage increased harvest of undesirable species

APPENDIX C: CLIMATE CHANGE PRIMER DEVELOPED FOR SAN LUIS VALLEY FIELD OFFICE

Vulnerability From Future Climate, 2050

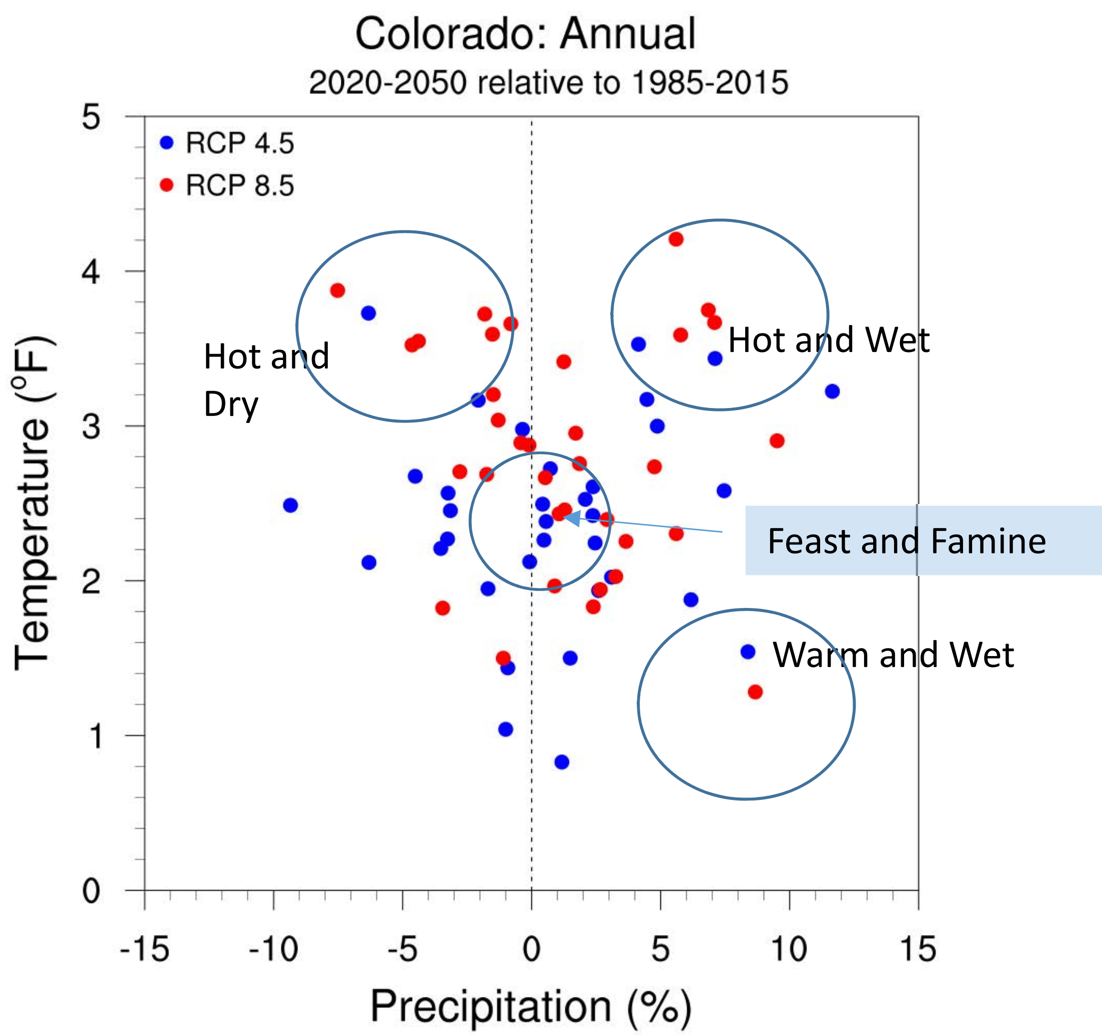
General Outline

- Overview of future climate
- Vulnerability assessment:
  - Methods
  - Results
  - Review of Summary Documents
- Next Steps
  - Develop adaptation strategies
    - Utilize social and ecological vulnerabilities assessments
    - Discuss the limitations

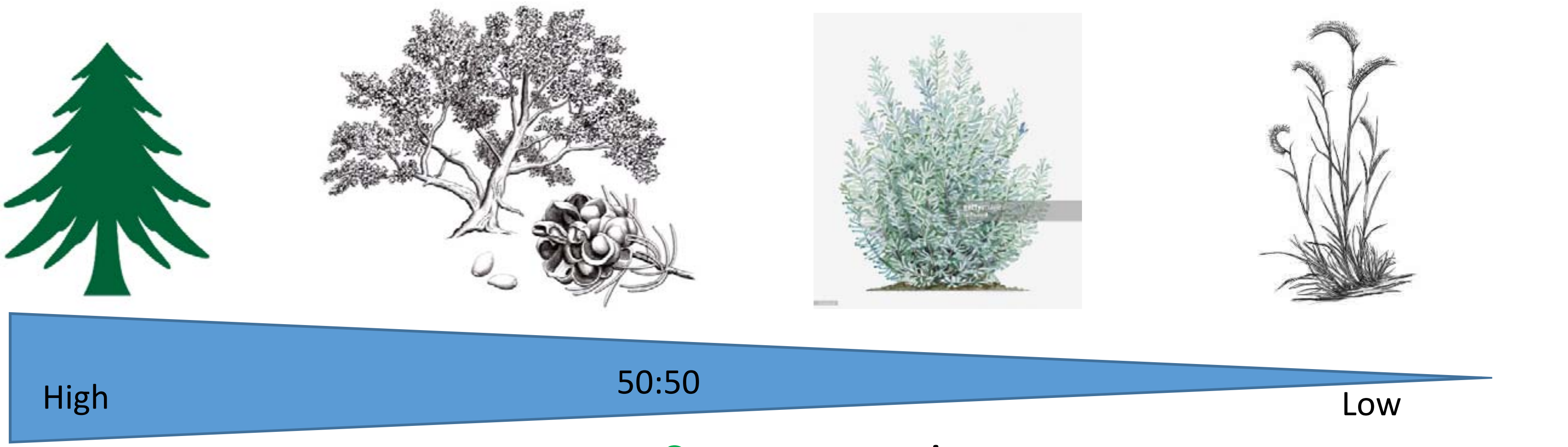
Future Climate Scenarios

Future Projections (2020-2050)

- 34 GCMs from CMIP5
- 2 Emissions Scenarios
- Warming by 1-4 °F
- Precip changes by -5% to 10% (4 scenarios of <-5%; 12 scenarios of >+5%)



Vegetation Correlated to Amount and Timing of Precipitation



Winter: Summer moisture

High

Deep soil moisture due to low ET in winter

Shallow soil moisture due to high ET in summer

Colorado's percent summer precipitation is variable. The San Luis Valley floor receives the majority of its precipitation during late summer months (J-A-S)

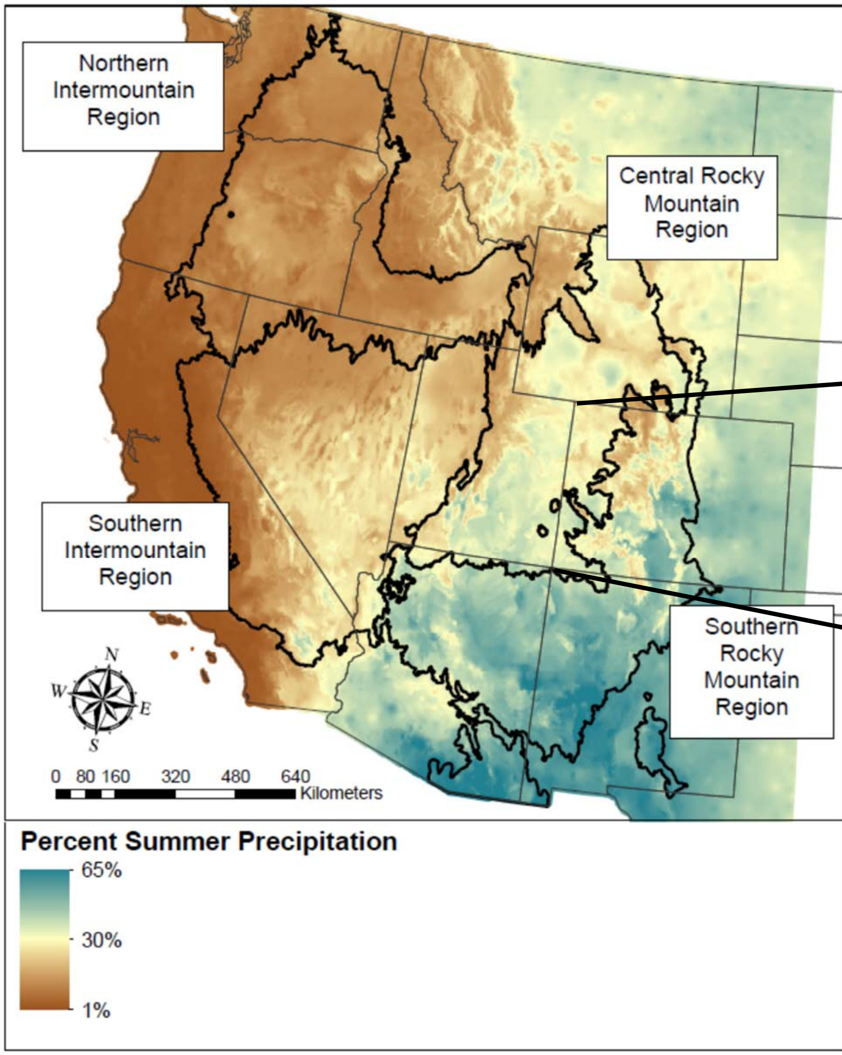
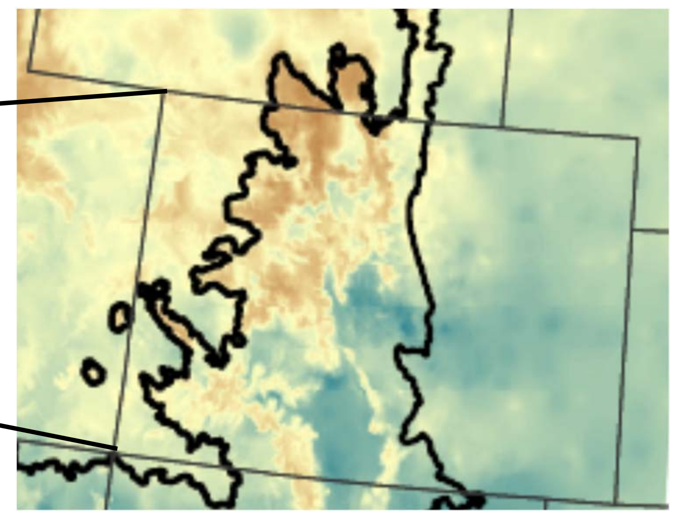


Figure 6—The percent of summer precipitation (July, August, and September) based on 30-year normal annual values for the western United States (PRISM 2016).



From Board et al. 2018

Changes in Temperature by Mid-Century

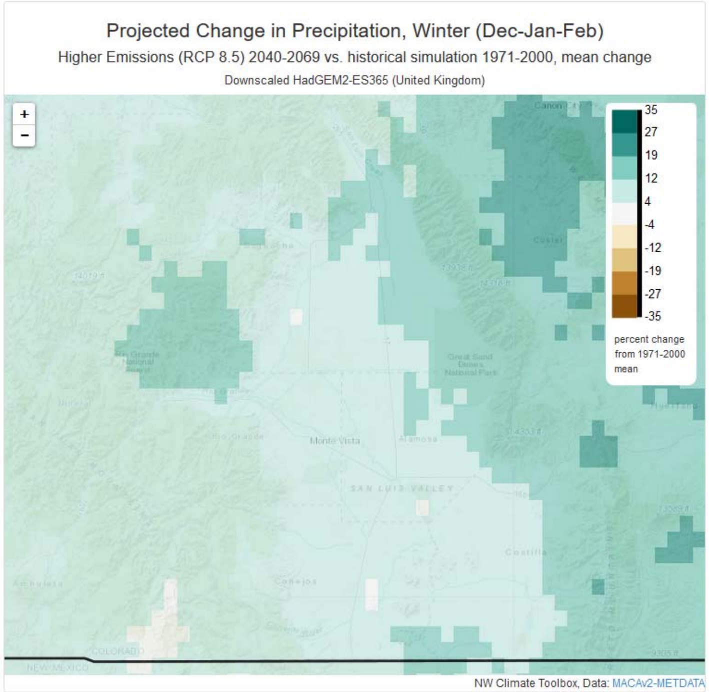
SLV ONLY	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Change between 2000 (1985-2015) and 2035 (2020-2050)	**hadgem2.es.1.rcp85**	*miroc-esm.1.rcp85*	*cesm1-bgc.1.rcp85*	*cnrm-cm5.1.rcp45*
Annual temperature increase °F (°C)	3.6 (2.0)	3.2 (1.8)	2.6 (1.4)	1.8 (1.0)
Winter temperature increase °F (°C)	3.0 (1.7)	3.6 (2.0)	3.0 (1.6)	2.4 (1.3)
Spring temperature increase °F (°C)	3.0 (1.7)	3.4 (1.9)	2.1 (1.1)	1.5 (0.8)
Summer temperature increase °F (°C)	4.5 (2.5)	2.2 (1.2)	2.7 (1.5)	2.0 (1.1)
Fall temperature increase °F (°C)	4.0 (2.2)	3.5 (1.9)	2.6 (1.4)	1.2 (0.7)

Changes in Precipitation by Mid-Century

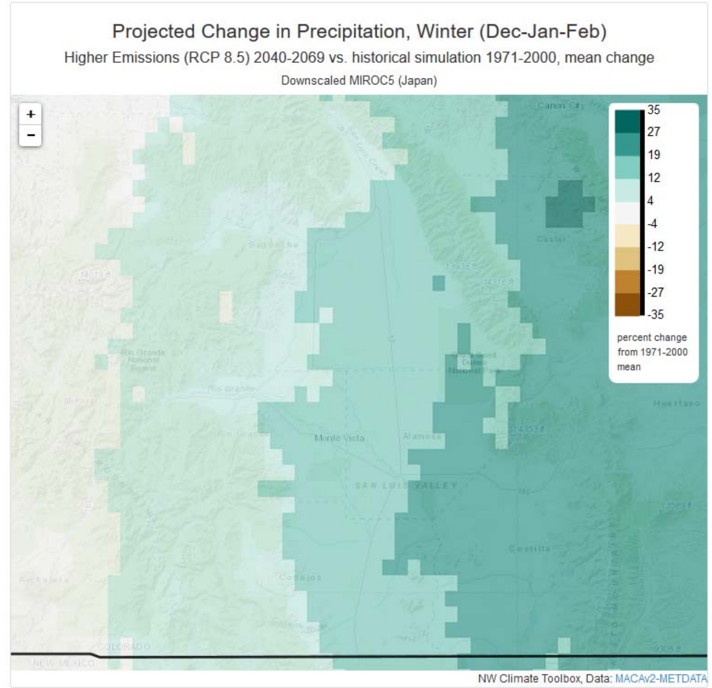
SLV ONLY	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Change between 2000 (1985-2015) and 2035 (2020-2050)	**hadgem2.es.1.rcp85**	*miroc-esm.1.rcp85*	*cesm1-bgc.1.rcp85*	*cnrm-cm5.1.rcp45*
Annual precipitation change (%)	1%	13%	1%	10%
Winter precipitation change (%)	27%	19%	4%	7%
Spring precipitation change (%)	-4%	26%	3%	8%
Summer precipitation change (%)	-13%	-2%	3%	12%
Fall precipitation change (%)	-2%	15%	-6%	12%
Summer monsoon (Jul-Aug ppt)	decrease by 11%	decrease by 4%	no change but large year to year fluctuation	increase by 17%

Change in Winter Precipitation (%)

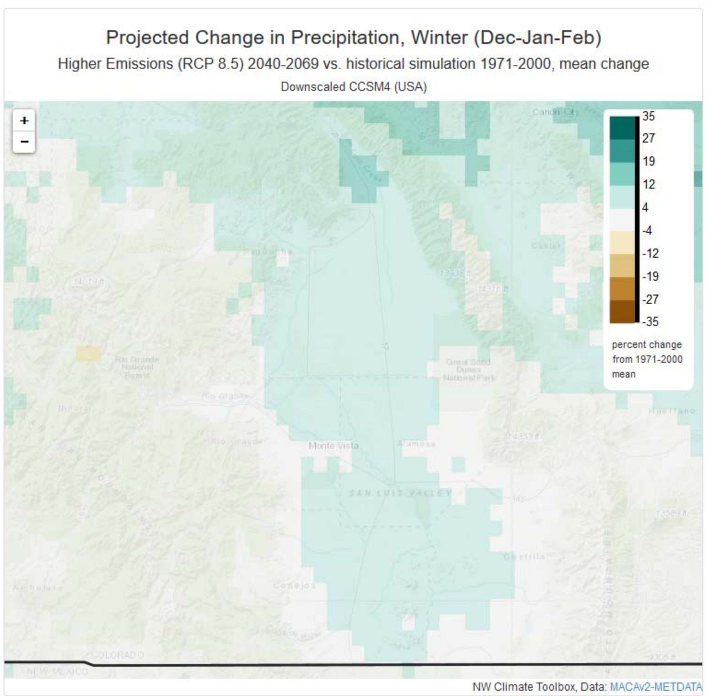
Hot & Dry



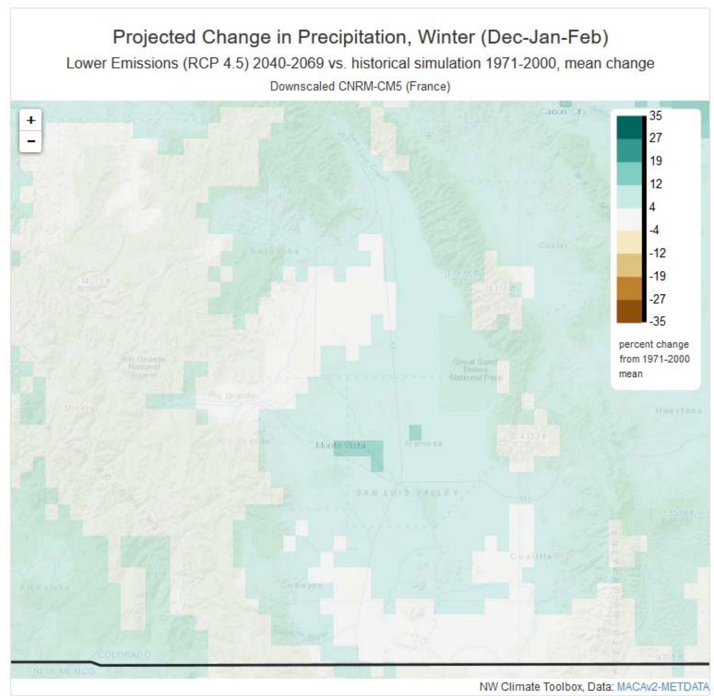
Hot & Wet



Feast & Famine

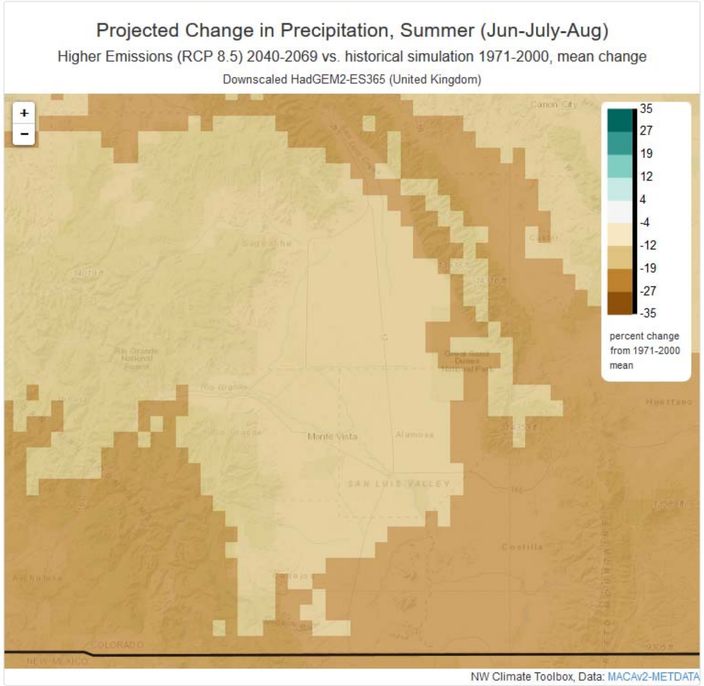


Warm & Wet

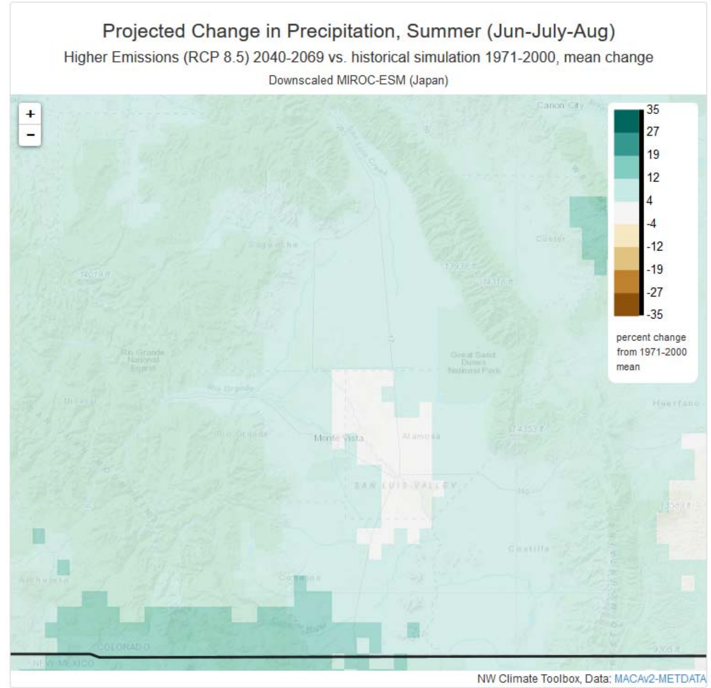


Change in Summer Precipitation (%)

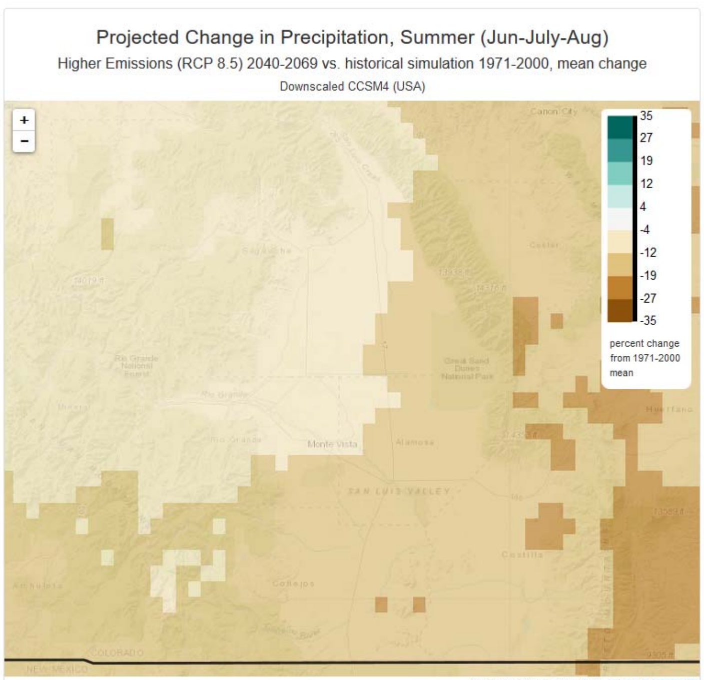
Hot & Dry



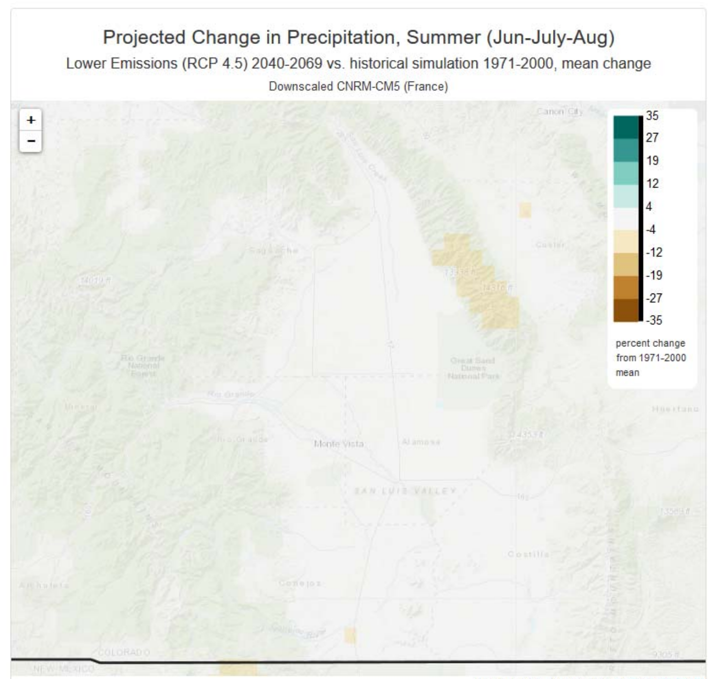
Hot & Wet



Feast & Famine



Warm & Wet



Changes in Hydrology by Mid-Century

SLV ONLY	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Change between 2000 (1985-2015) and 2035 (2020-2050)	**hadgem2.es.1.rcp85**	*miroc-esm.1.rcp85*	*cesm1-bgc.1.rcp85*	*cnrm-cm5.1.rcp45*
April 1 SWE change	0%	-31%	-19%	-6%
Total Runoff	-11%	15%	-13%	6%
Apr-Sep Soil water storage change	-23%	-14%	-14%	-6%

Changes in Drought and Fire by Mid-Century

SLV ONLY	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Change between 2000 (1985-2015) and 2035 (2020-2050)	*hadgem2-ao.1.rcp85*	*canesm2.1.rcp85*	*cesm1-bgc.1.rcp85*	*gfdl-esm2m.1.rcp45*
Severe Drought years (like 2002) frequency	every 5-10 years	about once in 10 years - more often for center of SLV	every 5-10 years in southern portion	<1 per decade
Severe Drought duration	1-2 years	1-2 years	1-3 years lower elev worst	1 year
Fire frequency	greater fire frequency, especially in high elevation	some increase in fire frequency	fire risk during dry years is very high due to high fuel load from wet years	same as current
Fire season length	noticeably longer	longer	somewhat longer and large year to year fluctuations	same as current

Drought vs. Aridification

Pulse Drought – short-term extreme droughts

Press Drought—Chronic reductions in water availability (aridification).

Indices to Measure Drought

- Pulse Droughts
  - Climate Water Deficit
  - Palmer Drought Severity Index
  - LERI and EDDI
  - FDSI
- Press Drought
  - Trend in average growing season soil moisture
  - Trend in potential evapotranspiration

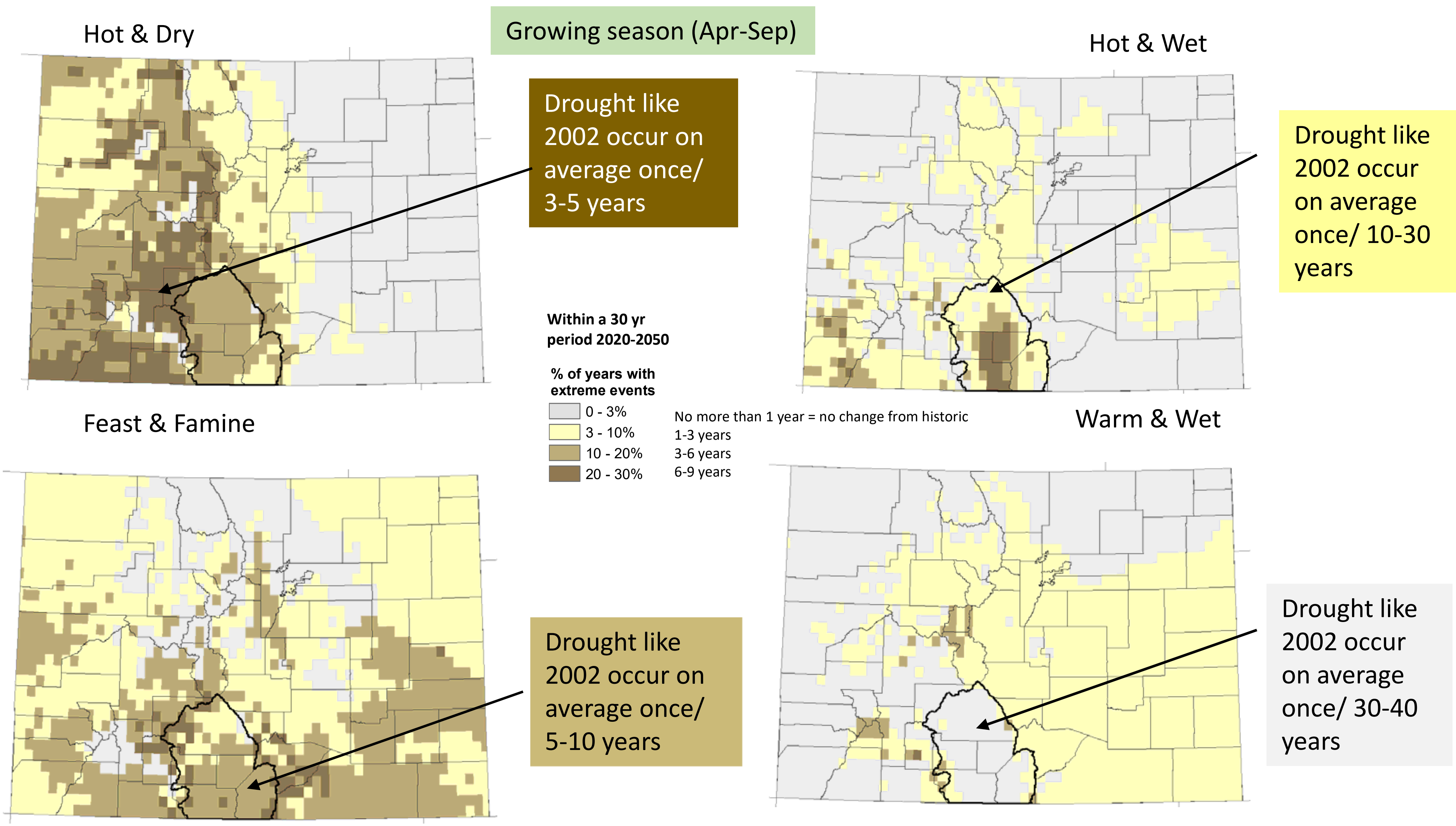
Climate Water Deficit (extreme drought)

Climate Water Deficit (CWD), defined by Stephenson (1998) is quantified as the amount of water by which **Potential Evapotranspiration (PET)** exceeds **Actual Evapotranspiration (AET).** It effectively integrates the combined effects of solar radiation, evapotranspiration, and air temperature.

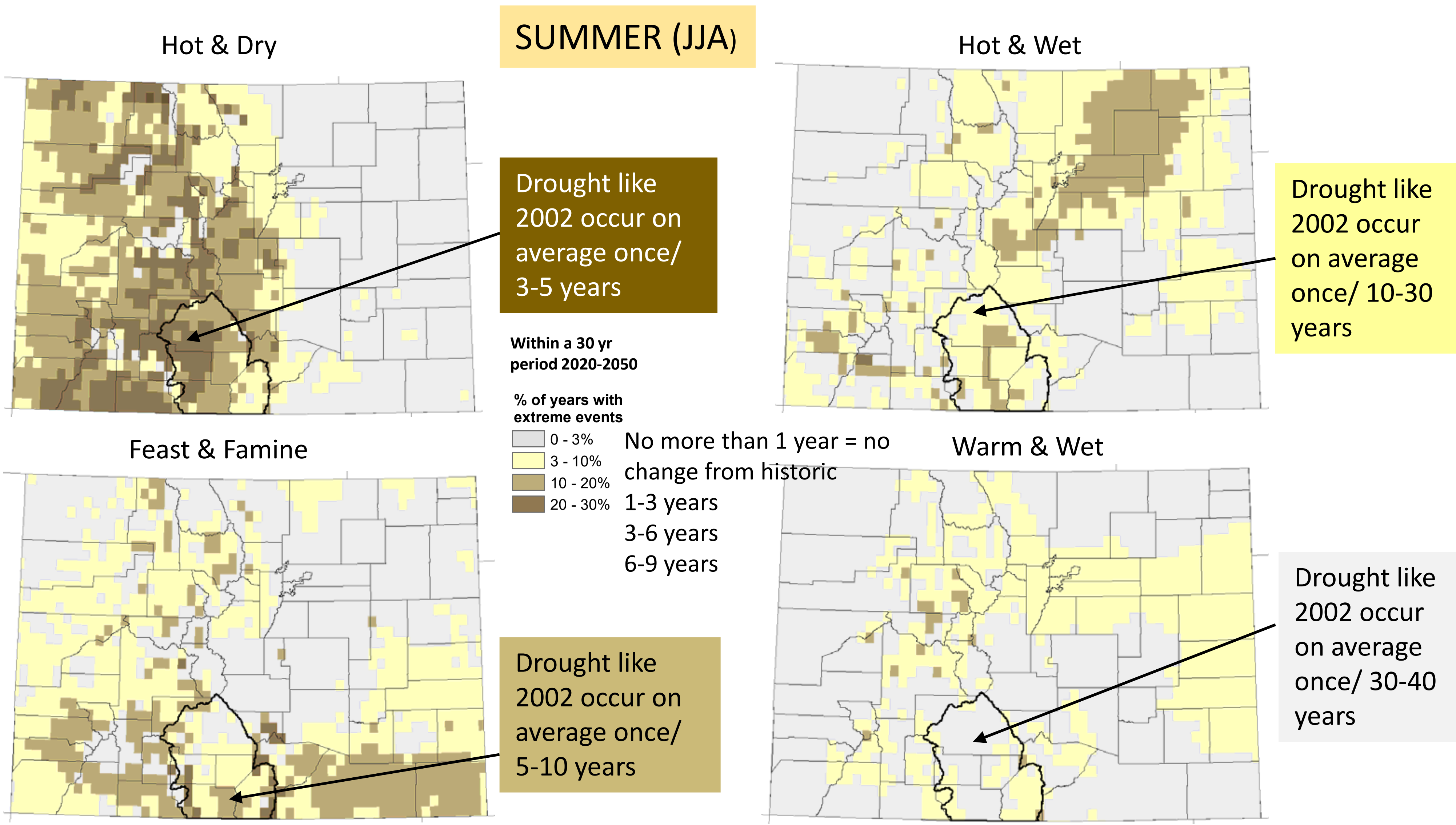
It is an estimate of drought stress on soils and plants and may serve as an effective control on vegetation cover types.

CWD = PET-AET

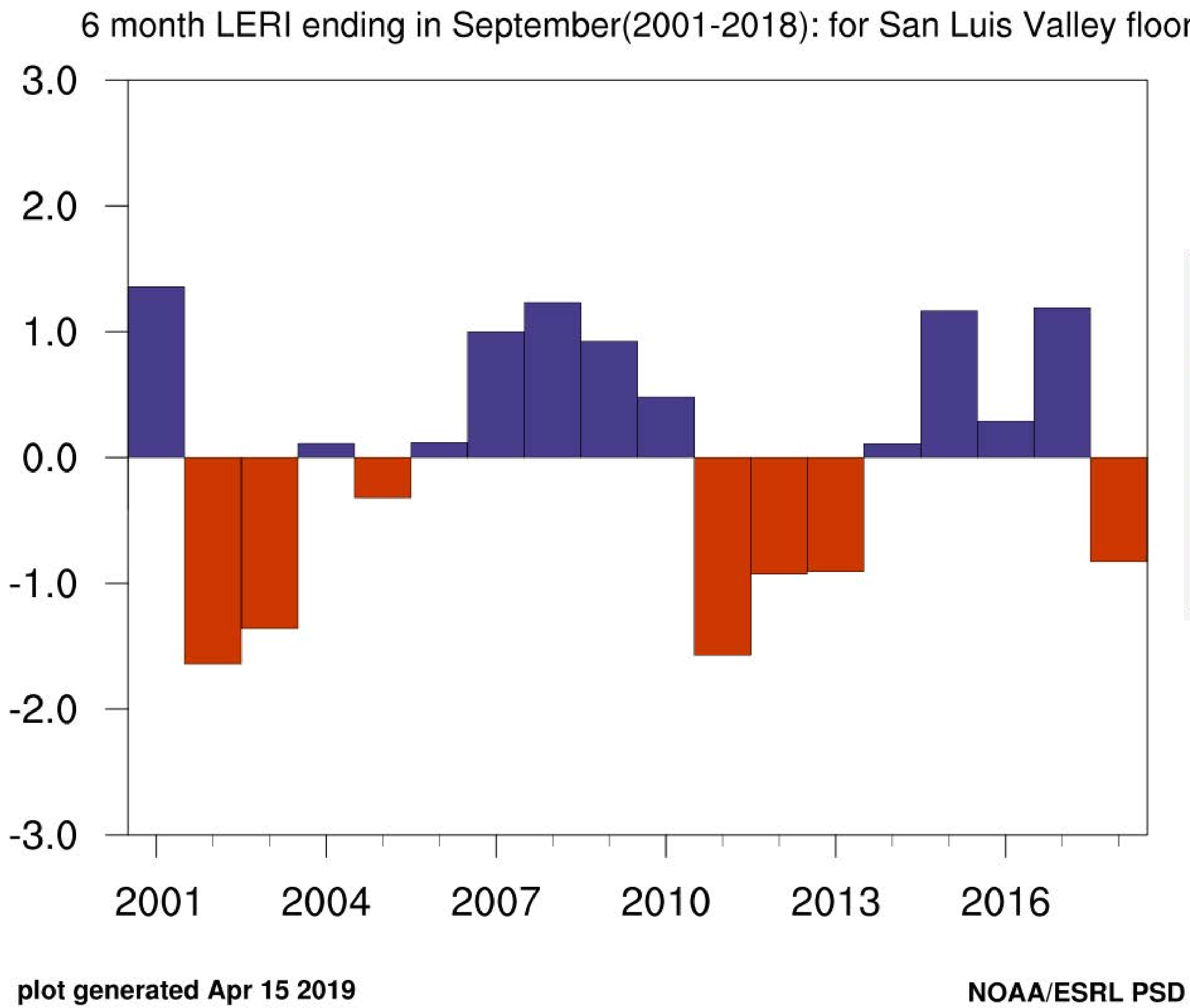
Frequency of Extreme Drought events (Climate Water Deficit) for mid-century compared to 1985-2015

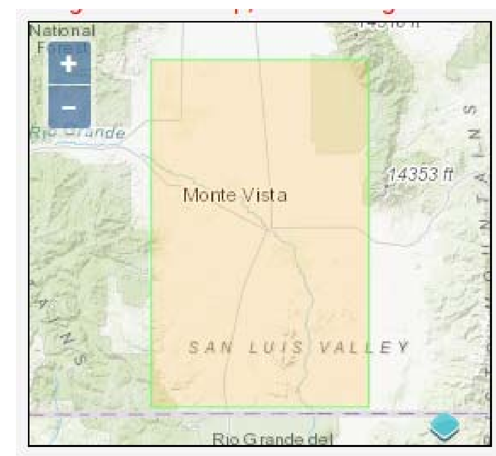


Frequency of Extreme Drought Events (Climate Water Deficit) for mid-century compared to 1985-2015

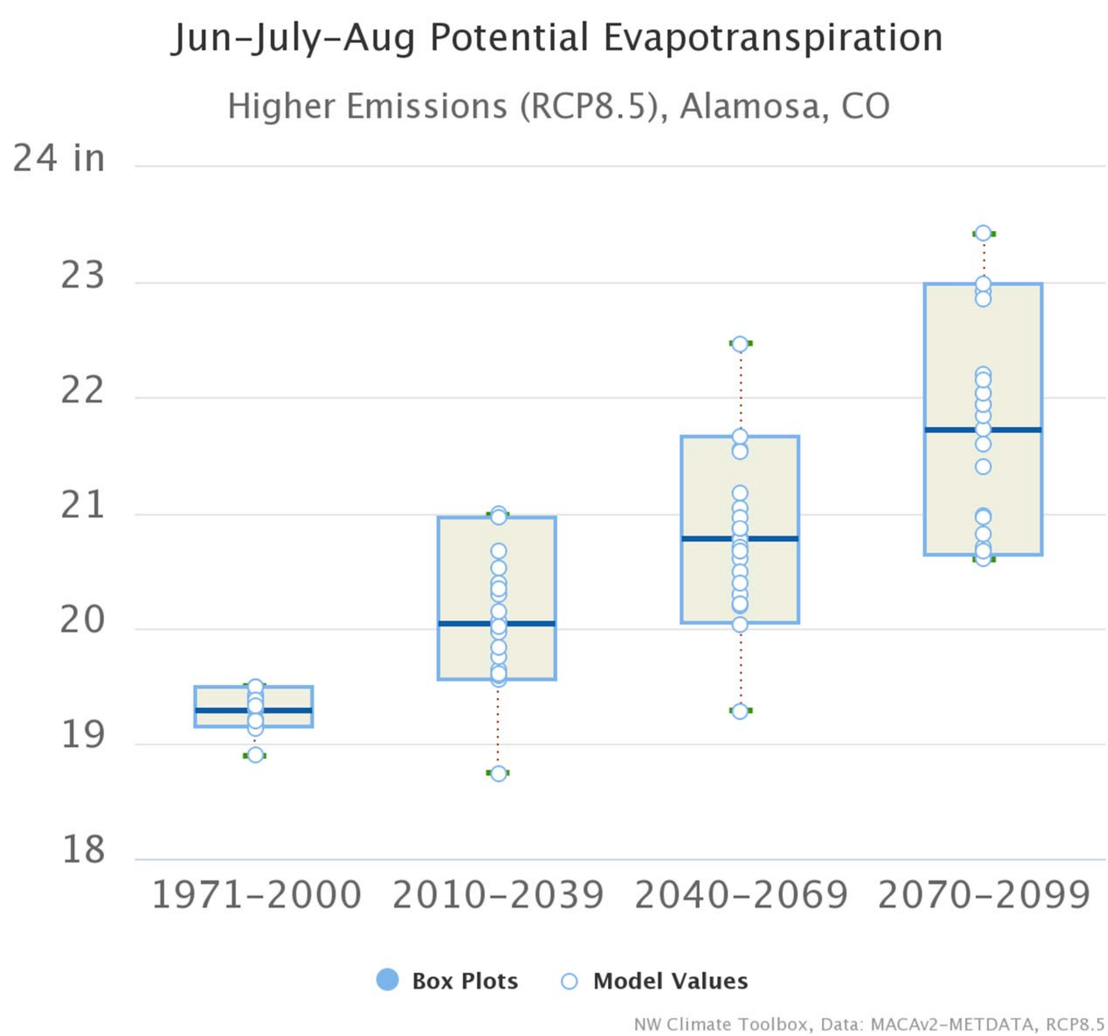


LERI – Landscape Evaporative Response Index

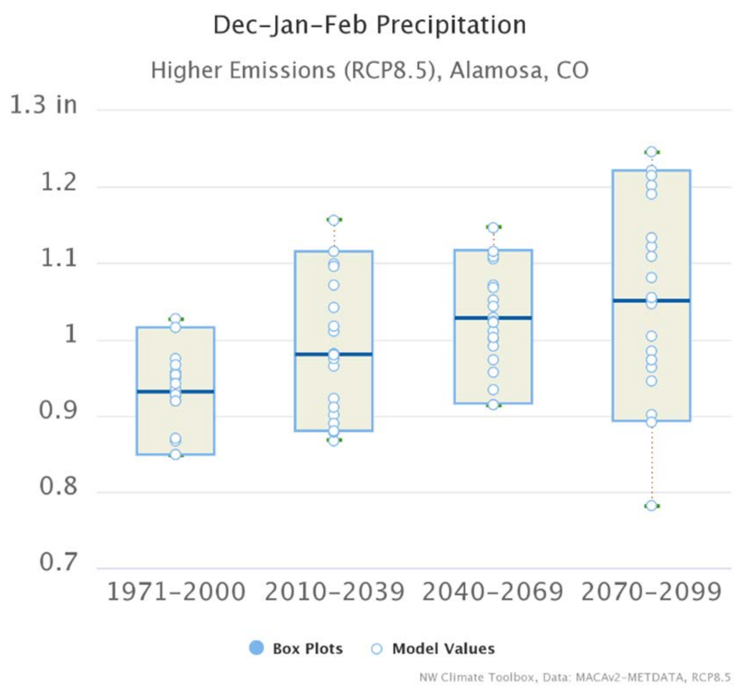


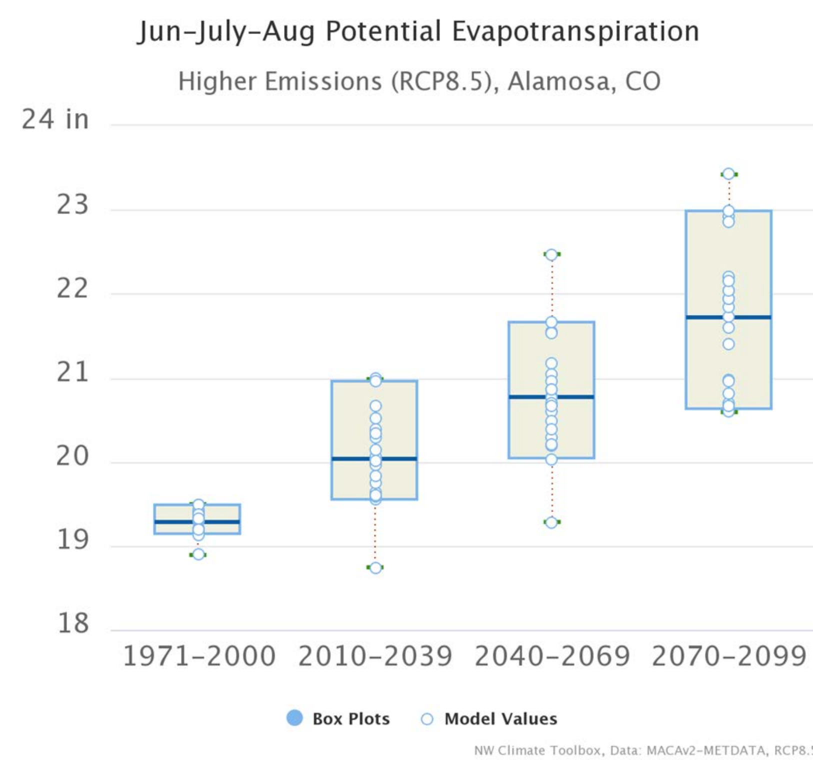


Potential Evapotranspiration: Aridification (Press Drought)



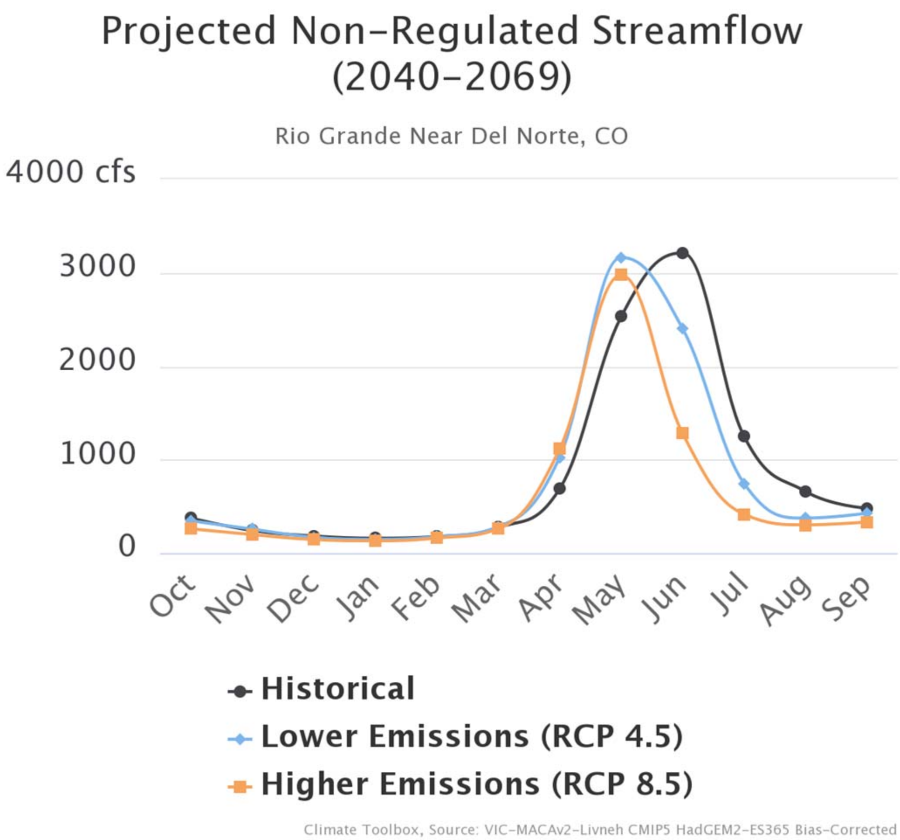
By 2050, the potential evapotranspiration is projected to be above the historic range. The result will be drier soils and a higher demand for irrigation water for current crops.


Dec-Jan-Feb Precipitation
Higher Emissions (RCP8.5), Alamosa, CO
1.3 in
1.2
1.1
1
0.9
0.8
0.7
1971-2000
2010-2039
2040-2069
2070-2099
Box Plots
Model Values
NW Climate Toolbox, Data: MACAv2-METDATA, RCP8.5

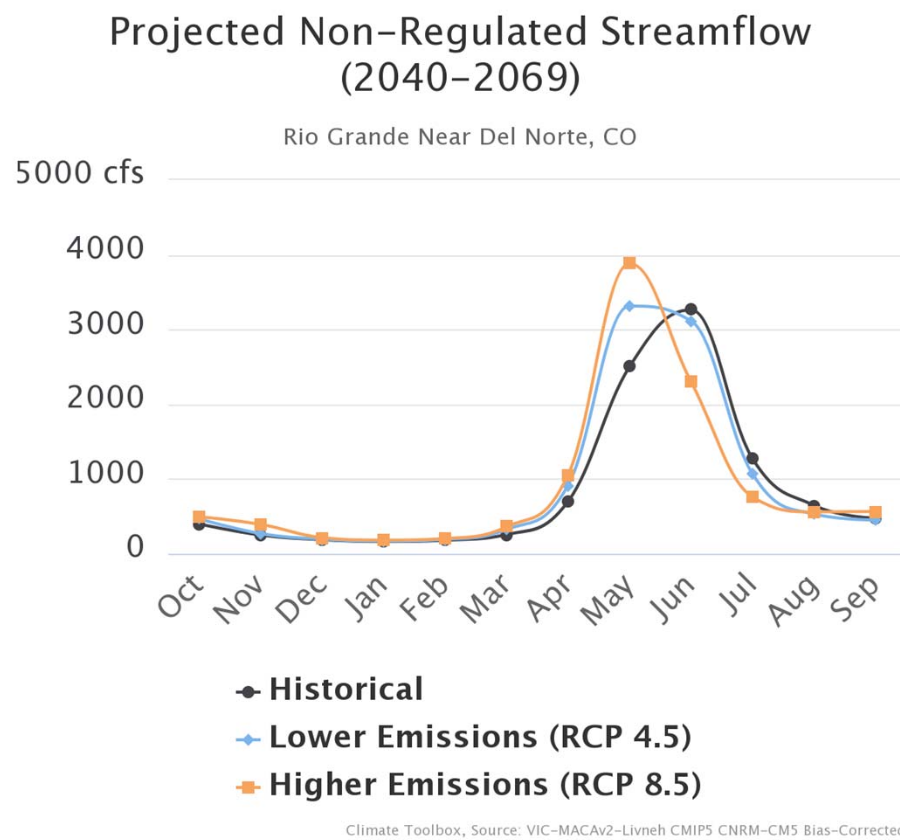

Jun-July-Aug Potential Evapotranspiration
Higher Emissions (RCP8.5), Alamosa, CO
24 in
23
22
21
20
19
18
1971-2000
2010-2039
2040-2069
2070-2099
Box Plots
Model Values
NW Climate Toolbox, Data: MACAv2-METDATA, RCP8.5

Streamflow and Runoff

Hot & Dry



Warm & Wet



Peak runoff shifts from June to May; amount of runoff varies by scenario

Local Projections: Water

Higher Emissions (RCP 8.5)

Alamosa, CO (37.47° N, 105.87° W)

	2000s	2025s	2055s	2085s
	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)
PREC /PET	7.3" /39.6"	7.5" /42.8"	7.4" /46.2"	7.4" /49.9"
WATER DEFICIT	-32.3"	-35.3"	-38.8"	-42.5"

NW Climate Toolbox, Data: gridMET & MACAv2-METDATA

Local Projections: Growing Season

Higher Emissions (RCP 8.5)

Alamosa, CO (37.47° N, 105.87° W)

	2000s	2025s	2055s	2085s
	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)	ANNUAL (Jan-Dec)
FIRST FREEZE /LAST FREEZE	Sept 19 /May 31	Sept 25 /May 22	Oct 2 /May 12	Oct 1 /May 4
LENGTH	110 days	125 days	143 days	151 days

NW Climate Toolbox, Data: gridMET & MACAv2-METDATA

Local Projections: Fire Danger (Summer/Fall)

Higher Emissions (RCP 8.5)

Trickle Mountain (38.16° N, 106.40° W)

	2000s	2025s	2055s
Season	SUMMER(Jun-Aug)/ FALL(Sept-Nov)	SUMMER(Jun-Aug)/ FALL(Sept-Nov)	SUMMER(Jun-Aug)/ FALL(Sept-Nov)
FUEL MOISTURE(SUMMER) /(FALL)	10.6% /13%	10.6% /12.8%	10.3% /12.6%
EXTREME DANGER(SUMMER) /(FALL)	7.6days /0.5days	9.8days /1.1days	13.3days /1.5days

NW Climate

Local Projections: Fire Danger (Winter/Spring)

Higher Emissions (RCP 8.5)

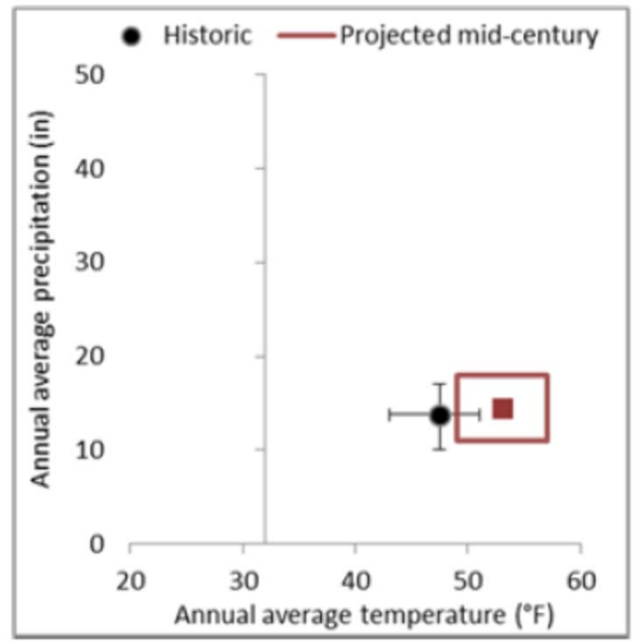
Trickle Mountain (38.16° N, 106.40° W)

	2000s	2025s	2055s
Season	WINTER(Dec-Feb)/ SPRING(Mar-May)	WINTER(Dec-Feb)/ SPRING(Mar-May)	WINTER(Dec-Feb)/ SPRING(Mar-May)
FUEL MOISTURE(WINTER) /(SPRING)	15.7% /10.7%	15.4% /10.6%	14.9% /10.1%
EXTREME DANGER(WINTER) /(SPRING)	0days /2.8days	0.1days /5.6days	0.1days /8.8days

NW Climate Toolbox, Data: gridMET & MACAv2-METDATA

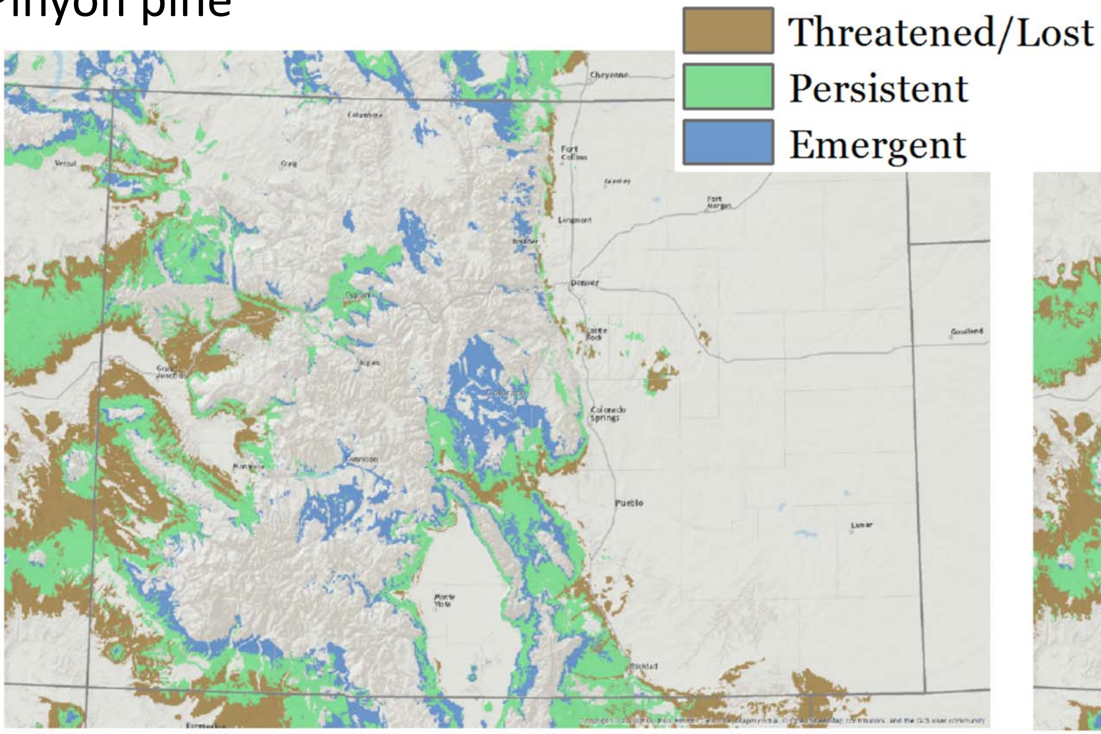
Biological Niche Models

- Use known locations of species to find important past climate variables (Maxent models)
- Make new models with predicted future climate data
- Assess future status: expanding, stable, or contracting

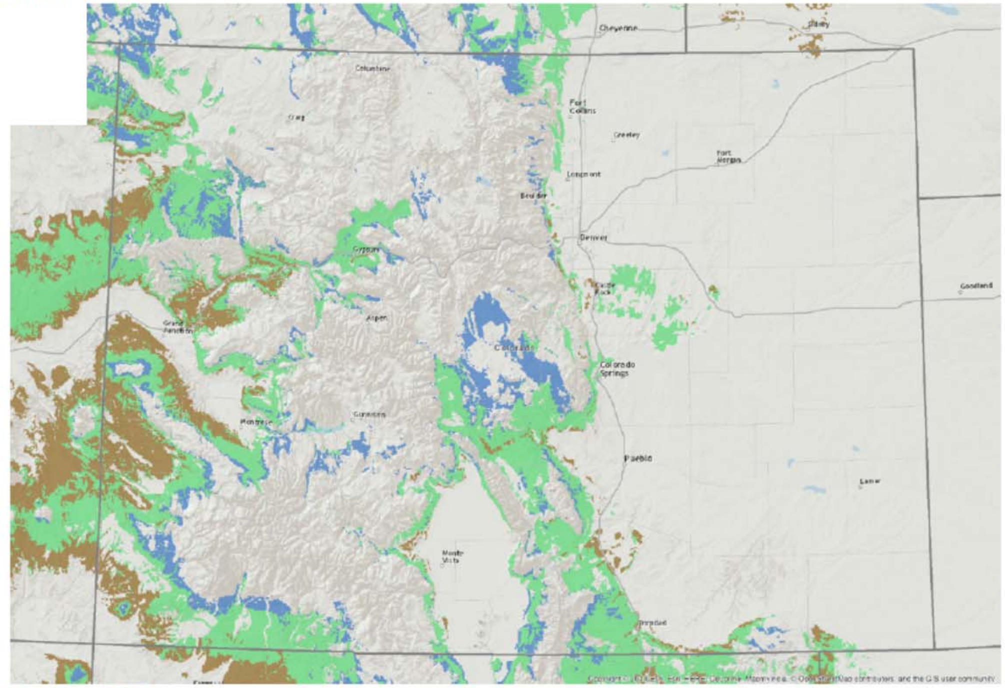


State wide Pinyon Pine precipitation and temperature range, comparing historic to future. From CNHP 2015

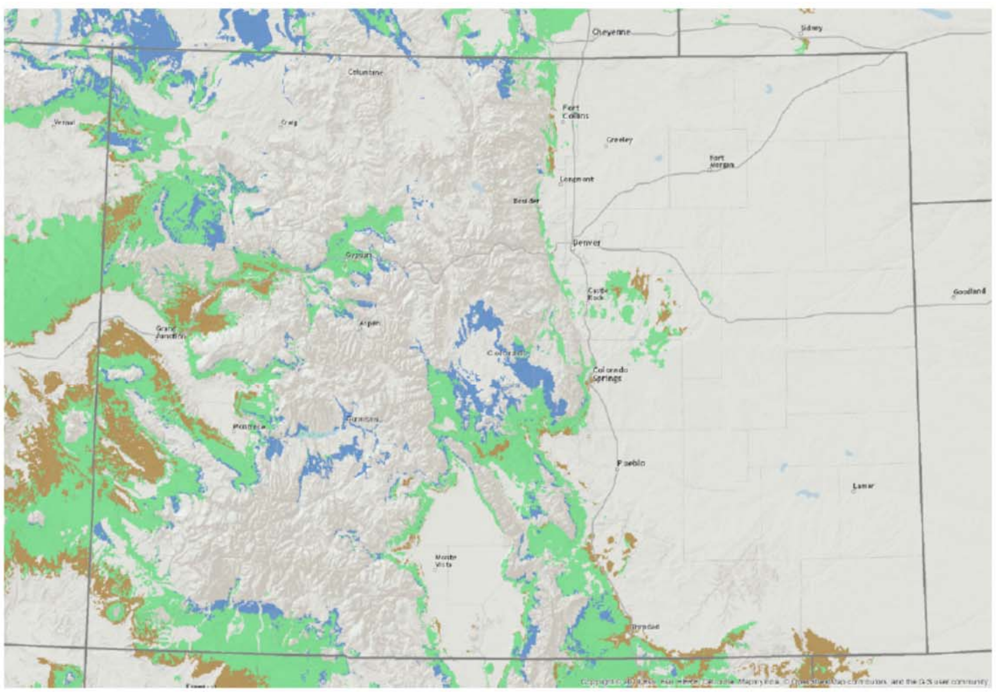
Pinyon pine



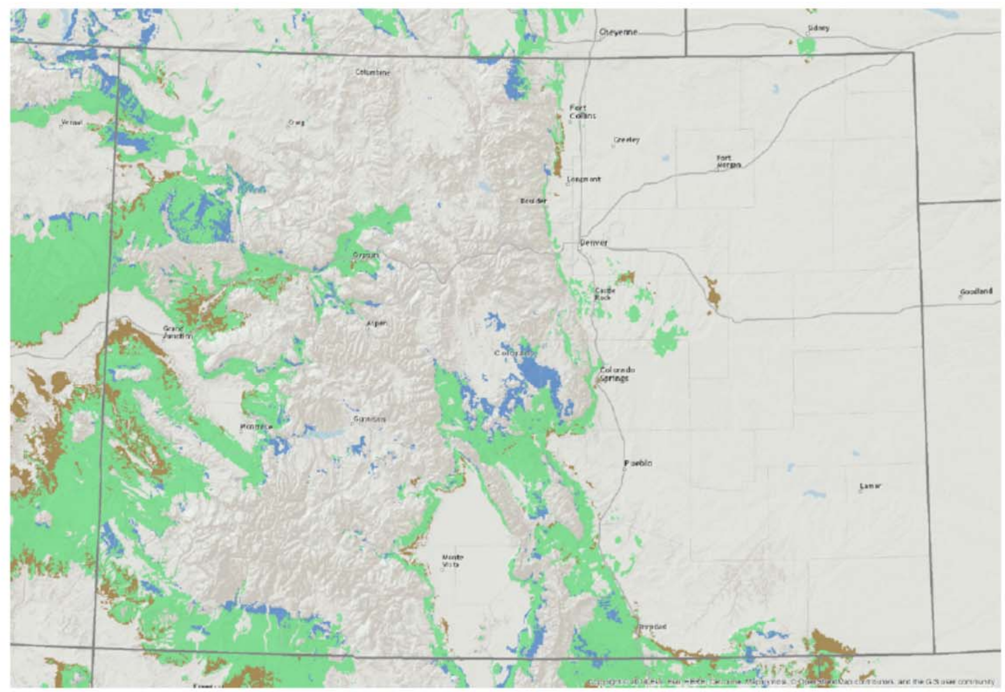
a) Hot & Dry Scenario



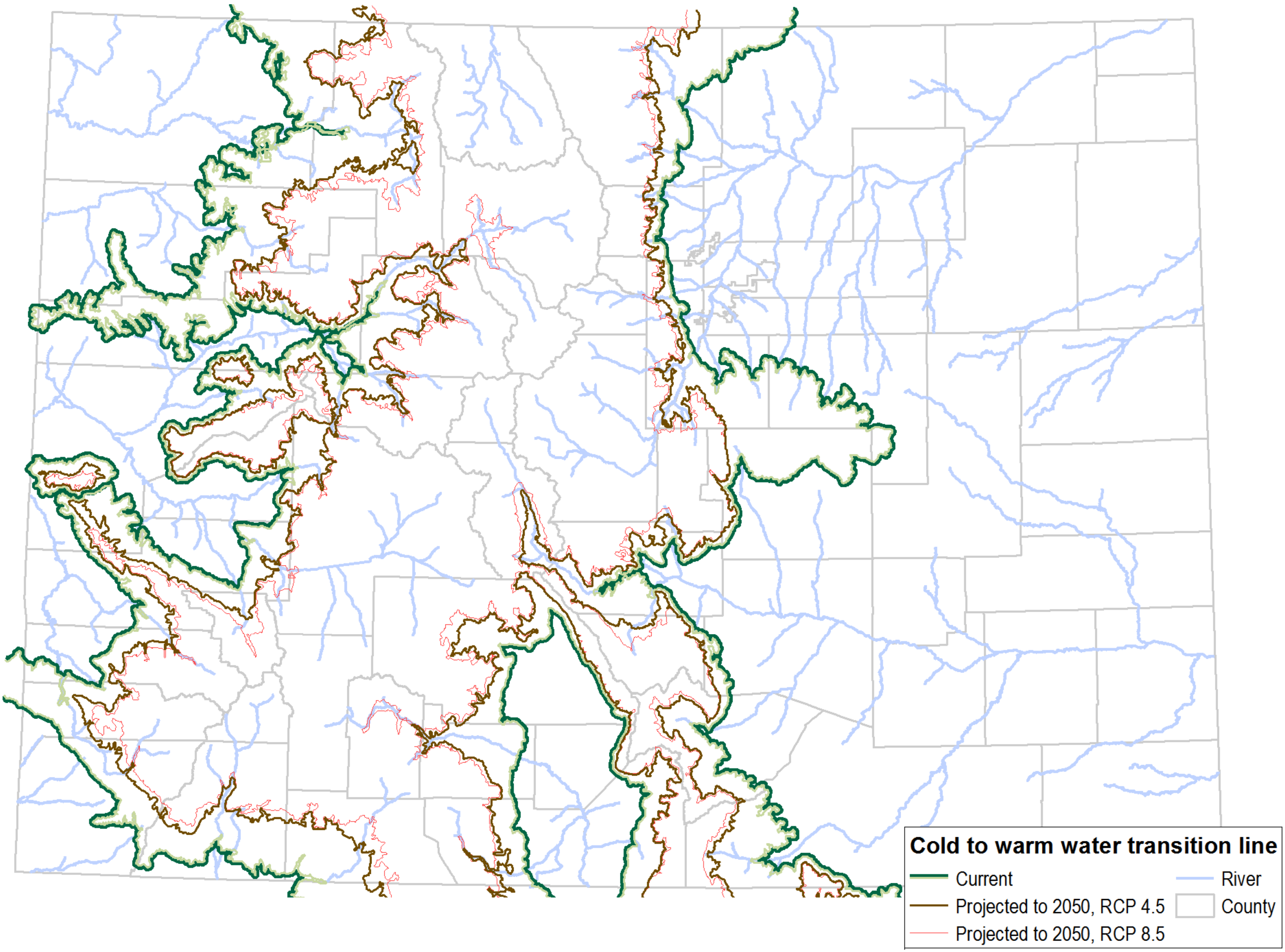
b) Hot & Wet Scenario



c) Feast or Famine Scenario



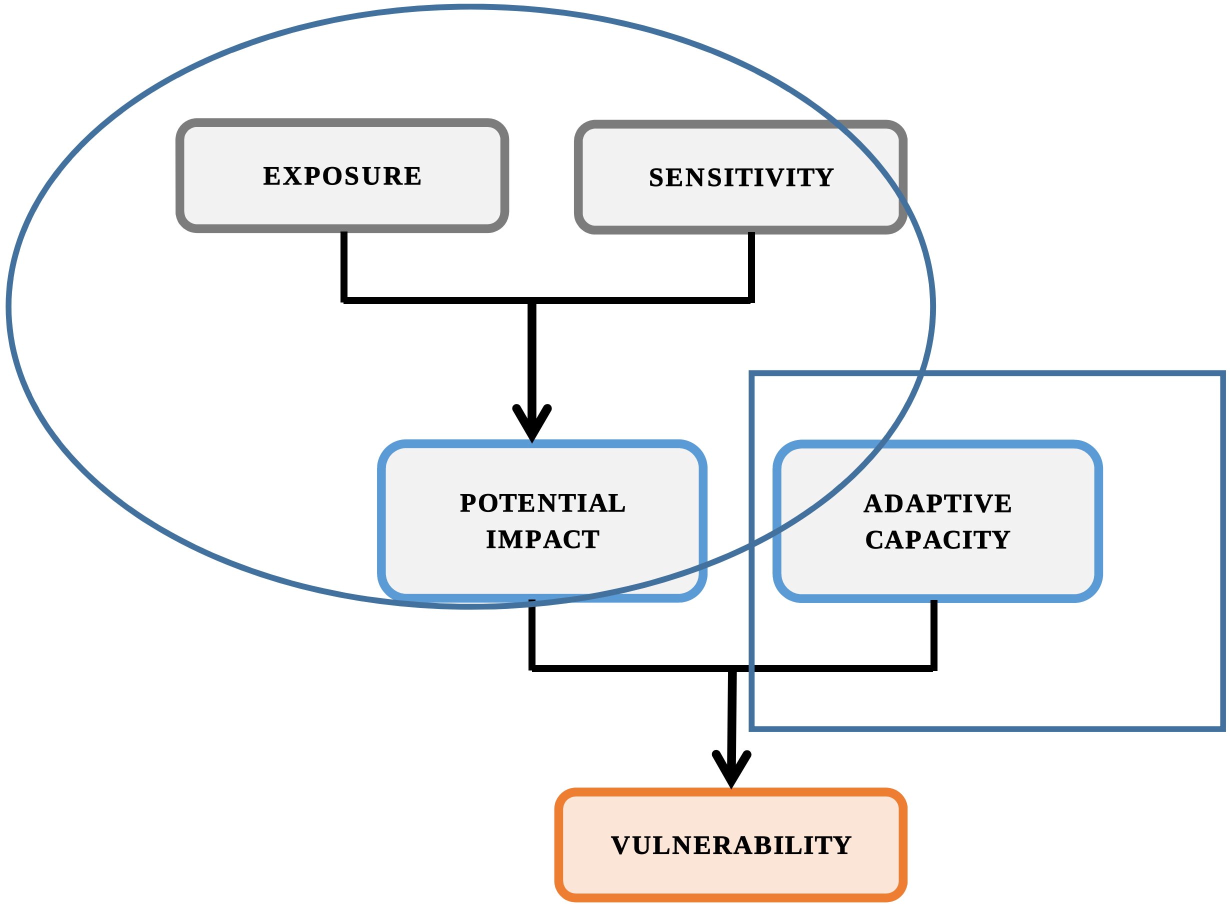
d) Warm & Wet Scenario


Cold to warm water transition line
Current
Projected to 2050, RCP 4.5
Projected to 2050, RCP 8.5
River
County

Vulnerability Assessment for SLV Values

Assessing vulnerability

This is the
primary part of
our vulneribilty
exercise



This is the
primary piece
for strategies,
that could be an
outcome in
future meetings

Glick et al. 2011 - *Scanning the Conservation Horizon*

Values Assessed for Vulnerabilities in the San Luis Valley

Pinyon-Juniper

Sagebrush

Montane Grassland

Winterfat Shrublands

Stream & Riparian

Wetlands

Ranching

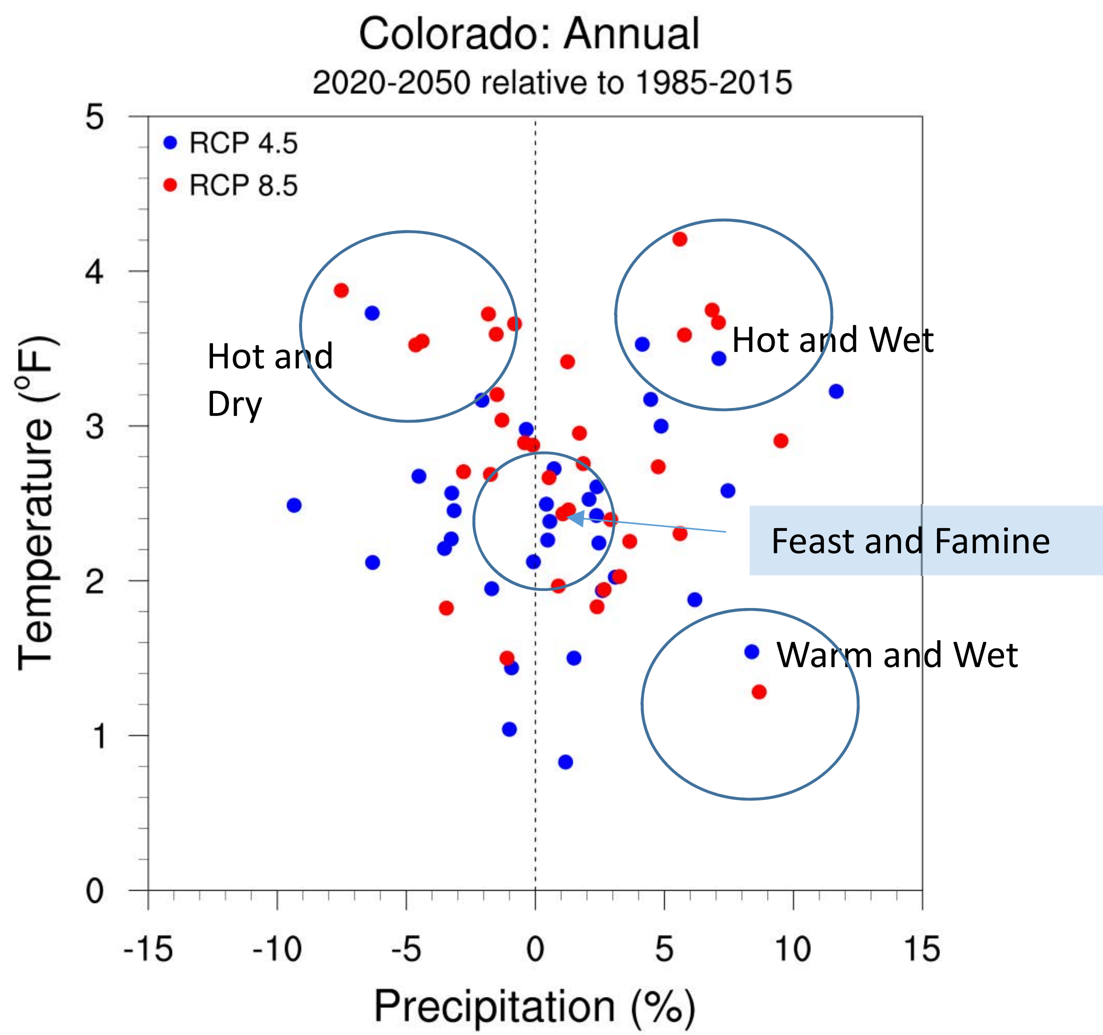
Big Game Hunting

Why Do We Want Vulnerability Assessment

- Vulnerability assessments help us determine attributes that are most sensitive and how likely they are to be exposed to sensitive attributes.
- Once we have this foundation, we can ask if we can do anything to reduce the impact, i.e., increase their adaptive capacity.
  - These become strategies to reduce the impact
  - We can also look at what is already being done to deal with impacts

Assessing Value Indicators Across 4 Climate Scenarios

- While we are assessing indicators across four climate scenarios, we don't want to forget that non-climate stressors exist and can compound vulnerabilities.



Assessment Definitions

- **Ecological-Social System:** broad categories of values chosen by stakeholders that include both natural ecosystems and the people who interact with them.
- **Nested ecological-social target:** specific type of plant community, habitat, species, or livelihood associated with ecological-social system of concern.
- **Key Attribute:** specific characteristic feature or process crucial to the health of the target that is assessed for vulnerability.
- **Measurable Climate Indicator:** trait or environmental influence that is affected by temperature or precipitation, and can be scored for degree of positive or negative effect on the target.
- **Impact Assessment Metric:** quantifiable climate-derived dataset used to assess the amount and direction (+ or -) of impact to the key attribute under future climate scenarios.
- **Threshold for Metric:** data values that determine positive or negative outcome under different climate scenarios.
- **Confidence Categories:** Confidence categories reflect 1) how much is known about the influence of climate on the target, and 2) the extent to which available data allows us to assign impact ranks.

Impact Scoring

Score	Definition
-3	Severity of impact is high and scope widespread (>75% of the area)
-2	Not widespread, but severe; OR severity is low-mild but widespread
-1	Impact is low or severe, however if severe, the scope is small
0	No impact
1	Slight postitive impact for much of the target
2	Positive impact for much of the target
3	Widespread positive impact, with expected significant increases

Example: Pinyon-Juniper

- Measurable Climate Indicators:
  - Regeneration
  - Mortality
  - Fire Risk
  - Loss of Persistent stands
  - Loss of PJ obligate birds (PIJA, GRVI, JUTI)

- Impact Assessment Metric:
  - Winter moisture
  - Frequency of severe growing season drought
  - Change in environmental suitability

Winter Moisture as Indicator

4 Climate Scenarios

SLV ONLY	Hot and Dry	Hot and Wet	Feast and Famine	Warm and Wet
Change between 2000 (1985-2015) and 2035 (2020-2050)	**hadgem2.es.1.rcp85**	*miroc-esm.1.rcp85*	*cesm1-bgc.1.rcp85*	*cnrm-cm5.1.rcp45*
Winter precipitation change (%)	27%	19%	4%	7%

Measurable Climate Indicator	Impact Assessment Metric	Thresholds for Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet
Pinyon and juniper regeneration	Winter moisture	Percent departure	2	2	0	1

Score	Definition
-3	Severity of impact is high and scope widespread (>75% of the area)
-2	Not widespread, but severe; OR severity is low-mild but widespread
-1	Impact is low or severe, however if severe, the scope is small
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3	Widespread positive impact, with expected significant increases

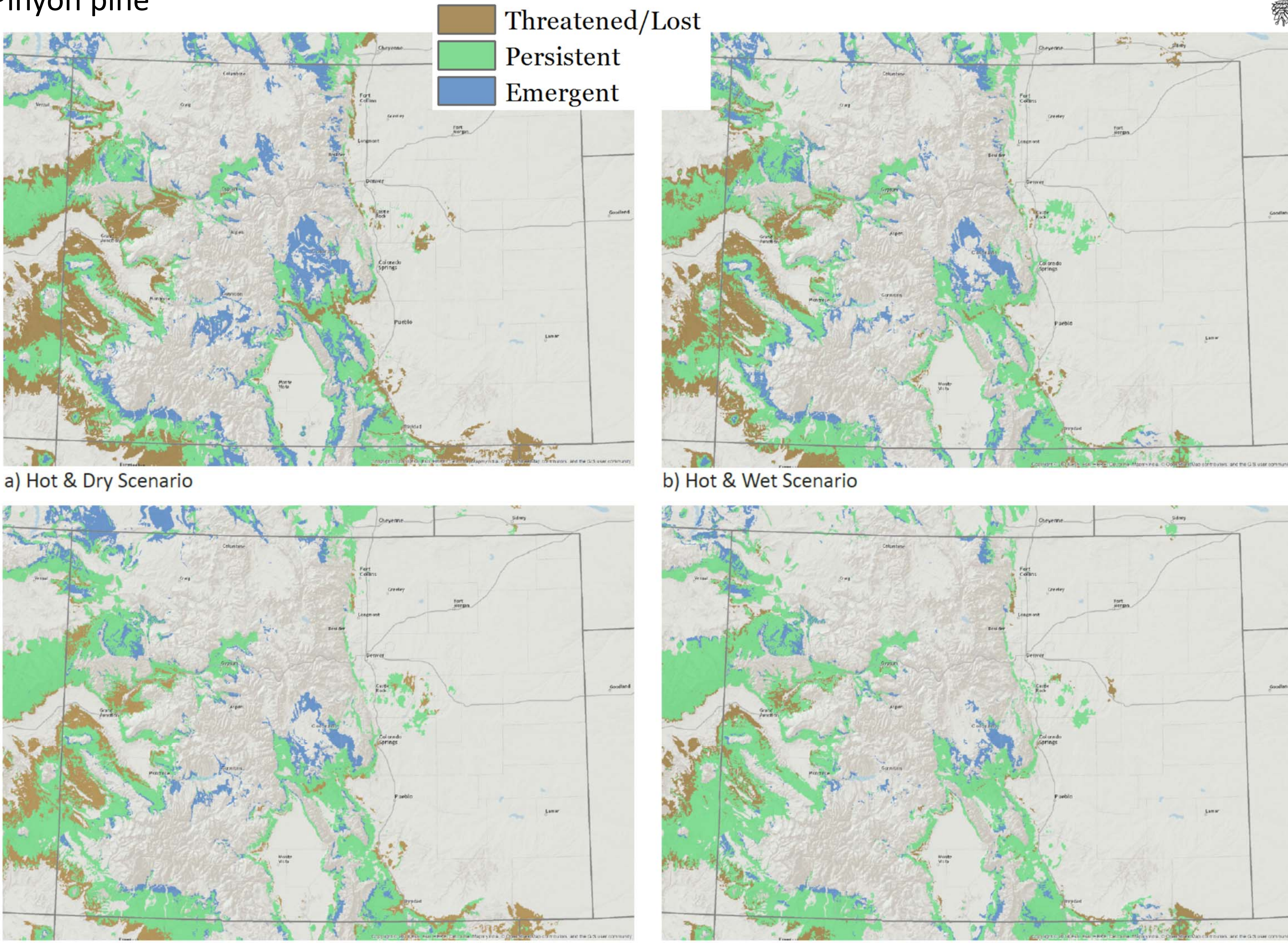
Example: Pinyon-Juniper

Measurable Climate Indicator	Impact Assessment Metric	Thresholds for Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet
Pinyon and juniper regeneration	Winter moisture	Percent departure	2	2	0	1
Pinyon and juniper mortality	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0
Increased fire risk	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0
Loss of persistent PJ stands	Change in environmental suitability	PIED & JUMO bioclimatic niche models	-1	-1	-1	-1
Loss of PJ obligate birds, e.g., Pinyon jays, Grey Vireo, and Juniper titmouse	Change in environmental suitability	PIED & JUMO bioclimatic niche models	-1	-1	-1	-1

Low Vulnerability

Score	Definition
-3	Severity of impact is high and scope widespread (>75% of the area)
-2	Not widespread, but severe; OR severity is low-mild but widespread
-1	Impact is low or severe, however if severe, the scope is small
0	No impact
1	Slight postitive impact for much of the target
2	Positive impact for much of the target
3	Widespread positive impact, with expected significant increases

Pinyon pine



a) Hot & Dry Scenario

b) Hot & Wet Scenario

c) Feast or Famine Scenario

d) Warm & Wet Scenario

Winterfat Shrub-Grassland Climate Impacts Summary
Moderately Vulnerable

Measurable Climate Indicator	Impact Assessment Metric	Thresholds for Metric	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet
Shallow-rooted shrub, grass, forb production	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0
Blue grama abundance	Spring (AMJ) Minimum Temperature (MAM average temp as a surrogate)	1 C increase leads to a 1/3 loss of blue grama growth	-3	-3	-2	-2
Blue grama mortality	Frequency of severe growing season drought (like 2002 and 2012)	Extreme event frequency (Climate Water Deficit Apr-Sep)	-3	-1	-3	0
Winterfat seed production	Growing season moisture (JJA)	Percent departure	-2	0	0	2
Winterfat flowering & seedling recruitment	Winter moisture	Percent departure	2	2	0	1
Cheatgrass abundance	Spring and fall moisture enhances cheatgrass germination	> 5% Change in average spring or fall precipitation	-1	-3	0	-3

Score	Definition
-3	Severity of impact is high and scope widespread (>75% of the area)
-2	Not widespread, but severe; OR severity is low-mild but widespread
-1	Impact is low or severe, however if severe, the scope is small
0	No impact
1	Slight postitive impact for much of the target
2	Positive impact for much of the target
3	Widespread positive impact, with expected significant increases

Vulnerability Summary

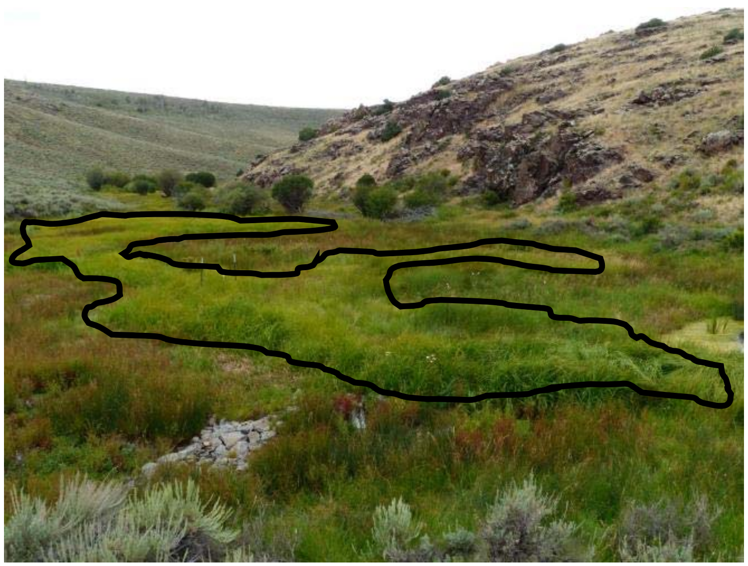
Ecological-Social System	Hot & Dry	Hot & Wet	Feast & Famine	Warm & Wet	Overall Vulnerability
Pinyon-Juniper	-1	0	-2	0	Low
Shrub-steppe winterfat	-2	-1	-1	0	Moderate
Montane grassland	-2	-1	-1	-1	Moderate
Sagebrush	0	0	-1	-1	Low
SLV wildlife	-2	-1	-2	-1	Moderate
Wetland	-3	-2	-3	-1	High
Riparian & Streams	-3	-3	-3	-1	High
Ranching	-3	-1	-3	0	Moderate
Big game hunting	-2	-1	-2	-1	Moderate

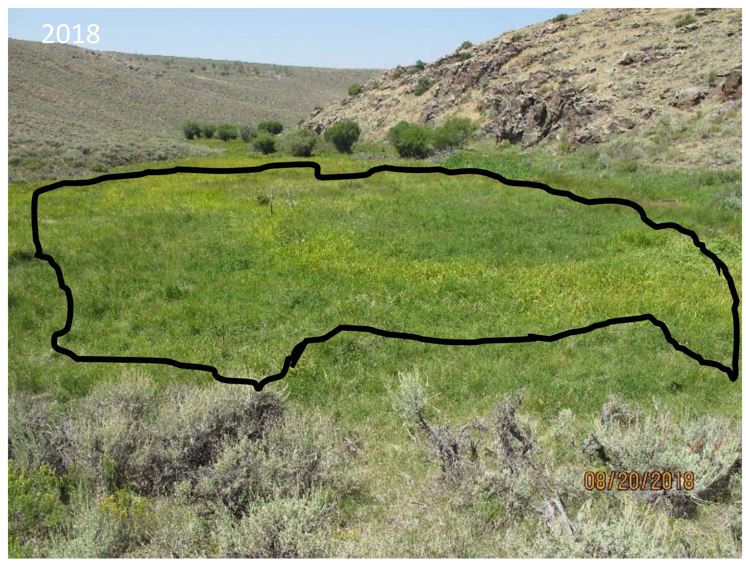
Why Do We Want Vulnerability Assessment

- Vulnerability assessments help us determine what attributes are most sensitive and how likely they are to be exposed to the issue that makes a value sensitive.
- Once we have this foundation, we can ask if we can do anything to reduce the impact, i.e., increase the adaptive capacity.
  - These become strategies to reduce the impact
- The following breakout group is designed to review, edit, and add to the vulnerability assessment. Thus building the foundation for strategies.

Building Strategies—Next Step

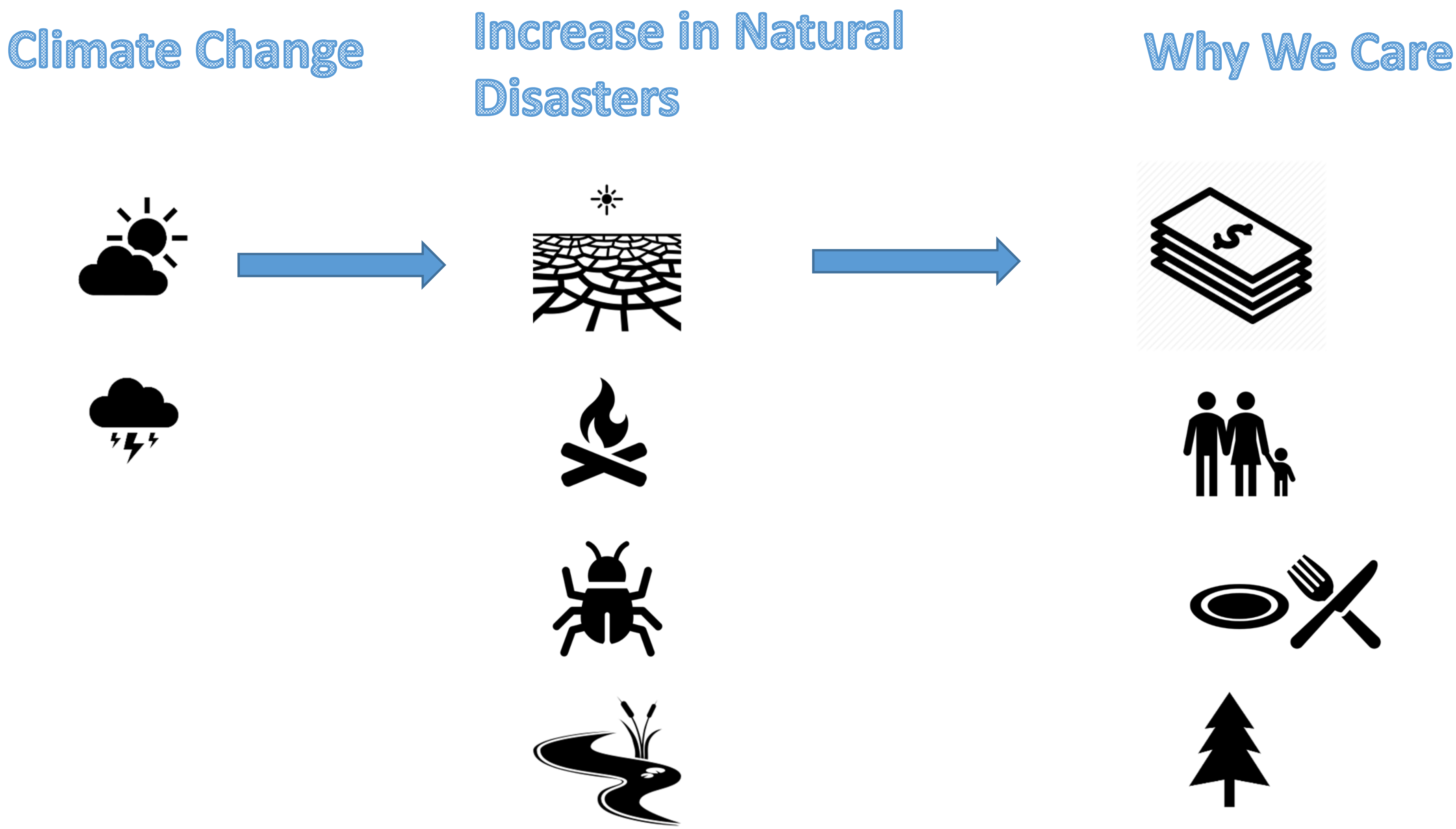
An Example of an Adaptation Strategy Associated with Less Runoff





The black polygon represents the wetland area. In general the wetland area occupied approx. 25% of the floodplain in 2012 and nearly 100% in 2018.

2012 and 2013 photos by Claudia Strijek


Climate Change
Increase in Natural Disasters
Why We Care

Mitigate

Reduce Fossil Fuel Use

- Create low-carbon transportation
- Build low-carbon power plants
- Build high efficiency cooling and heating systems

Adapt

Build Climate-Smart Communities

- Construct storm ready infrastructure
- Build climate-smart dwellings, e.g., fire and flood resistant buildings
- Build capacity and diversity in livelihoods

Develop Natural Solutions

To maintain and improve ecosystem services, thus buffering impacts and sequestering carbon

- Identify and Protect climate refugia
- Improve resilience
- Plan for transformation

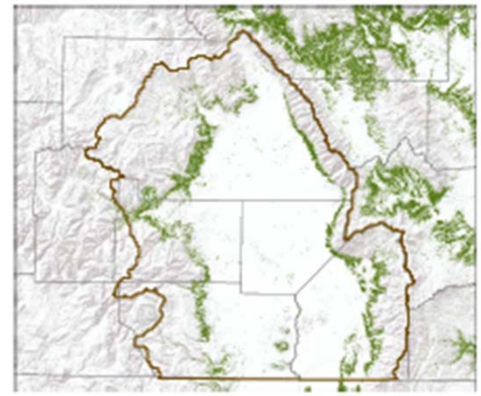
Building Strategies—Next Step

- Utilize social and ecological vulnerabilities assessments
- Several ways to build strategies, but in-person meetings would be best

Vulnerability Summaries Overview

- Let’s end by walking through one of the word documents that summarizes the vulnerability
- Your homework is to review and edit the word documents

Pinyon-Juniper Woodlands



Climate Vulnerability Score: Low vulnerablity

Pinyon-juniper woodlands in the San Luis Valley are distributed on the foothills around the perimeter of the valley floor, generally at elevations of 7,950 to 8,950 ft, with additional stands at similar elevations on hills and mesas in the southern portion of the valley.

Pinyon-juniper woodlands are influenced by climate, fires, insect-pathogen outbreaks, and livestock grazing (West 1999, Eager 1999). Although it is clear that the structure and condition of many pinyon-juniper woodlands has been significantly altered since European settlement (Tausch 1999), in recent years there has been an emerging recognition that not all of these woodlands are dramatically changed by anthropogenic influence. Increasing density of pinyon juniper woodlands and expansion into adjacent grassland or shrubland are well documented in some areas, but is not a universal phenomenon in the western U.S. (Romme et al. 2009).

Both pinyon pine and juniper are fairly slow growing, and can live for hundreds of years, a life cycle that is well adapted to xeric habitats, but is less suitable for quickly changing conditions. Although individuals of both species become reproductive after a few decades, most seed production is due to mature trees of 75 years of age or older (Gottfried 1992). Both species reproduce only from seeds, and do not resprout after fire. Cone production of mature pinyon pine takes three growing seasons, and the large seeds have a fairly short life span of 1-2 years (Ronco 1990). Juniper cones (often called berries) may require 1-2 years of ripening before they can germinate (Gottfried 1992). The smaller seeds of juniper are generally long-lived, surviving as long as 45 years. Birds are important dispersers of both pinyon pine and juniper seed (Gottfried 1992).

APPENDIX D: SUMMARY FACT SHEETS

Colorado Bureau of Land Management
ECOLOGICAL VULNERABILITY ASSESSMENT

SUMMARY OF FINDINGS

The Colorado office of the Bureau of Land Management (BLM), which administers 8.4 million acres of Colorado's landscapes, is facing an increasingly dynamic management environment. Changes are driven by explosive growth in human population and energy development, as well as more extreme weather and more frequent and severe disturbance events. To provide context for future decision-making, the Colorado Natural Heritage Program (CNHP) worked with BLM to conduct climate change vulnerability assessments for 98 BLM Sensitive Species and 22 ecosystems from a statewide perspective. Though methods varied for species, terrestrial systems, and aquatic systems, all assessments addressed primary components of vulnerability: ***exposure*** to stress from climate change, ***sensitivity*** to that stress, and ***resilience*** or ***adaptive capacity*** (i.e., ability to persist in the face of stress).

RESEARCH QUESTIONS:

- ***Which of Colorado's animals, plants, and ecosystems will be most vulnerable to the effects of climate change?***
- ***What are the key climate factors driving vulnerability?***
- ***What do we know about how the species or ecosystem interacts with climate in the context of public land uses and management actions?***

Vulnerability = extent to which a species or ecosystem can not adapt to the potential impacts of future climate.

SPECIES VULNERABILITY

We evaluated 36 animal and 62 rare plant species using the NatureServe Climate Change Vulnerability Index. The Index scores exposure according to projections for temperature and moisture availability across each species' distribution. We calculated these scores using an ensemble average climate model under a mid-Century timeframe and a high emissions scenario. Sensitivity and adaptive capacity are scored according to 20 life history and habitat factors related to dispersal ability and barriers to movement, tolerances for temperature and precipitation, habitat and food resource specificity, reliance on disturbance regimes or interspecific interactions, and genetics. Subscores are combined into an overall vulnerability score of Extremely Vulnerable, Highly Vulnerable, Moderately Vulnerable, or Presumed Stable.

Forty-two percent of the animals were ranked Extremely or Highly Vulnerable (Table 1, Figure 1). Fish species, in particular, were ranked on the extremely vulnerable end of the range; other taxonomic groups were generally more evenly distributed. Primary factors driving vulnerability for fish include barriers to movement, potential for decreased stream flows and increased stream temperatures, reliance on specific habitat features for spawning, and concerns related to lack of genetic variation and potential for hybridization. Presence of barriers is also an issue for other species ranked highly vulnerable, as is reliance on moist environments for some or all of the life cycle (e.g., breeding ponds for boreal toads, mesic brood rearing meadows for Sage-grouse, playas for Long-billed Curlew and Western Snowy Plover). Other factors presumed to increase vulnerability include the potential for increased wildfire frequency and severity (both Sage-grouse species), and, ironically, impacts from human efforts to combat climate change (e.g., increased renewable energy development - Long-billed Curlew, Western Snowy Plover).

Nearly all of the rare plant species (59 of 62) were ranked Extremely Vulnerable. The only exceptions were *Amsonia jonesii* (Moderately Vulnerable), *Camissonia eastwoodiae* and *Oenothera acutissima* (both Highly Vulnerable). None of the plants scored as Presumed Stable. Extreme vulnerability for rare plants is generally due to their highly restricted distributions, natural barriers to movement and relatively limited dispersal ability, and/or pollinator specificity. Restriction to a moist hydrological niche or to uncommon geologic substrates also tend to increase the vulnerability of most of Colorado's rare plants.

Table 1. Vulnerability scores and key vulnerability factors for animal species.

English Name	*Species*	Score	Key Vulnerability Factors
Boreal Toad	*Anaxyrus boreas boreas*	HV	barriers, cool/moist niche, hydrology
Canyon Treefrog	*Hyla arenicolor*	MV	barriers, hydrology
Great Basin Spadefoot	*Spea intermontana*	PS	
Northern Leopard Frog	*Lithobates pipiens*	MV	hydrology
American Peregrine Falcon	*Falco peregrinus anatum*	PS	
Black Swift	*Cypseloides niger*	PS	
Brewer's Sparrow	*Spizella breweri*	PS	
Burrowing Owl	*Athene cunicularia hypugaea*	MV	dependence on other species, low genetic diversity, modeled response
Golden Eagle	*Aquila chrysaetos*	MV	wind energy impacts, modeled response
Greater Sage-grouse	*Centrocercus urophasianus*	HV	vulnerable habitat component
Gunnison Sage-grouse	*Centrocercus minimus*	HV	barriers, vulnerable habitat component
Long-billed Curlew	*Numenius americanus*	HV	vulnerable habitat component
Mountain Plover	*Charadrius montanus*	PS	
Northern Goshawk	*Accipiter gentilis*	MV	cool niche, vulnerable habitat component
Western Snowy Plover	*Charadrius alexandrinus nivosus*	HV	hydrology
Western Yellow-billed Cuckoo	*Coccyzus americanus occidentalis*	MV	hydrology, vulnerable habitat
White-faced Ibis	*Plegadis chihi*	MV	hydrology
Bluehead Sucker	*Catostomus discolobus*	HV	barriers, hydrology, cool niche, vulnerable habitat
Bonytail Chub	*Gila elegans*	**EV**	barriers, hydrology, vulnerable habitat
Colorado Pikeminnow	*Ptychocheilus lucius*	**EV**	barriers, hydrology, vulnerable habitat, low genetic diversity
Colorado River Cutthroat Trout	*Oncorhynchus clarkii pleuriticus*	**EV**	barriers, cool niche, hydrology, vulnerable habitat
Flannelmouth Sucker	*Catostomus latipinnis*	HV	barriers, hydrology, vulnerable habitat
Humpback Chub	*Gila cypha*	**EV**	barriers, hydrology, vulnerable habitat, low genetic diversity
Razorback Sucker	*Xyrauchen texanus*	HV	barriers, hydrology, vulnerable habitat
Rio Grande Cutthroat Trout	*Onchorhynchus clarkii virginalis*	**EV**	barriers, hydrology, vulnerable habitat, low genetic diversity
Roundtail Chub	*Gila robusta*	HV	barriers, hydrology, vulnerable habitat, low genetic diversity
Great Basin Silverspot	*Speyeria nokomis nokomis*	HV	barriers, hydrology, dependence on other species, low genetic diversity
American Beaver	*Castor canadensis*	MV	hydrology
Desert Bighorn Sheep	*Ovis canadensis nelsoni*	MV	barriers, modeled response
Fringed Myotis	*Myotis thysanodes*	PS	
Gunnison's Prairie Dog	*Cynomys gunnisoni*	PS	
Townsend's Big-eared Bat	*Corynorhinus townsendii*	PS	
White-tailed Prairie Dog	*Cynomys leucurus*	PS	
Desert Spiny Lizard	*Sceloporus magister*	PS	
Longnose Leopard Lizard	*Gambelia wislizenii*	PS	
Midget Faded Rattlesnake	*Crotalus oreganus concolor*	HV	barriers, vulnerable habitat component

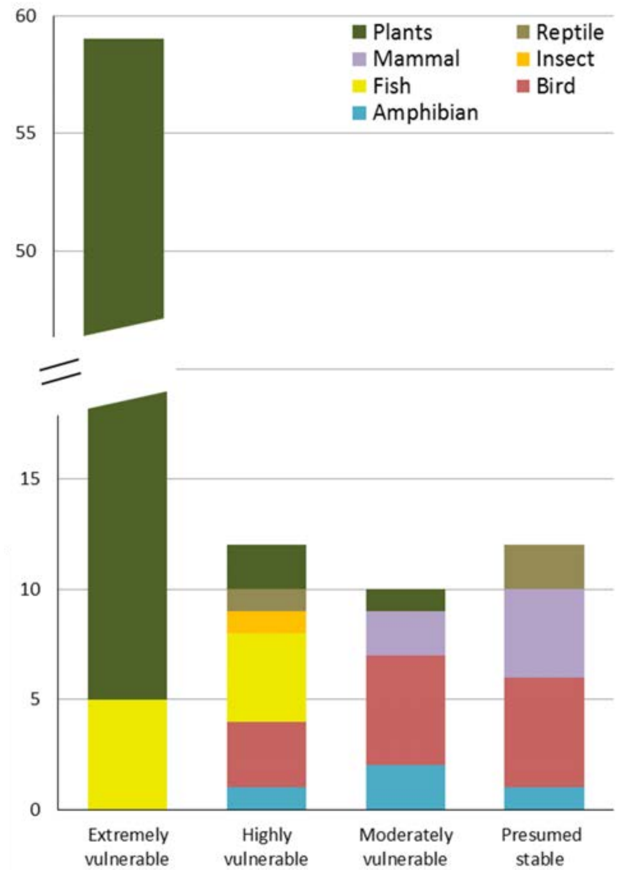


Figure 1.Species vulnerability by scoring category and taxonomic group.

TERRESTRIAL ECOSYSTEM VULNERABILITY

We assessed 16 terrestrial ecosystem types for ***exposure-sensitivity*** and ***resilience-adaptive capacity***. Sub-scores from these two components were combined to obtain overall vulnerability scores of Very High, High, Moderate, or Low. We evaluated *exposure-sensitivity* in GIS using an ensemble average of 34 climate projection models for the Continental US, under the highest emission scenario and a mid-century timeframe. For each ecosystem, we defined a bioclimatic envelope (i.e., the range of temperatures and precipitation experienced across its Colorado distribution currently and in the recent past). We then calculated the proportion of each system's distribution that is projected to be "out of range" —i.e., where 1) future annual mean temperature is expected to be greater than the warmest annual mean temperature currently experienced by that ecosystem, and 2) projected mean precipitation is expected to be either lower than current, or higher than current but still insufficient to compensate for increased temperatures.

The *resilience-adaptive capacity* score summarizes indirect effects and non-climate stressors that may interact with climate change to influence the adaptive capacity and resilience of an ecosystem. Factors evaluated are adapted from the methodology used by Manomet Center for Conservation Science and Massachusetts Division of Fish and Wildlife (MCCS and MAFW 2010), combined under five headings:

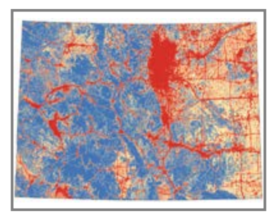
1. Bioclimatic envelope & range—expected effects of limited elevational or bioclimatic ranges; Colorado distribution at southern edge of range.

2. Dispersal rate and growth form—ability of ecosystem's component species to shift ranges relatively quickly; seed-dispersal capability, vegetative growth rates, and stress-tolerance.

3. Biological stressors—whether expected future biological stressors (invasive species, grazers and browsers, pests and pathogens) have an increased effect due to changing climate.

4. Extreme events—whether an ecosystem is more vulnerable to extreme events (fire, drought, floods, windstorms, dust on snow, etc.) that are projected to become more frequent and/or intense.

5. Landscape condition—summary of the overall condition of the ecosystem, derived from a landscape integrity model based on anthropogenic disturbance.



The majority of ecosystems were ranked with low or moderate vulnerability in our analysis (Figures 2 and 3, Table 2). Ecosystems with low exposure and high resilience could be the beneficiaries of future conditions, while those with high exposure and low resilience are likely to experience range contractions and/or significant changes in species composition and overall condition.

Figure 3 shows the relationship between current bioclimatic envelope and projected future bioclimatic envelope for each ecosystem. The amount of overlap between the dots (annual means) and whiskers (10th and 90th percentiles) and the box gives a relative indication of how similar or different these climate variables may be in the future compared to conditions experienced by each ecosystem in the recent past. Future projections are for warmer conditions than current means for all ecosystems, though there is some overlap with the current range of temperatures for all ecosystems except sandsage and alpine. Projected mean annual precipitation is roughly equivalent or slightly higher than current for all ecosystems. Projected future precipitation, even if slightly above current levels, is generally insufficient to compensate for the drying effects of warmer temperatures. Hydrologic modeling for the Colorado River and other basins (e.g., Nash and Gleick 1991, 1993) indicates that, as a generalized rule-of-thumb, for each 1.8°F (1°C) of warming, an approximate 5% increase in precipitation is required for runoff levels to remain unchanged. With projected mid-century temperatures increasing 4°F or more, few areas in Colorado are projected to receive sufficient compensatory precipitation to maintain *status quo* (e.g., Figure 4). Thus, all ecosystems are likely to be affected to some extent by climate change.

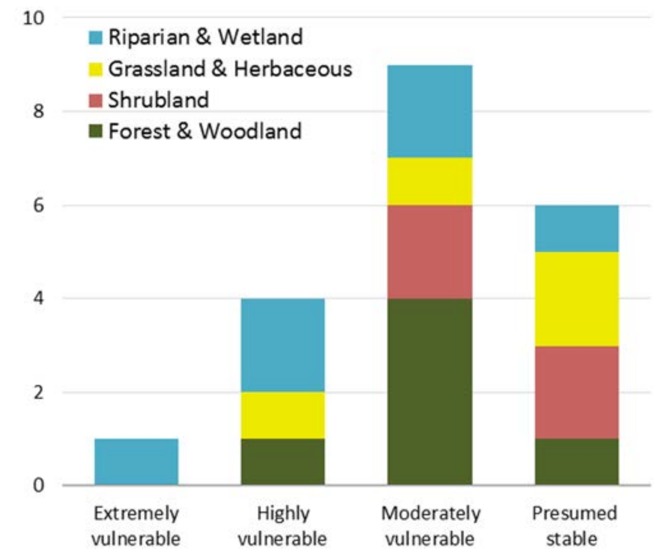


Figure 2. Summary of vulnerability scores for ecological systems.

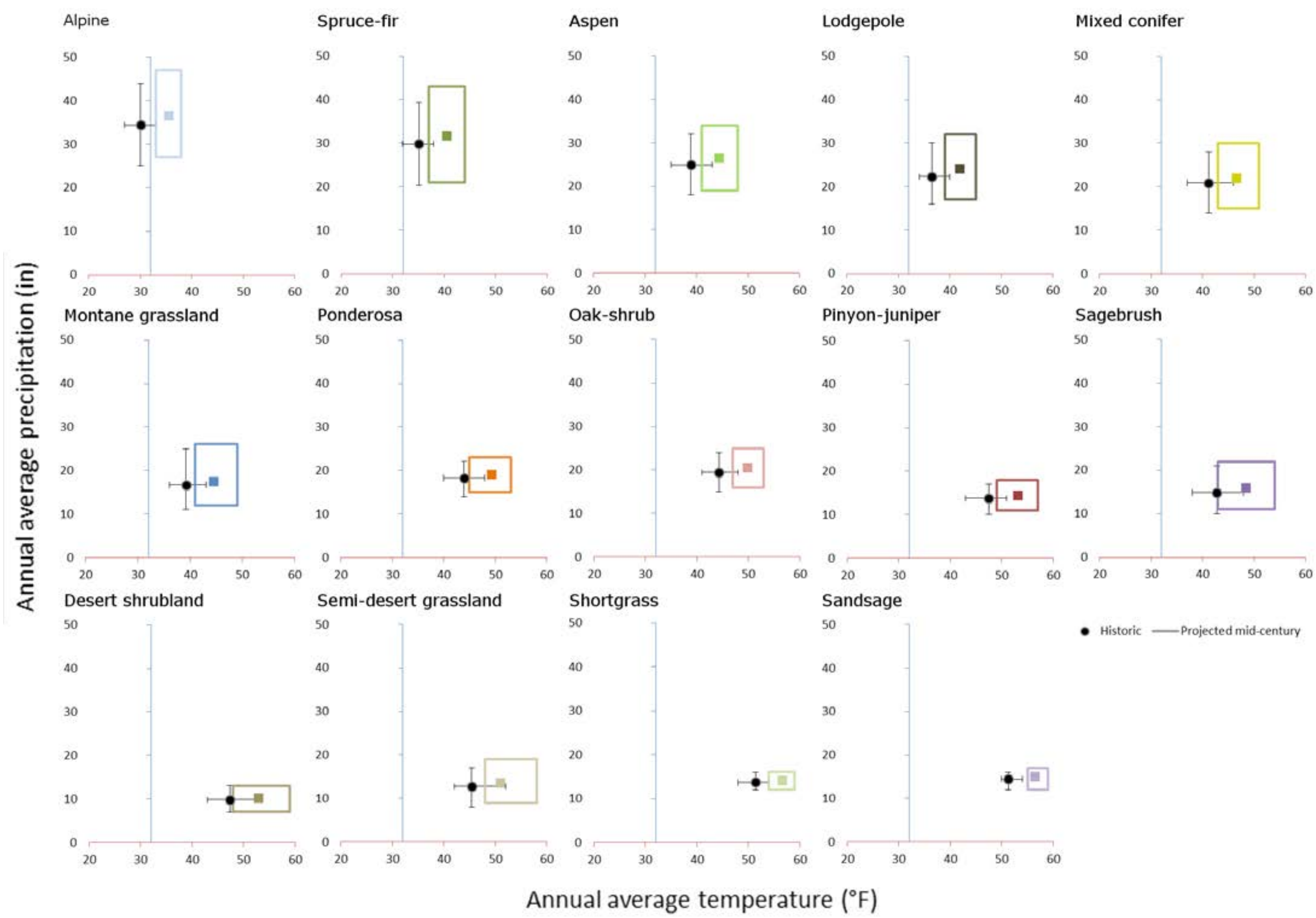


Figure3. Comparison of current and future projected temperature and precipitation for each ecosystem. Current conditions are represented by the dot (mean), whiskers (10-90% percentiles). Future conditions are represented by the box. The blue line (y-axis) represents freezing temperature.

Table 2. Vulnerability scores and key vulnerability factors for ecological systems.

Habitat		Climate factor(s)	Consequences	Other considerations
Aspen	L	Warmer and dry conditions	Aspen decline, especially at lower elevations	May benefit from fire increase, small patches in conifer forest may expand after conifer mortality
Lodgepole	M	Drought, warmer temperatures	Fire and insect outbreak; range contraction	
Mixed Conifer	M	Warmer and dry conditions	Change in relative species abundance or conversion to other type	Diverse species composition makes it likely that some species will thrive
Pinyon-juniper	H	Warmer and dry conditions	Change in relative species abundance favoring juniper; fire and insect outbreak; reduced pinyon pine cone production	Soil types affect distribution
Ponderosa	M	Drought	Fire and insect outbreak	Wildland-Urban Interface complicated management
Spruce-fir	M	Drought	Fire and insect outbreak	Slow dispersal, short growing season increases vulnerability over time
Desert shrubland	M	Soil moisture	Conversion to other type	Highly altered
Oak & mixed mtn. shrub	L	Drought, last frost date variability	Dieback with drought and late frost; may increase by resprouting after fire	Anthropogenic disturbance
Sagebrush	L	Drought	Increase in invasive species such as cheatgrass; fire	Variable by subspecies
Sandsage	M	Extended drought	Soil mobilization	Loss of native biodiversity
Alpine	L	Extended growing season with earlier snowmelt	Conversion to other type that includes shrubs or trees	Barriers to dispersal
Montane grassland	M	Drought, warmer temperatures	Woody species invasion, exotics; potential to expand into burned forest areas	Highly altered
Semi-desert grassland	L	----	May increase	Poor connectivity
Shortgrass Prairie	H	Extended drought, warmer summer nighttime temperatures	Change in relative species abundance, woody species invasion, or conversion to other type	Anthropogenic disturbance
Riparian - East	H	Warmer and drier conditions, runoff amount & timing	Earlier peak flows, low late summer flows, change in relative species abundance	Highly altered due to diversions and dams, agricultural land use patterns
Riparian - Mtn.	L	Warmer temperatures, runoff timing	Earlier peak flows, low late summer flows, change in relative species abundance	Connectivity
Riparian - West	**VH**	Warmer and drier conditions, runoff amount & timing	Earlier peak flows, low late summer flows, change in relative species abundance	Highly altered due to diversions and dams, agricultural land use patterns
Wetland - East	H	Warmer, drier conditions	Lower water tables, reduced input	Strict irrigation control, highly altered
Wetland - Mtn.	M	Warmer temperatures, snowmelt timing	Potential change in species composition	Groundwater-driven types more stable
Wetland - West	M	Drier conditions	Lower water tables, reduced input	Highly altered

BLM acreage and management responsibility is not equally distributed across all of Colorado's ecosystems. Colorado BLM lands are primarily dominated by three ecosystems: pinyon-juniper (38%), sagebrush (29%), and desert shrub (10%). Our results indicate that, of these, pinyon-juniper is the highest priority upland ecosystem for additional analysis and identification of climate-adaptation management strategies (Figure 5). And though the West Slope riparian system is a very minor component of the landscape in terms of acres, its importance is greatly disproportionate to its size. Thus, with a ranking of Very High for overall vulnerability, it too is a high priority for additional assessment. Figure 5 shows vulnerability of important ecosystems present on BLM lands according to exposure/sensitivity and resilience/adaptive capacity sub-scores, as well as BLM's relative responsibility for each system.

FRESHWATER ECOLOGICAL SYSTEMS

Freshwater ecosystems include (images opposite page, top to bottom): *rivers* (perennial stream reaches orders 5-7 and their major tributaries), *streams* (smaller order

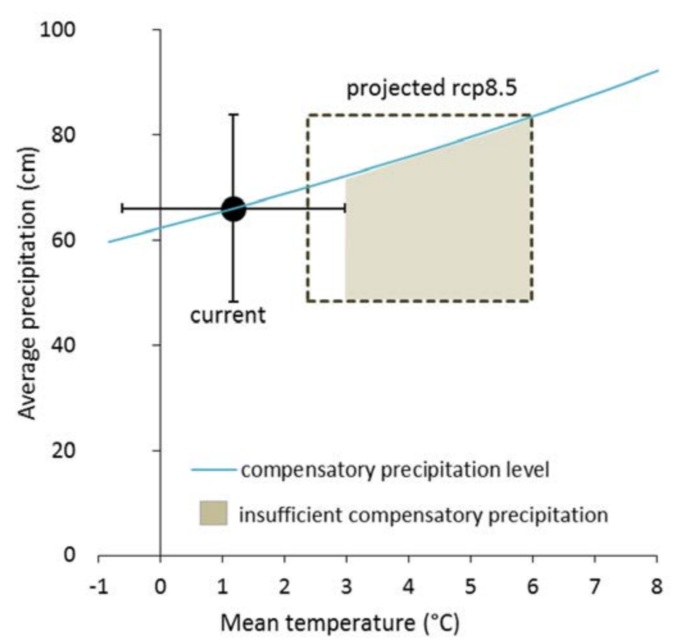


Figure 4. Relationship between projected temperature increase and amount of increased precipitation that would be required to maintain status quo in terms of moisture availability.

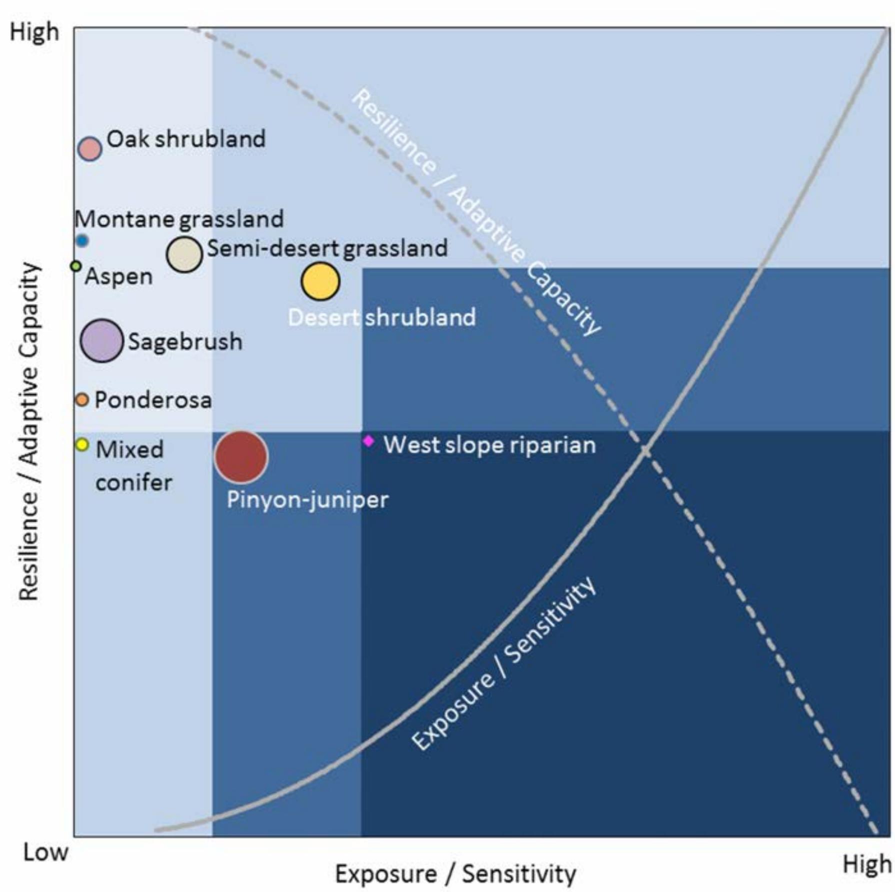


Figure 5. Vulnerability scores for ecological systems, with relative importance of each system to BLM indicated. Exposure/sensitivity and resilience/adaptive capacity are scored on opposite scales, where high exposure = more vulnerable, while high resilience = less vulnerable. The size of the dots represent the relative proportion of each system on BLM lands in Colorado. Background colors from light blue to dark blue represent the continuum from low vulnerability to high vulnerability.

reaches, perennial or intermittent), *lakes* (water bodies smaller than 3 km^2 in area), and *reservoirs* (impoundments $\geq$ 3 km^2). We assessed freshwater habitats according to elevation (high and low) and regional location within the state (eastern plains, mountains, and western slope).

To estimate exposure/sensitivity, we developed a model of projected change in water temperature around a cold to cool-water fisheries transition line (Figure 6). We used mean July air temperatures to estimate water temperature contour lines across the state, and then applied projected future air temperature to estimate transitions from cold-water conditions to warm-water conditions. The modeled transition line was used to assign stream and river reaches to cold, transitional, or warm water categories. Exposure to climate change was evaluated by comparing the total stream length currently falling in each category with the totals under projected high-emissions, mid-century conditions. Note that, because air temperature was a proxy for water temperature, cold-water releases from reservoir storage are not accounted for in the model.

Resilience/adaptive capacity was evaluated for freshwater systems in the same way as terrestrial systems, with slight variations in scoring factors. Both terrestrial and freshwater systems were evaluated for biological stressors, extreme events, and landscape condition. However, for freshwater systems we evaluated restriction to

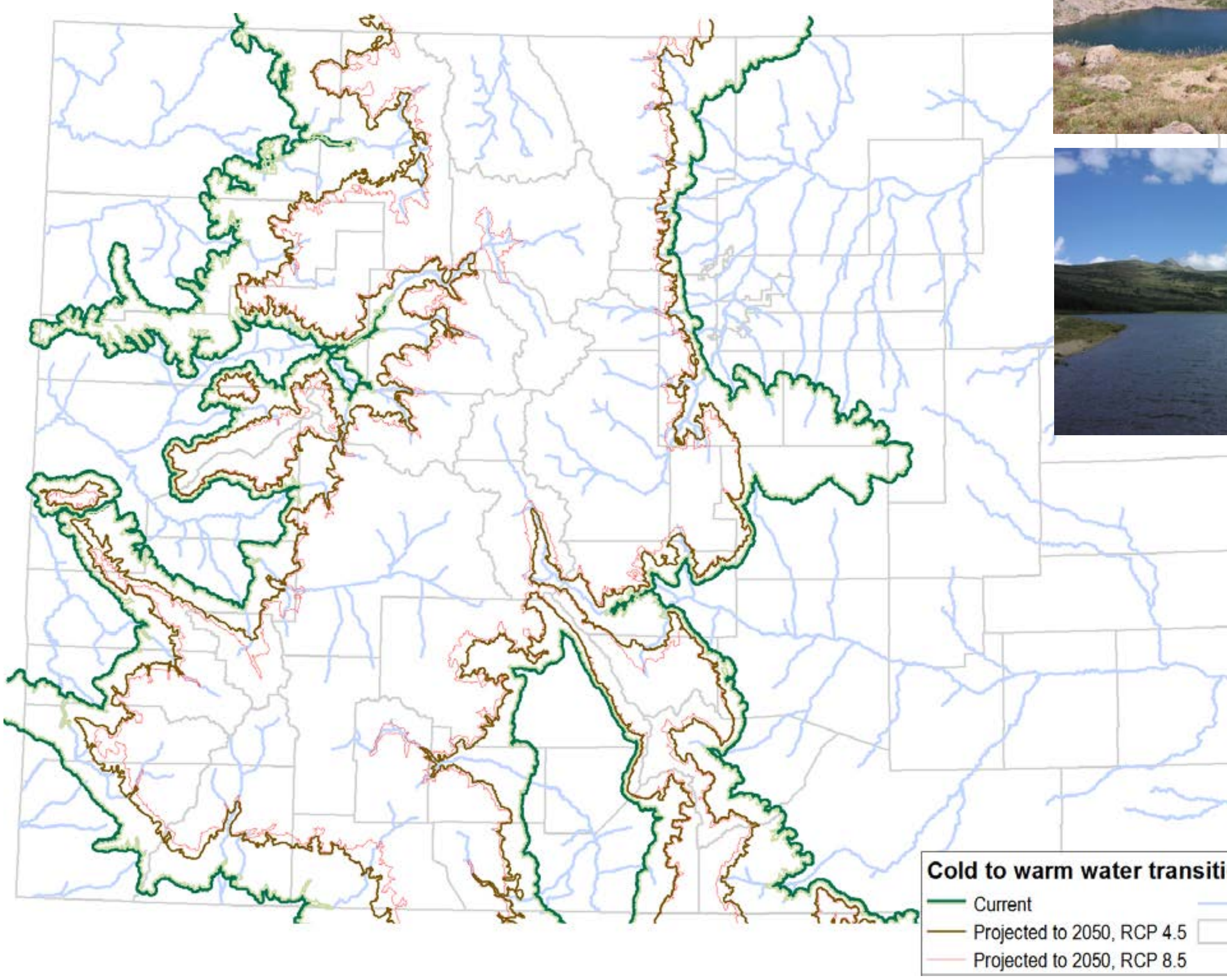


Figure 6. Modeled transition from cold water to warm water conditions by mid-Century under low and high emissions scenarios.

specific hydro-geomorphic setting and vulnerability to change in snowmelt instead of the bioclimatic envelope and dispersal/growth rate factors that were applied to terrestrial systems.

Three of the 10 regional ecosystem subtypes assessed have an overall vulnerability rank of High, and two are ranked Very High (Table 3, Figure 7). The primary factor contributing to High or Very High vulnerability ranks for freshwater ecosystems is the projected change in the location of transition zone between warm and cold water areas. Lakes and reservoirs at all elevations are projected to experience temperatures outside the current range, as well as effectively drier conditions. Warmer and drier conditions for lower elevation lakes and reservoirs are likely to result in generally lower water levels under pressure from municipal and agricultural consumers.

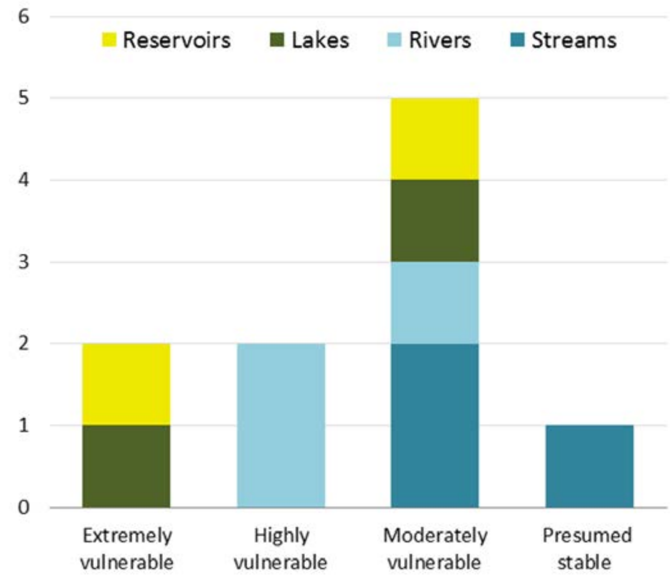


Figure 7. Vulnerability scores for freshwater ecological systems.

Table 3. Vulnerability scores and key vulnerability factors for freshwater ecological systems.

Ecosystem	Vulnerability	Climate factor(s)	Consequences	Other considerations
Streams – west	Moderate	Warming water temps	Loss of cool-water reaches	Connectivity; altered hydrology due to diversions
Streams – mountain	Low	Timing and amount of snowmelt/runoff	Altered hydrographs	Connectivity (including transbasin diversion), potential for increased wildfire disturbance
Streams – east	Moderate	Warmer and drier conditions	Loss of perennial reaches	Connectivity; altered hydrology due to diversions
Rivers – west	High	Warming water temps	Loss of cool-water reaches, low summer flows	Connectivity (including transbasin diversion), potential for increased wildfire disturbance
Rivers – mountain	Moderate	Timing and amount of runoff	Altered hydrographs	Connectivity (including transbasin diversion)
Rivers – east	High	Timing and amount of runoff	Altered hydrographs	Connectivity; altered hydrology due to dams and diversions
Lakes – high	Moderate	Warmer and drier conditions	Reduced water quality	Nitrogen deposition
Lakes – low	**Very High**	Warmer and drier conditions	Low water levels	Municipal & agricultural supply pressure
Reservoirs – high	Moderate	Timing and amount of snowmelt/runoff	Earlier high water levels	Flood control releases, reduced later storage
Reservoirs – low	**Very High**	Warmer and drier conditions	Low water levels	Municipal & agricultural supply pressure

For details on methods and results of this study, see the full technical report: Colorado Natural Heritage Program. 2015. Climate Change Vulnerability Assessment for Colorado Bureau of Land Management. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Available at www.cnhp.colostate.edu.

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Literature Cited: Manomet Center for Conservation Science and Massachusetts Division of Fisheries and Wildlife. 2010. Climate Change and Massachusetts Fish and Wildlife: http://www.manomet.org/science-applications/climate-change-energy; Nash, L.L. and P.H. Gleick. 1991. Sensitivity of streamflow in the Colorado Basin to Climatic Changes. Journal of Hydrology 125:221-241.

Colorado Bureau of Land Management

MODELING ECOLOGICAL RESPONSE TO SUPPORT ADAPTATION STRATEGIES

SUMMARY OF FINDINGS

RESEARCH QUESTIONS:

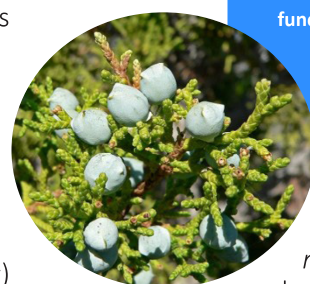
- ***How might different climate scenarios influence future distribution of vulnerable ecosystems?***
- ***What strategies might improve the ability of species and ecosystems to adapt to changing conditions, and where should we employ those strategies?***

Adaptation = management strategies that promote ecological resilience, maintain ecological function, and support sustainable ecosystem services in the face of a changing climate.

Overview

In 2015, the Colorado Natural Heritage Program (CNHP) completed a statewide vulnerability assessment for Colorado BLM. In that assessment, we determined that the pinyon-juniper ecosystem was the highest priority for additional analysis and adaptation strategy development. Of the ecosystems that make up the majority of BLM lands, pinyon-juniper ranked as most vulnerable, primarily due to potential for significant impacts to two-needle pinyon pine (CNHP 2015).

In order to develop adaptation strategies for addressing ecosystem vulnerability, we need to know how and where climate might change, as well as how and where ecosystems might respond. Building on previous and ongoing work (e.g., Rondeau et al. 2017), we developed rangewide models for two-needle pinyon pine (*Pinus edulis*) and the two juniper species primarily associated with pinyon pine in Colorado— Utah juniper (*Juniperus osteosperma*) and one-seed juniper (*J. monosperma*) (current distributions shown in Figure 1). The purpose of the models was to determine where habitat suitability for those species may improve or deteriorate, based on our best understanding of how each species may respond to projected future climate variables. The models will support our ongoing collaboration with BLM and other partners on identification of adaptation strategies.



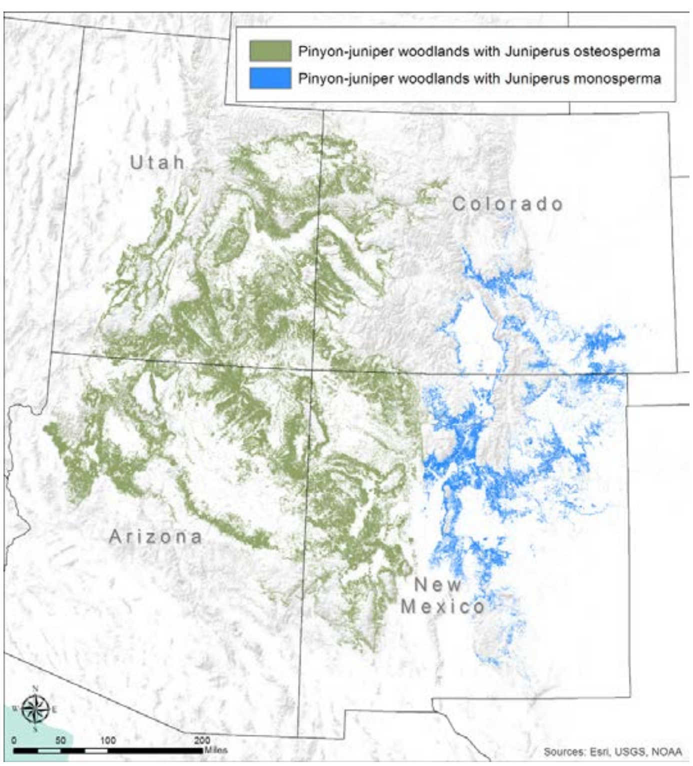


Figure 1. Current distribution of pinyon pine (*Pinus edulis*) with Utah juniper (green) and one-seed juniper (blue).

Potential Future Climate Scenarios

To accommodate uncertainty in climate projections, we developed our models using four scenarios representing the variety of future conditions we might expect. Each scenario was developed using one Global Circulation Model/emission scenario combination, selected in collaboration with a climate scientist. The four climate models capture the basic range of wetter to drier and warmer to hotter projected for the southwestern U.S. (Figure 2) by mid-century (i.e., 30-year period around 2050). We called these scenarios “Hot & Dry,” “Hot & Wet,” “Warm & Wet,” and “Feast or Famine.”

For each climate scenario, we interpreted how changes in projected temperature and precipitation may translate into climate and weather patterns, and what those changes might mean for pinyon pine and the two juniper species. Examples include changes in amount, seasonality, and form of precipitation (e.g., rain v. snow), timing and seasonality of temperature changes, and ecological consequences

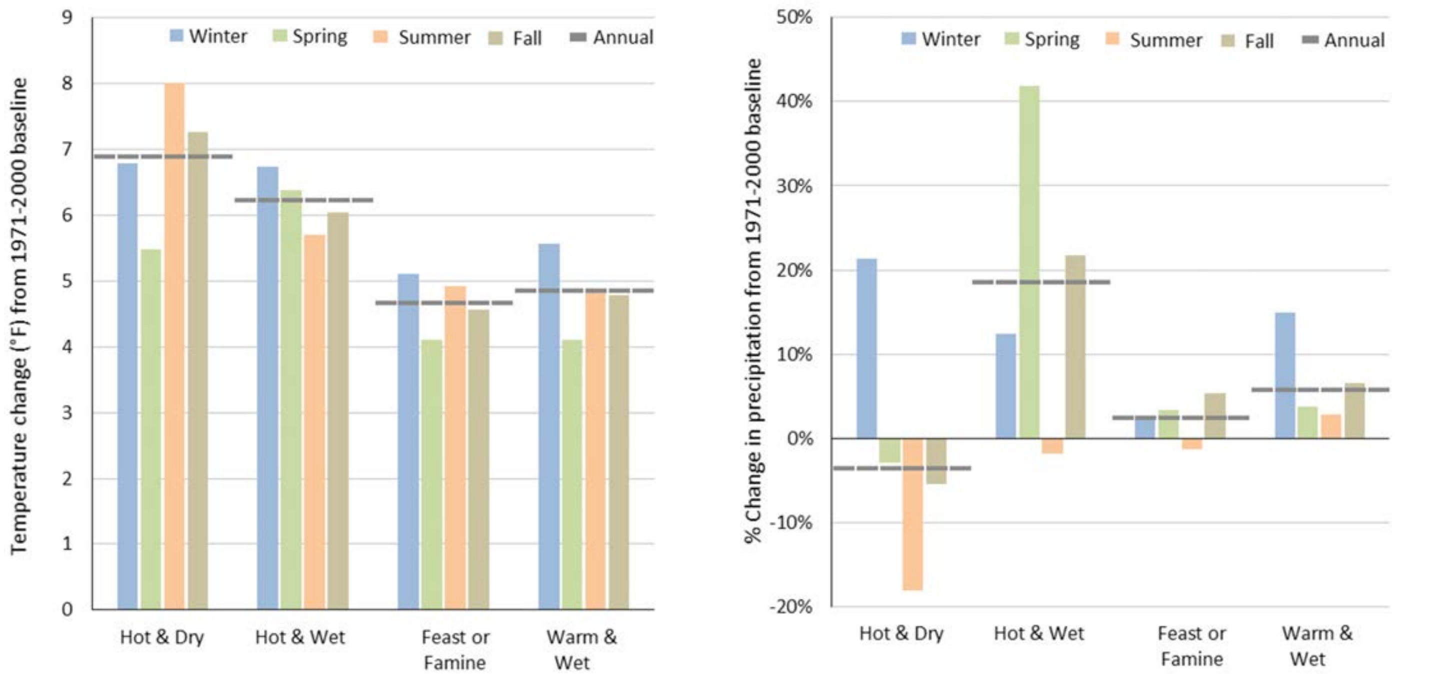


Figure 2. Projected seasonal changes under each future climate scenario for temperature (left) and precipitation (right). Dashed lines represent projected annual mean for each scenario. Zero (x-axis) represents current mean. Note that increased precipitation may not result in increased moisture availability due to higher temperatures (e.g., Nash and Gleick 1991).

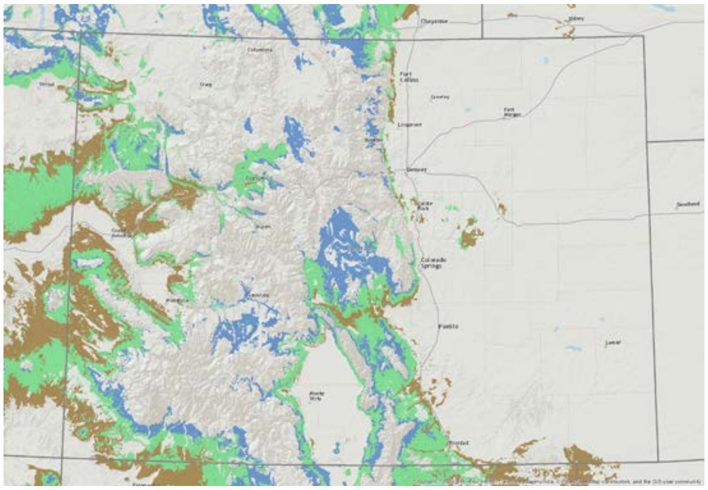
(e.g., length of growing season, requirements for successful reproduction) (Table 1).

Ecological Response Models

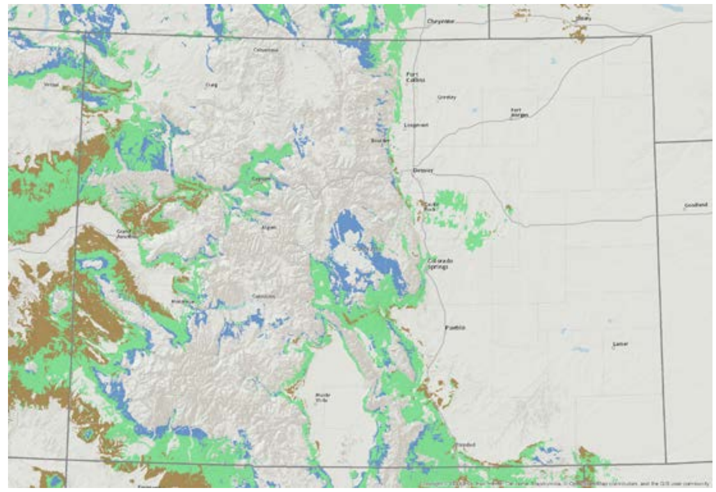
We developed spatial ecological response models based on distribution modeling of the dominant tree species (pinyon pine and the two juniper species), and projected those models out to a mid-century time frame under the four climate scenarios. These models (e.g., Figure 3) depict areas where suitable climate is likely to persist, likely to be emergent (i.e., new areas where climate will become suitable), or unlikely to remain in place. The most important variables influencing the model for each species are presented in Table 2.

Table 1. Summary of estimated impacts of projected changes in temperature and precipitation for each future climate scenario.

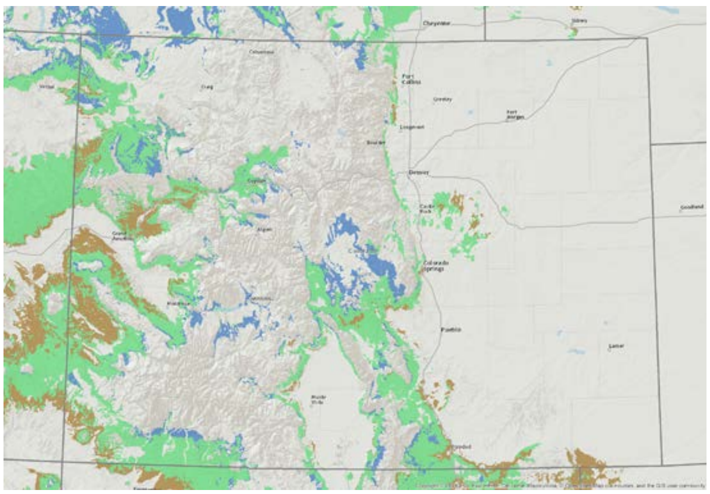
Scenario	Statewide Effects (compared to 1971-2000 baseline)
Hot and Dry	Annual mean temperature increase of >6°F, with temperatures warming most in summer and fall. This, combined with a decrease in annual precipitation, results in snowline moving up in elevation by about 1500 ft, as well as frequent severe multi-year droughts. Winters are >20% wetter, but other seasons 3-18% drier, and summer monsoon decreases by 20%. Runoff peak flows are 2 weeks earlier, and volume decreases substantially (>15%).
Hot and Wet	Annual mean temperature increase of >6°F, with temperatures warming at similar levels across all seasons, combined with a 18% increase in annual precipitation. Even with increased winter precipitation, permanent snow lines are likely to be more than 1200 ft higher, and rain on snow events more frequent. Spring precipitation is 30% higher, and higher temperatures mean that peak runoff will be 2 weeks earlier. Summer monsoon decreases by almost 10%.
Feast or Famine	Annual mean temperature increase of over 4°F, with temperatures warming most in winter may lead to a +900 ft elevation change for permanent snow lines and frequent severe droughts. Annual precipitation shows little overall change (2%) but with large year-to-year variation. Winter and spring are likely to be wetter (11% and 3%), but other seasons drier, including a 5% reduction in monsoon moisture. Peak runoff may be 1-2 weeks earlier, with reduced volume (5-10%).
Warm and Wet	Annual mean temperature increase about 5°F with temperatures warming most in winter, combined with a 6% increase in annual precipitation results in a +600 ft elevation change for permanent snow lines. Drought frequency is similar to the recent past. Peak runoff is 1-2 weeks earlier, but with volumes generally unchanged. Summer monsoon remains similar to historic levels.



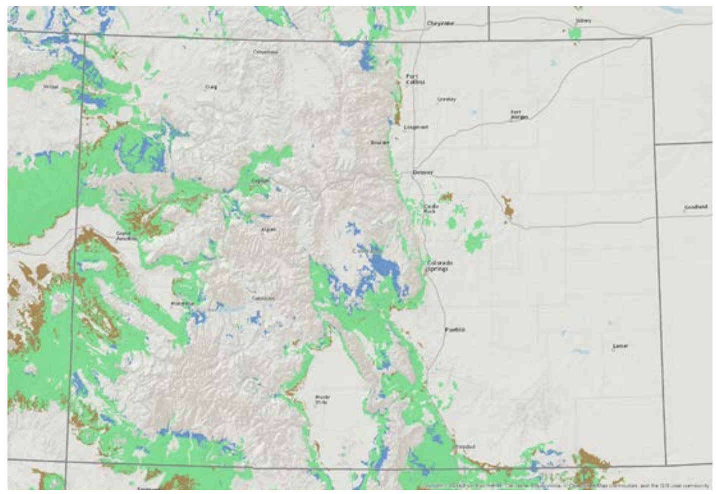
a) Hot & Dry Scenario



b) Hot & Wet Scenario



c) Feast or Famine Scenario



d) Warm & Wet Scenario

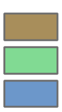
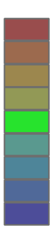
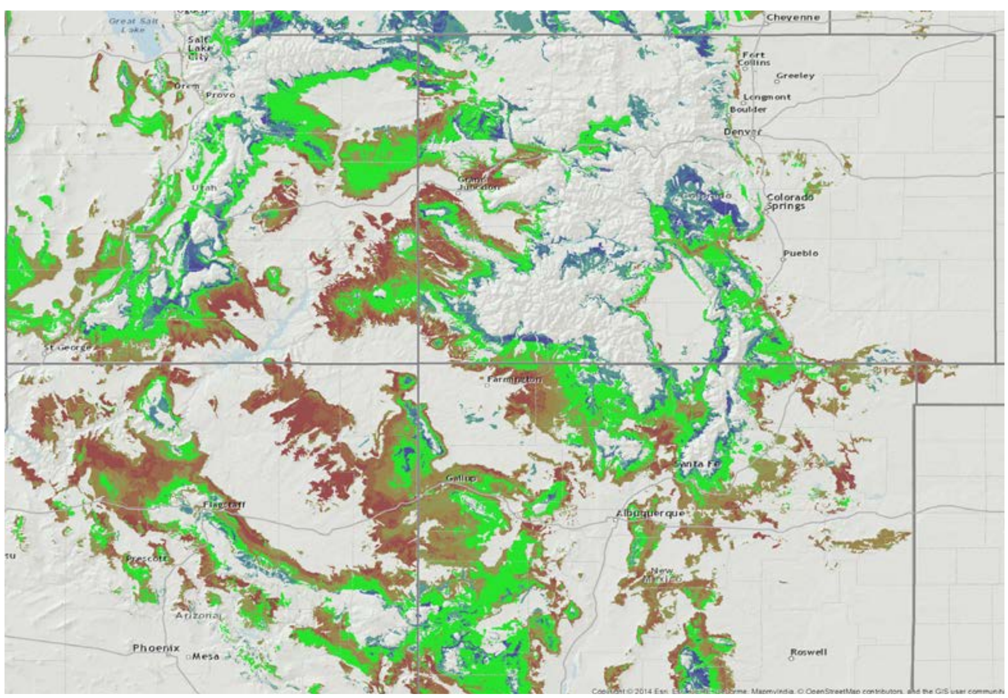


Figure 3. Projected climate suitability for pinyon pine (*Pinus edulis*) at mid-Century under four scenarios (a-d), and degree of agreement among models (e). In map 3e, the more saturated each color, the higher the agreement between climate models on projected suitability. Comparable models were also created for the juniper species.





e) degree of agreement among climate models

Table 2. Most important environmental variables influencing the models for pinyon pine, Utah juniper, and one-seed juniper.

	Top 3 variables influencing the model			Other variables with some influence
Species	1	2	3	
Pinyon Pine	Summer mean temp	Winter precip	Summer precip	Available water supply, soil pH, % organic matter, percent sand.
Utah Juniper	Winter precip	Summer precip	Summer mean temp	Winter max temp, % organic matter, pH, % silt, available water supply, slope.
One-seed Juniper	Summer precip	Winter max temp	Summer max temp	Spring precip, autumn precip, % organic matter, % clay, pH, and % silt.

Future habitat categories for two-needle-pinyon and Utah juniper were originally developed by considering all possible combinations of a variety of factors, including current suitability, current occupation, direction of change, and proximity to source of seed. These combinations were simplified and rolled up into three final primary future habitat categories (Figure 3).

It is important to note that both pinyon and juniper are long-lived species reaching reproductive age only after many decades. Therefore, the lag time between when an area becomes suitable or unsuitable, and the presence or absence of these species on a site may be considerable. In addition, myriad physical and ecological factors other than climate may influence the actual distribution of any species. Thus, the proper interpretation of these maps is that *climate may be suitable* for species establishment and persistence, *not* that the species *will be there*.

Adaptation Strategies

Ecological response models can be used to identify potential intervention points, where management actions may facilitate increased ecosystem resilience and enhanced adaptive capacity under future climate conditions. The next steps in our ongoing work will include convening BLM managers to further explore the general adaptation strategies presented in Table 3, and to partner with social scientists in co-development of adaptation strategies that address both ecological and human livelihood concerns.

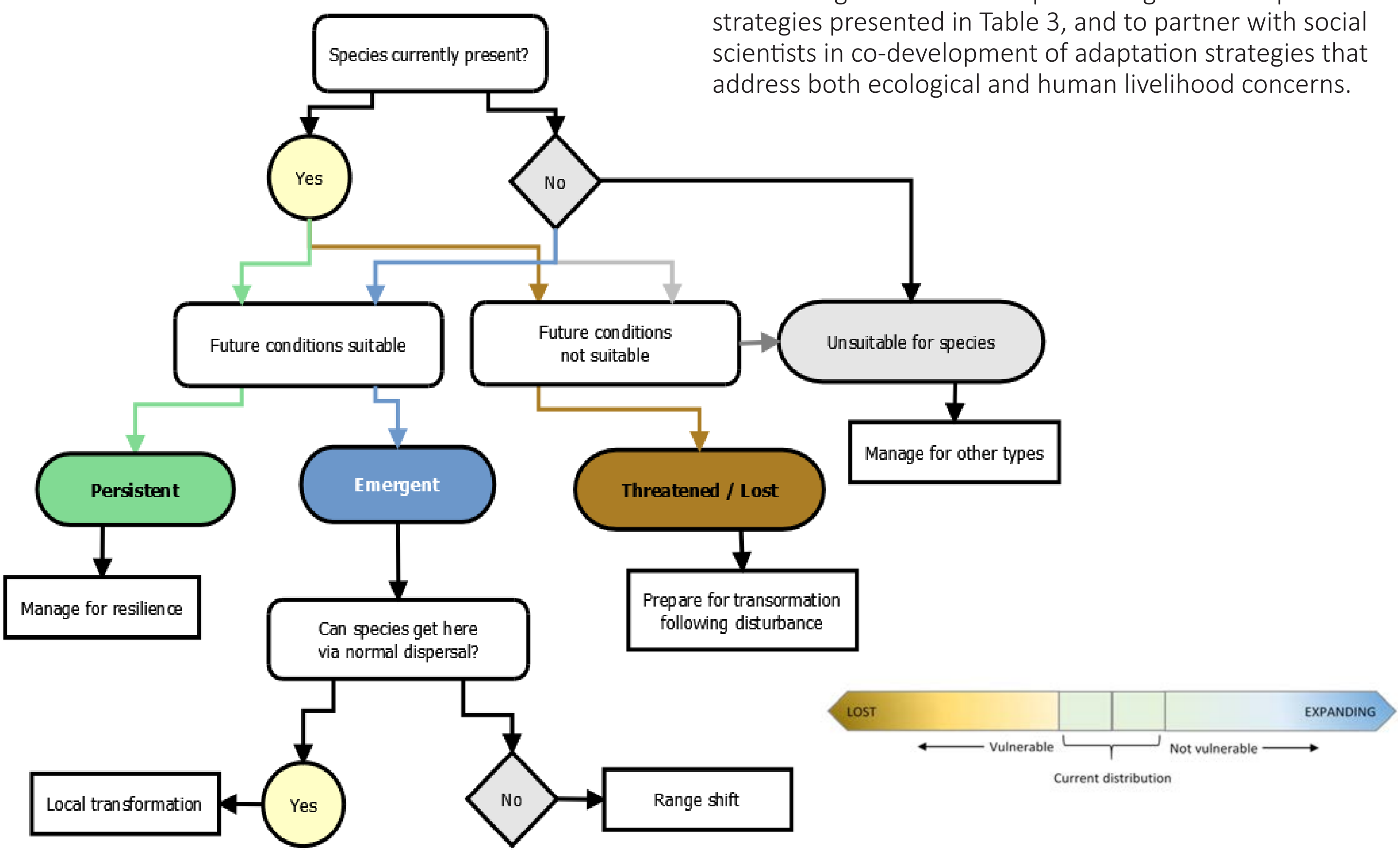


Figure 4. Decision support tool for using ecosystem response models to guide adaptation strategy selection.

Table 3. General adaptation strategies by ecological response categories.

Map Category	Description	General Adaptive Strategy	Details
Persistent	Areas where each species (*P. edulis*, *J. osteosperma*, and *J. monosperma*) and the pinyon-juniper assemblage is currently present, and where future bioclimatic conditions (e.g., climate, soils) will remain suitable for the persistence of the species through mid-century.	Manage for ecological resilience (e.g., to disturbance).	Map and identify the persistent areas, where climatic conditions are likely to remain stable under all future scenarios.
Emergent (areas not currently occupied, but likely to be suitable in the future).	Local transformation: improving, stable, or newly suitable habitat near existing seed sources, such that the species should be able to establish in emergent areas under normal migration rates.	Allow transformation, with assistance (planting) as needed.	For pinyon pine, incorporate presence of seed dispersers. Identify areas where the transformation may be in conflict with other ecosystems of concern (e.g., juniper into sagebrush).
	Range shift: future suitable habitat not within a likely distance to be colonized naturally under normal migration rates.	Consider assisted migration, unless there are conflicting resource issues.	Assisted migration means planting seedlings in areas where the species would not naturally disperse within the time frame under consideration. Genetic considerations may be important.
Threatened / Lost	Areas where the species is currently present, but where future climate conditions are not likely to be suitable for the species. High likelihood of eventual loss, or failure to re-establish following disturbance events.	Reduce management actions that disturb soils; consider allowing post-disturbance transformation.	Develop management plans that move toward expected future conditions (e.g., using a climate-smart seed mix—one that contains species expected to thrive in the area under future conditions—for restoration projects). Map and identify areas that potentially will be lost under all future scenarios vs. areas lost only under certain future conditions.
Not suitable	Areas that are not and will not be suitable for the species.	Manage for other types.	

Funding generously provided by Colorado Bureau of Land Management. Because this work is ongoing, a technical report is not yet available. In the interim, for additional information please contact Lee Grunau (CNHP), lee.grunau@colostate.edu, or Bruce Rittenhouse (BLM), brittenh@blm.gov.

Photo: Pinyon-juniper in Dominguez Canyon, Colorado.
Renee Rondeau

Literature Cited:

Colorado Natural Heritage Program [CNHP]. 2015. Climate Change Vulnerability Assessment for Colorado Bureau of Land Management. K. Decker, L. Grunau, J. Handwerk, and J. Siemers, editors. Colorado State University, Fort Collins, Colorado.

Nash, L.L. and P.H. Gleick. 1991. Sensitivity of streamflow in the Colorado Basin to Climatic Changes. Journal of Hydrology 125:221-241.

Rondeau, R., M. Bidwell, B. Neely, I. Rangwala, L. Yung, and C. Wyborn. 2017. Pinyon-Juniper Landscape: San Juan Basin, Colorado Social-Ecological Climate Resilience Project. North Central Climate Science Center, Ft. Collins, Colorado.

Colorado State University

Colorado Bureau of Land Management

MODELING FISH HABITAT RESPONSE TO SUPPORT CLIMATE ADAPTATION STRATEGIES

SUMMARY OF FINDINGS

Overview

In 2015, the Colorado Natural Heritage Program (CNHP) completed a statewide vulnerability assessment for Colorado BLM. In that assessment, we determined that, as a group, native fish are by far the most vulnerable of the animal species we assessed (CNHP 2015). Our next goal was to conduct additional analyses on the highest priority species to lay the groundwork for development of adaptation strategies.

In collaboration with BLM fisheries biologists, we identified two key information needs: a means of determining *where* fisheries projects would most likely be successful over the long term, and a way to evaluate potential fisheries projects through a climate lens. Though both cold-water and warm-water species are vulnerable to impacts from climate change, BLM fisheries managers highlighted the particular need for cold-water fisheries (including native and sport species) management decisions in the near term. Given this, we defined target species for additional assessment as:

- Cutthroat trout (*Oncorhynchus clarkii*)
- Rainbow trout (*Oncorhynchus mykiss*)
- Brook trout (*Salvelinus fontinalis*)
- Brown trout (*Salmo trutta*)
- Bluehead sucker (*Catostomus discobolus*)
- Mountain whitefish (*Prosopium williamsoni*)

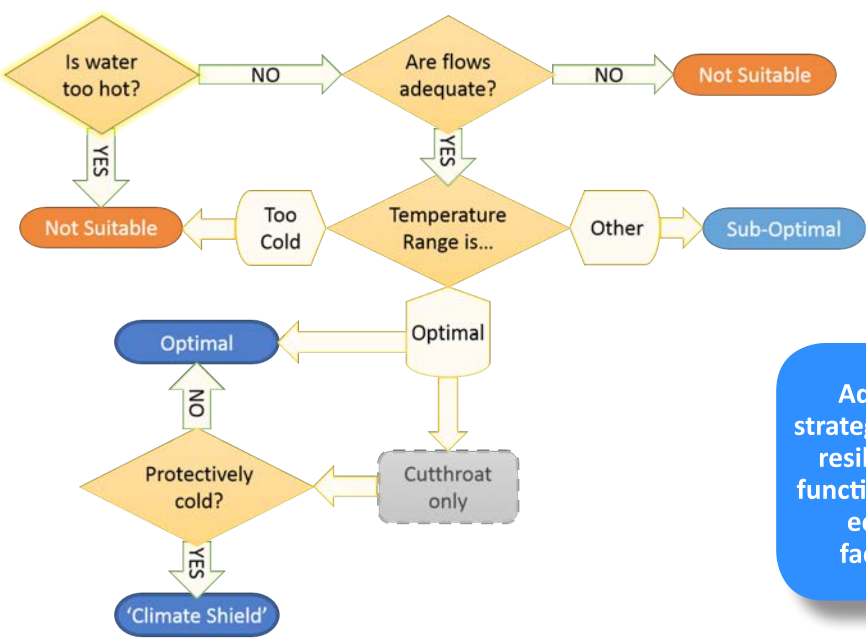


Figure 1. Decision tree (simplified) used to apply temperature and flows criteria.

Future Habitat Suitability Models

To address the first information need, we built upon existing methods originally developed by Isaak and others (e.g., Climate Shield, NorWeST) to model future habitat suitability in Colorado on a mid-Century (2040) timeframe for our target species.

We used existing data sources for stream flow, slope, and water temperature requirements of each species as basic criteria for habitat suitability inputs, following the generalized flow diagram depicted in Figure 1. Micro-scale habitat requirements (e.g., pools and riffles), other measures of water quality, and interactions among fish species could not be addressed with available input data, so these factors could not be represented in the models. Also, known limitations exist with input datasets, which are themselves models based on a limited number of gauges across the state. Though known errors exist, the models can be used to make general determinations on where habitat improvement projects may be most appropriate. Results of this modeling exercise are shown in Figures 2-8. See Fink et al. (2019) for details on data inputs and technical methods, available at www.cnhp.colostate.edu.

Evaluation Framework for Fisheries Projects

As management and conservation resources are limited and needs are great, it is crucial to leverage previous work whenever possible. In 2016, Nelson et al. developed a decision support framework specifically for purposes compatible with our second information need: a way to evaluate management goals and strategies for fisheries within the context of climate change. Their work, which focused on native salmonids (cold-water species) in the northern Rocky Mountains, resulted in a three-

Adaptation = management strategies that promote ecological resilience, maintain ecological function, and support sustainable ecosystem services in the face of a changing climate.

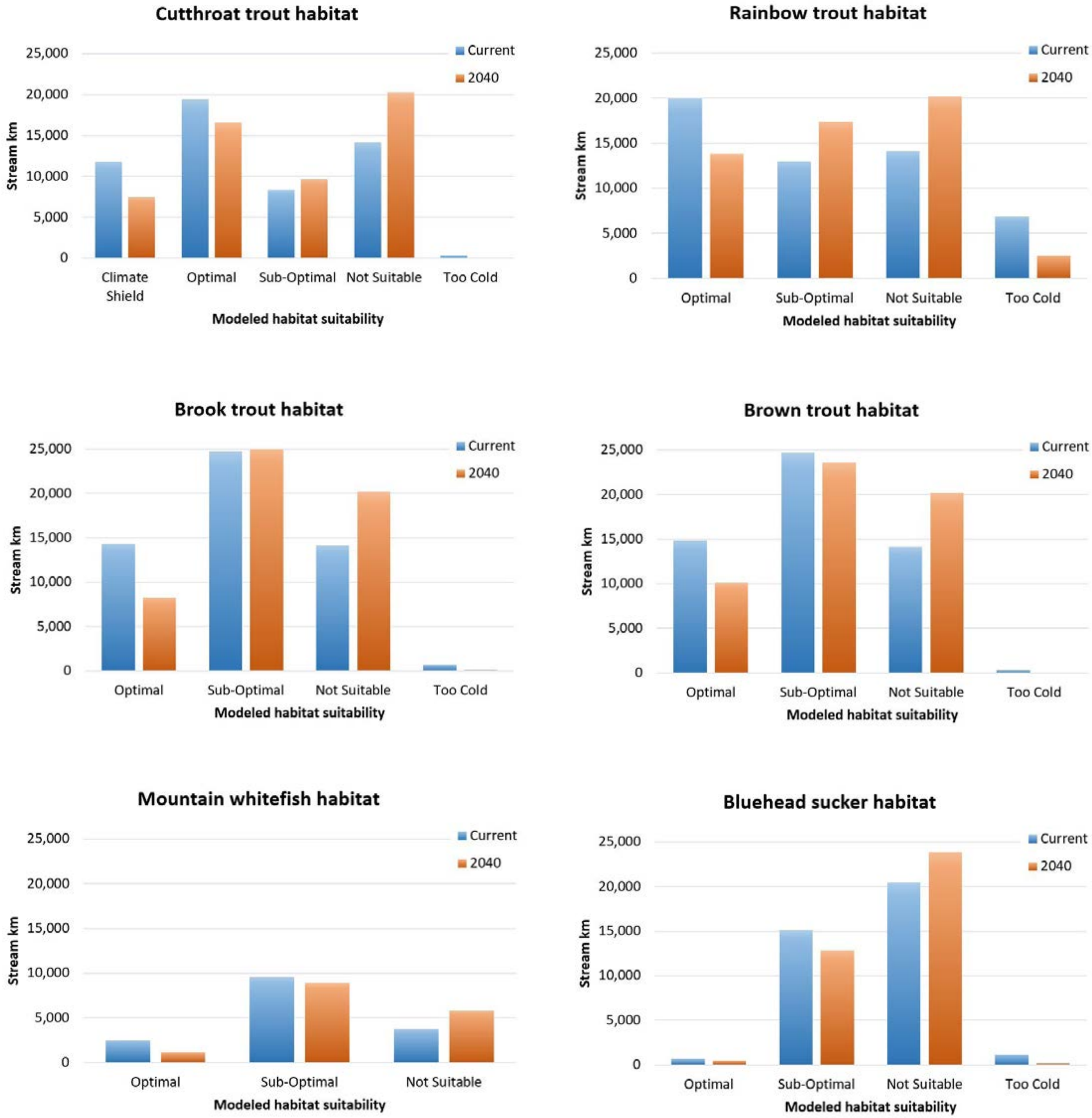


Figure 2. Model results showing comparison of current and future habitat suitability in terms of stream kilometers. The "Climate Shield" category for cutthroat trout is water cold enough to minimize invasion of, and hybridization with, other trout species (Isaak et al. 2012). The "Too Cold" category refers to water that is too cold for reproduction, not necessarily survival of individuals. Amount of optimal habitat is reduced for all species by 2040.

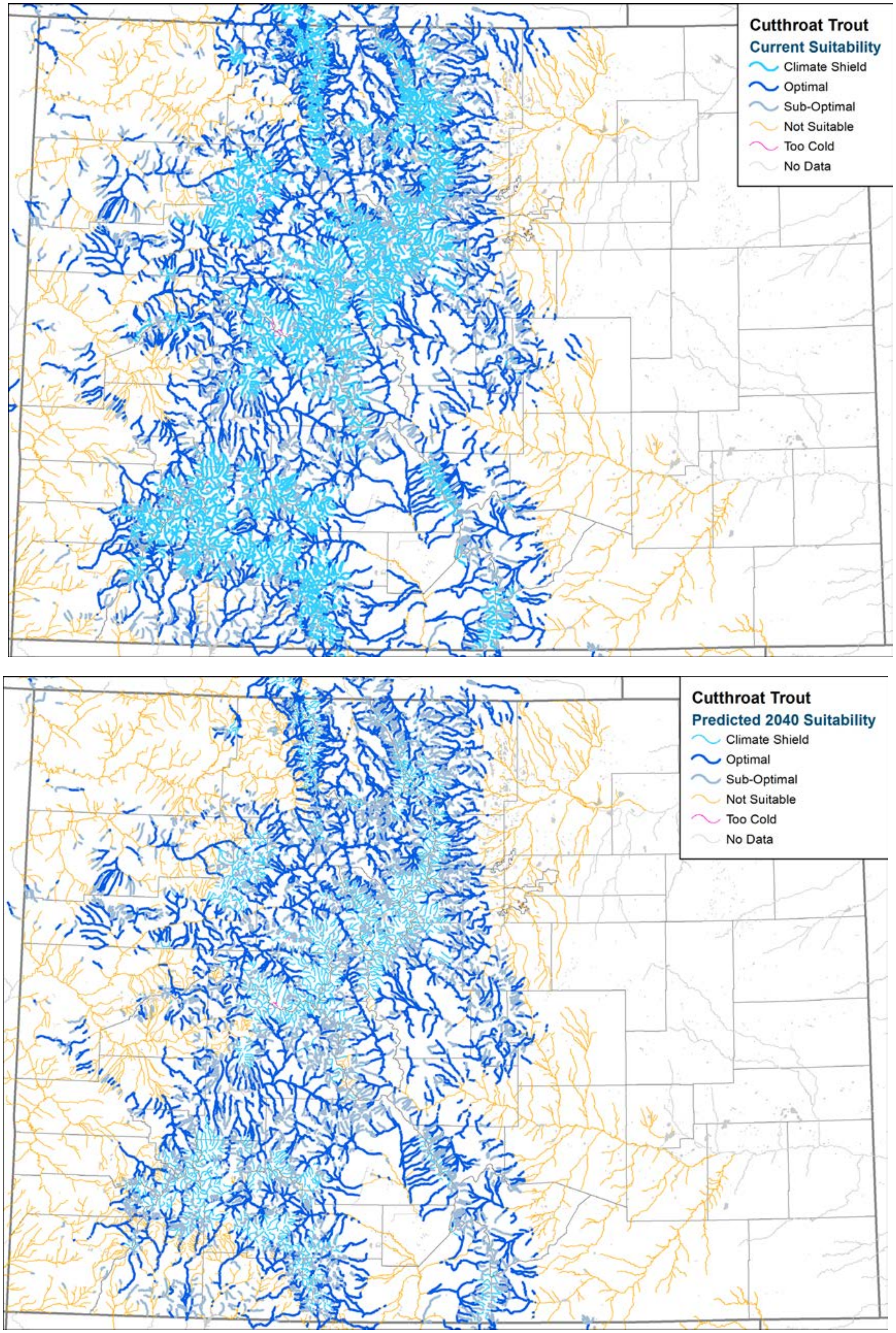
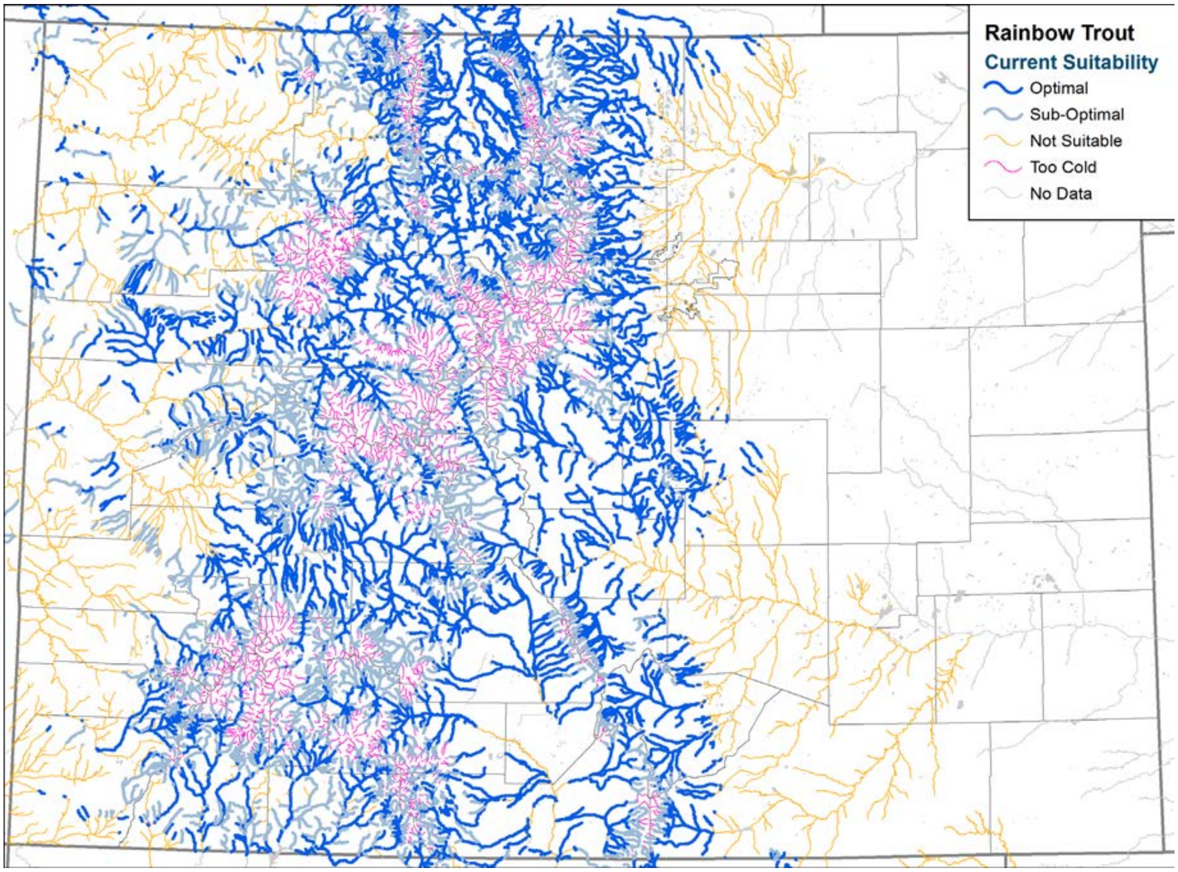


Figure 3. Modeled current (top) and future (bottom) habitat suitability for cutthroat trout in Colorado. See Isaak et al. (2012) for additional information on Climate Shield. Limitations in underlying flows data can be seen in the cutthroat models, where the Dolores River drainage modeled as Not Suitable though it is known to support this species.



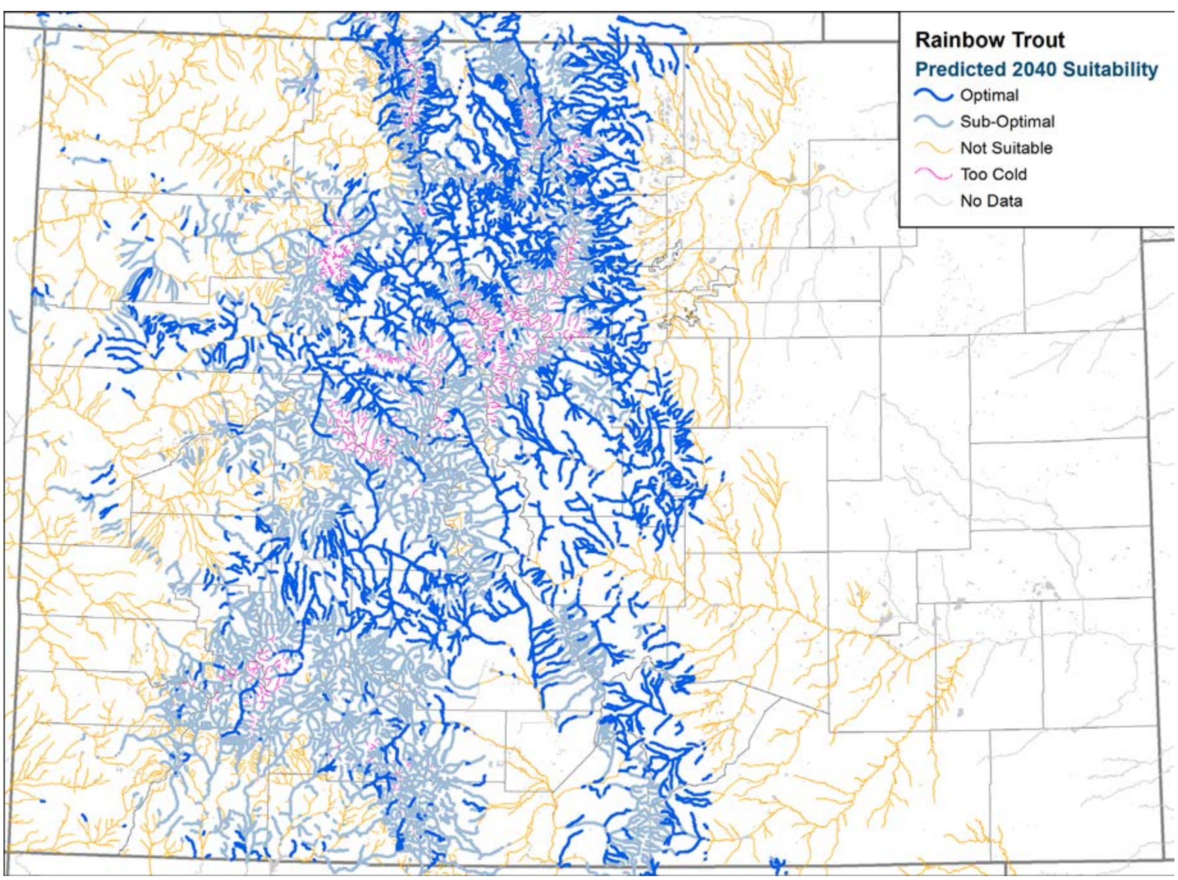


Figure 4. Modeled current (top) and future (bottom) habitat suitability for rainbow trout in Colorado.

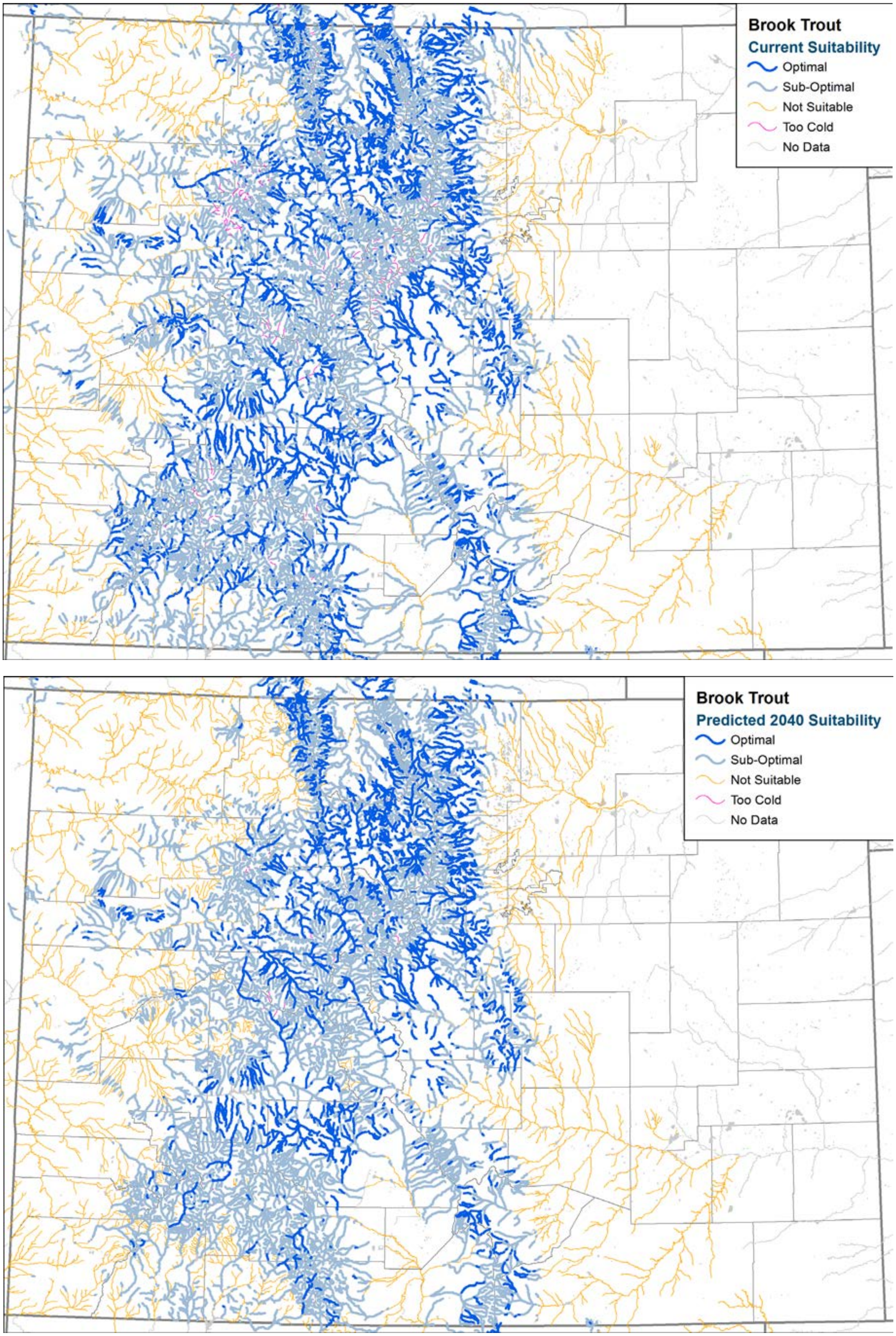
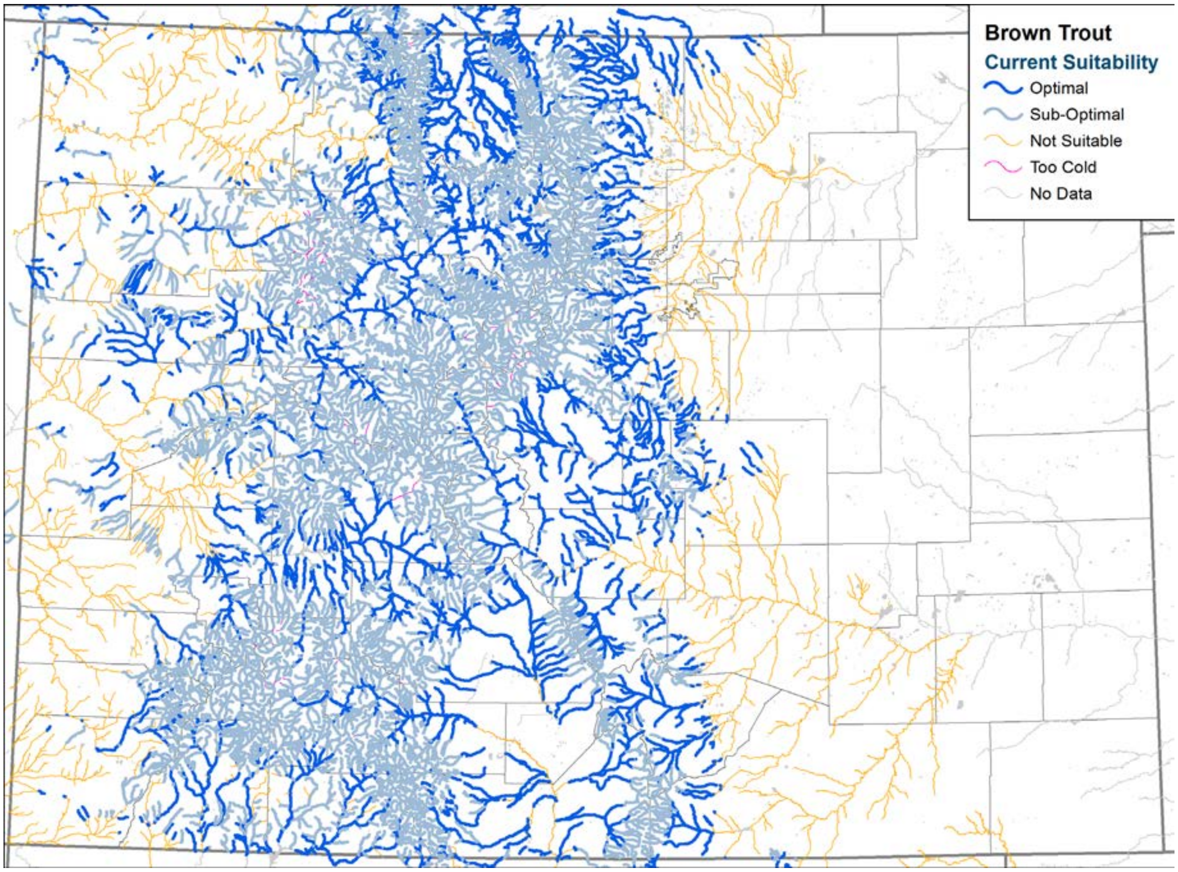


Figure 5. Modeled current (top) and future (bottom) habitat suitability for brook trout in Colorado.



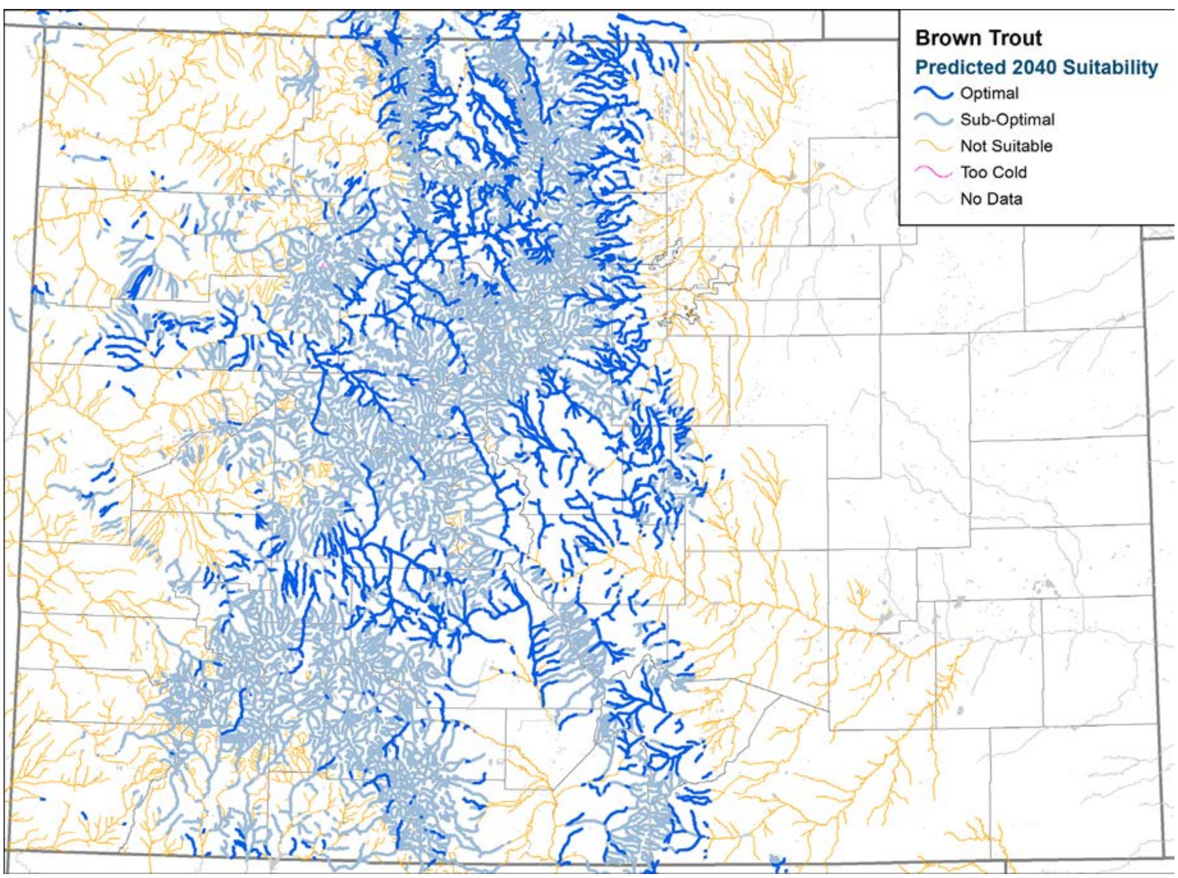
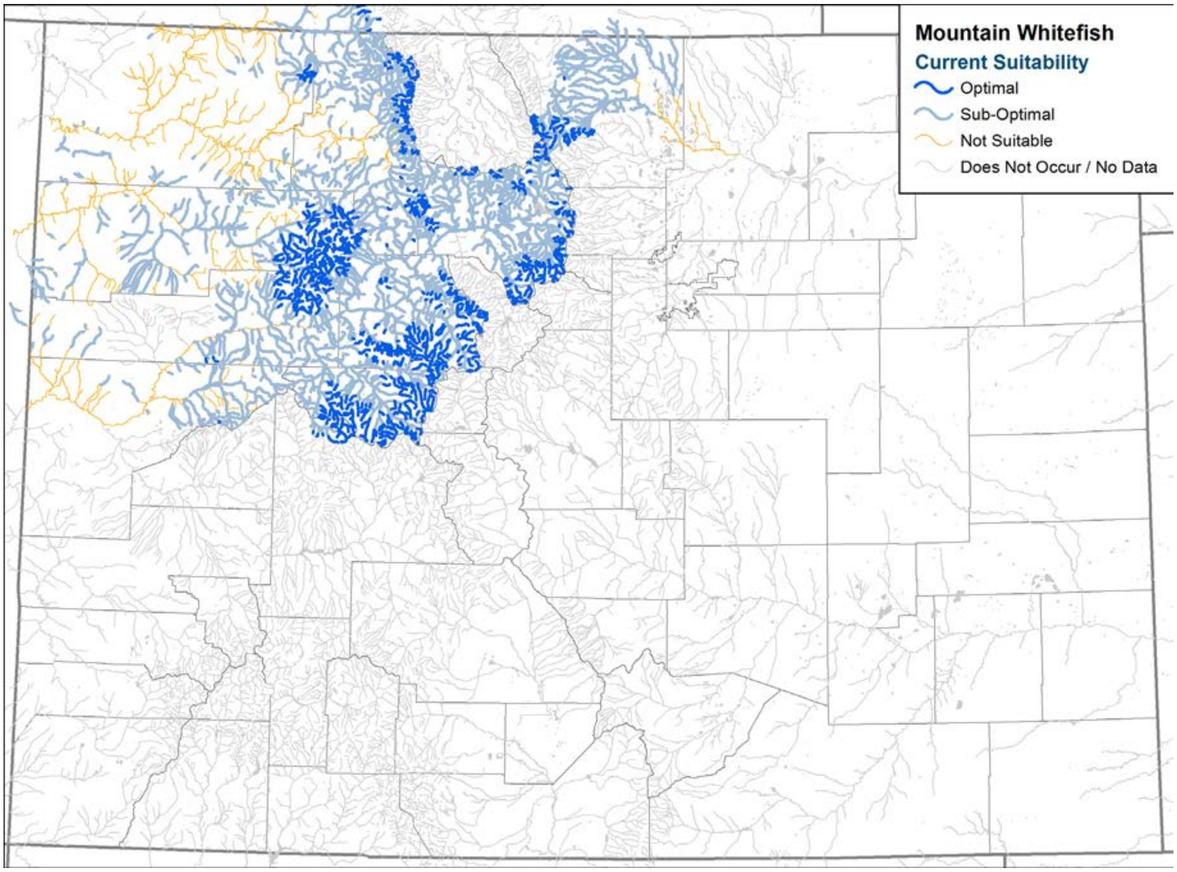


Figure 6. Modeled current (top) and future (bottom) habitat suitability for brown trout in Colorado.



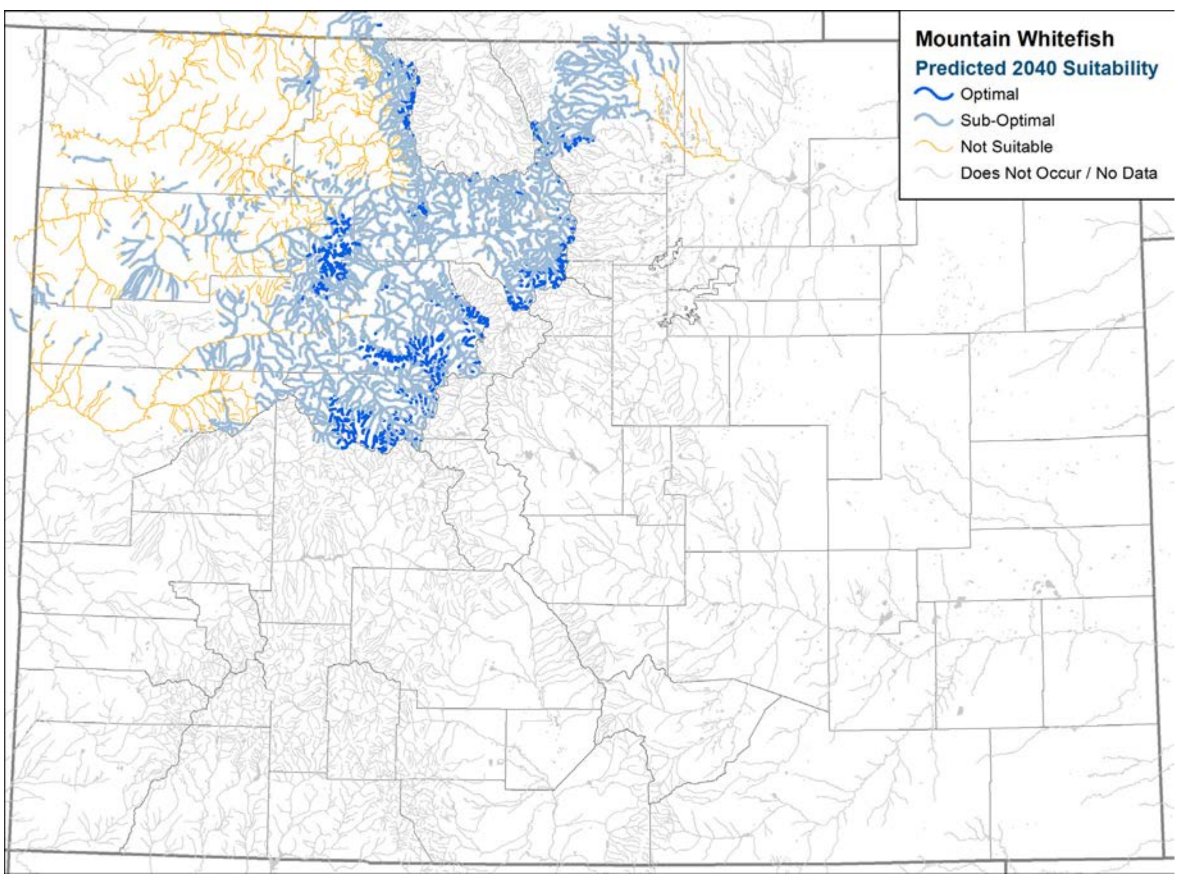


Figure 7. Modeled current (top) and future (bottom) habitat suitability for mountain whitefish in Colorado.

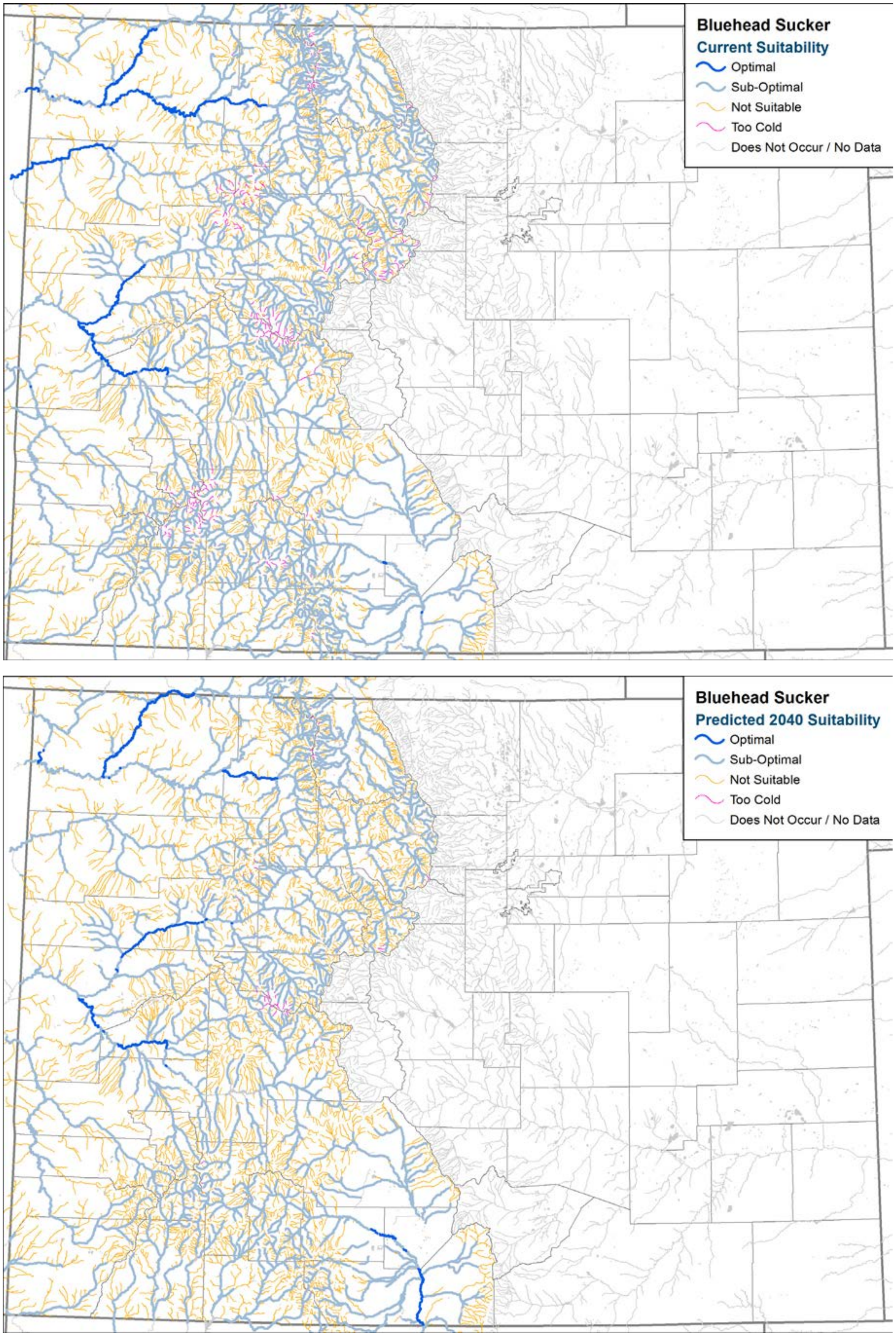


Figure 8. Modeled current (top) and future (bottom) habitat suitability for bluehead sucker in Colorado.

step matrix that considers key vulnerabilities (habitat suitability, threats from non-native fish, and connectivity) and aligns those with options for management goals and implementation strategies.

The BLM fisheries managers agreed that Nelson et al.'s framework offered an excellent tool for assessing vulnerability and documenting decision rationale, since the basic data and assumptions behind the framework are correct and relevant to Colorado cold-water fisheries. One key disconnect, however, is the treatment of non-native sport fish. In Nelson et al.'s framework, non-native species are (correctly) treated as one of the key vulnerabilities for native salmonids, based on the considerable potential for conflict related to hybridization and competition among the species. However, a reality of multiple-use resource management is the need to find balance between conservation needs of native species, and social / economic benefits of non-native sport fisheries. Thus, we adapted the language in Nelson et al.'s framework to reflect this multiple-use management need, but otherwise maintained the framework as originally developed. See Nelson et al. (2012) and Fink et al. (2019) for additional information.

STEP ONE in Climate Adaptation Decision Support Framework, modified from Nelson et al. 2016.

Key Factor of Vulnerability	HABITAT SUITABILITY To what extent will climate change alter habitat suitability for the population?	THREATS FROM UNDESIRABLE FISH To what extent will climate change increase the threat that undesirable fish present to the population?	CONNECTIVITY To what extent will climate change alter the degree of connectivity of the population to a larger network of populations and suitable habitat?
Climate-related Questions to Consider	• Are stream temperatures expected to remain (or become) suitable? • Are other key habitat conditions (e.g., streamflow quantity and timing, sediments, patch size, etc.) expected to remain or become suitable as climate changes? • Are climate-driven changes likely to interfere with life-history requirements of focal species (e.g., changes in winter flooding might influence spawning success)? • Is the population in an area naturally more resilient to changing climate conditions (i.e., because of the elevation, size of the habitat patch, connection to lakes that provide vertical temperature stratification, or the presence of features that could buffer warming such as groundwater upwelling or cold-air drainages)? • Could climate-driven changes in human water use and management affect stream flow quantity, quality and timing?	• Are undesirable fish currently present? • If undesirable fish are currently present, might climate change alter the influence of undesirable fish on desirable fish (e.g., via hybridization, competition, predation)? • If undesirable fish are currently absent, could climate change potentially increase the invasion threat (i.e., by altering habitat conditions or disturbance events that might facilitate invasion)?	• Is the population currently isolated, or is it connected to a larger network of populations and habitat? • If currently connected to a larger network, do you expect this connectivity to remain given changing climate conditions (e.g. is the existing habitat vulnerable to fragmentation by changing stream flows and temperatures)? • Are features present (e.g. culverts, low water crossings) that could become barriers to fish movement under changing stream flows? • If currently isolated, is the population like to persist given changing climate conditions and associated extreme events (e.g., wildfire, floods, erosion)?
Assess Vulnerabilities	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on habitat suitability: A -Habitat likely to remain or become suitable B - Habitat likely to become marginal (i.e., at or near thresholds for focal species) C - Habitat likely to become unsuitable	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on undesirable fish: D - Threats from undesirable fish likely to be low E - Threats from undesirable fish likely to be high (because already present or likely to increase)	Considering your answers above, choose the most appropriate level of vulnerability of the population to climate change effects on connectivity: F - Population likely to be connected to a larger network G - Population likely to remain or become isolated

If you answered:	Go to Box:	If you answered:	Go to Box:	If you answered:	Go to Box:
A D F	1	B D F	2	C D F	3
A E F	4	B E F	5	C E F	6
A D G	7	B D G	8	C D G	9
A E G	10	B E G	11	C E G	12

Funding generously provided by Colorado Bureau of Land Management. The technical report is available at http://cnhp.colostate.edu. For additional information please contact Michelle Fink (michelle.fink@colostate.edu) or Lee Grunau (lee.grunau@colostate.edu).

References:

Colorado Natural Heritage Program [CNHP]. 2015. Climate Change Vulnerability Assessment for Colorado Bureau of Land Management. K. Decker, L. Grunau, J. Handwerk, and J. Siemers. Colorado State University, Fort Collins, Colorado.

Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the Face of Environmental Change: Supporting Information for BLM Planning in Colorado. Colorado Natural Heritage Program, Colorado State University, Fort Collins, CO.

Isaak, D., C.C. Muhlfeld, A.S. Todd, R. Al-Chokhachy, J. Roberts, J.L. Kershner, K.D. Fausch, and S.W. Hostetler. 2012. The past as prelude to the future for understanding 21st-Century climate effects on Rocky Mountain trout. Fisheries 37(12):542-556.

Nelson, R., Cross, M., Hansen, L., and G. Tabor. 2016. A three-step decision support framework for climate adaptation: Selecting climate-informed conservation goals and strategies for native salmonids in the northern U.S. Rockies. Wildlife Conservation Society, EcoAdapt, Center for Large Landscape Conservation. Bozeman, MT, USA. http://rmpf.weebly.com/cold-water-ecosystem-management-tool.html.

NorWeST. 2019. Regional database and modeled stream temperatures. https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml.

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