Colorado Wildlife Action Plan Enhancement: Climate Change Vulnerability Assessment

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Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

SWAP	State Wildlife Action Plan
AFWA	Association of Fish and Wildlife Agencies
AUC	Area under curve
BCCA	Bias Corrected Constructed Analogs
BOR	Bureau of Reclamation
BRT	Boosted Regression Trees
CIRES	Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder
CMIP	Climate Model Diagnosis and Intercomparison Project (Phase 3 published in 2007, Phase 5 published in 2013)
CNHP	Colorado Natural Heritage Program
CPW	Colorado Parks and Wildlife
DJF	Winter months
JJA	Summer months
MAFW	Massachusetts Division of Fish and Wildlife
MAM	Spring months
MCCS	Manomet Center for Conservation Science
NCCSC	North Central Climate Science Center
NRCS	Natural Resources Conservation Service
NOAA	National Oceanic and Atmospheric Administration
ppm	parts per million
ppt	precipitation
RCP	Representative concentration pathway
SAHM	Software for Assisted Habitat Modeling
SON	Fall months
SSURGO	Soil Survey Geographic database
STATSGO	State Soil Geographic database
USGS	United States Geological Survey

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Introduction

State wildlife action plans (SWAPs) were originally developed in 2005 by all 50 states and five U.S. territories as a prerequisite for the receipt of federal funds through the Wildlife Conservation and Restoration Program and the State Wildlife Grants Program. These plans compile steps and strategies necessary to conserve wildlife species and their habitats so that adequate management action is undertaken before federal action under the ESA is required. SWAPs are intended to "assess the health of the state's wildlife and habitats, identify the problems they face, and outline the actions that are needed to conserve them over the long term" (AFWA 2006). A SWAP is required to address eight key elements, including descriptions of the distribution, abundance, and condition of species and their habitats, research and conservation action priorities, monitoring and review, and broad public participation.

Most of the original SWAPs did not address climate change. In recognition of the growing threat posed by this factor, the Association of Fish and Wildlife Agencies (AFWA) has recommended that states incorporate the impacts of climate change into the ten-year SWAP revisions required to be completed by 2015, and provided guidance for this task (AFWA 2009, 2012). As recommended in the AFWA best-practices document, the revised SWAP will address potential impacts, opportunities and vulnerabilities under likely future climatic conditions. The integration of climate change is intended to be part of a dynamic, iterative, multi-scale process that will focus management actions on strategies that are effective under both current and future climates. This analysis is based on a relatively short temporal scale (i.e., suited to agency planning horizons and attentive to uncertainty levels in projected climate models) and the use of a limited but representative set of potential change scenarios.

A primary tool recommended by the AFWA best-practices is the vulnerability assessment for ecosystem responses to climate change. The components of vulnerability were described by Glick et al. (2011) and consist of projected *exposure* to climate change, *sensitivity* of the species or ecosystem to expected changes, and the *adaptive capacity* of the species or ecosystem to respond to changes (Figure 1). Although this diagram is straightforward and conceptually simple, the individual components of exposure, sensitivity, and adaptive capacity can be difficult to calculate with any precision. Uncertainty comes from both the degree of variation in the many climate projection models, and from the gaps in our knowledge of the target species or habitat. In addressing these components, we hope to identify which ecosystems are most or least vulnerable to climate change as well as the type and spatial pattern of the most significant impacts. This information is expected to help land managers identify areas where action may mitigate the effects of climate change, recognize potential novel conditions that may require additional analysis, and characterize uncertainties inherent in the process.

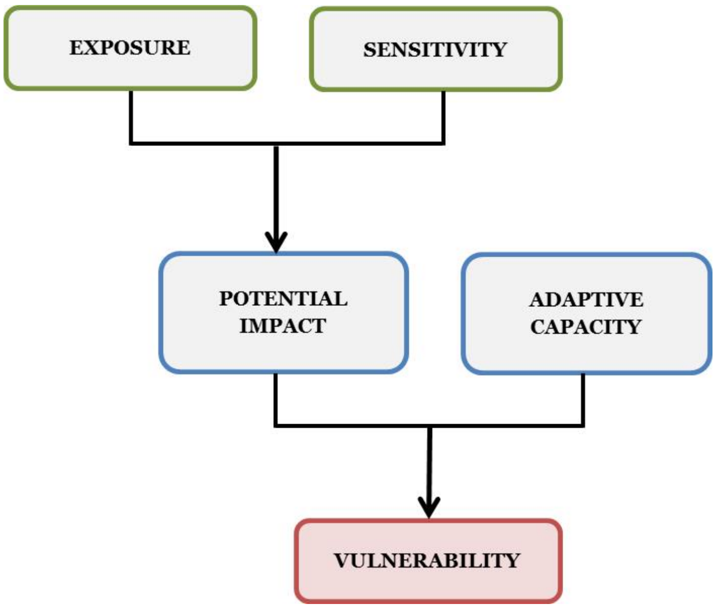


Figure 1. Components of vulnerability (Glick et al. 2011).

During the revision of Colorado's current SWAP, the Colorado Natural Heritage Program (CNHP), Colorado Parks and Wildlife (CPW), North Central Climate Science Center and U.S. Geological Service Fort Collins Research Center collaborated to produce climate change vulnerability assessments for high priority wildlife habitats in the state. Our objectives were to:

1. Evaluate exposure and sensitivity of priority habitats by identifying the degree of climate change expected between current and future conditions for climate factors believed to influence the distribution of the habitat.
2. Evaluate adaptive capacity of each habitat by assessing factors that affect the resilience of the habitat to change in landscape condition, invasive or problematic native species presence, dynamic process alteration between past and current conditions, and the characteristic bioclimatic envelope of the habitat.
3. Produce summary vulnerability ratings for priority habitats.

Methods

In consultation with CPW, CNHP identified 13 target habitats to be assessed (Table 1). The selection of habitats was based on their importance to Colorado wildlife Species of Greatest Conservation Need (previously identified in the 2005 SWAP process). The vulnerability of habitats was assessed under two primary headings: exposure-sensitivity, and resilience-adaptive capacity. Scores for these two factors were combined to obtain an overall vulnerability rank.

Table 1. Habitats assessed for vulnerability to climate change. Habitats marked with an asterisk were not modeled.

Target Habitats	
Forest and Woodland	**Grassland**
Lodgepole pine forest	Foothill & mountain grassland*
Pinyon-Juniper woodland	Shortgrass prairie
Ponderosa pine forest	**Riparian & Wetland**
Spruce-Fir forest	Playas*
Shrubland	Riparian woodland & shrubland *
Oak & mixed mountain shrubland	Wetlands*
Sagebrush shrubland	**Other**
Sandsage shrubland	Alpine

Exposure and Sensitivity Assessment

We used spatial analysis methods to evaluate the exposure and sensitivity to climate change for each habitat. Climate data was acquired with the assistance of the USGS Fort Collins Science Center and the North Central Climate Science Center. For each habitat, projected change is summarized both narratively and graphically, where possible.

Exposure to climate envelope shift for important variables

Our goal was to identify climate variables that were most influential in determining the distribution of a habitat and evaluate projected future change by mid-century for each variable. We used three sources of information for this: 1) habitat distribution modeling (for a subset of habitat types); 2) expert review; and 3) literature review. For nine of the upland habitat types, we used models of current distribution for each habitat to identify important climate variables for that habitat. Due to limitations in the resolution of climate data, no models were constructed for the four additional habitat types (marked by * in

Table 1). Variables used and importance ranks for each habitat model were reviewed by CPW habitat managers and CNHP ecologists, in conjunction with a literature review. In some instances, models were re-run to incorporate feedback received or applicable published data. Because of the high correlation between many variables, the high AUC values of all models regardless of which correlated values were chosen, and the difficulty of interpreting some metrics, we did not rely solely on the modeling process to identify important variables for each habitat. To clarify interpretation, we chose to focus the final analysis on variables that represented seasonal rather than monthly climate information, and we substituted means for variables based on the standard deviation of a mean (originally used to investigate variability).

Five climate variables per habitat were used to evaluate exposure and sensitivity (Table 5) by assessing the degree to which future conditions within the current mapped distribution of a habitat were projected to be outside the core range of current conditions, i.e., the "range shift" (Figure 3). For each variable, the percent of current mapped acreage that is projected to fall below or above (depending on the direction of greatest stress in the "worst case" – e.g., either warmest or driest conditions) the current range is calculated. Exposure-sensitivity ranks are calculated from the average of the five range shift proportions. Uncertainty in this process comes from the probability that there are important climate variables that we either don't know about, or can't model. Additionally, critical variables controlling the distribution of a habitat may not be climate related (e.g., soils). Our intent was to use the best currently available information to make a best estimate of vulnerability with available information.

Current distribution models

Modeling methods were developed with the assistance of USGS Fort Collins Science Center and the North Central Climate Science Center. Presence points for each modeled habitat type were derived from plot locations in the VegBank database (Peet et al. 2013) and from plot locations collected by CNHP and others in past vegetation inventory and survey projects. Point locations were converted to centroids on the 1 km reference grid used as the project template; only cells with a single habitat type were retained, to avoid ecotonal areas transitional between habitat types. Points for all habitats were checked against ground appearances on recent aerial imagery, and with reference to the known distribution of significant patches of this habitat type. For each habitat, the points of all the other types were used as absence points. Modeling was performed with the SAHM (Morisette et al. 2013) package in VisTrails (NYU-Poly and Univ. of UT 2014).

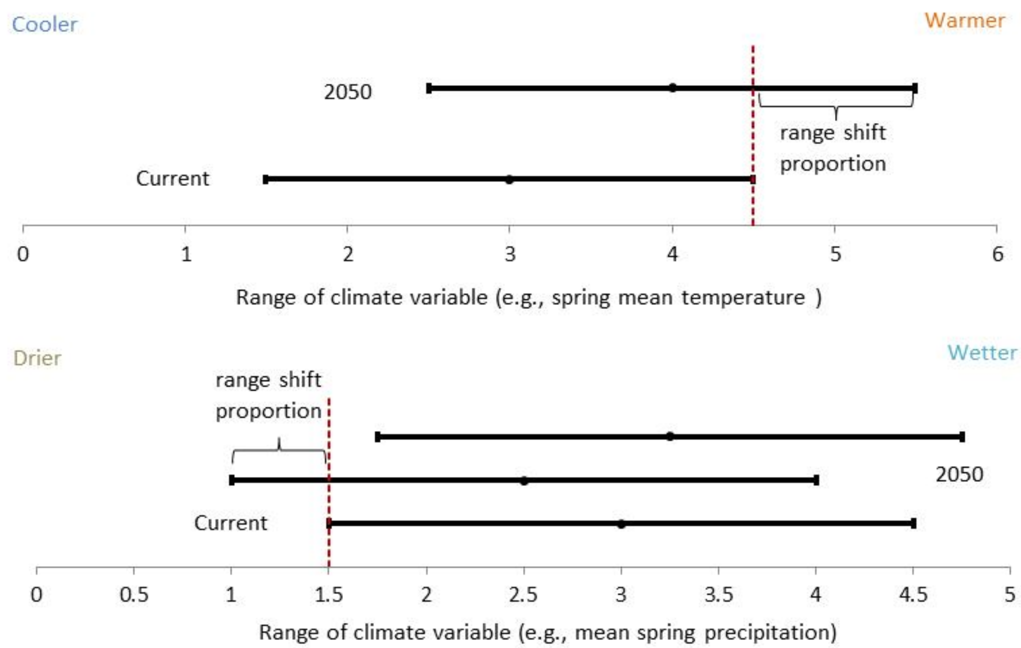


Figure 3. Generalized example of assessing the range shift for temperature or precipitation variables. The dashed line indicates the limit of the current range for that variable within a specific habitat.

Although some apparently causal relationships between environmental variables and the presence of primary component-species are documented for most of our habitats, there is substantial uncertainty remaining, as well as a lack of data that could be used to model some of the variables known to be important. We had available spatial data for 44 climate variables and 5 soil variables for the study area (Table 2). Climate variables were generated from 1km Daymet 1980-2012 normals (Thornton et al. 2012); soil variables were generated from STATSGO and SSURGO databases (NRCS 1994, 2012) and converted to 1km rasters. As expected, a correlation analysis showed high collinearity between temperature variables, between precipitation variables, and between soil variables. Being mindful of the potential for climate factors chosen in current models to exhibit different patterns in future projections as compared to the current normal period (Braunisch et al. 2013), we were reluctant to retain only a single variable each for precipitation and temperature. In an effort to retain representative climate variables at different temporal scales (e.g. monthly, seasonally, annually) we grouped our 44 climate variables into 11 categories (Table 3). Collinearity was greatly reduced (although not entirely eliminated) by the procedure of selecting a single variable from each of the groups. Additional variables in each group were retained for model initiation if below 0.75 correlation.

We tested four modelling techniques: boosted regression trees (BRT), generalized linear models, multivariate adaptive regression splines, and random forests. Although all techniques produced models with very high AUC values, we chose to use BRT as providing the best spatial results with regard to the known present distribution of each habitat type.

Table 2. Metrics used in habitat models. Unless otherwise noted, metrics were calculated for each year in the time range (the 32 year period 1980-2012), and then averaged over all years.

Metric	Description
Temperature	
Mean January temperature	((tmax+tmin)/2)
Mean July temperature	((tmax+tmin)/2)
Total annual growing degree days, base 0°C	daily ((tmax+tmin)/2) summed across all days where this number is above 0°C
Annual frost free days	days/year where tmin > 0°C
Annual very hot days	days/year where tmax > 38°C
Annual very cold days	days/year where tmin < -34°C
Date of first frost	Julian date where tmin first <= 0°C in the summer/fall
Variability of first frost	standard deviation of first frost over the full time range
Date of last frost	Julian date where tmin last <= 0°C in the spring/summer
Variability of last frost	standard deviation of last frost over the full time range
Mean summer temperature	((tmax+tmin)/2) averaged over June-August
Maximum summer temperature	tmax averaged over June-August
Mean winter temperature	((tmax+tmin)/2) averaged over December-February
Minimum winter temperature	tmin averaged over December-February
Precipitation	
Total precipitation for each month (12 metrics)	sum of daily precipitation for the month
Total precipitation for each season (4 metrics)	sum of the daily precipitation for the 3 month period
Variability of seasonal precipitation (4 metrics)	standard deviation of seasonal ppt over the full time range
Total annual precipitation	sum of daily precipitation for the year
Variability of annual precipitation	standard deviation of annual ppt over the full time range
Seasonal drought days (4 metrics)	days/season where ppt < 5mm
Annual drought days	days/year where ppt < 5mm

Metric	Description
Annual heavy precipitation days	days/year where ppt > 25mm
Total heavy precipitation days	total days where ppt > 25mm over the full time period
Total measurable precipitation days	total days where ppt > 10mm over the full time period
Soil	
Soil depth (cm)	Due to the coarse scale of STATSGO and the incomplete nature of SSURGO in Colorado, soil depth and composition were derived from both STATSGO alone and a combination of STATSGO and SSURGO. Whichever version explained the most variation in each model was chosen.
Percent sand	
Percent clay	
Percent silt	

Table 3. Variable groups used in distribution modeling.

Precipitation
Monthly mean precipitation warm months (AMJJA)
Monthly mean precipitation cold months (SONDJF) average
Annual/seasonal (DJF, MAM, JJA, SON) precipitation totals or drought
Variability of annual/seasonal precipitation totals or drought
Extreme precipitation events
Multi-year precipitation totals
Temperature
Growing season indicators (growing degree days, frostfree days, first and last frost days and variability, temperatures of warmest or coldest months)
Variability of first and last frost dates
Extreme cold events
Extreme hot events
Soil
Soil depth and composition (sand/silt/clay %)

Mid-century climate projections

Projected future and modeled historic bias corrected, 1/8 degree statistically downscaled daily climate data (BOR 2013) for the top variables (totaling at least 75% of the relative influence in the final model, or identified as important by other sources) were calculated using the GeoDataPortal package (Talbert 2014) of VisTrails and *ad hoc* python code provided by the NCCSC. We used 12 models (Table 4), averaged over 1980-2005 to represent "historic" or “current” normals, and averaged over 2035-2060 under the CMIP5 RCP6 scenario to represent mid-century projections (2050; BCCA 2013). An 1/8 degree resolution is approximately 12 km. This is the finest resolution currently available for projected daily data. RCP6 is the second highest Representative Concentration Pathway (van Vuuren et al. 2011) used in the Climate Model Diagnosis and Intercomparison Project, phase 5 (CMIP5), estimating the equivalent of 850 ppm of CO_2 beyond the year 2100, making it loosely equivalent to the A2 emissions scenario from CMIP3 (830 ppm CO_2 by 2100. Note, however, that RCPs use radiative forcing instead of CO_2 emissions and so are not directly comparable). CPW personnel selected RCP6 for use in this project. The 12 models chosen are all climate projection models calculated under RCP6.

Table 4. BCCA CMIP5 Models used for analysis.

Modeling Center (or Group)	**Institute ID**	**Model Name**
Beijing Climate Center, China Meteorological Administration	BCC	bcc-csm1-1_rcp60_r1i1p1
National Center for Atmospheric Research	NCAR	CCSM4_rcp60_r1i1p1
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3_rcp60_r1i1p1
		GFDL-ESM2G_rcp60_r1i1p1
		GFDL-ESM2M_rcp60_r1i1p1
Institut Pierre - Simon Laplace	IPSL	IPSL-CM5A-LR_rcp60_r1i1p1
		IPSL-CM5A-MR_rcp60_r1i1p1
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine - Earth Science and Technology	MIROC	MIROC5_rcp60_r1i1p1
Japan Agency for Marine - Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM_rcp60_r1i1p1 MIROC-ESM-CHEM_rcp60_r1i1p1
Meteorological Research Institute	MRI	MRI-CGCM3_rcp60_r1i1p1
Norwegian Climate Centre	NCC	NorESM1-M_rcp60_r1i1p1

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in the above table) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

The different initial conditions and forcing algorithms used by each modeling center result in a range of outcomes from the different models, reflecting the inherent uncertainty in projecting future climatic conditions. Precipitation projections in particular vary widely from model to model. To capture the range of uncertainty in the most useful way possible, the central 80% of the 12-model range was chosen to represent the "reasonable range" of possible future climate for each metric (Figure 2). A raster for the lower end of each metric was produced by adding 10% of the range to the minimum cell value, and for the higher end by subtracting 10% of the range from the maximum cell value. In evaluating habitat exposure to climate change, we generally concentrated on the "worst case" end of the range, representing either the warmest projected conditions for temperature variables or the driest projected conditions for precipitation variables. Although a number of models project increased precipitation for our area, we focused on potentially drier alternatives to account for the drying effects of increasing temperature. This gives managers the option to plan for the "worst case" change in climate.

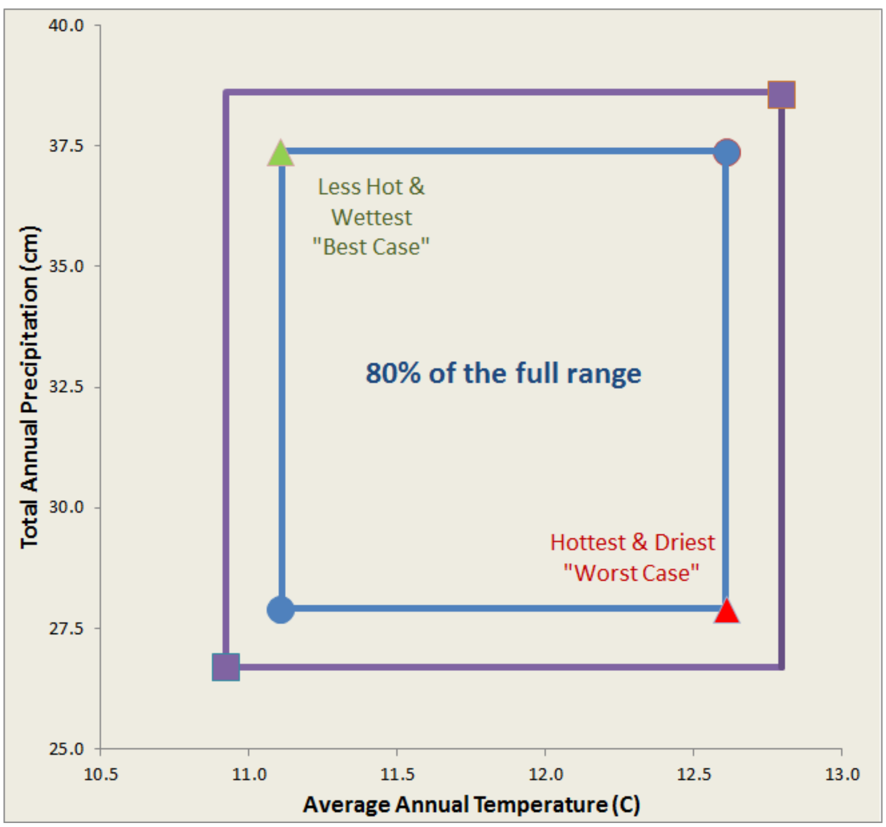


Figure 2. Illustration of method for summarizing the 12 climate projection models.

Table 5. Climate variables used to assess each habitat (shaded cells).

Habitat Target	Winter ppt	Spring ppt	Summer ppt	Fall ppt	Annual ppt	Heavy ppt days	Drought days	Date of last frost	Date of first frost	Winter min temp	Winter avg temp	Spring avg temp	Summer avg temp	Annual avg temp	GDD (base 0)	Very hot days	Very cold days
Forest and Woodland																	
Lodgepole pine forest	■	■	■								■						■
Pinyon-Juniper woodland	■	■	■										■				■
Ponderosa pine forest			■	■						■			■			■	
Spruce-Fir forest	■	■								■			■		■		
Shrubland																	
Oak & mixed mountain shrub		■	■				■	■						■			
Sagebrush shrubland	■	■	■						■							■	
Sandsage shrubland	■	■					■								■	■	
Grassland																	
Foothill & mountain grassland	■				■		■				■		■				
Shortgrass prairie					■	■	■					■	■				
Riparian & Wetland																	
Playas		■	■				■					■	■				
Riparian woodland & shrubland Wetlands																	
West			■	■								■	■			■	
Mountains	■	■				■					■	■					
East		■	■				■					■	■				
Other																	
Alpine	■	■				■							■		■		

Resilience-Adaptive Capacity Assessment

This rank summarizes indirect effects and non-climate stressors that may interact with climate change to influence the adaptive capacity and resilience of a habitat. 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 (Table 6). Factors were scored on a scale of 0 (low resilience) to 1 (high resilience).

Table 6. Description of factors used to assess resilience-adaptive capacity.

Assessment factor	Description
Bioclimatic envelope and range	This factor summarizes the expected effects of limited elevational or bioclimatic ranges for a habitat. Suitable conditions for habitats at upper elevations may be eliminated. Habitats with narrow bioclimatic envelopes may be more vulnerable to climate change. Finally, habitats that are at the southern edge of their distribution in Colorado may be eliminated from the state under warming conditions.
Growth form and intrinsic dispersal rate	This factor summarizes the overall ability of the habitat's component species to shift their ranges in response to climate change relatively quickly. Characteristics of growth form, seed-dispersal capability, vegetative growth rates, and stress-tolerance are considered.
Vulnerability to increased impact by biological stressors	This factor summarizes whether expected future biological stressors (invasive species, grazers and browsers, pests and pathogens) have had, or are likely to have, an increased effect due to interactions with changing climate. Climate change may result in more frequent or more severe outbreaks of these stressors. Habitats that are currently vulnerable to these stressors may become more so under climate change.
Vulnerability to increased frequency or intensity of extreme events	This factor evaluates characteristics of a habitat that make it relatively more vulnerable to extreme events (fire, drought, floods, windstorms, dust on snow, etc.) that are projected to become more frequent and/or intense under climate change.
Other indirect effects of non-climate stressors – landscape condition	This factor summarizes the overall condition of the habitat at the landscape level across Colorado, and is derived from a landscape integrity score indexing the degree of anthropogenic disturbance (Rondeau et al. 2011, Lemly et al. 2011).

Bioclimatic envelope and range

Each habitat was scored for elevation exposure, southern edge of range, annual precipitation range, and growing degree days range. Habitats restricted to high elevations received a score of 0, other habitats scored 1. Likewise, habitats at the southern edge of their continental range in Colorado were assigned a score of 0, and other habitats scored 1.

Annual precipitation and growing degree days range were calculated as the proportion of total variable range in Colorado in which the habitat had significant presence mapped. These four scores were averaged to produce a single score for this factor.

Growth form and intrinsic dispersal rate

Scores of 0 (low resilience), 0.5 (uncertain or moderate resilience), and 1 (high resilience) were assigned to each habitat based on growth form of the dominant species (i.e., trees scored 0, shrubs and herbaceous scored 1), and other information derived from the literature regarding the dispersal abilities of those species.

Vulnerability to increased attack by biological stressors

For each biological stressor to which a habitat is believed vulnerable, 0.33 was subtracted from a default score of 1, to produce the final habitat score.

Vulnerability to increased frequency or intensity of extreme events

For each non-biological stressor to which a habitat is believed vulnerable, 0.33 was subtracted from a default score of 1, to produce the final habitat score.

Landscape condition

The average value across the statewide landscape integrity models (Rondeau et al. 2011, Lemly et al. 2011) for each habitat was calculated as a value between 0 and 1.

Vulnerability Assessment Ranking

We loosely followed the methodology of the NatureServe Habitat Climate Change Vulnerability Index (Comer et al. 2012). For each habitat, its projected exposure to climate change and its presumed sensitivity to that change are combined into a single rank. This rank incorporates the projected degree of change (exposure) for five climate variables believed to be important in determining the distribution of that habitat (sensitivity). The exposure-sensitivity rank is combined with a rank summarizing the resilience and adaptive capacity of the habitat.

Exposure-Sensitivity Ranking

This rank summarizes the degree of projected change (exposure) for five climate variables per habitat. Variables are those to which the habitat is sensitive, based on our three sources of information. For each variable, the percent of current mapped acreage that is projected to fall below or above (depending on the direction of greatest stress in the “worst case” scenario – e.g., either warmest or driest conditions) one standard deviation of the current mean is compared with the percentage under current conditions. A negative value indicates improving conditions for that habitat, while a positive value indicates exposure conditions that are presumed to be more stressful. The values are averaged for a combined score that is intended to indicate the relative degree of impact to the habitat from changing climate.

Resilience-Adaptive Capacity Ranking

Scores for the five factors are based on both spatial analysis and literature review. Rankings for this sub-score are opposite to the direction of the exposure-sensitivity ranking scheme (i.e., a positive value indicates "better" and a negative value indicates "worse.") The rounded average of the five sub-rankings determines the final Resilience-Adaptive Capacity rank.

Overall Vulnerability Ranking

The Exposure-Sensitivity rank and the Resilience-Adaptive Capacity rank are combined (Figure 4) according to the scheme presented below (Comer et al. 2012).

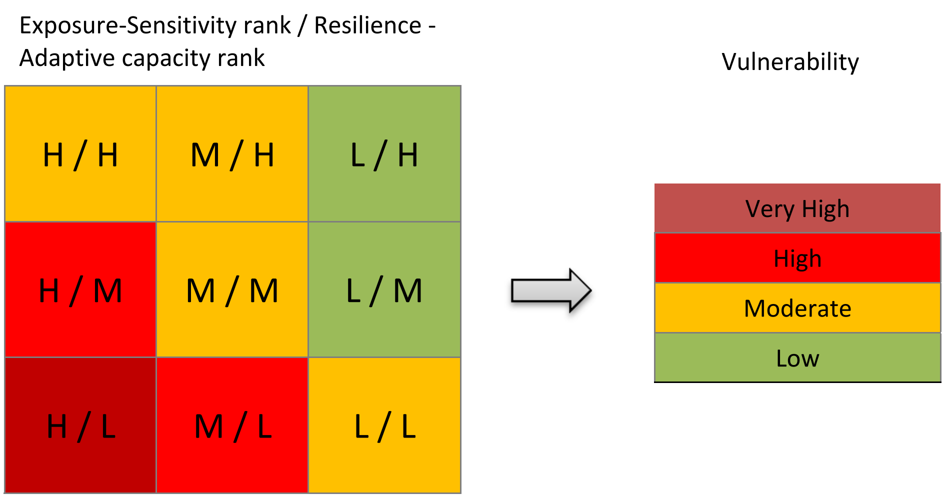


Figure 4. Vulnerability ranking matrix.

Very High: Habitats have high vulnerability to climate change when exposure and sensitivity are high, and adaptive capacity and resilience are low. Under these circumstances, transformation of the habitat is most likely to occur in upcoming decades.

High: High vulnerability to climate change results from combining either high or moderate exposure-sensitivity with low or medium adaptive capacity-resilience. Under either combination, climate change is likely to have noticeable impact.

Moderate: Moderate vulnerability to climate change results from a variety of combinations for exposure-sensitivity and adaptive capacity-resilience. The number of possible combinations indicates a degree of uncertainty in the vulnerability ranking. Under circumstances where the two factors are essentially balanced, vulnerability is thought to be reduced, but still of concern.

Low: Low vulnerability to climate change occurs when a habitat combines low exposure and sensitivity with high or moderate adaptive capacity and resilience. For these habitats climate change stress and its effects are expected to be least severe or absent.

Results

Statewide patterns of mid-century climate change in Colorado

Projections based on 12 models run under RCP6 for the 30-year period centered on 2050 indicate that all areas of Colorado will experience some degree of warming (Table 7, Figures 5-7), and potentially changes in pecipitation as well. Temperature change projections are regarded as more certain (Barsugli pers. comm.), and there is general agreement that conditions have already warmed to some degree (Lucas et al. 2014); uncertainty for temperature change is largely regarding the magnitude of the projected change. Precipitation projections for Colorado are more variable than those for temperature. Some model projections are drier than current conditions and some are wetter (Figures 8-10); statewide patterns of precipitation are also variable between models. In combination with expected changes in temperature, however, even a wetter scenario may not be sufficient to maintain runoff and soil moisture conditions similar to those of the recent past. Climate projections presented here are summaries of long term trends and do not track inter-annual variation, which will remain a source of variability, as it has been in the past. Our analysis focused on a single representative concentration pathway and a limited subset of available global circulation models; at this point in time we have no way of knowing if this is the scenario that will be found valid by mid-century.

Table 7. Projected changes (relative to 1980-2012) by mid-21st century (30-year period centered around 2050) for Colorado as a whole, shown as statewide mean (stdev).

Projected changes by mid-21st century*	Lower (10%) range		Upper (90%) range	
Change in annual avg. temperature	1.04°C (0.04)	1.87°F (0.07)	2.28°C (0.11)	4.10°F (0.20)
Change in summer avg. temperature	1.30°C (0.07)	2.34°F (0.13)	2.78°C (0.15)	5.00°F (0.27)
Change in winter avg. temperature	0.59°C (0.15)	1.06°F (0.27)	2.52°C (0.15)	4.54°F (0.27)
Change in annual precipitation	-41.73 mm (26.54)	-1.64 in (1.04)	53.70 mm (25.59)	2.11 in (1.01)
Change in summer precipitation	-29.86 mm (17.26)	-1.18 in (0.68)	8.60 mm (4.87)	0.34 in (0.19)
Change in winter precipitation	-8.44 mm (9.39)	-0.33 in (0.37)	17.34 mm (14.12)	0.68 in (0.56)

*Projections are based on 12 BCCA CMIP5 RCP6 models

Temperature

Statewide, annual mean temperatures under the warmest projected conditions would increase by at least 2°C (3.6°F). In general, mountainous areas, including the San Luis Valley, will warm slightly less (0.2-0.3°C; 0.4-0.5°F) than elsewhere. Temperatures in northeastern and northwestern Colorado are projected to increase by around 2.4°C (4.3°F), with increases of around 2.0°C (3.6°F) in central parts of the state. Winter temperatures show a similar pattern, with the greatest potential warming (2.6-2.8°C; 4.7-5.0°F) projected for non-mountainous areas in the northern half of the state. Although average winter minimum temperatures remain below freezing statewide, increasing mean winter temperatures are likely to greatly expand the area experiencing winter means above freezing. Projected increases in summer mean temperatures are greatest on the eastern plains (2.6-3.1°C; 4.7-5.6°F), and are least in mountainous areas under the warmest scenario. Summer minimum temperatures (i.e., warm nights) are also projected to increase. Currently most of Colorado's alpine areas have average summer minimum temperatures that dip below freezing. Under the warmest scenario, these cold summer night temperatures would be largely eliminated from many parts of the state.

Precipitation

In contrast to temperature projections, changes in precipitation could be positive or negative. Under the driest projected conditions, eastern Colorado, the southern San Juan Mountains, and the San Luis Valley could see decreases of 1-4 inches or more in annual precipitation. Under the wettest projected conditions, most areas would experience an increase in annual precipitation, especially the northern and central mountains. Under projected wetter conditions, mountain areas are most likely to see an increase in winter precipitation, and the far eastern plains most likely to see somewhat more summer precipitation. Under projected drier conditions, the greatest decrease in winter precipitation is for the southwestern part of the state, and summer decreases are greatest on the eastern plains. Projected statewide patterns of precipitation are generally similar to those observed in the recent past, but with a slight tendancy for eastern and southern parts of the state to be relatively drier than they have been. The local effects of Colorado's complex topography add an additional element of uncertainty to projections of precipitation that have an underlying resolution of 1/8th degree (~12km).

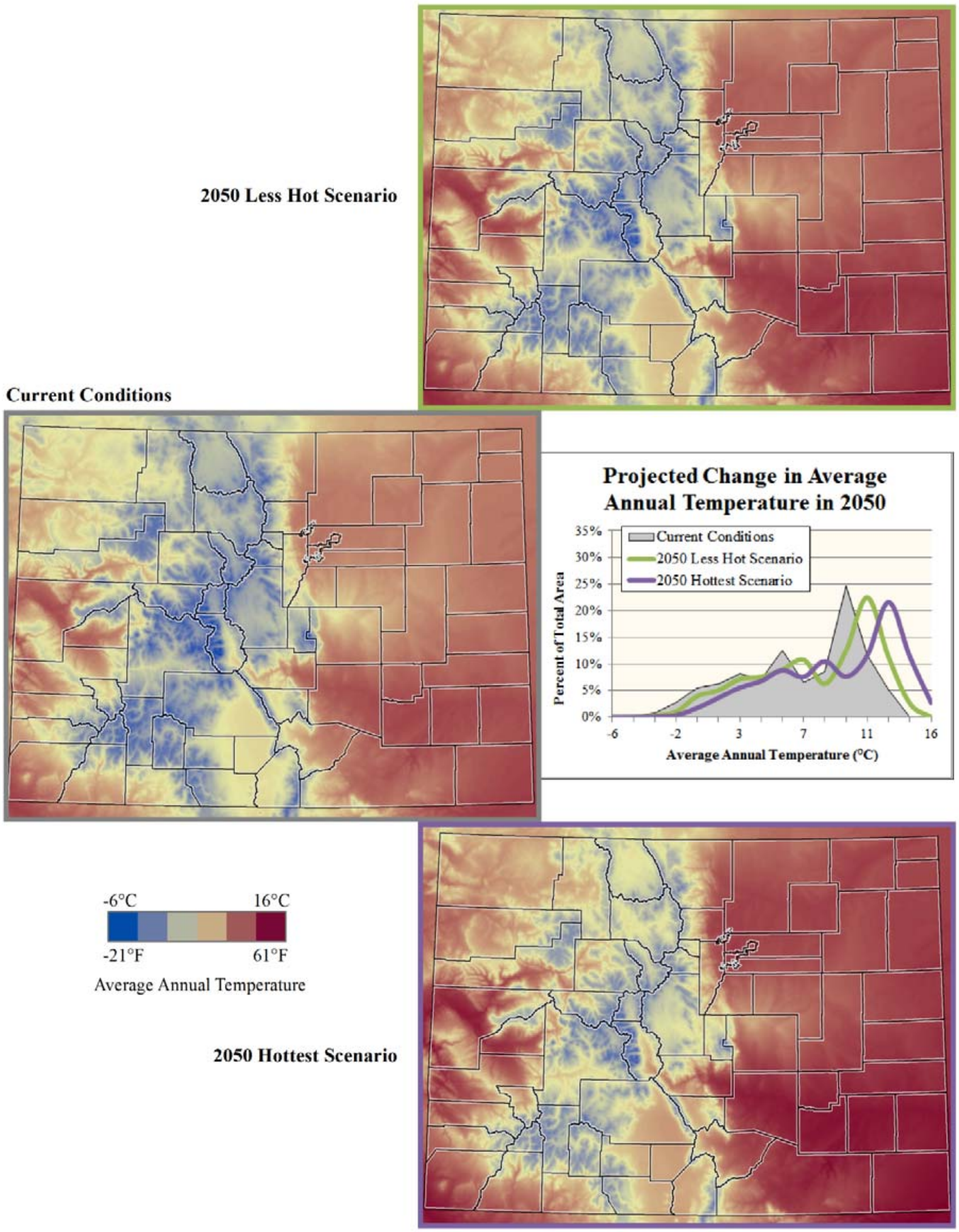


Figure 5. Annual mean temperature, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

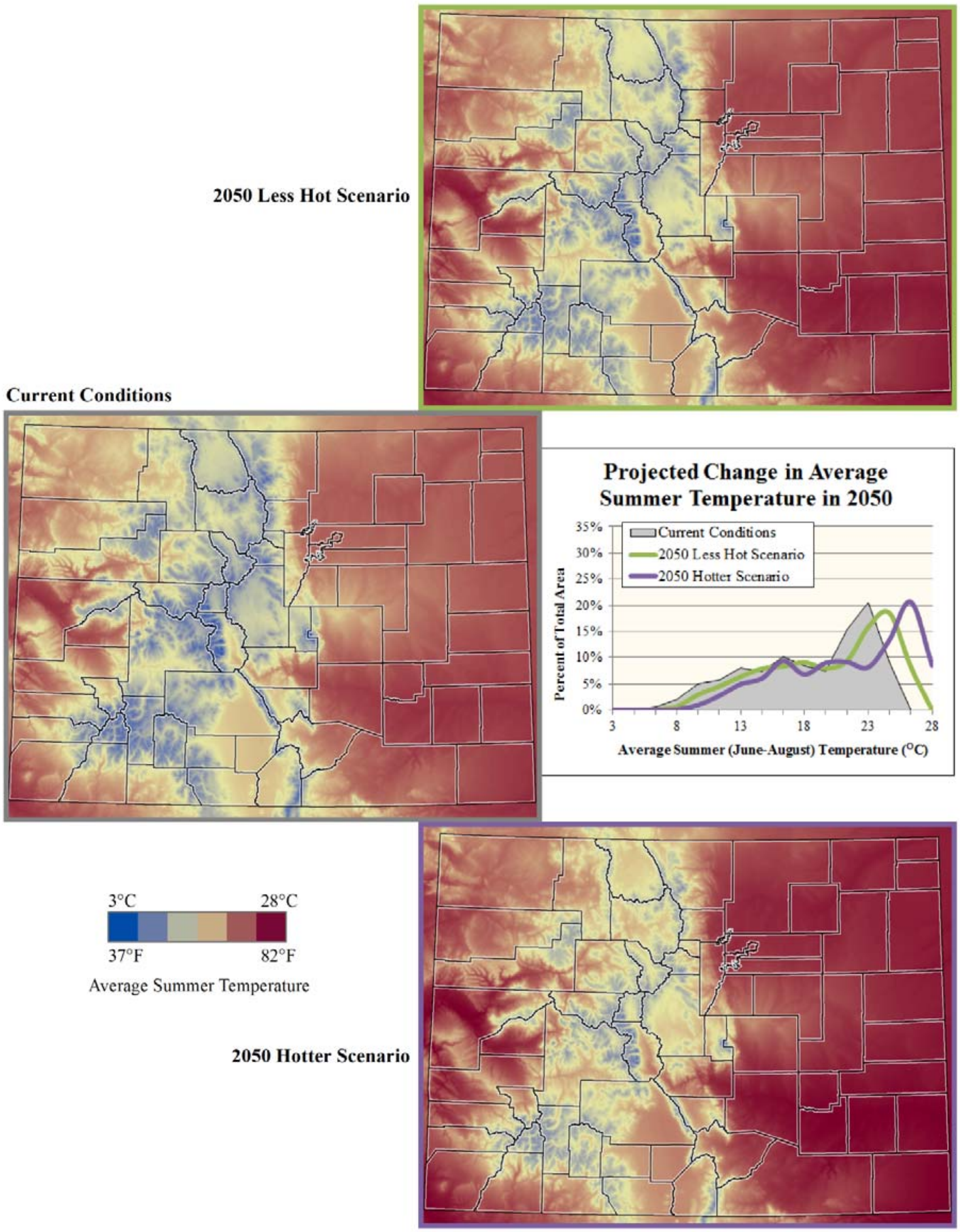


Figure 6. Mean summer temperature, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

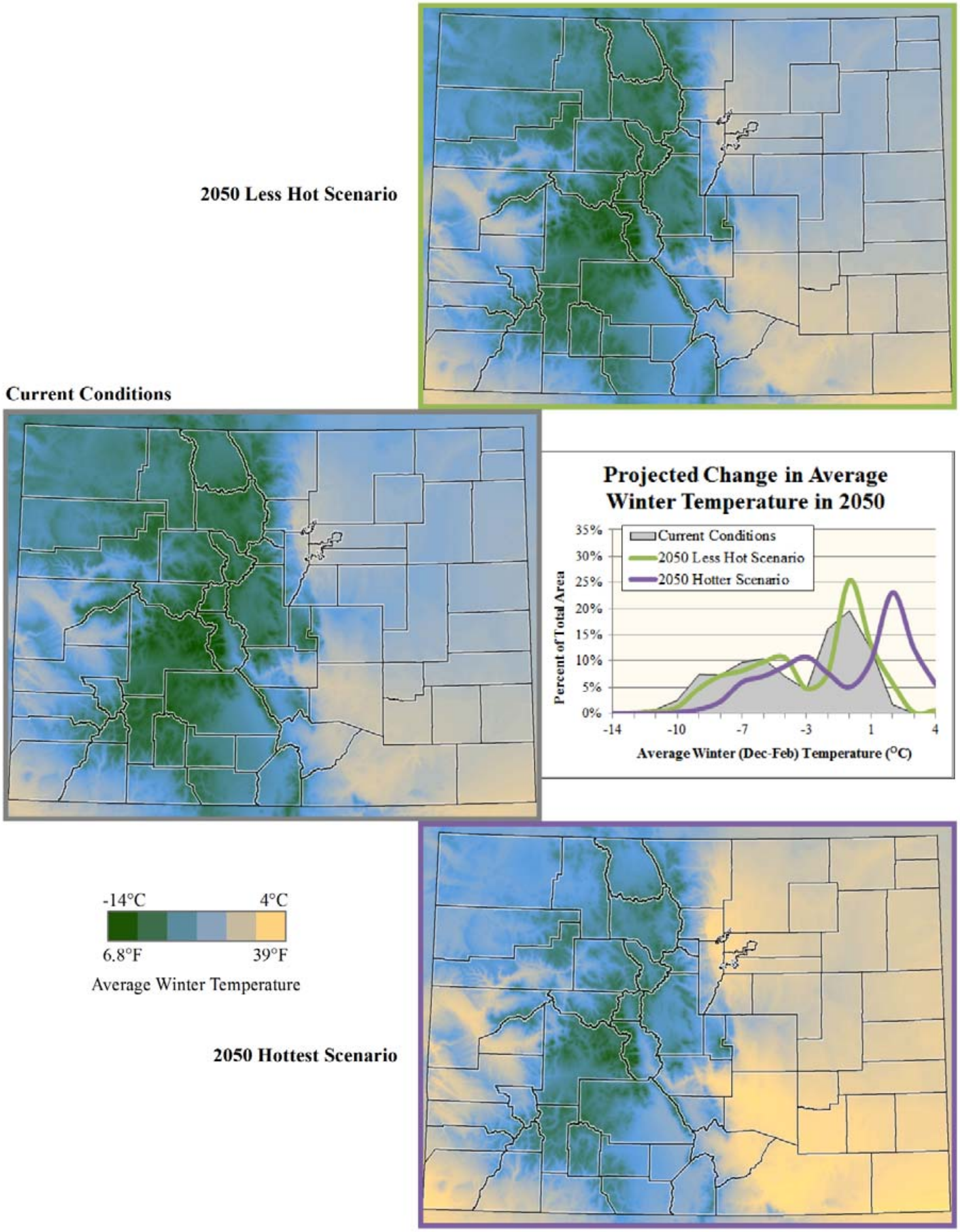


Figure 7. Mean winter temperature, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

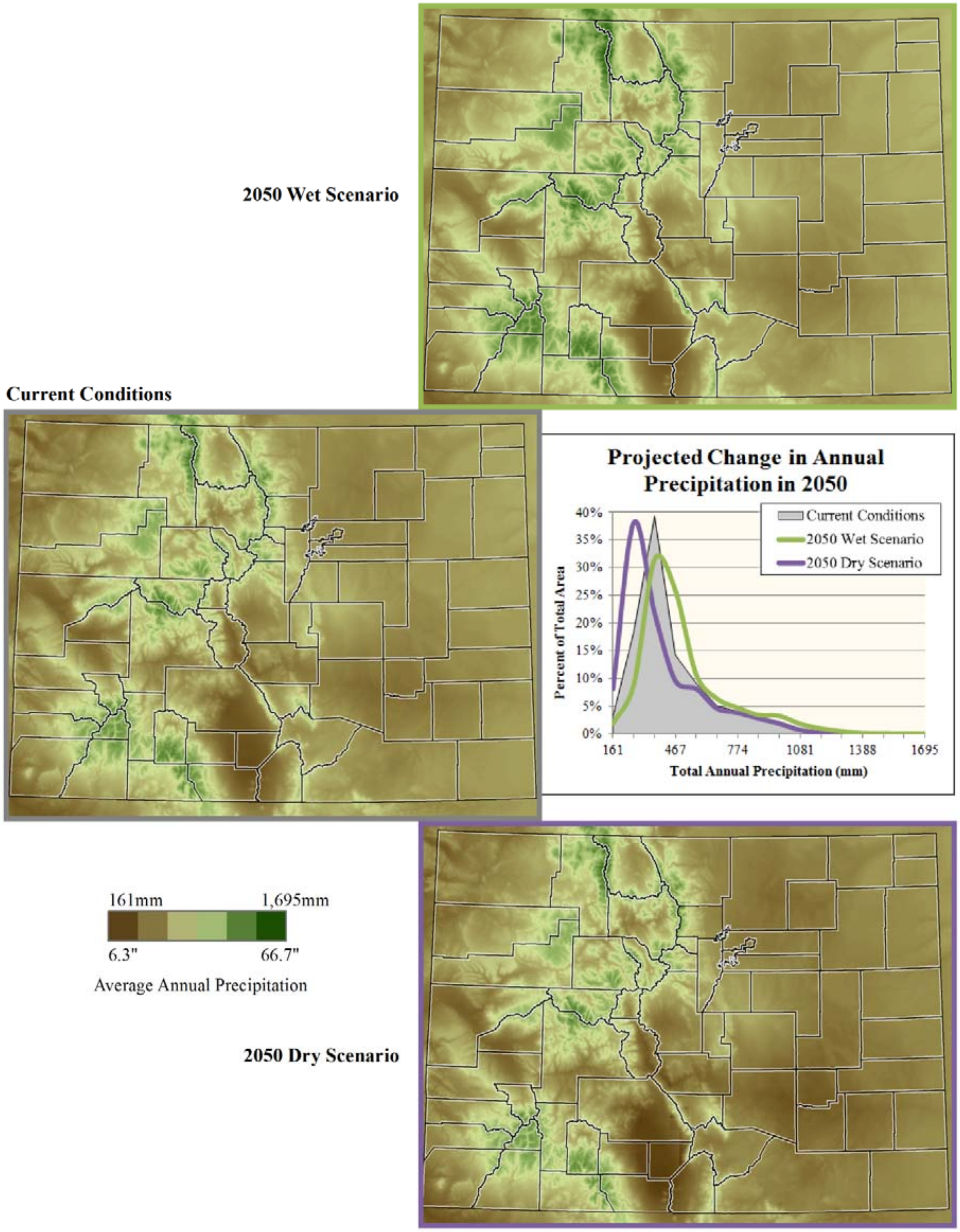


Figure 8. Annual precipitation, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

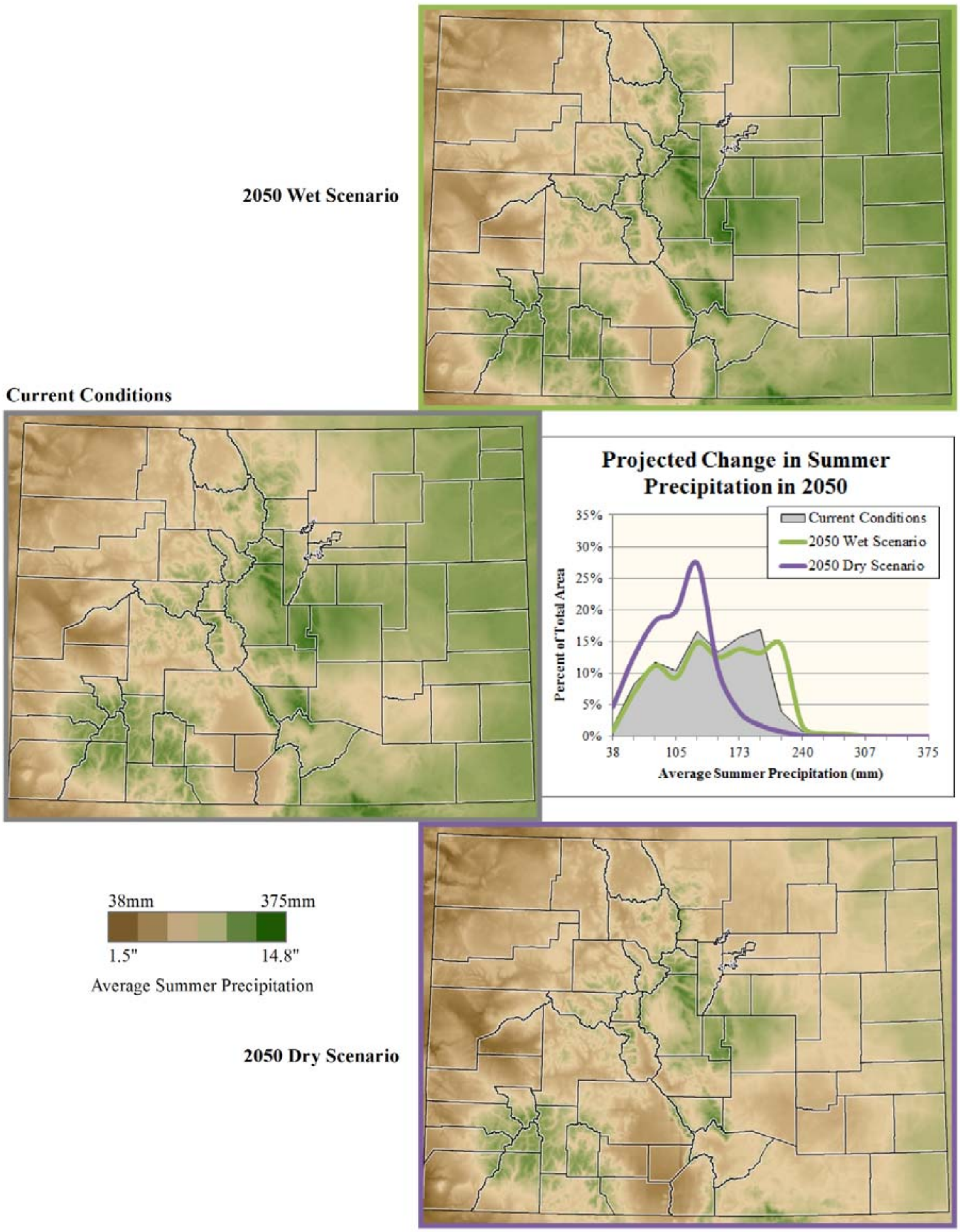


Figure 9. Summer precipitation, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

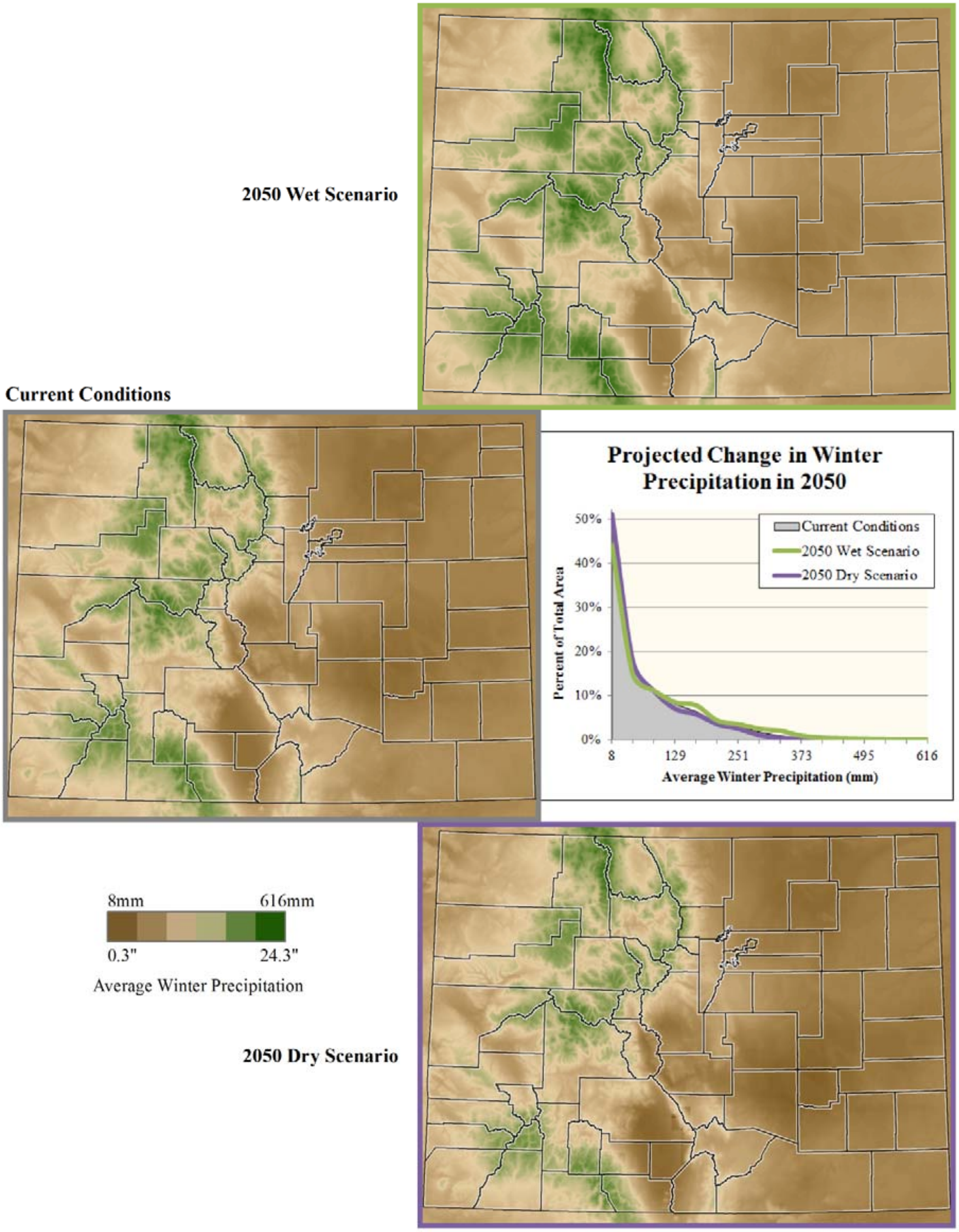


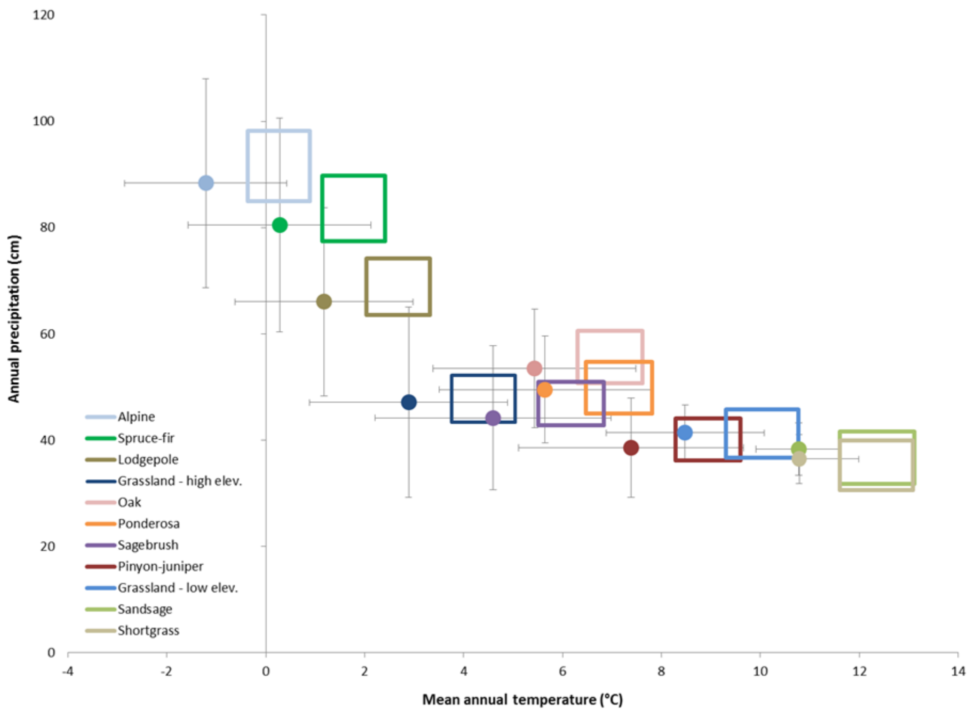
Figure 10. Winter precipitation, comparison of historic normals with projected conditions at mid-21st century for best and worst case ends of model range.

Habitat-specific patterns of mid-century climate change in Colorado

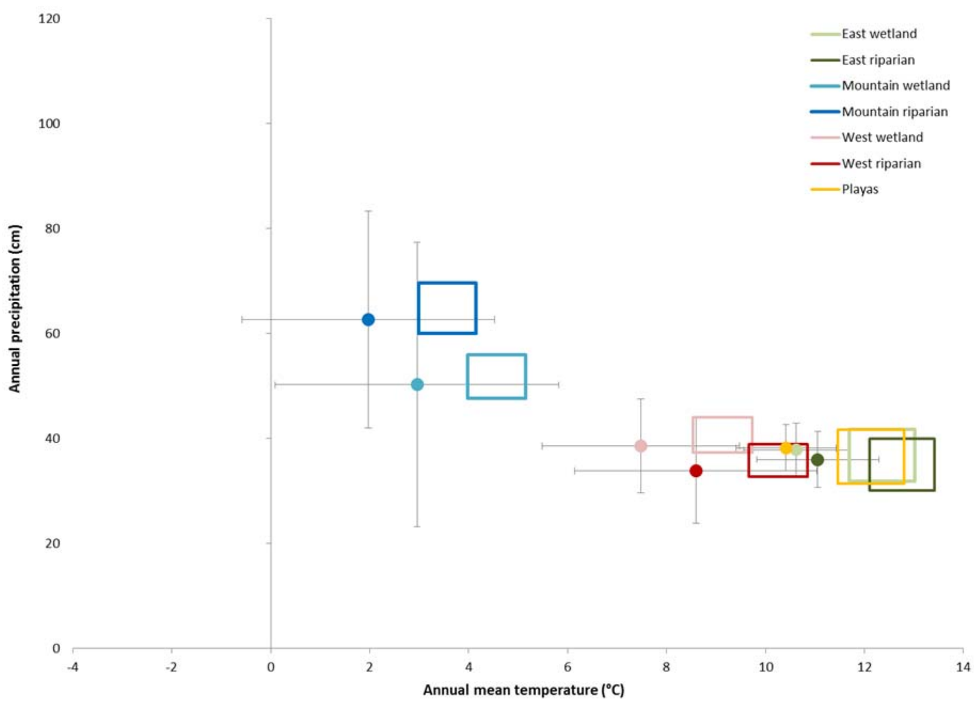
A comparison of the current climate envelope for annual and seasonal patterns of temperature and precipitation with projected values (Figure 11) shows that future conditions for most habitats in their currently occupied range will be warmer, but probably still within the range of tolerance for most constituent species. The projected range of future precipitation tends towards wetter for higher elevation habitats, and drier for lower elevation habitats. Habitats of the eastern plains are generally projected to be drier and warmer. Due to increasing temperature patterns, even a slight increase in precipitation may result in overall drier conditions for soil moisture.

Seasonal patterns of temperature and precipitation show different patterns. The elevational separation of habitats is not evident for summer precipitation, although temperature gradients remain (Figure 12). Warming trends are similar to those seen in the annual summary, but precipitation tends toward drier conditions in comparison with the recent past. Projected changes for winter temperature and precipitation means show less potential warming, and more potential increase in precipitation (Figure 13).

Within the time frame and emissions scenario used for our analysis, the projected climate conditions for our focal habitats indicate that by mid-century habitat envelopes are shifting, but may still be within the range of the constituent organisms, at least in part. In general, most habitats will not shift quickly, but we will likely begin to see altered composition and potential for novel combinations.

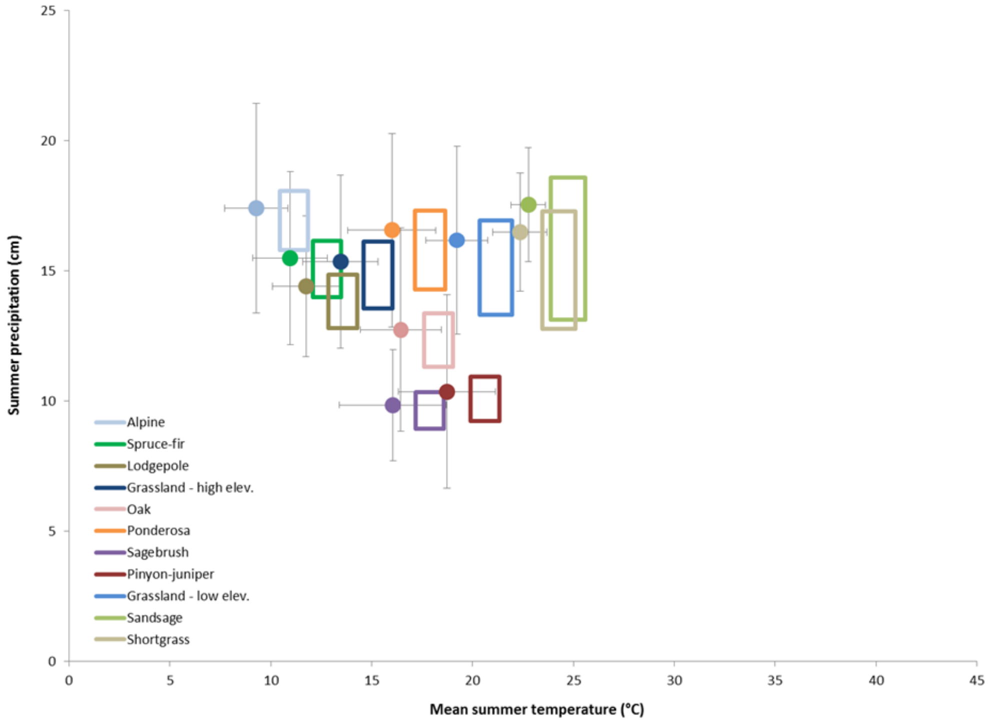


(a)

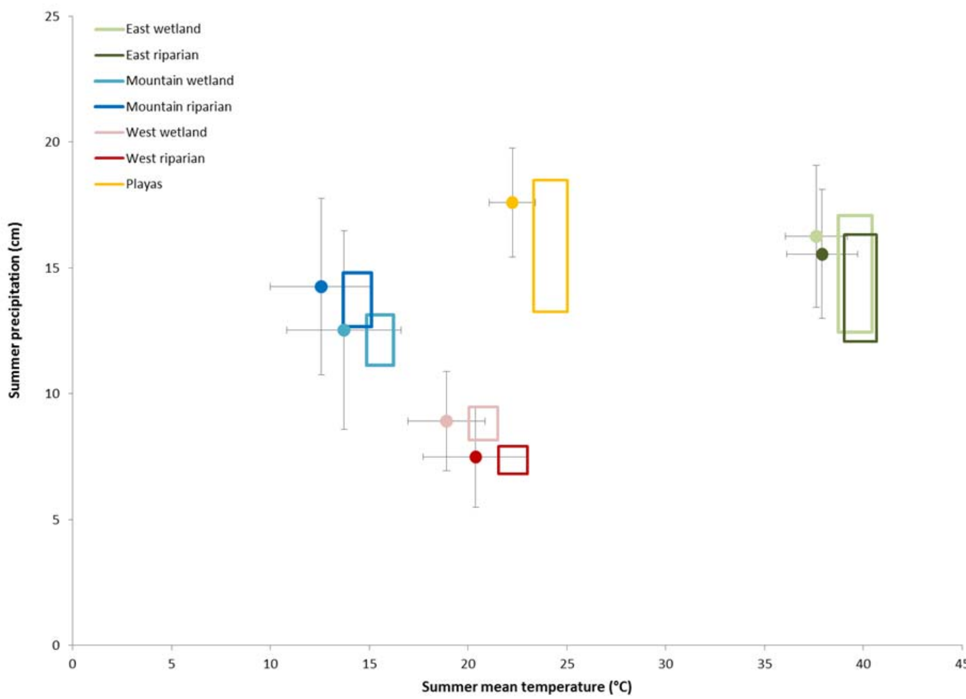


(b)

Figure 11. Current Colorado annual mean temperature and precipitation and projected mid-century region of change for (a) upland habitats and (b) wetland and riparian habitats. Circles represent historic means with error bars representing one std. dev. Squares represent the middle 80% percent of the range of projected mid-century change (12 models under RCP6).

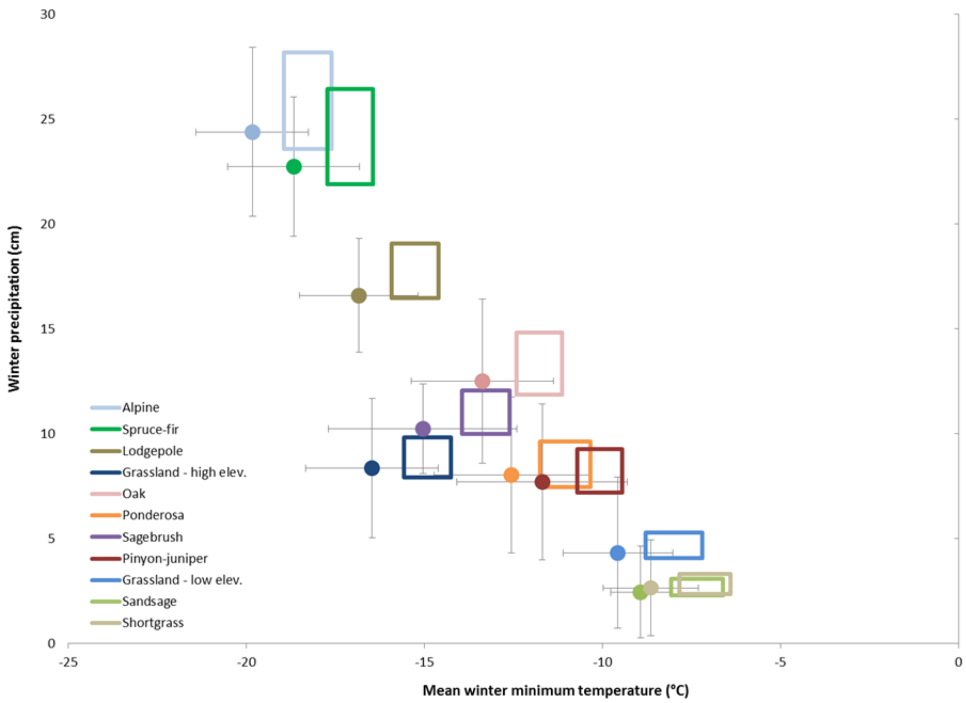


(a)

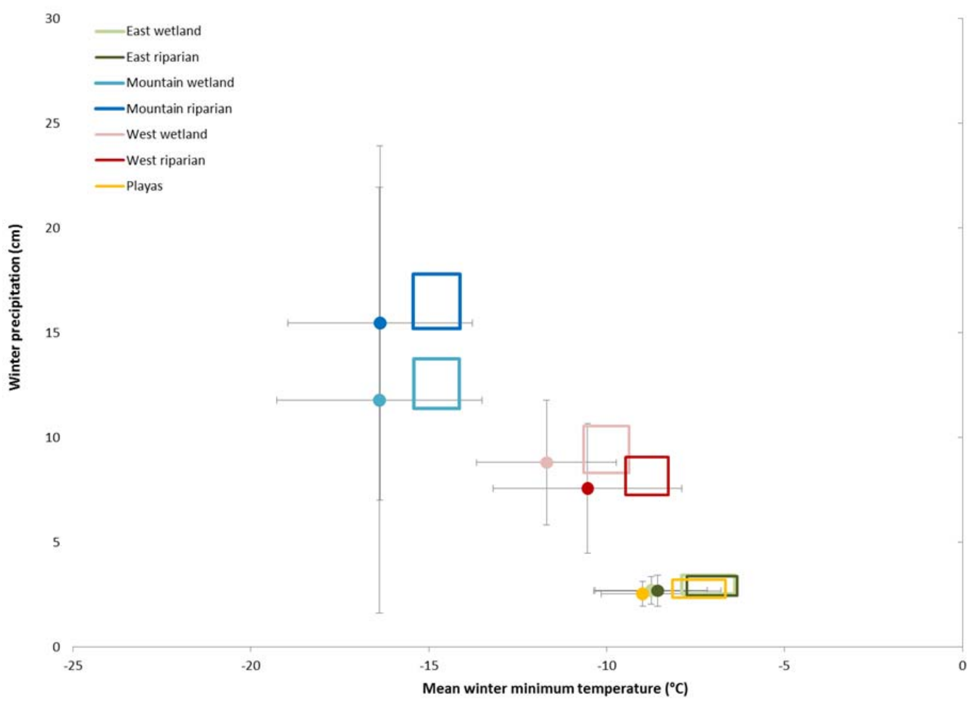


(b)

Figure 12. Current Colorado summer mean temperature and precipitation and projected mid-century region of change for (a) upland habitats and (b) wetland and riparian habitats. Circles represent historic means with error bars representing one std. dev. Squares represent the middle 80% percent of the range of projected mid-century change (12 models under RCP6).



(a)



(b)

Figure 13. Current Colorado mean winter minimum temperature and precipitation and projected mid-century region of change for (a) upland habitats and (b) wetland and riparian habitats. Circles represent historic means with error bars representing one std. dev. Squares represent the middle 80% percent of the range of projected mid-century change (12 models under RCP6).

Habitat vulnerability ranks

Three of the 18 habitats or habitat subgroups assessed have an overall vulnerability rank of High (Table 8). In general, habitats of the eastern plains have the greatest exposure to change, and those of higher elevations are moderately exposed. Under a more severe emissions scenario, and longer time-frame, these habitats would be subject to increased exposure. Most habitats were assessed as having moderate resilience. Additional discussion for individual habitats is provided below.

Table 8. Vulnerability rank summary for all assessed habitats.

Habitat Target	Exposure - Sensitivity final ranking	Resilience - Adaptive capacity final ranking	Combined ranks	Overall vulnerability rank
Forest and Woodland				
Lodgepole pine forest	Low	Low	L/L	Moderate
Pinyon-Juniper woodland	Low	Low	L/L	Moderate
Ponderosa pine forest	Moderate	Moderate	M/M	Moderate
Spruce-Fir forest	Moderate	Moderate	M/M	Moderate
Shrubland				
Oak & mixed mountain shrub	Low	High	L/H	Low
Sagebrush shrubland	Low	Moderate	L/M	Low
Sandsage shrubland	High	High	H/H	Moderate
Grassland				
Foothill & mountain grassland - high	Moderate	Moderate	M/M	Moderate
Foothill & mountain grassland - low	High	Moderate	H/M	High
Shortgrass prairie	High	Moderate	H/M	High
Riparian & Wetland				
Playas	Moderate	Low	M/L	High
Riparian woodland & shrubland - west	Low	Low	L/L	Moderate
Riparian woodland & shrubland - mountain	Low	Moderate	L/M	Low
Riparian woodland & shrubland - east	Low	Moderate	L/M	Low
Wetlands - west	Low	Moderate	L/M	Low
Wetlands - mountain	Low	Moderate	L/M	Low
Wetlands - east	Moderate	Moderate	M/M	Moderate
Other				
Alpine	Moderate	Moderate	M/M	Moderate

Potential biome shifts

Rehfeldt et al. (2012) modeled the North American biomes of Brown et al. (1998) for future climate scenarios. Within Colorado, recent past conditions are suitable for eight biome types, approximately corresponding to the alpine, spruce-fir, montane conifer (encompassing ponderosa, mixed conifer, and aspen, with inclusions of other montane non-treed vegetation types), oak-mixed mountain shrub, pinyon-juniper woodland, sage-desert grassland, shortgrass, and desert shrubland (Figure 14). As predicted by the model consensus for 2060, biomes in the state are expected to shift to the extent that suitable area for alpine is eliminated in favor of spruce-fir, together with a potential for novel combinations of conifers at elevations previously dominated by spruce-fir forests. The zone suitable for the various conifer and aspen types is predicted to expand substantially, potentially moving into southern areas currently occupied by oak-mixed mountain shrubland. Areas favorable to oak-mixed mountain shrubland are also projected to expand northward, into areas currently occupied by pinyon-juniper and/or sagebrush grassland. Conditions suitable for desert shrubland are also predicted to expand considerably into areas currently occupied by sagebrush-grassland (or agriculture). In the southern plains, some area is projected to become dry enough for semi-desert grasslands to displace shortgrass.

Because we did not model projected future distribution of habitats, a comparison of the biome models of Rehfeldt et al. (2012) with our results is not straightforward. Furthermore, modeled biome types do not crosswalk to our habitat types in a clear one-to-one relationship; a number of types are simply not addressed well by a particular biome. However, projected biome changes are in broad agreement with our analysis of Colorado's more extensive habitats, except for those of the eastern plains. Our low exposure ranking of pinyon-juniper and oak-mixed mountain shrub corresponds with the projected expansion of these biomes into areas that are currently cooler than future projections. Moderate exposure rankings for most of Colorado's coniferous forest types are reflected in the projected rearrangement of biome types where conditions in alpine areas become favorable for tree growth, and lower elevation forests are likely to change in structure and composition as they expand into additional habitat. The high exposure ranking for habitats of the eastern plains is not matched by a modeled biome shift, except in the southern plains where shortgrass prairie may unable to maintain its current distribution.

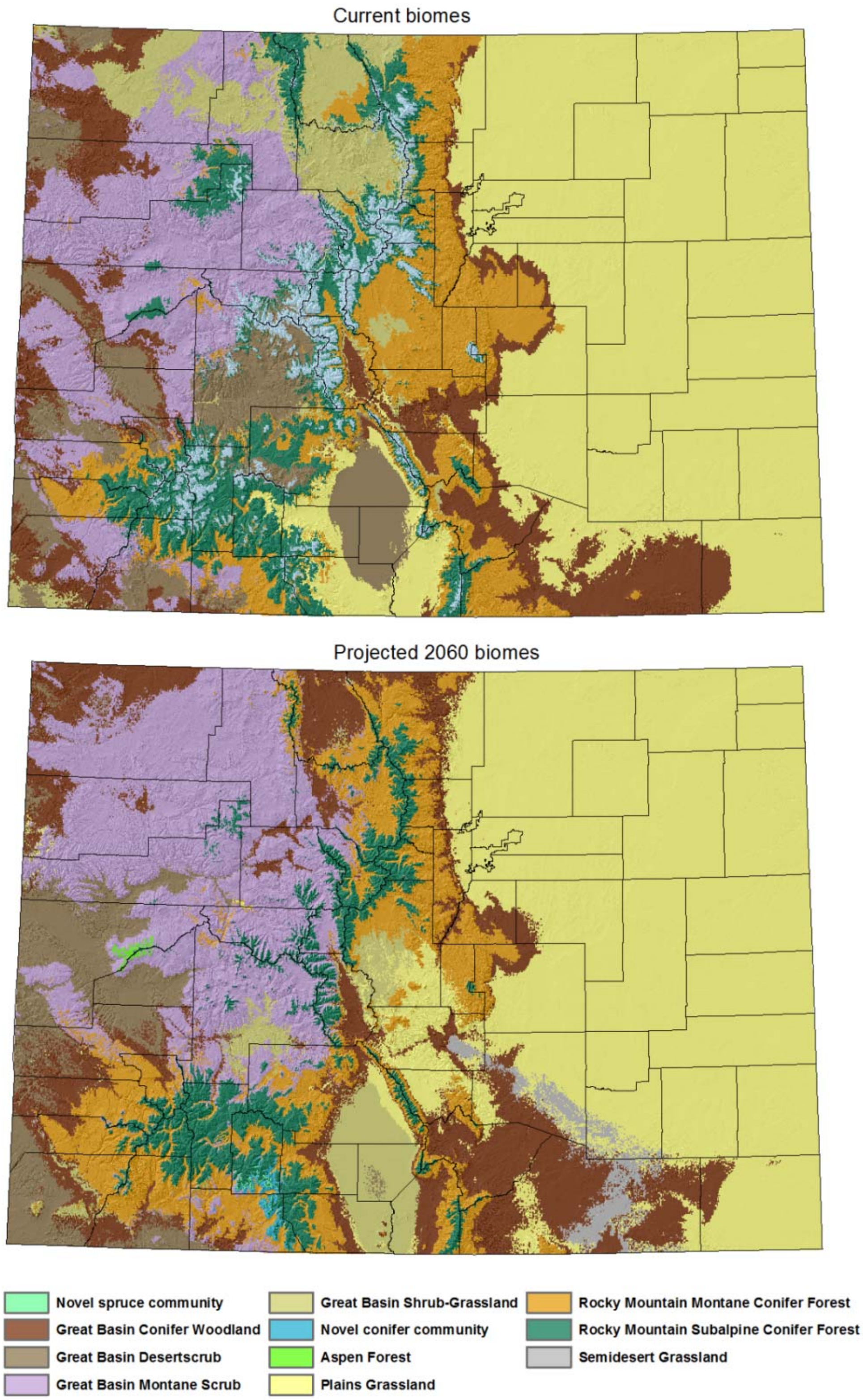


Figure 14. Potential biome shifts by 2060 (Rehfeldt et al. 2012).

Conclusions

The majority of habitat types were ranked as moderately vulnerable in our analysis, however, the division between moderately and highly vulnerable is less clear than the separation between low and moderate vulnerability (Figure 15). The true vulnerability level of habitats near the moderate-high division is likely to be determined by their degree of adaptive capacity, which we were not able to evaluate with precision, and which can be affected by management actions to some extent.

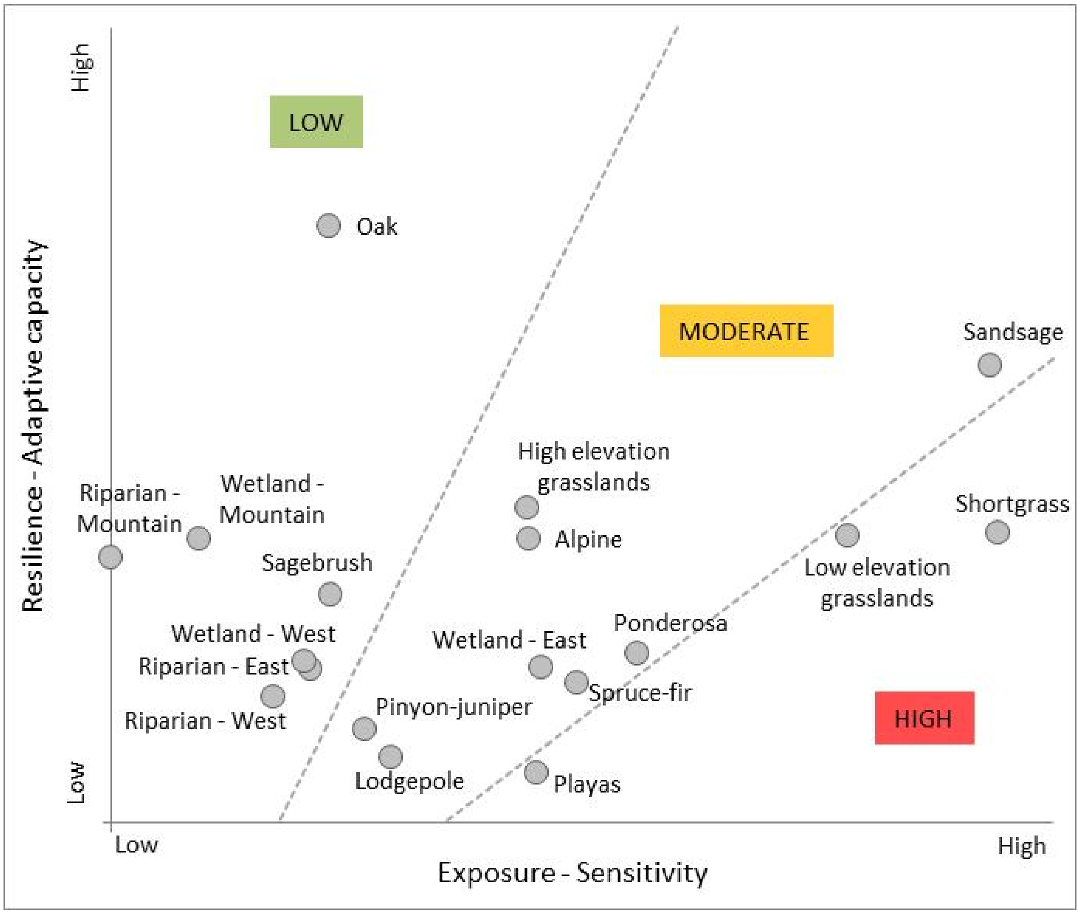


Figure 15. Exposure-Sensitivity versus Resilience-Adaptive capacity scores for habitats included in this evaluation. Vulnerability ranks of Low, Moderate, and High are relative categories indicating an approximate priority of each habitat for management and planning for climate change.

By mid-century, under a medium-high radiative forcing scenario (RCP6.0), we can expect to see warmer temperatures statewide, especially on the eastern plains. Warmer temperatures are likely to include more heat waves, fewer cold snaps, and generally extended frost-free periods. Although these conditions could benefit many species if precipitation remains adequate, the warming trend is likely to be accompanied by drier conditions in many areas. Even if precipitation levels at higher elevations are essentially unchanged, warmer conditions will lead to more precipitation falling as rain instead of snow, a decreased snowpack, earlier runoff, and earlier dry conditions in late summer (Lucas et al. 2014). All of these factors may interact with stressors such as fire, forest pests and diseases, drought, and anthropogenic disturbance to alter the future trajectory of a particular habitat.

Comparison of the current range of climate variables with the projected range (Figures 11-13 above) indicates substantial current and future overlap of climatic conditions for some habitat groups. For instance, alpine, spruce-fire, and, in some cases lodgepole pine, are clearly close in climatic tolerance, while ponderosa pine, oak-shrub, and sagebrush form a group sharing similar climatic conditions at lower elevations. The interaction of climatic conditions with other environmental factors and biogeographic history shapes the distribution of habitats that we currently observe. Furthermore, the time lag between when climate conditions become suitable or unsuitable for a species and the eventual colonization or elimination of that species in an area adds another level of uncertainty to projections of future habitat distribution. Climate changes over the past few decades are probably already facilitating a gradual shift of habitats that will become more apparent by mid-century.

Our analysis of the range of future uncertainty focused on “worst case” outcomes in order to provide a vulnerability prioritization of key habitats that will facilitate a pragmatic “no-regrets” planning strategy for CPW staff dealing with the ongoing effects of climate change in Colorado.

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TERRESTRIAL ECOSYSTEM VULNERABILITY ASSESSMENT SUMMARIES

Forest and Woodland Habitats

Lodgepole forest

Pinyon-juniper woodland

Ponderosa pine forest and woodland

Spruce-fir forest

Shrubland Habitats

Oak-mixed mountain shrubland

Sagebrush shrubland

Sandsage shrubland

Grassland Habitats

Foothill-montane grassland

Shortgrass prairie

Riparian and Wetland Habitats

Playas

Riparian Woodlands and Shrublands

Wetlands

Other Habitats

Alpine

LODGEPOLE

Climate Influences

Lodgepole pine (*Pinus contorta*) is a northern species that does exceptionally well in very cold climates and can tolerate a wide range of annual precipitation patterns, from fairly dry to fairly wet, but generally grows only where annual precipitation is at least 18-20 inches (Mason 1915, Lotan and Perry 1983). Lodgepole pine forests are found on drier sites than spruce-fir forest, although snowfall is typically heavy in these forests. Summers are often quite dry, and lodgepole pine is dependent on snowmelt moisture for most of the growing season. In low snowpack years, growth is reduced (Hu et al. 2101).

Lodgepole pine is tolerant of very low winter temperatures, and in many lodgepole forests summer temperatures can fall below freezing, so there is no true frost-free season (Lotan and Perry 1983). Lodgepole pine is also able to take advantage of warm growing season temperatures, and a longer growing season due to warmer fall temperatures could favor the growth of lodgepole pine (Villalba et al. 1994, Chhin et al. 2008). In southern Colorado, white fir (*Abies concolor*) appears to take the place of lodgepole pine in coniferous forests of similar elevations. White fir appears to tolerate warmer temperatures than lodgepole pine (Thompson et al. 2000); under warmer conditions it may be able to move into areas currently occupied by lodgepole forest.

Exposure and Sensitivity Summary

Lodgepole pine forests are projected to experience winter temperatures warmer than the current in about one quarter of the current distribution. Projected winter and spring precipitation levels are generally within the current range, but summer precipitation for 21% of the current distribution is projected to be lower than the driest end of the current range.

Lodgepole

Climate variable (sources: M=model, E = expert review, L = literature review)	% projected range shift
Winter precipitation (L)	0%
Spring precipitation (M)	3%
Summer precipitation (M)	21%
Mean winter temperature (E)	25%
Very cold days (E)	25%
Average range shift	14.9%
Rank	L
Exposure-Sensitivity level	Low

Resilience Components

Lodgepole pine subspecies are widely distributed in North America, but Rocky Mountain lodgepole reaches the southern edge of its distribution in south-central Colorado. In Colorado, lodgepole pine forests range from about 8,500-11,000 ft. in elevation. Statewide, the annual average precipitation range for lodgepole forest is about 13.5-41 in. (35-105 cm), with a mean of 25" (64 cm). Lodgepole pine is able to tolerate much warmer temperatures than spruce-fir forest. Growing season length for lodgepole broadly overlaps that of the warmer end of the spruce-fir distribution.

Many lodgepole forests developed following fires. Lodgepole pines produce both open and serotinous cones, and can reproduce quickly after a fire. Following stand-replacing fires, lodgepole pine rapidly colonizes and develops into dense, even-aged stands (sometimes referred to as "dog hair" stands). This fire-adapted species has the potential to move into areas where spruce-fir forests burn.

Although invasive species are generally not a threat, lodgepole forests are vulnerable to the pest outbreaks that appear to increase with warmer, drier, drought-prone climates. Biological stressors that interact with fire dynamics of lodgepole forest include infestations of lodgepole pine dwarf-mistletoe and mountain pine beetle (Anderson 2003). Dwarf mistletoe reduces tree growth and cone production, and generally leads to earlier mortality (Hawksworth and Johnson 1989). Although lodgepole forests are still common across Colorado, most are experiencing widespread damage from a severe outbreak of mountain pine beetle. The pine beetle is a native species, and periodic outbreaks of this insect are part of the natural cycle that maintains Colorado's mountain forests. Lodgepole forests are expected to persist in Colorado (Kaufmann et al. 2008).

Adaptive Capacity Summary

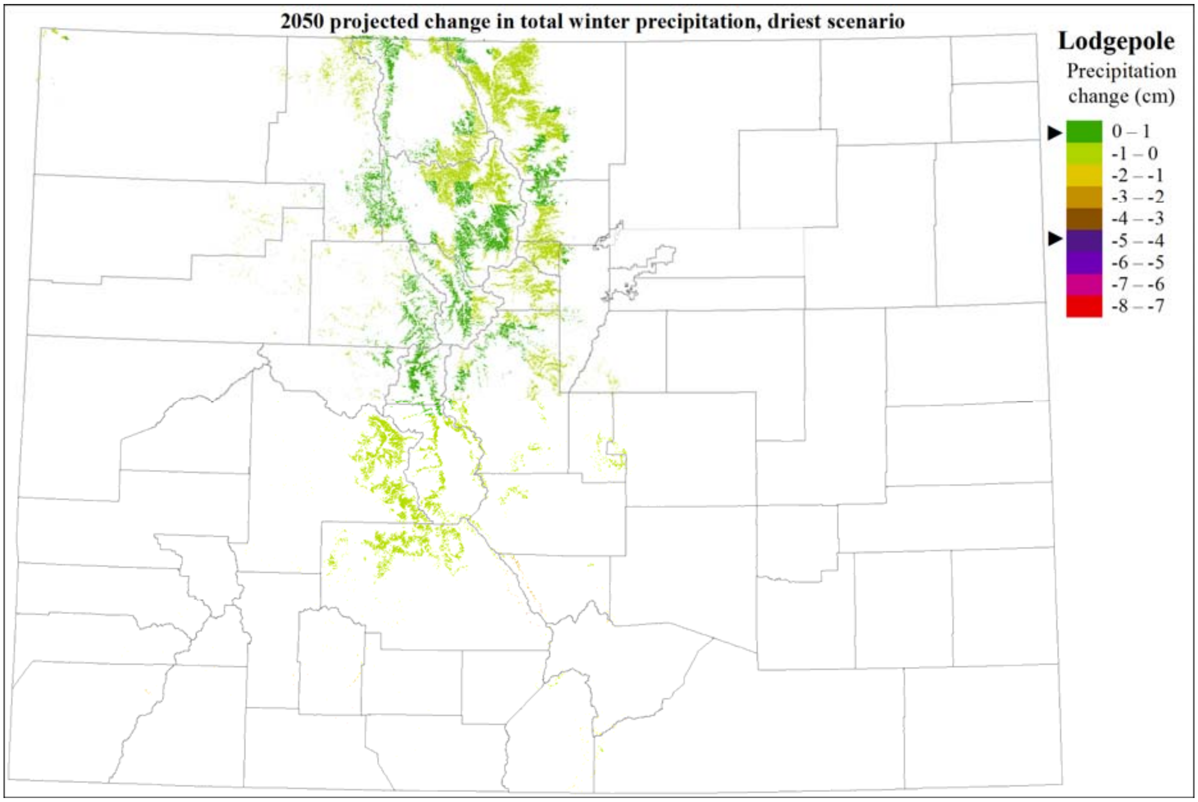
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Lodgepole	0.60	0	0.67	0.33	0.75	0.45	L	Low

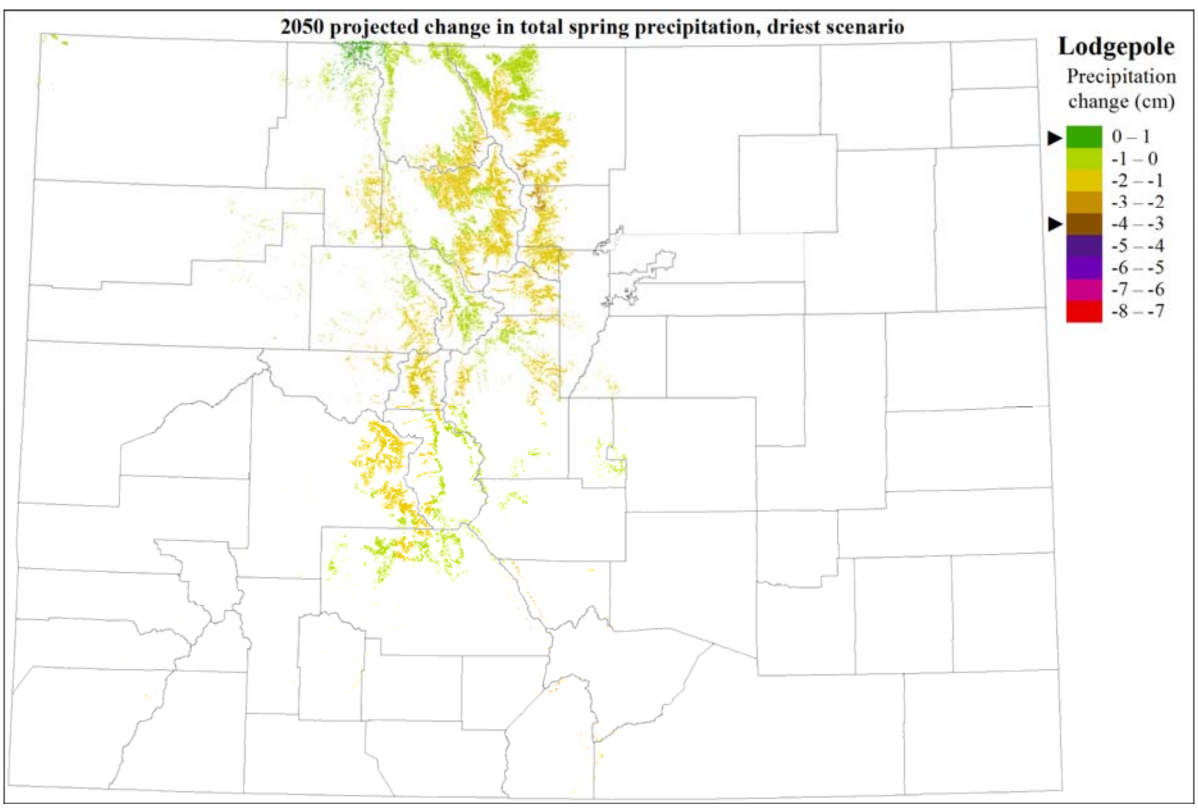
Vulnerability to Climate Change

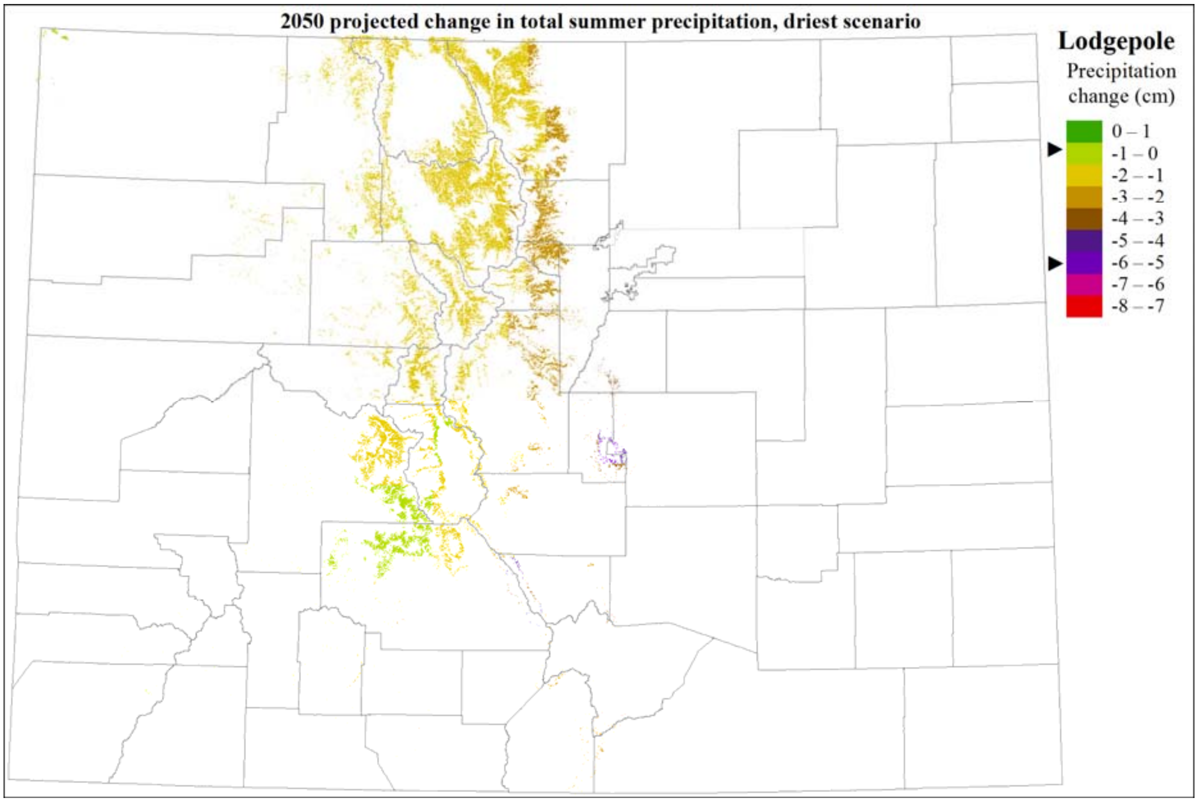
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Lodgepole pine forest	Low	Low	L/L	Moderate

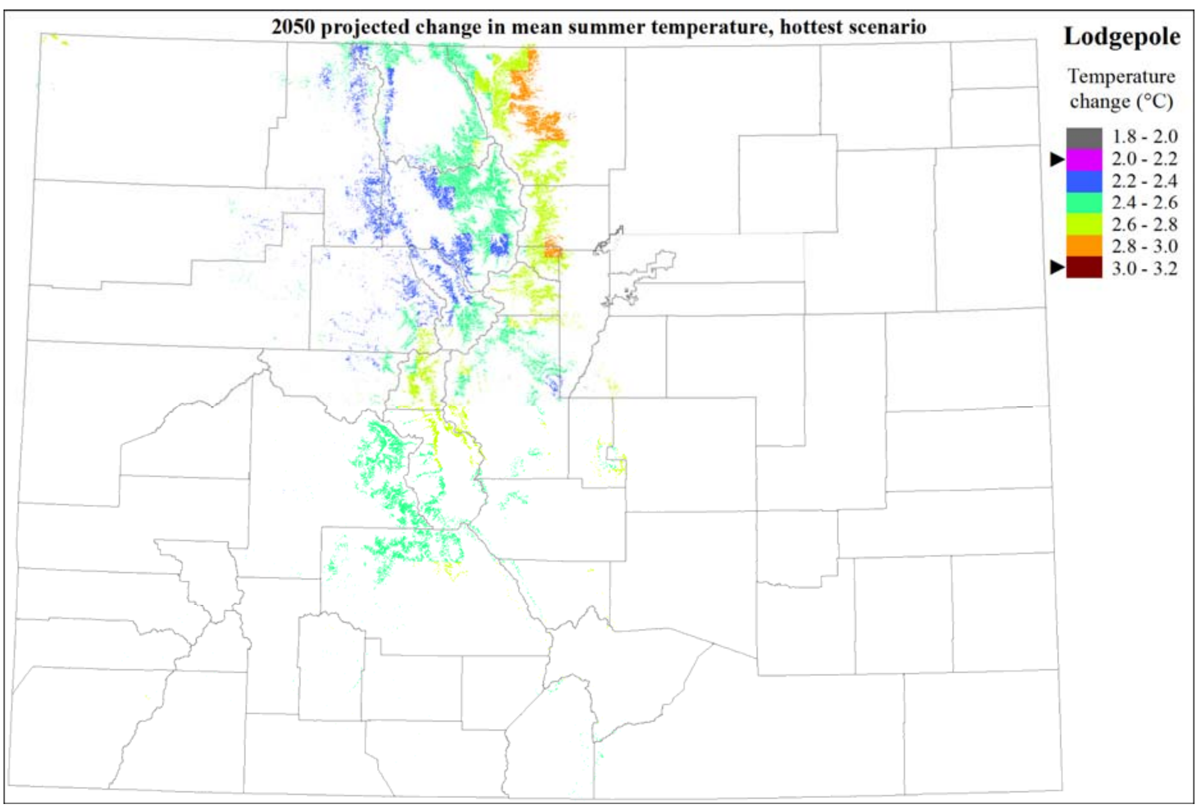
Lodgepole pine forest is ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are its vulnerability to forest disturbances that may increase in the future, and the fact that it is at the southern edge of its distribution in Colorado.

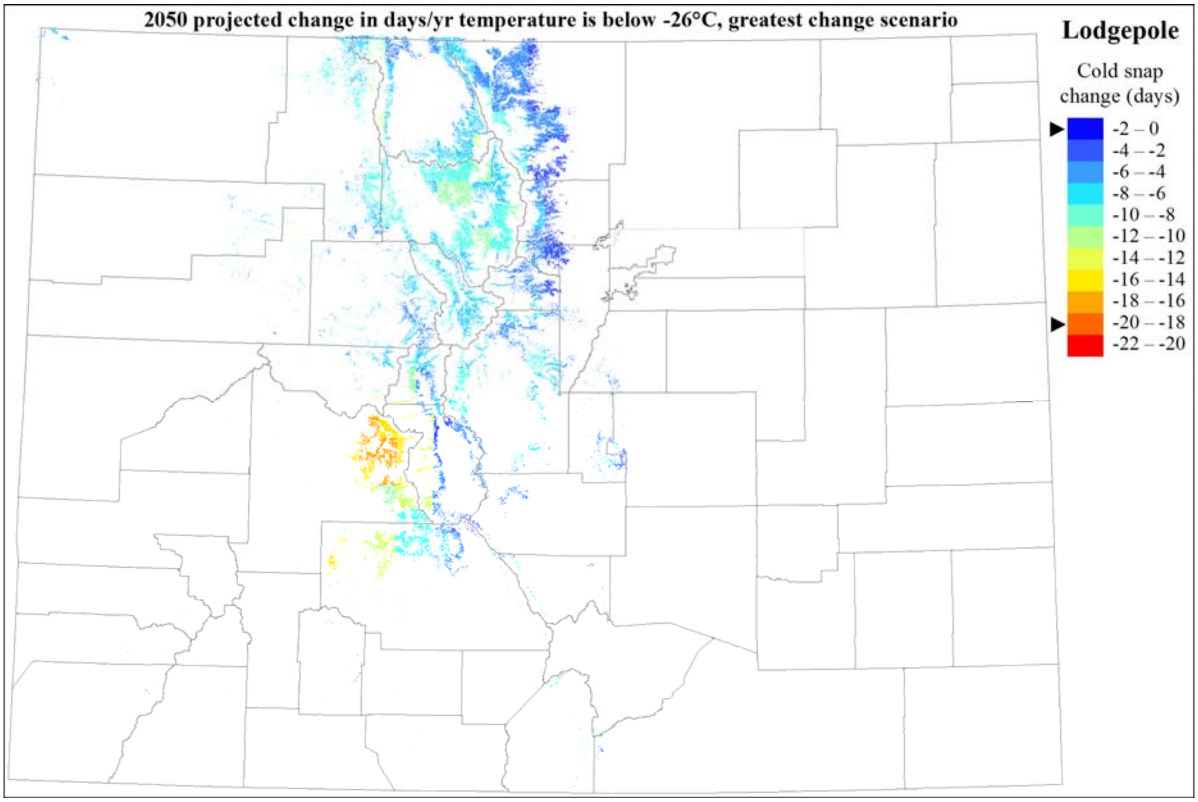
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for lodgepole pine forest. Legend pointers indicate the range of change for this habitat within the statewide extent of change. For winter precipitation, areas in the southern and western edge of the Colorado distribution are most exposed. For spring and summer precipitation, areas along the Front Range are most exposed to drier conditions. Warming during the growing season is projected to experience the greatest increase in the eastern portion of the Colorado distribution, and the number of very cold days in winter is projected to reduce the most in the south-western part of the distribution.


2050 projected change in total winter precipitation, driest scenario
Lodgepole
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total spring precipitation, driest scenario
Lodgepole
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total summer precipitation, driest scenario
Lodgepole
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in mean summer temperature, hottest scenario
Lodgepole
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2



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PINYON-JUNIPER

Climate Influences

These evergreen woodlands are adapted to cold winter minimum temperatures and low rainfall, and are often transitional between grassland or desert shrubland and montane conifer ecosystem (Brown 1994, Peet 2000). Since the last major glacial period, the distribution and relative abundance of the characteristic tree species has fluctuated dynamically with changing climatic conditions. Warming conditions during the past two centuries, together with changing fire regime, livestock grazing, and atmospheric pollution increased the ability of this ecosystem to expand into neighboring communities, at both higher and lower elevations (Tausch 1999). Variable disturbance and site conditions across the distribution of this ecosystem have resulted in a dynamic mosaic of interconnected communities and successional stages that may be naturally resilient.

Barger et al. (2009) found that pinyon pine (*Pinus edulis*) 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). Clifford et al. (2013) detected a strong threshold at 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 (*Juniperus* spp.) 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).

The pinyon-juniper habitat 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. Increased drought may drive fires and insect outbreaks, from which these woodlands would be slow to recover.

Exposure and Sensitivity Summary

Pinyon-juniper woodlands are projected to experience summer temperatures warmer than the current range in more than one third of the current distribution. Projected winter precipitation levels are generally within the current range, but spring and summer precipitation for 9-16% of the current distribution are projected to be lower than the driest end of the current range.

Pinyon-juniper

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Winter precipitation (L)	2%
Spring precipitation (M, L)	16%
Summer precipitation (M, E, L)	9%
Mean summer temperature (M, E)	38%
Very cold days (M, E)	3%
Average range shift	13.5%
Rank	L
Exposure-Sensitivity level	Low

Resilience Components

Pinyon-juniper, which forms the characteristic woodland of warm, dry lower elevations from about 4,600 to 8,500 ft., is widespread in Colorado's western canyons and valleys, as well as in the southern mountains. The North American distribution of this habitat is centered in the Colorado Plateau, generally southwest of Colorado. Stands are often adjacent to and intermingled with oak, sagebrush, or saltbush shrubland. The statewide range of annual average precipitation is about 10-23 in (25-60 cm), with a mean of 16 in (40 cm), similar to sagebrush shrubland. Growing season temperatures are greater in the range of pinyon-juniper than for many other woody vegetation types in Colorado.

Extended drought can increase the frequency and intensity of insect outbreaks and wildfire. Pinyon are susceptible to the fungal pathogen *Leptographium wageneri* var. *wageneri*, which causes black stain root disease, and to infestations of the pinyon ips bark beetle (*Ips confusus*)(Kearns and Jacobi 2005). The differential susceptibility of pinyon and juniper to drought and insect outbreaks could eventually result in these woodlands being dominated by juniper.

Pinyon pine stands are slow to recover from intense fires; the species reproduces only from seed and recovery is dependent on seed sources and/or adequate dispersal. Junipers are also slow-growing, and susceptible to being killed by fire. At Mesa Verde National Park, where pinyon-juniper woodlands have burned in five large fires since 1930, trees have not yet re-established. It is not known why trees have not been successful in these areas, which are now occupied by shrubland (Floyd et al. 2000).

Adaptive Capacity Summary

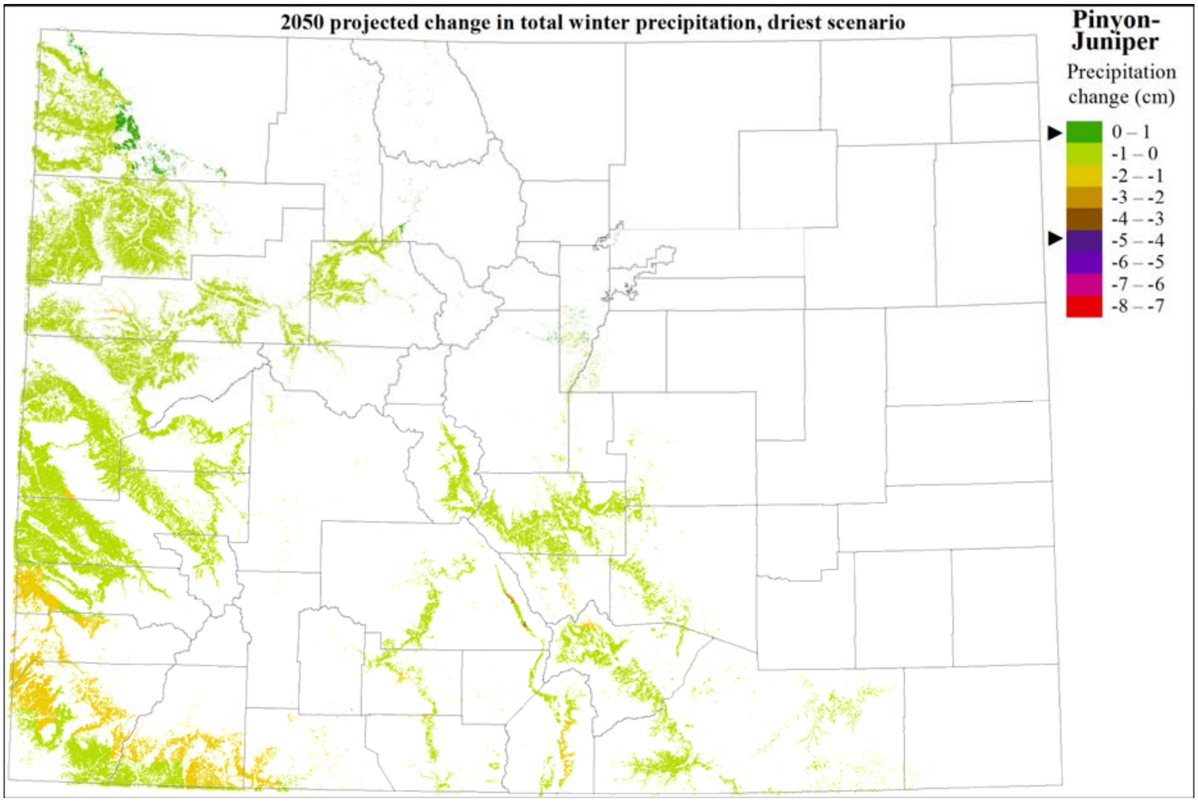
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Pinyon-juniper	0.87	0	0.67	0.33	0.592	0.47	L	Low

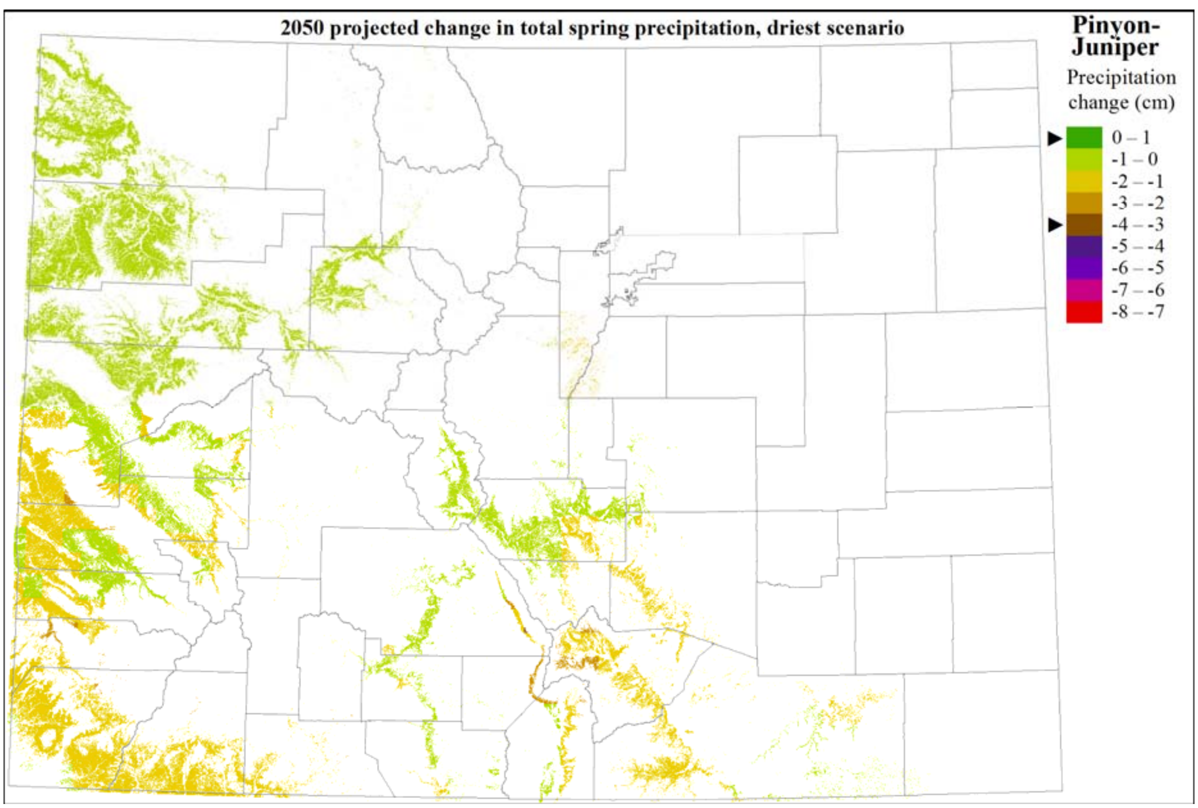
Vulnerability to Climate Change

	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Pinyon-Juniper woodland	Low	Low	L/L	Moderate

Pinyon-juniper woodlands are ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the vulnerability of these woodlands to stressors that are likely to increase under changing climate, and the extent to which the current landscape condition of the habitat has been impacted by anthropogenic disturbance.

Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for pinyon-juniper. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Areas in the southern part of the state are most exposed to potentially drier conditions, especially for summer precipitation. Temperature change does not show a clear pattern.


2050 projected change in total winter precipitation, driest scenario
Pinyon-Juniper
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total spring precipitation, driest scenario
Pinyon-Juniper
Precipitation change (cm)
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-1 – 0
-2 – -1
-3 – -2
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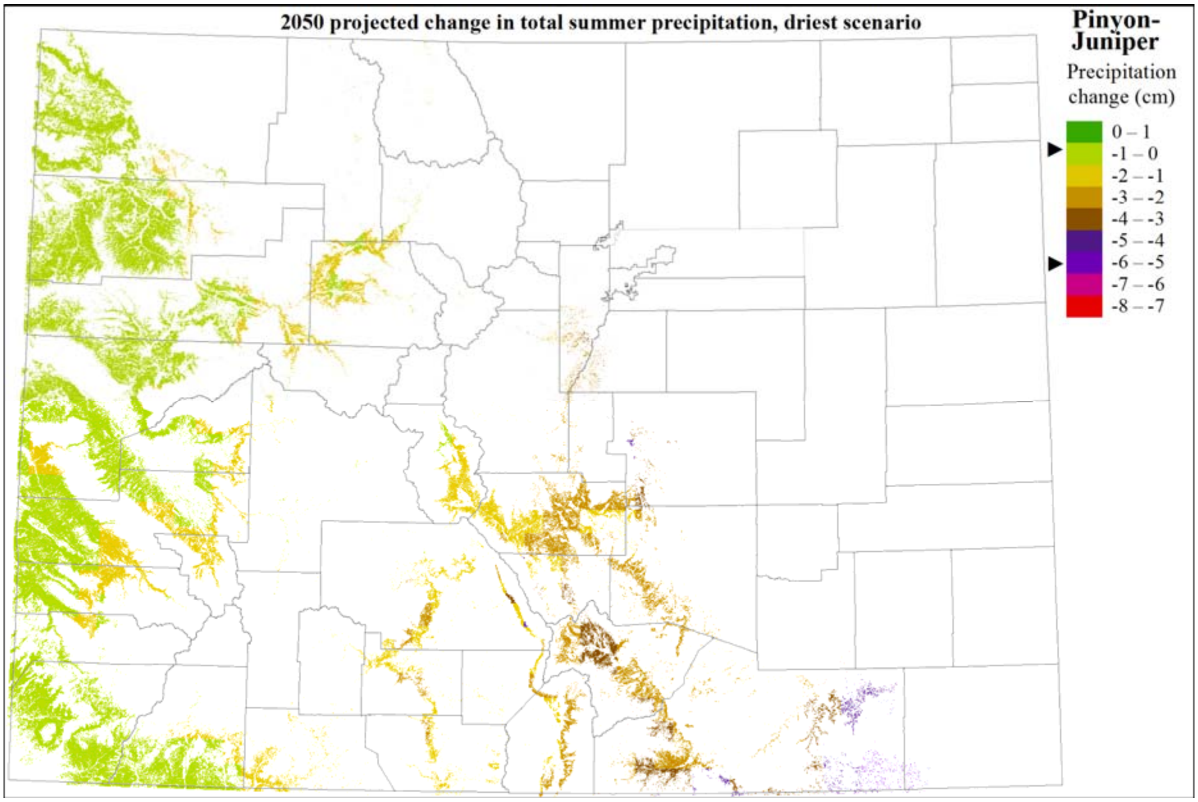
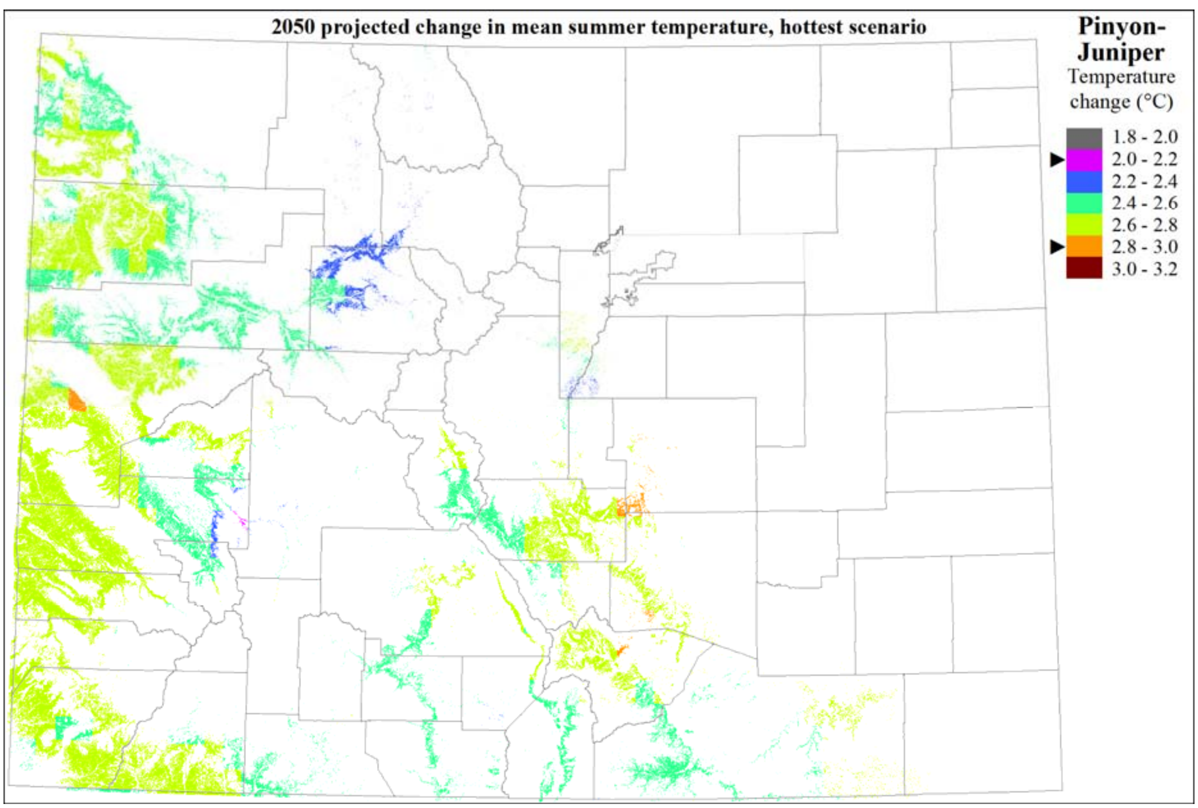
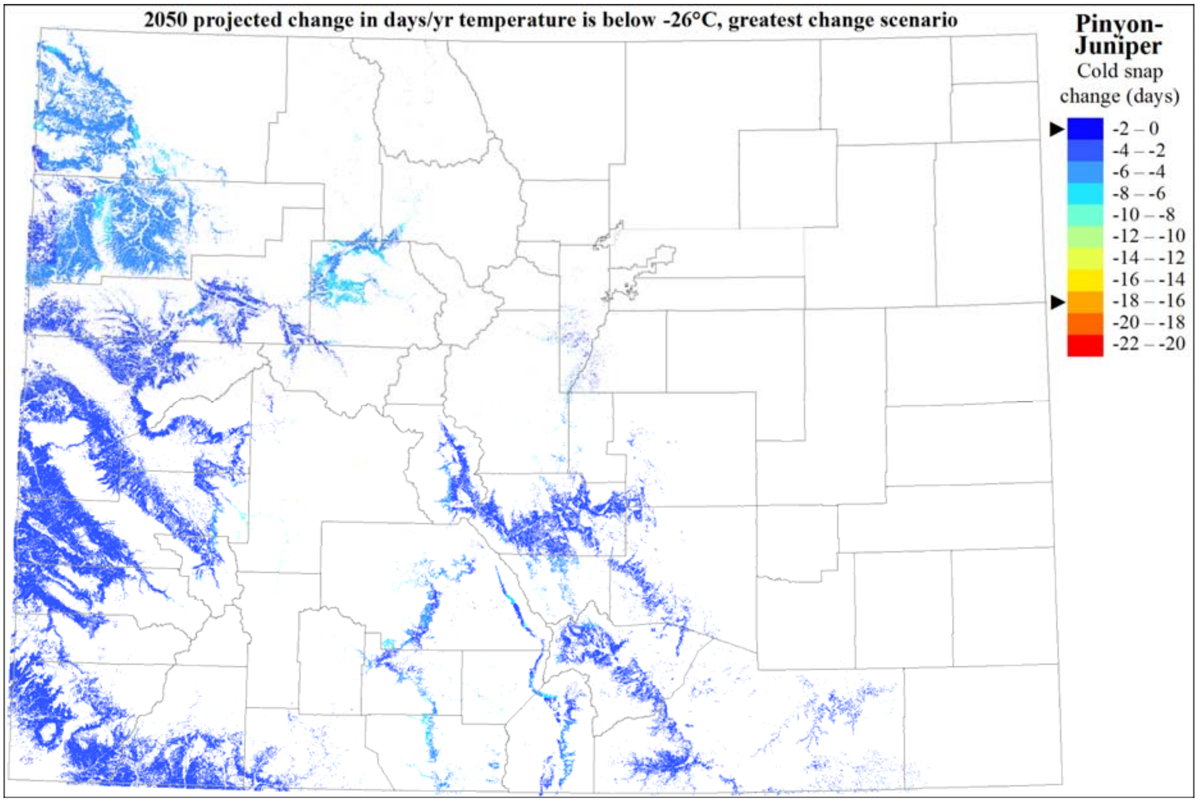
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total summer precipitation, driest scenario
Pinyon-Juniper
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in mean summer temperature, hottest scenario
Pinyon-Juniper
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2



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PONDEROSA

Climate Influences

Ponderosa pine (*Pinus ponderosa*) occupies relatively dry, nutrient-poor sites compared to other montane conifers, but shows wide ecological amplitude throughout its distribution. Rehfeldt et al. (2012) were able to predict the distribution of ponderosa pine largely through the use of summer and winter precipitation, and summer temperatures (as growing degree days >5 C). Although periodic seasonal drought is characteristic across the range of ponderosa pine, this species is generally found where annual precipitation is at least 13 inches (Barrett et al. 1980, Thompson et al. 2000). Ponderosa stands to the south of Colorado were primarily reliant on winter precipitation(Kerhoulas et al. 2013), while growth of Front Range stands was correlated with spring and fall moisture (League and Veblen 2006), indicating some variability in the ability of ponderosa pine to take advantage of seasonal water availability, depending on site factors and stand history. Consequently, vulnerability of ponderosa forests to changes in precipitation patterns may differ according to their location in Colorado.

Ponderosa pine is able to tolerate fairly warm temperatures as long as there is enough moisture, especially in the growing season. Optimal germination and establishment conditions occur when temperatures are above 50°F and monthly precipitation is greater than 1 inch (Shepperd and Battaglia 2002). Significant recruitment events may occur on burned areas when conditions are wet wetter than normal after a fire year, but normal precipitation may also be sufficient for seedling establishment in such cases (Mast et al. 1998). In lower elevation ponderosa woodlands of the Colorado Front Range, episodic recruitment of ponderosa pine was associated with high spring and fall moisture availability during El Niño events (League and Veblen 2006). A correlation between drought and low rates of ponderosa seedling recruitment has also been identified throughout the western Great Plains (Kaye et al. 2010). Drought in combination with future projected higher temperatures is likely to reduce ponderosa pine regeneration, especially in drier, lower elevation areas. The work of Brown and Wu (2005) suggests that coincident conditions of sufficient moisture and fewer fires are important for widespread recruitment episodes of ponderosa pine; such conditions may become less likely under future climate scenarios.

Increased drought may drive fires and insect outbreaks. Relative proportions of associated species (e.g., other conifers, aspen, understory shrubs and grasses) in ponderosa stands may change. This habitat is well adapted to warm, dry conditions if precipitation is not too much reduced, and may be able to expand into higher elevations.

Exposure and Sensitivity Summary

Ponderosa pine forest and woodlands are projected to experience summer temperatures warmer than the current range in more than one third of the current distribution, and projected winter temperatures are warmer than the current range for more than a quarter of the distribution. Projected summer and fall precipitation levels are projected to be lower than the driest end of the current range for nearly a quarter of the current distribution.

Ponderosa

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Summer precipitation (M, E, L)	19%
Fall precipitation (L)	23%
Mean winter minimum temperature (M, E)	27%
Mean summer temperature (E)	39%
Very hot days (E)	32%
Average range shift	19.2%
Rank	M
Exposure-Sensitivity level	Moderate

Resilience Components

Ponderosa woodlands are not found at high elevations, but instead form a broad zone of coniferous forest along the southern flank of the San Juan Mountains, as well as along the eastern mountain front, generally at elevations between 6,000 and 9,000 ft. These habitats are in within the central portion of their North American distribution in Colorado. Annual precipitation is similar to that for oak shrubland , with a range of 18.9- 35.8 in (30-80 cm) and a mean of 20 in (51 cm). Ponderosa occurs in a broad middle range of growing season lengths across the state.

Although seeds are typically not dispersed very far, ponderosa pine is often present in mixed conifer stands; these areas may provide a seed bank for regeneration or a shift to ponderosa pine. Recruitment is episodic, depending on precipitation and disturbance patterns. These forests are susceptible to outbreaks of the mountain pine beetle

(*Dendroctonus ponderosae*) and mistletoe infestations, both of which may be exacerbated by increased drought. Impacts of native grazers or domestic livestock could also alter understory structure and composition.

Ponderosa pine is well adapted to survive frequent surface fires, and mixed-severity fires are characteristic in these communities (Arno 2000). Although climate change may alter fire regimes slightly by affecting the community structure, fire is not expected to have a severe impact in the future for these stands, and may actually be beneficial in some areas.

Adaptive Capacity Summary

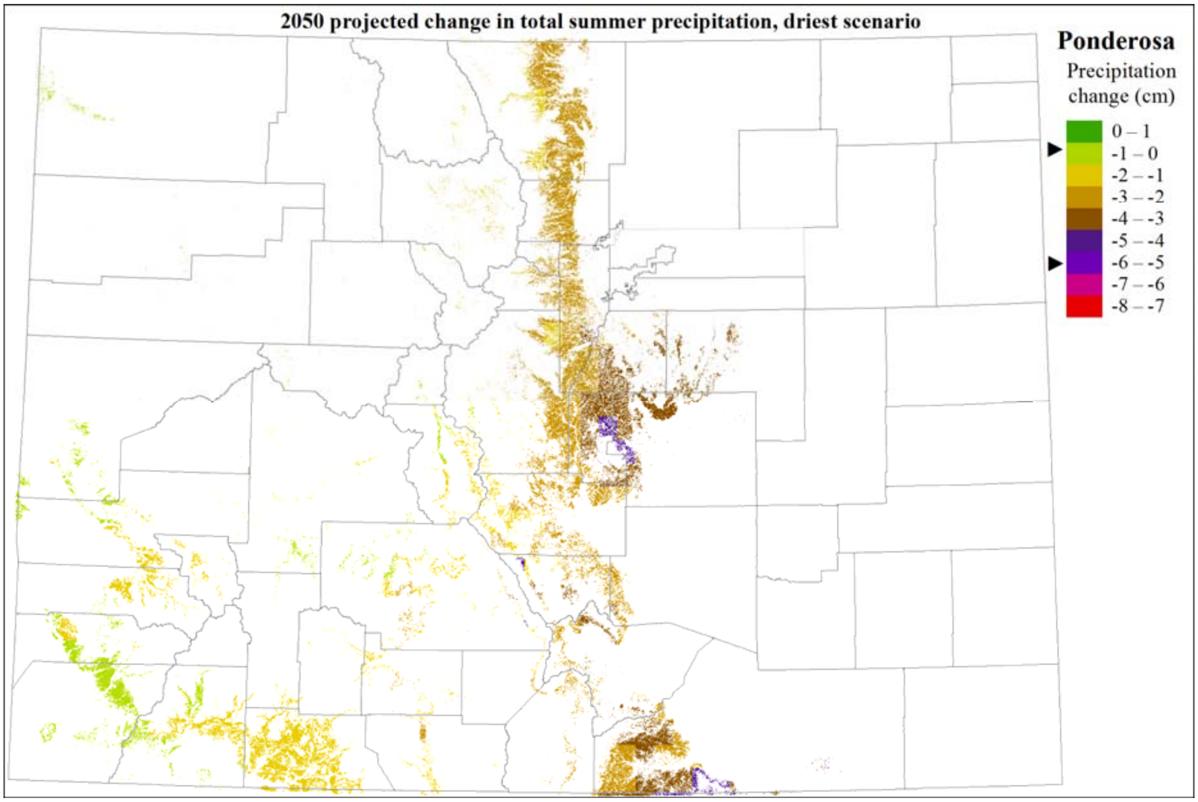
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Ponderosa	0.87	0	0.67	0.67	0.54	0.53	M	Moderate

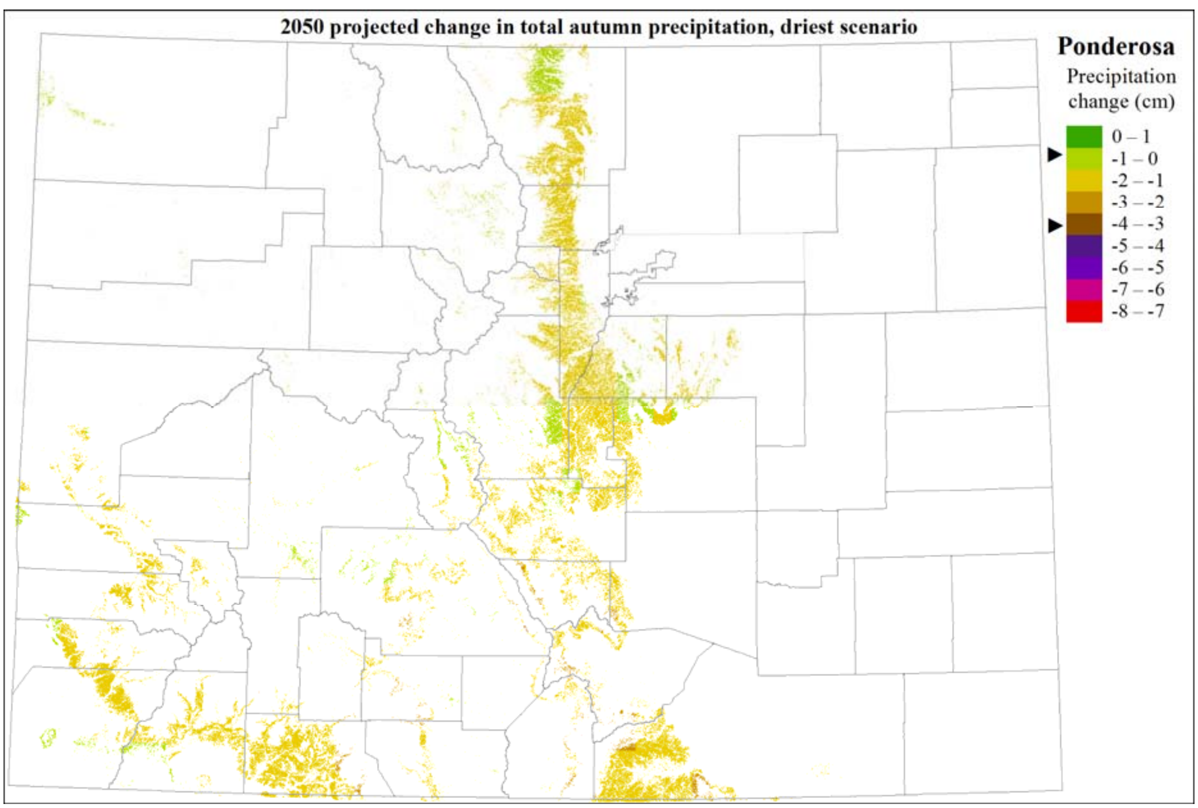
Vulnerability to Climate Change

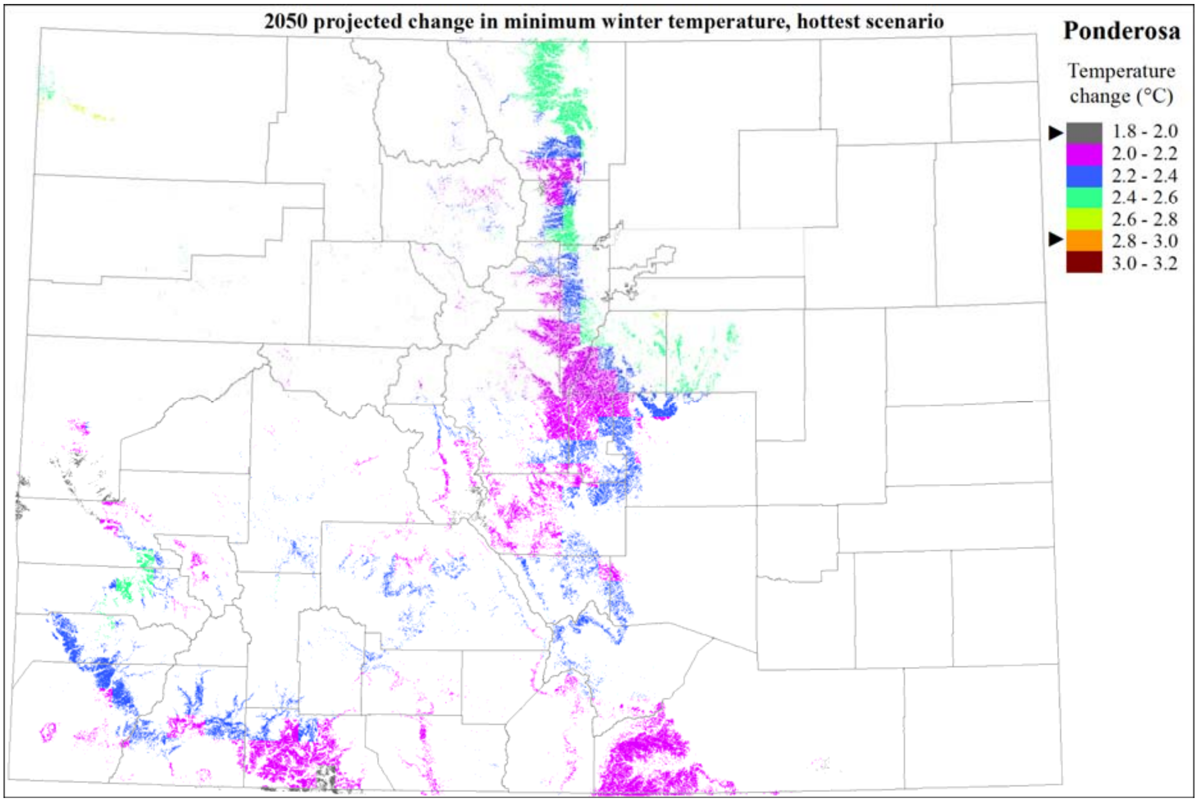
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Ponderosa pine forest & woodland	Moderate	Moderate	M/M	Moderate

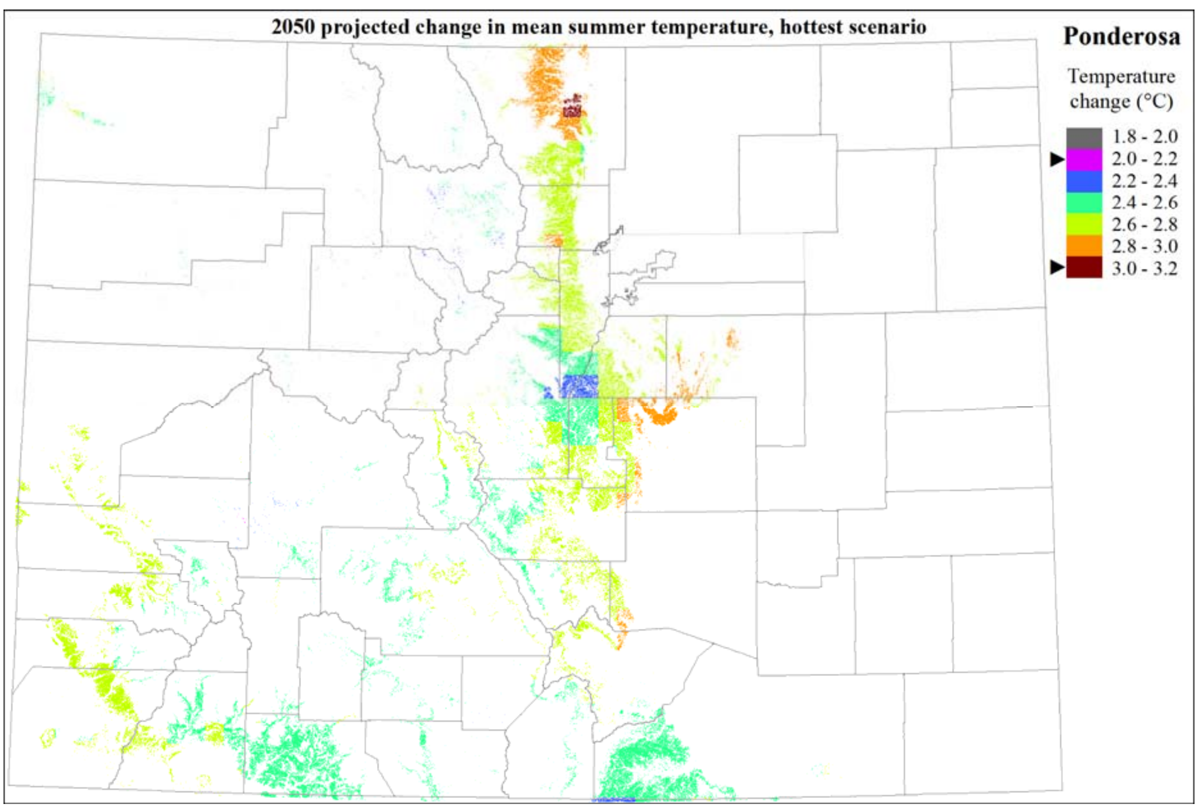
Ponderosa pine forests and woodlands are ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the exposure of large areas of this habitat to warmer temperatures that are likely to interact with forest disturbances that are, in turn, exacerbated by warm, dry conditions.

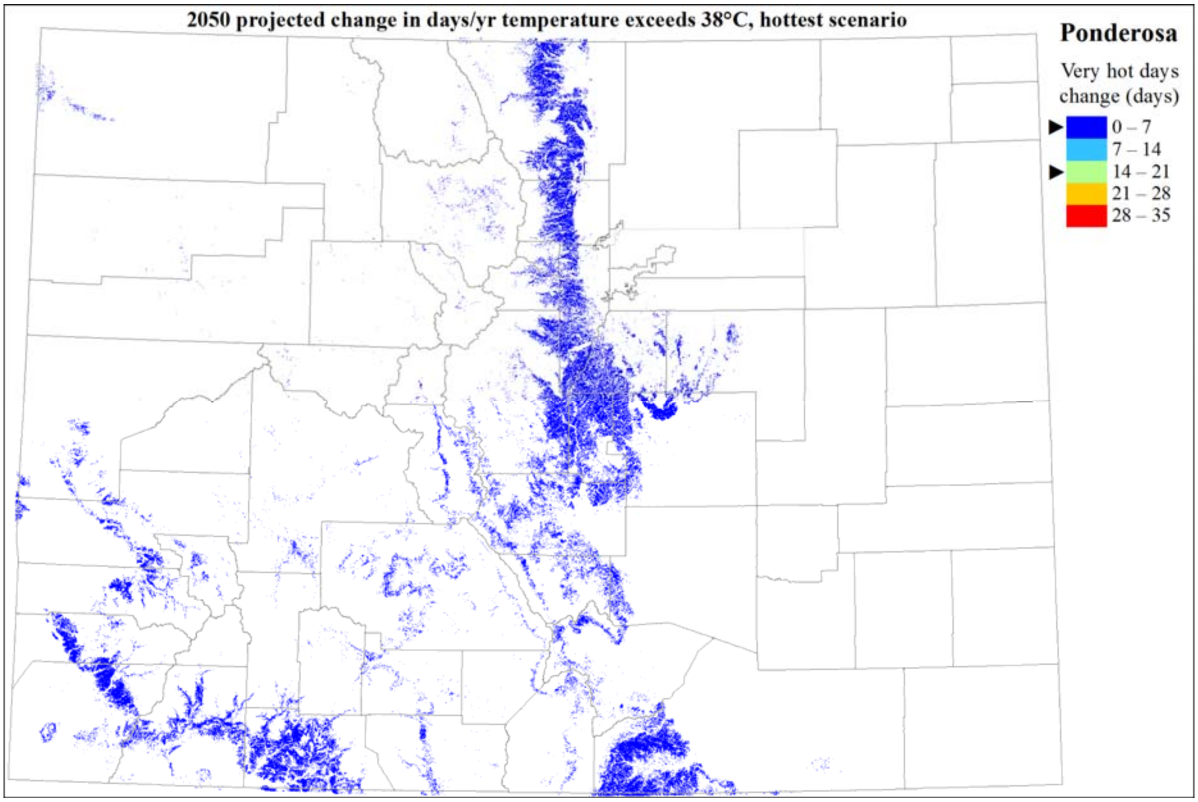
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for ponderosa habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Areas along the mountain front are projected to see the most decrease in summer and fall precipitation. The northern Front Range portion of the distribution is projected to experience the most warming. Very hot days (which may contribute to fire danger) may increase slightly throughout the distribution of ponderosa.


2050 projected change in total summer precipitation, driest scenario
Ponderosa
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total autumn precipitation, driest scenario
Ponderosa
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in minimum winter temperature, hottest scenario
Ponderosa
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2


2050 projected change in mean summer temperature, hottest scenario
Ponderosa
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2



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SPRUCE-FIR

Climate Influences

Spruce-fir forest typically dominates the wettest and coolest habitats below treeline. These areas are characterized by long, cold winters, heavy snowpack, and short, cool summers where frost is common (Uchytil 1991). Both Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are dependent on snowmelt water for most of the growing season, and in low snowpack years growth is reduced (Hu et al. 2101).

The length of the growing season is particularly important for both alpine and subalpine zones, and for the transition zone between alpine vegetation and closed forest (treeline). Treeline-controlling factors operate at different scales, ranging from the microsite to the continental (Holtmeier and Broll 2005). On a global or continental scale, there is general agreement that temperature is a primary determinant of treeline. Körner (2012) attributes the dominance of thermal factors at this scale to the relative consistency of atmospheric conditions over large areas, especially in comparison to more local influence of soil and moisture factors. Furthermore, there appears to be a critical duration of temperatures adequate for the growth of trees in particular (e.g. individuals >3m tall) that determines the location of treeline. At more local scales, soil properties, slope, aspect, topography, and their effect on moisture availability, in combination with disturbances such as avalanche, grazing, fire, pests, disease, and human impacts all contribute to the formation of treeline (Richardson and Friedland 2009, Körner 2012). Patterns of snow depth and duration, wind, insolation, vegetation cover, and the autecological tolerances of each tree species influence the establishment and survival of individuals within the treeline ecotone (Moir et al. 2003, Holtmeier and Broll 2005, Smith et al. 2009). In the Rocky Mountains, tree establishment was significantly correlated with warmer spring (Mar-May) and cool-season (Nov-Apr) minimum temperatures as well (Elliott 2012).

Spruce-fir forests currently occupy cold areas with high precipitation; warmer and drier climate conditions predicted by most models could result in an upward migration of these forests into the alpine zone. However, in Canadian spruce-fir forests, warmer than average summer temperatures led to a decrease in growth the following year (Hart and Laroque 2013). Since spruce-fir may be able to tolerate warmer summer temperatures, the lower extent of this habitat type could remain at current levels for some time, even if growth is reduced.

The current location of treeline is a result of the operation of climatic and site-specific influences over the past several hundred years, and does not exactly reflect the current climate (Körner 2012). The treeline position lag time behind climate change is estimated to be 50-100+ years, due to the rarity of recruitment events, the slow growth and frequent setbacks for trees in the ecotone, and competition with already established alpine vegetation (Körner 2012). Nevertheless, on the basis of historic evidence, treeline is generally expected to migrate to higher elevations as temperatures warm, as permitted by local microsite conditions (Smith et al. 2003, Richardson and Friedland 2009, Grafius et al. 2012).

Furthermore, the lag time of decades or longer for treeline to respond to warming temperatures may allow the development of novel vegetation associations (Chapin and Starfield), and make it difficult to identify temperature constraints on the distribution of this habitat (Grafius et al. 2012). The gradual advance of treeline is also likely to depend on precipitation patterns. Seedling establishment and survival are greatly affected by the balance of snow accumulation and snowmelt. Soil moisture, largely provided by snowmelt, is crucial for seed germination and survival. Although snowpack insulates seedlings and shields small trees from wind desiccation, its persistence shortens the growing season and can reduce recruitment (Rochefort et al. 1994).

Exposure and Sensitivity Summary

Spruce-fir forests are projected to experience winter and summer temperatures warmer than the current range in a significant portion of their current distribution. Projected winter and spring precipitation levels are generally within the range of the current distribution.

Spruce-fir

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Winter precipitation (L)	2%
Spring precipitation (M, E)	5%
Mean winter minimum temperature (E)	31%
Mean summer temperature (M, E, L)	43%
Growing degree days - base 0 (L)	43%
Average range shift	23.3%
Rank	M
Exposure-Sensitivity level	Moderate

Resilience Components

Spruce-fir forests in Colorado have a wide elevational range, extending from about 8,900 ft. up to over 12,000 ft. Although not as restricted as alpine habitats, spruce-fir forests are generally limited to higher, cooler elevations, and are also near the southern extent of their continental range in Colorado. Statewide, annual average precipitation is slightly lower than for alpine with a range of about 16-47 in. (40-120 cm) and a mean of 31 in. (80 cm). Spruce-fir requires a longer growing season than alpine habitat, but is successful at much cooler temperatures than most other forest types. Spruce-fir forests accumulate more annual growing degree days than alpine areas, but fewer than for other forested types.

Subalpine fir seeds require cold-moist conditions to trigger germination (Uchytil 1991), and there is some indication that Engelmann spruce seeds germinate faster at relatively low temperatures (Smith 1985), giving it a competitive advantage over less cold-tolerant species. Under warmer conditions, however, current spruce-fir communities may be gradually replaced by a mixed-conifer forest. There are no obvious barriers to the gradual dispersal of seedlings into adjacent, newly suitable habitat, although the dominant species are generally slow-growing.

Although these subalpine forests are not susceptible to increased prevalence of invasive species, they are vulnerable to outbreaks of the native pest species spruce bud worm and spruce beetle. Warmer temperatures (both winter and summer) are likely to facilitate these infestations; current distribution of spruce-fir habitat may therefore be at increased risk of significant mortality. Insect outbreaks are also typically associated with droughts.

Historic natural fire-return intervals in these forests have been on the order of several hundred years, and the tree species are not adapted to more frequent fires. With an increase in droughts and faster snowmelts, we might expect an increase in forest fire frequency and extent within this zone. It is not known if spruce-fir forests will be able to regenerate under such conditions, especially in lower elevation stands, and there is a potential for a reduction in spruce-fir forests, at least in the short term.

Adaptive Capacity Summary

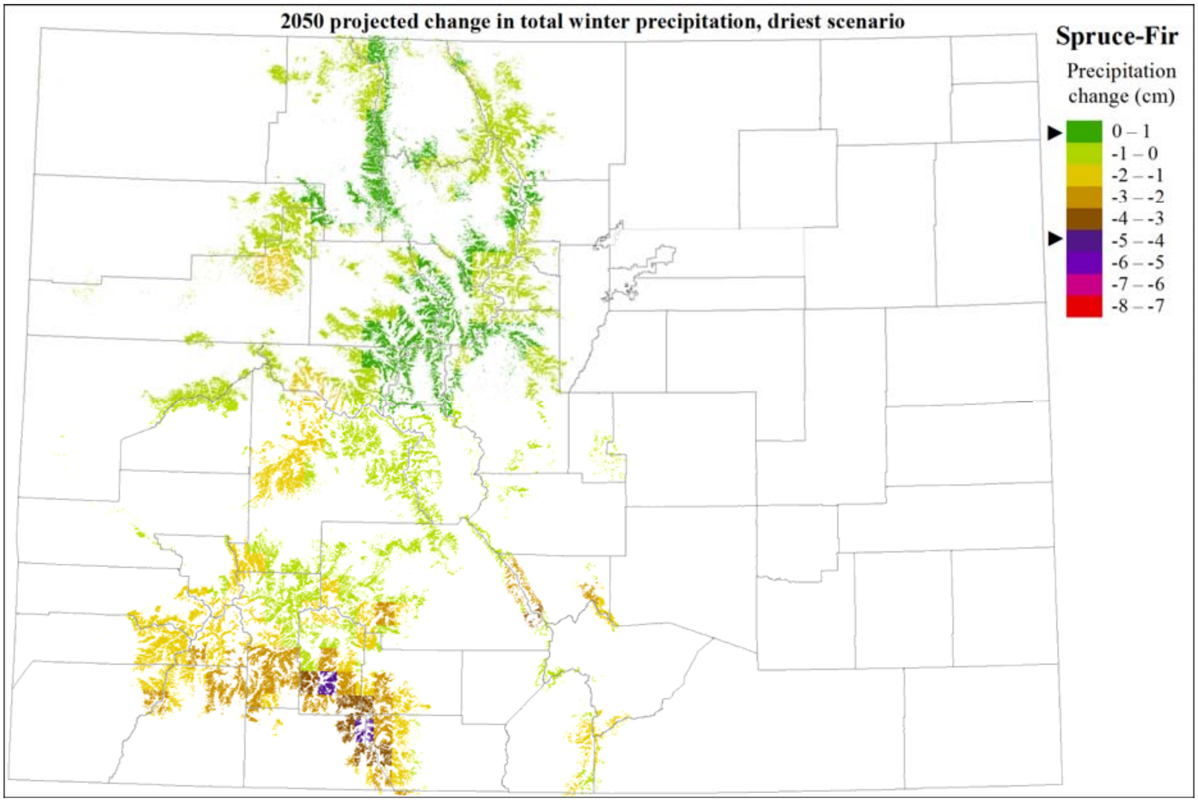
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Spruce-fir	0.37	0	0.67	0.67	0.89	0.51	M	Moderate

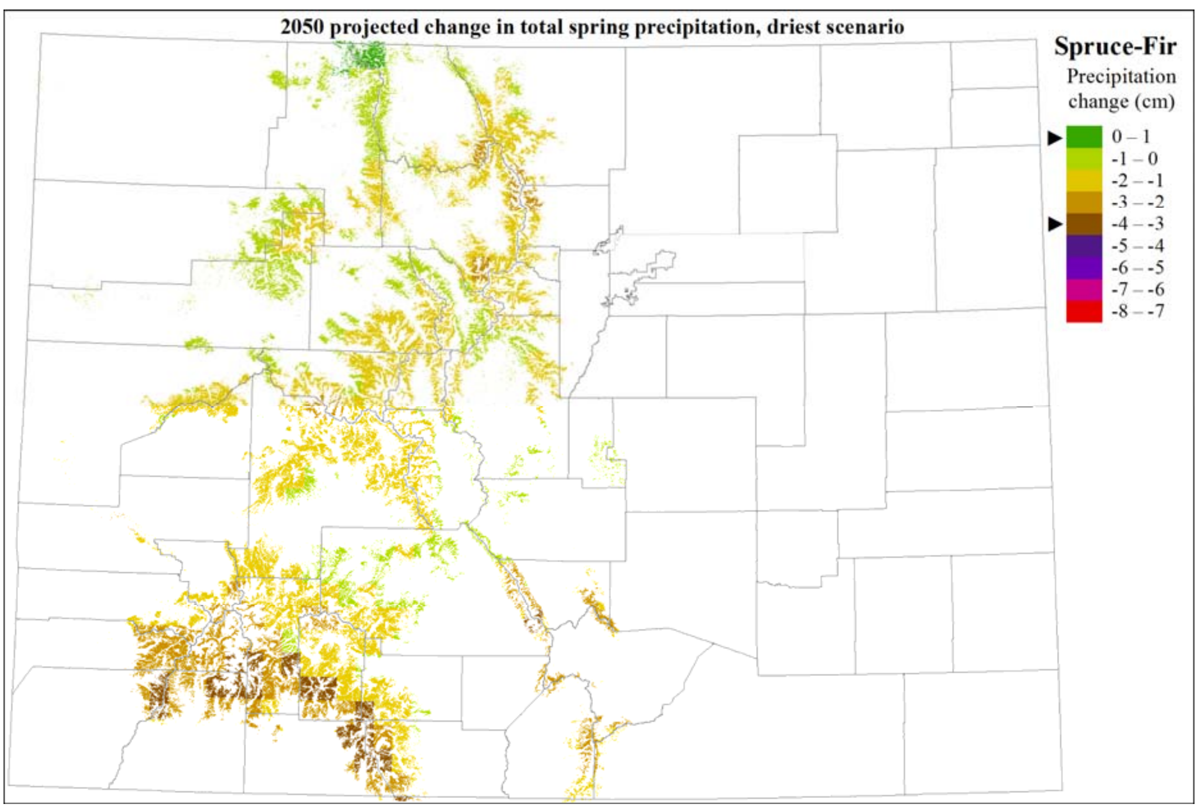
Vulnerability to Climate Change

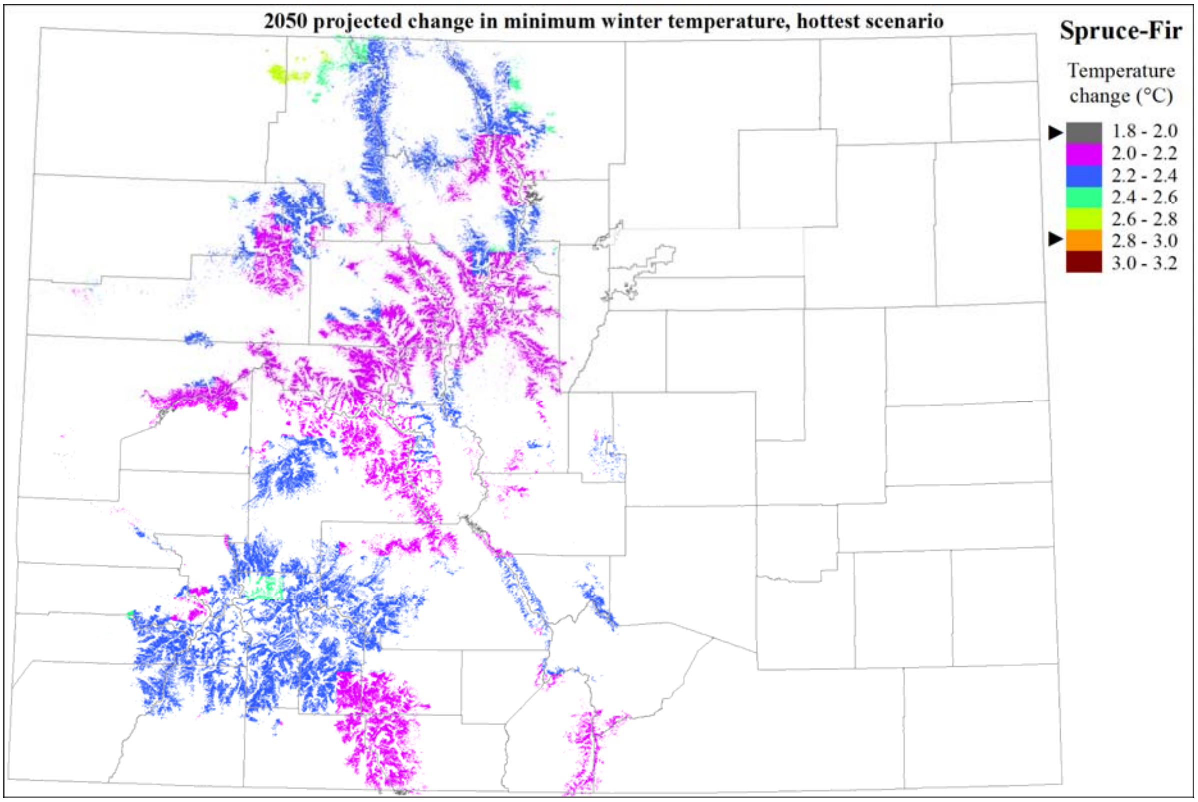
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Spruce-Fir forest	Moderate	Moderate	M/M	Moderate

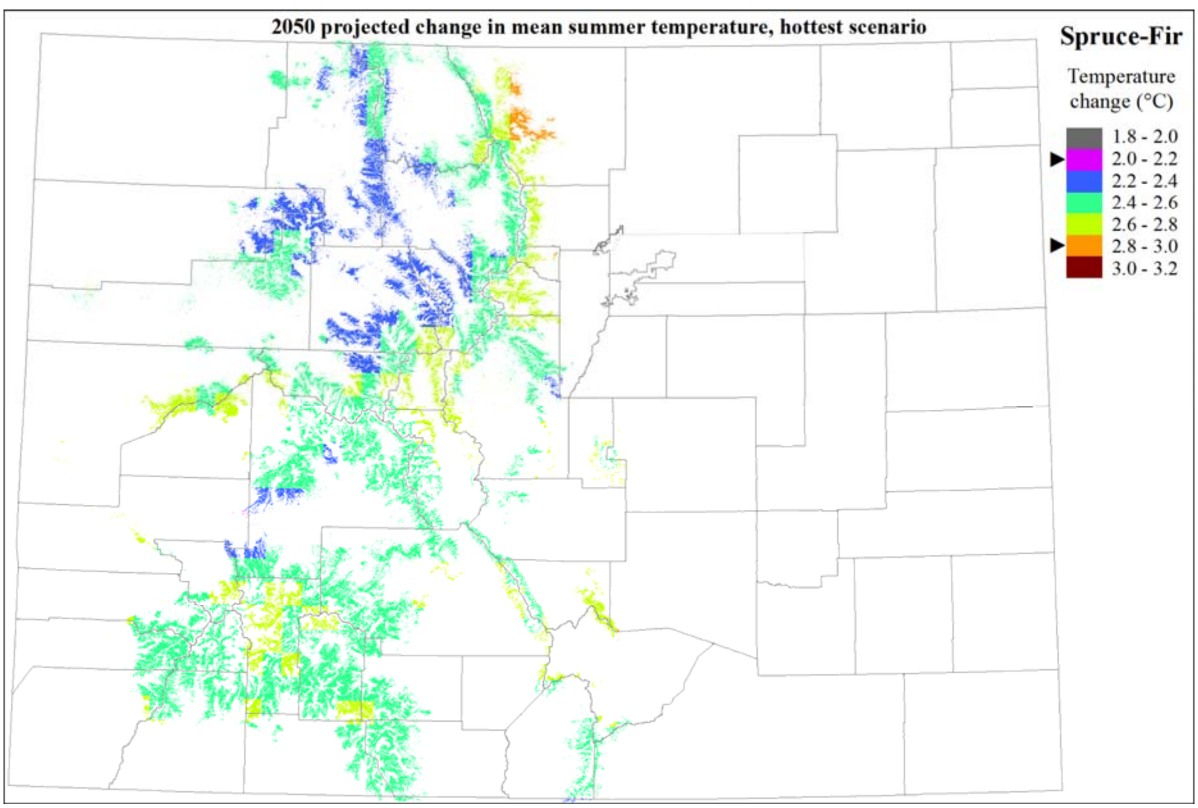
Spruce-fir forests are ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the restriction of these habitats to higher elevations in Colorado, and the relatively narrow biophysical envelope. The majority of the North American distribution of Engelmann spruce and subalpine fir is to the north of Colorado. The slow growth and dispersal of these forests also contributes to their vulnerability.

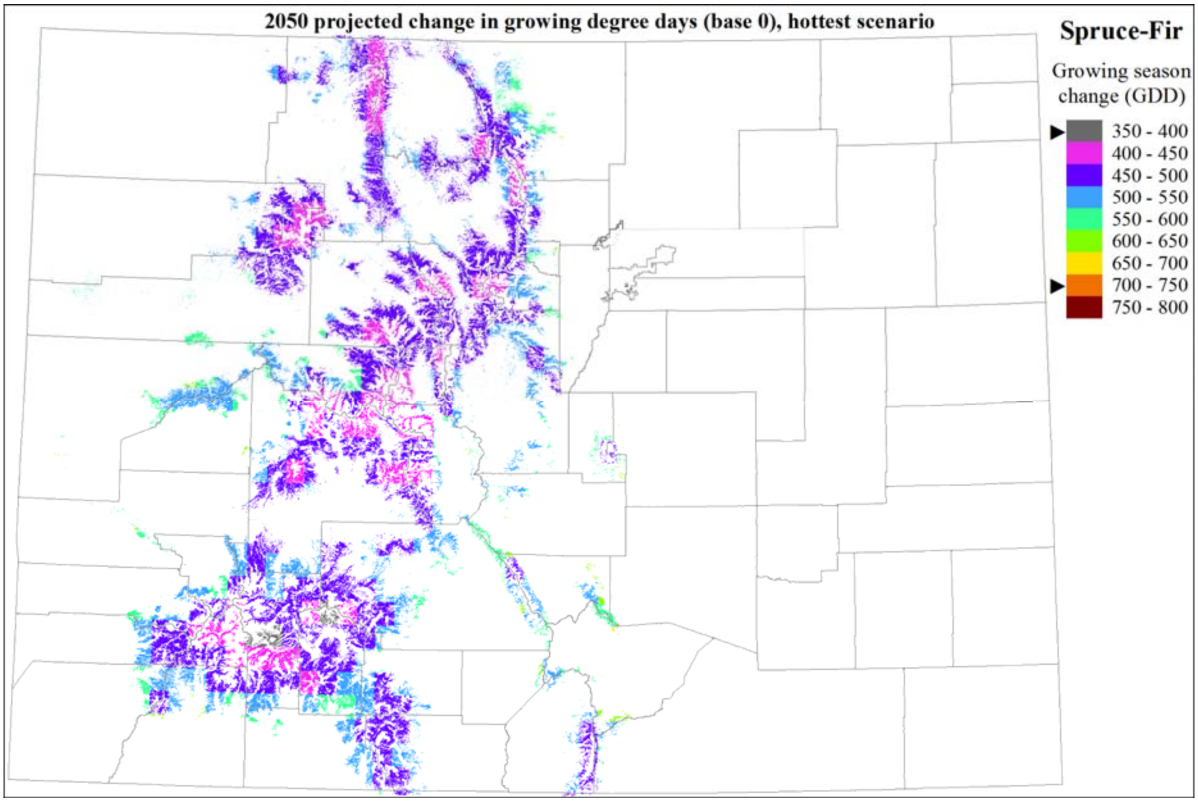
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for spruce-fir habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Areas on the southern flank of the San Juan Mountains are projected to experience the greatest reductions in winter and spring precipitation under a dry scenario, while northern portions of the range are little changed. Winter minimum temperatures are projected to warm by at least 2°C throughout the range, and summer mean temperatures may increase even more, especially in northern Colorado. Overall, the growing season for spruce-fir forests in the state is expected to increase, which could eventually facilitate the migration of this habitat to higher elevations.


2050 projected change in total winter precipitation, driest scenario
Spruce-Fir
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total spring precipitation, driest scenario
Spruce-Fir
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in minimum winter temperature, hottest scenario
Spruce-Fir
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2


2050 projected change in mean summer temperature, hottest scenario
Spruce-Fir
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2



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OAK-MIXED MOUNTAIN SHRUB

Climate Influences

In general, the upper and lower elevational limits of Gambel oak (*Quercus gambelii*) shrubland are believed to be controlled by temperature and moisture stress. Neilson and Wullstein (1983) found that seedling mortality was primarily due to spring freezing, grazing, or summer drought stress. At more northern latitudes, the zone of tolerable cold stress is found at lower elevations, but, at the same time, the areas where summer moisture stress is tolerable are at higher elevations. Neilson and Wullstein (1983) hypothesize that the northern distributional limit of Gambel oak corresponds to the point where these two opposing factors converge. Oak shrublands are typically found in areas with mean annual temperatures between 7 and 10°C (12.6-18.0°F ; Harper et al. 1985). At higher, cooler elevations, acorn production may be limited by the shortness of the growing season, and most reproduction is likely to be vegetative (Christensen 1949). Warming temperatures may increase both acorn production and seedling survival.

Oaks are most likely to do well under warmer temperatures, although droughts and late frosts may affect the frequency of establishment through seedling recruitment by reducing the acorn crop in some years.

Exposure and Sensitivity Summary

Oak and mixed mountain shrublands are projected to experience temperatures warmer than the current range in more than one third of the current distribution, as well as a shift to earlier date of last spring frost in some areas. Projected spring and summer precipitation levels are projected to be lower than the driest end of the current range for a small part of the current distribution.

Oak

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Spring precipitation (M, E)	8%
Summer precipitation (M, E, L)	13%
Drought days (M, L)	6%
Date of last frost in spring (M, E, L)	-8%
Mean annual temperature (L)	38%
Average range shift	13.4%
Rank	L
Exposure-Sensitivity level	Low

Resilience Components

Oak and mixed mountain shrublands are widespread in the western half of Colorado, and along the southern stretch of the mountain front at elevations from about 6,000- 9,000 feet. The elevation range of this habitat is similar to that of ponderosa pine, and these habitats are often adjacent. Stands dominated by Gambel oak are common in the southern part of Colorado, but are completely interspersed with stands dominated by other shrub species, especially serviceberry (*Amelanchier* spp.) with mahogany (*Cercocarpus* spp.) at higher elevations. These habitats are not limited to higher elevations, and are not at the southern extent of their North American distribution in Colorado. Average annual precipitation for oak shrubland is about 12-32 in (30-80 cm), with a mean of 21.5 in (52 cm). Precipitation amounts for mixed mountain shrubland are probably slightly higher. Growing season is similar to that of ponderosa and higher elevation sagebrush.

Gambel oak reproduces primarily by sprouting of new stems, especially after disturbances such as logging, fire, and grazing, although recruitment from seedlings does occur (Brown 1958, Harper et al. 1985). The extensive clonal root system of Gambel oak is a primary contributor to its ability to survive during periods when seedling establishment is impossible. Historic natural fire return intervals were on the order of 100 years in Mesa Verde (Floyd et al. 2000); under such conditions of low fire frequency, vulnerable newly sprouted stems are able to persist and form dense thickets.

Non-oak dominated montane shrublands are of variable species composition, depending on site conditions such as elevation, slope, aspect, soil type, moisture availability, and past history. Species present may include mountain mahogany (*Cercocarpus montanus*), skunkbush sumac (*Rhus trilobata*), cliff fendlerbush (*Fendlera rupicola*), antelope bitterbrush (*Purshia tridentata*), wild crab apple (*Peraphyllum ramosissimum*), snowberry (*Symphoricarpos* spp.), and serviceberry (*Amelanchier* spp.). Most of these species reproduce both vegetatively and by seedling recruitment, as well as resprouting easily after fire. Variable disturbance patterns may account for the local dominance of a particular species (Keeley 2000). Although fire is an obvious source of disturbance in these shrublands, snowpack movements (creep, glide, and slippage) may also provide significant disturbance in slide-prone areas (Jamieson et al. 1996).

In some areas, oak stands are vulnerable to increased prevalence of invasive species such as cheatgrass and knapweeds. Currently there are few invasives in the stands dominated by serviceberry and mahogany. These shrublands are highly fire tolerant. It is possible for this system to move up in elevation, especially if fires open up some of the adjacent forested ecosystems.

Adaptive Capacity Summary

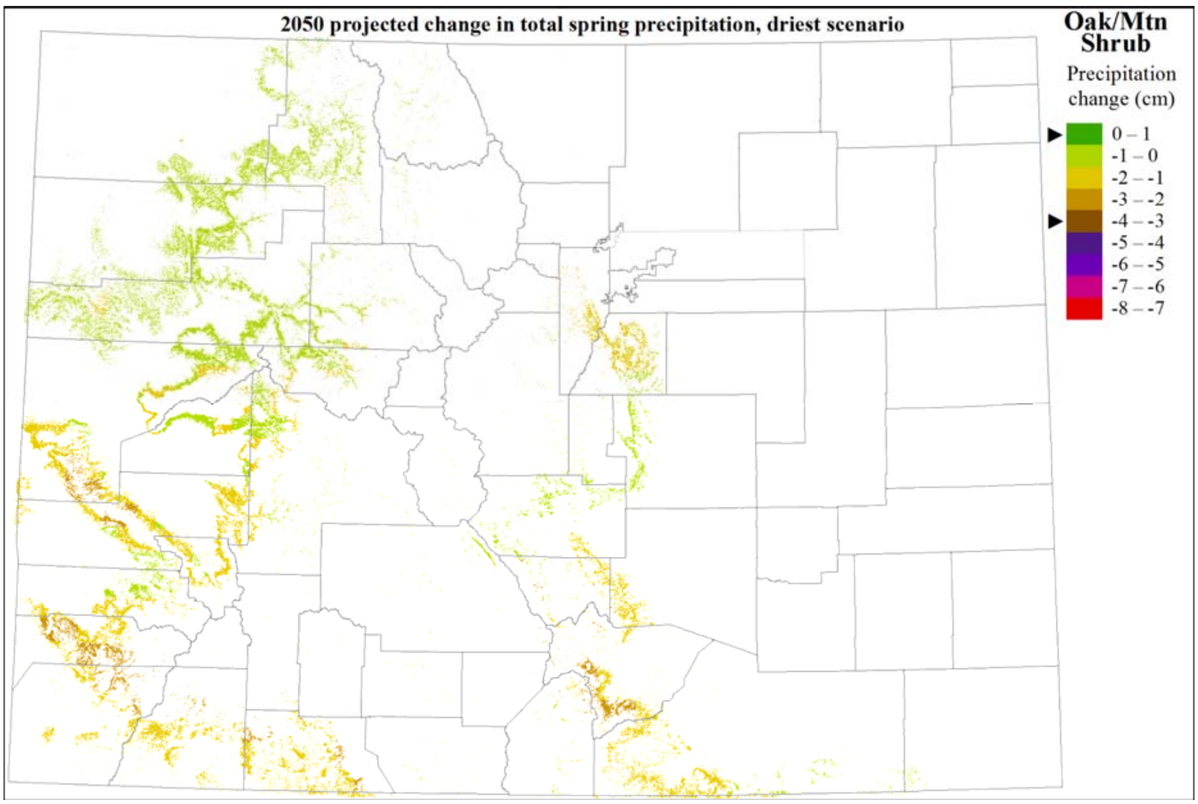
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Oak	0.89	1	1	1	0.49	0.85	H	High

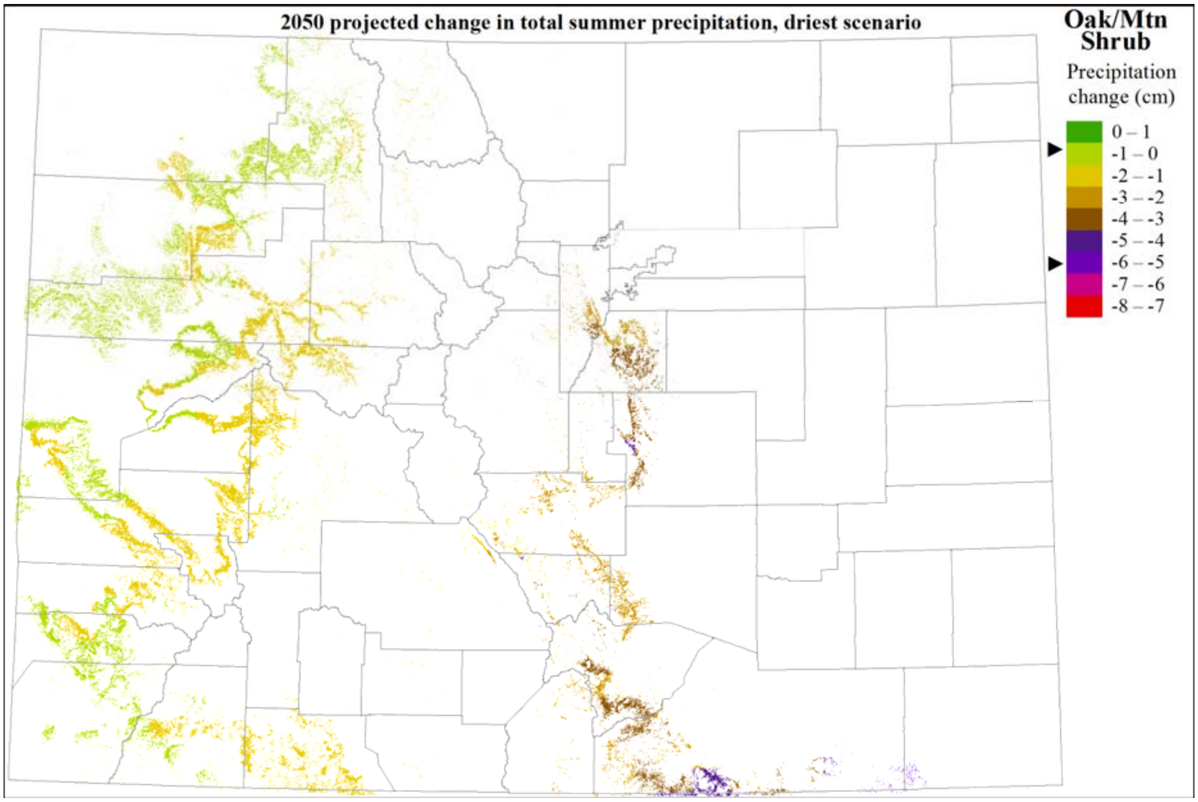
Vulnerability to Climate Change

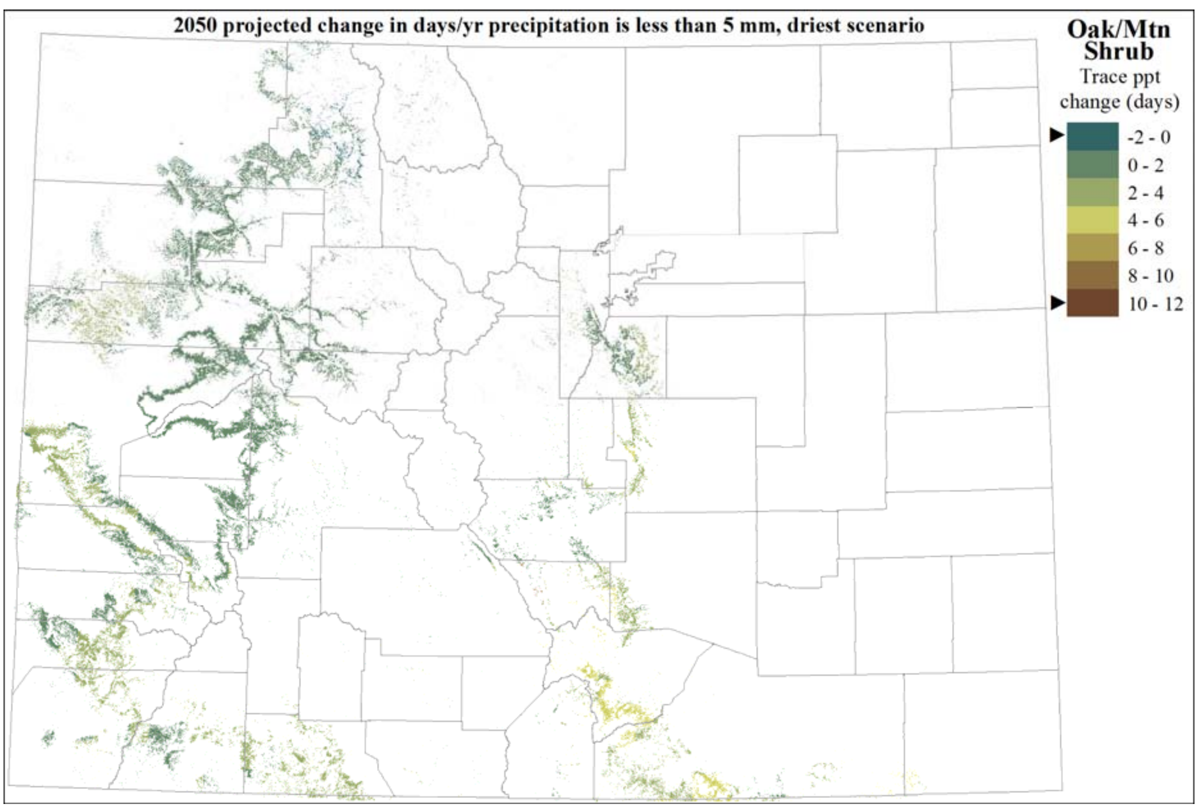
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Oak & mixed mountain shrub	Low	High	L/H	Low

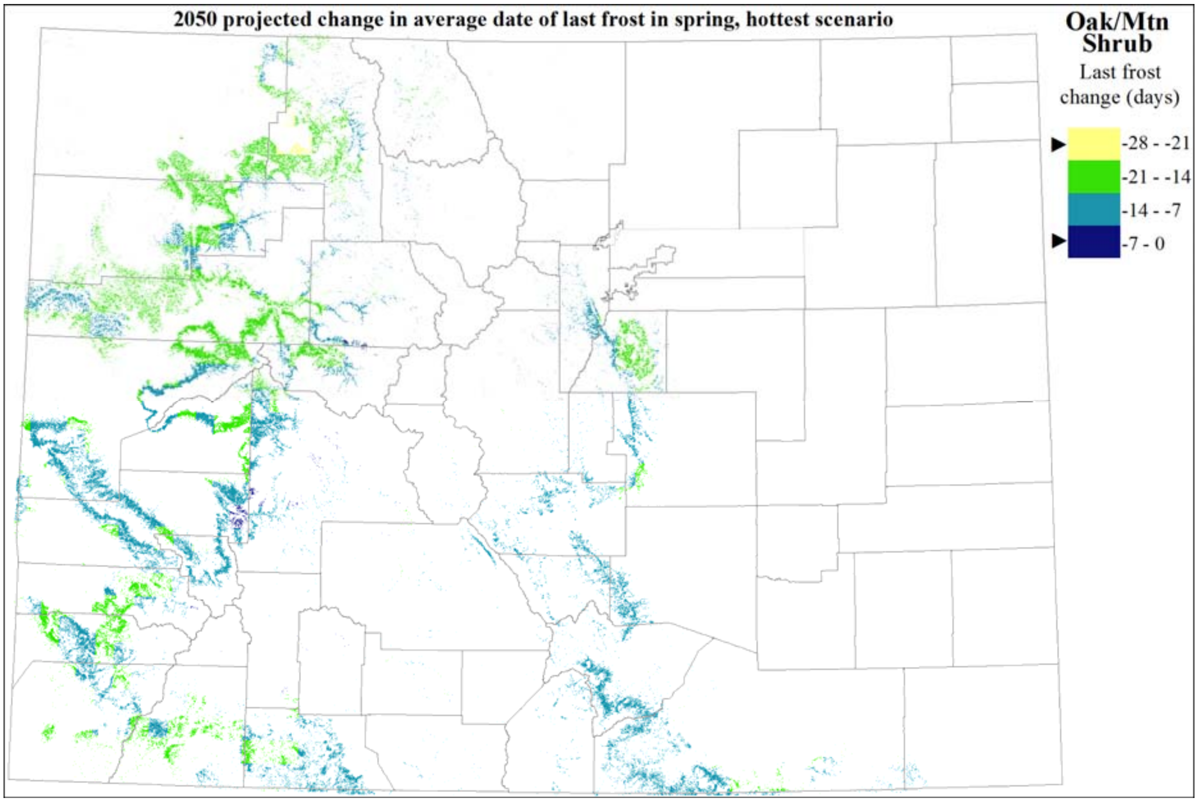
Oak and mixed mountain shrublands are ranked as having low vulnerability to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the wide ecological amplitude of these shrublands in Colorado, and their ability to withstand or recover from disturbance relatively quickly, which offsets the lower landscape condition score due to past anthropogenic disturbance levels.

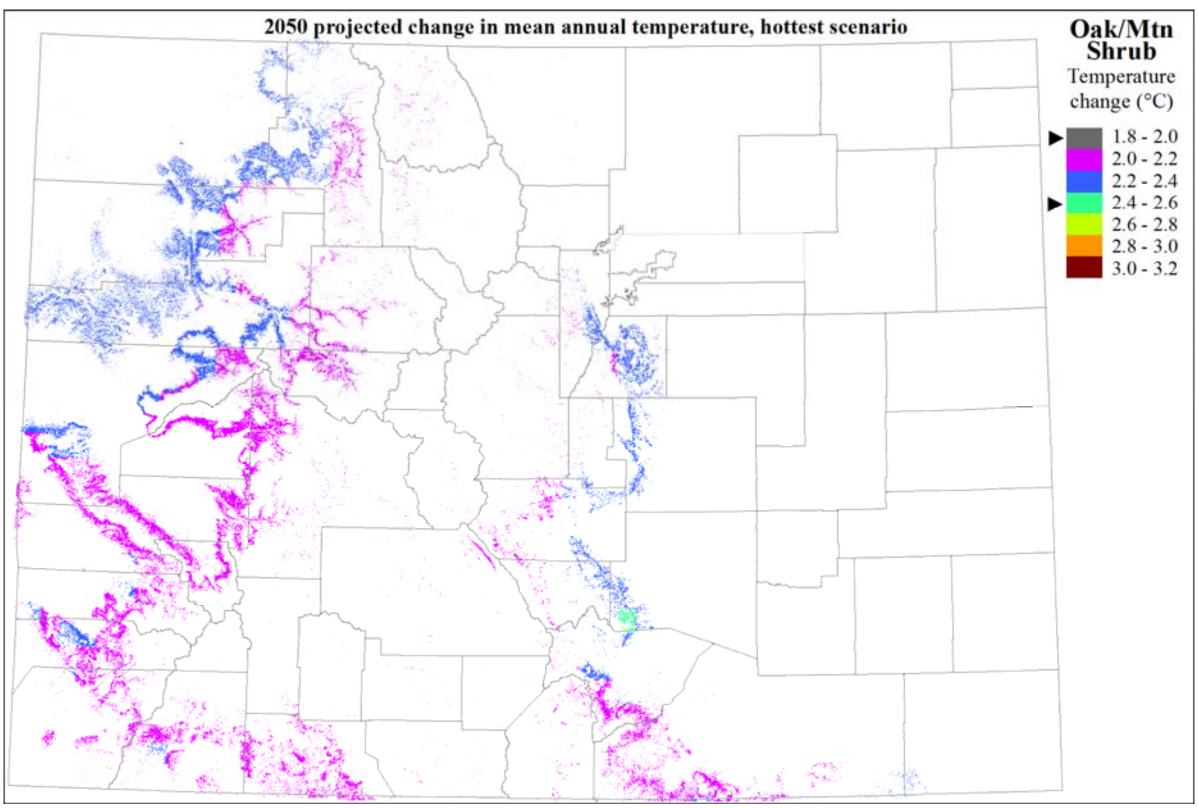
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for oak and mixed mountain shrub habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Precipitation during the growing season is projected to decrease most in the southern and eastern portions of the distribution of this habitat within Colorado, although it is likely to remain well within the tolerance of these shrublands. The projected shift to 1-2 weeks earlier last frosts in spring would be beneficial for this habitat, and although annual mean temperatures are projected to increase by at least 2°C in the hottest scenario, this is also likely to remain within the tolerance of most occurrences.




2050 projected change in total summer precipitation, driest scenario
Oak/Mtn Shrub
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in days/yr precipitation is less than 5 mm, driest scenario
Oak/Mtn Shrub
Trace ppt change (days)
-2 - 0
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12


2050 projected change in average date of last frost in spring, hottest scenario
Oak/Mtn Shrub
Last frost change (days)
-28 - -21
-21 - -14
-14 - -7
-7 - 0


2050 projected change in mean annual temperature, hottest scenario
Oak/Mtn Shrub
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2

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SAGEBRUSH

Climate Influences

As evaluated herein, the three subspecies of big sagebrush (basin big sagebrush, *Artemisia tridentata* ssp. *tridentata,* mountain big sagebrush, *A. tridentata* ssp. *vaseyana,* and Wyoming big sagebrush, *A. tridentata* ssp. *wyomingensis*) are combined as sagebrush habitat. In general, Wyoming big sagebrush is found in drier, warmer areas where precipitation is more likely to be in the form of rain, while mountain big sagebrush is found at higher, cooler elevations where snow is the dominant form of precipitation (Howard 1999, Johnson 2000). Changes in temperature and precipitation patterns may result in shifts in the relative abundance and distribution of the three subspecies.

Bradley (2010) points out that sagebrush shrublands in the western U.S. are currently found across a wide latitudinal gradient (from about 35 to 48 degrees north latitude), which suggests adaptation to a correspondingly wide range of temperature conditions. However, because these shrublands are apparently able to dominate a zone of precipitation between drier saltbush 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). Seasonal timing of precipitation is important for sagebrush habitats; summer moisture stress may be limiting if winter precipitation is low (Germino and Reinhardt 2014). Seedlings of mountain big sagebrush were more sensitive to freezing under reduced soil moisture conditions (Lambrecht et al. 2007).

Under experimental warming conditions in a high-elevation population, mountain big sagebrush had increased growth, suggesting that longer growing season length could facilitate the expansion of sagebrush habitat into areas that were formerly too cold for the shrub (Perfors et al. 2003). However, Poore et al. (2009) found that high summer temperatures resulted in lower growth rate, due to increased water stress. Winter snowpack was critical for sagebrush growth; lower elevations are probably at more risk from temperature impacts in comparison to upper elevations due to less snow and, consequently greater water stress.

Schlaepfer et al. (2012) modeled future distribution of the big sagebrush ecosystem in the western U.S. Over the entire study area, sagebrush distribution was predicted to decrease, especially under higher CO_2 emissions scenarios. The strongest decreases are in the southern part of the range, while the distribution is predicted to increase at higher elevations and in more northern areas.

Exposure and Sensitivity Summary

Sagebrush shrublands are projected to experience an increase in number of very hot days in comparison with the current range in more than one quarter of the current distribution, and fall frost dates are likely to be later for some areas as well. Projected winter precipitation levels are generally within the current range, but spring and summer precipitation for 6-12% of the current distribution are projected to be lower than the driest end of the current range.

Sagebrush

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Winter precipitation (L)	0%
Spring precipitation (E, L)	6%
Summer precipitation (M, E, L)	12%
Date of first frost in fall (E)	13%
Very hot days (M)	27%
Average range shift	11.7%
Rank	L
Exposure-Sensitivity level	Low

Resilience Components

These shrublands are primarily found in the western part of the state, at elevations from about 5,000 to 9,500 ft. The North American distribution of sagebrush habitat is largely to the west and north of Colorado. The three subspecies of big sagebrush show an elevational separation, with mountain big sagebrush in wetter, cooler conditions of higher elevations, and Wyoming big sagebrush in the warmest and driest conditions at lower elevations (Howard 1999). Due to the adaptations of the various subspecies, the range of annual average precipitation for sagebrush habitats is fairly wide, from about 8-40 in (20-100 cm), with a mean of 18 in (45 cm). Growing season heat accumulation is also highly variable across the range of the habitat, for the same reason.

Because these are generally shrublands of lower elevations, they are not expected to be limited by a requirement for cooler, high elevation habitat. Although sagebrush is generally a poor seeder, with small dispersal distances, there are no apparent barriers to dispersal for these shrublands. These stands may also be somewhat vulnerable to changes in phenology.

Other stressors for sagebrush shrublands are invasion by cheatgrass and expansion of pinyon-juniper woodlands. 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. There is no information on the vulnerability of this ecosystem to insect or disease outbreak.

Although sagebrush tolerates dry conditions and fairly cool temperatures it is not fire adapted, and none of the subspecies resprout after fire (Tirmenstein 1999). Sagebrush shrubland is likely to be severely impacted by intense fires that enhance wind erosion and eliminate the seed bank (Young and Evans 1989). Increased drought may increase fire frequency and severity, eliminating sagebrush in some areas, especially at drier sites of lower elevations. Increased fire frequency and severity in these shrublands may result in their conversion to grasslands dominated by exotic species.

Adaptive Capacity Summary

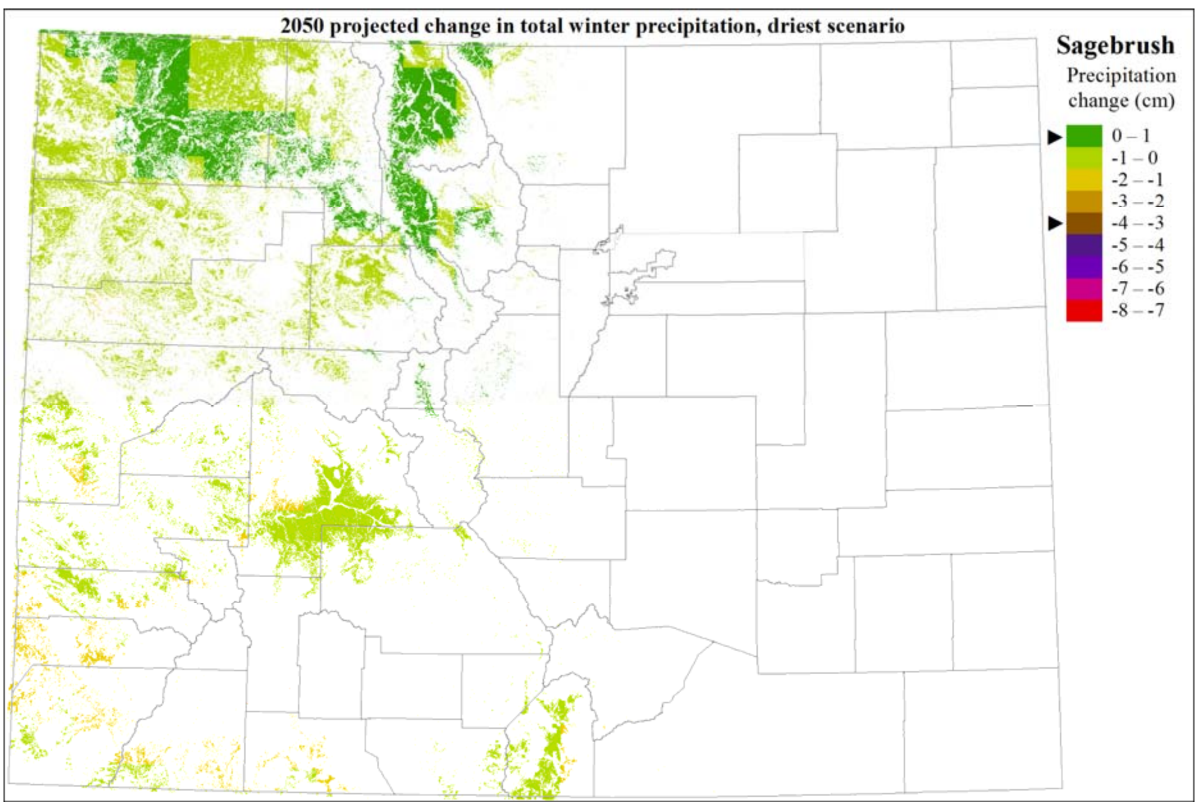
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Sagebrush	0.93	0.5	0.67	0.33	0.53	0.57	M	Moderate

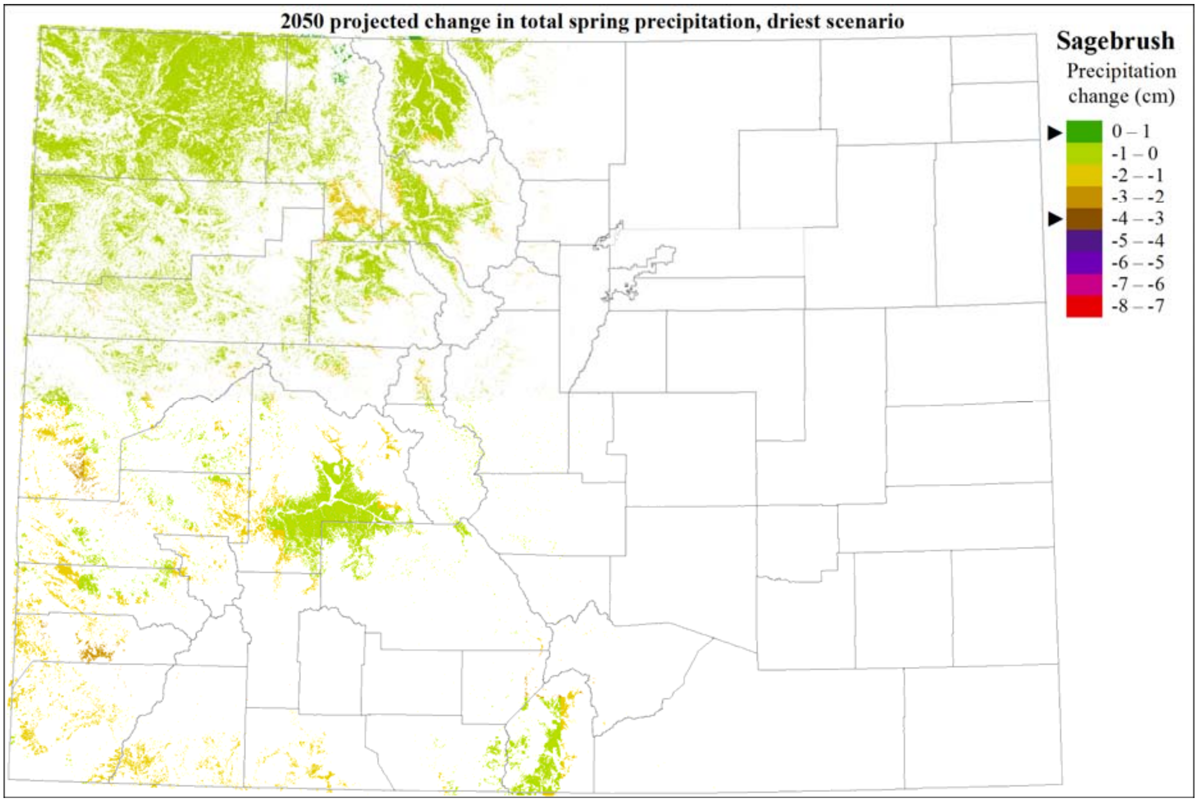
Vulnerability to Climate Change

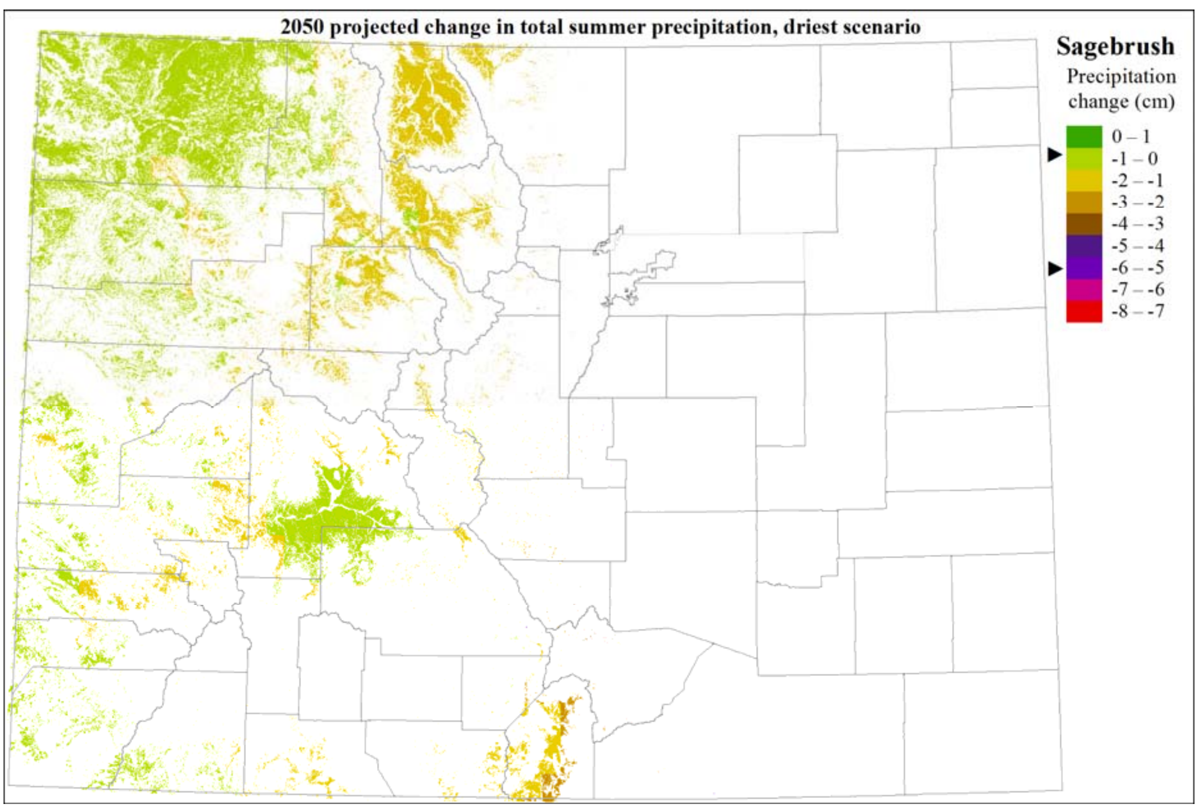
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Sagebrush shrubland	Low	Moderate	L/M	Low

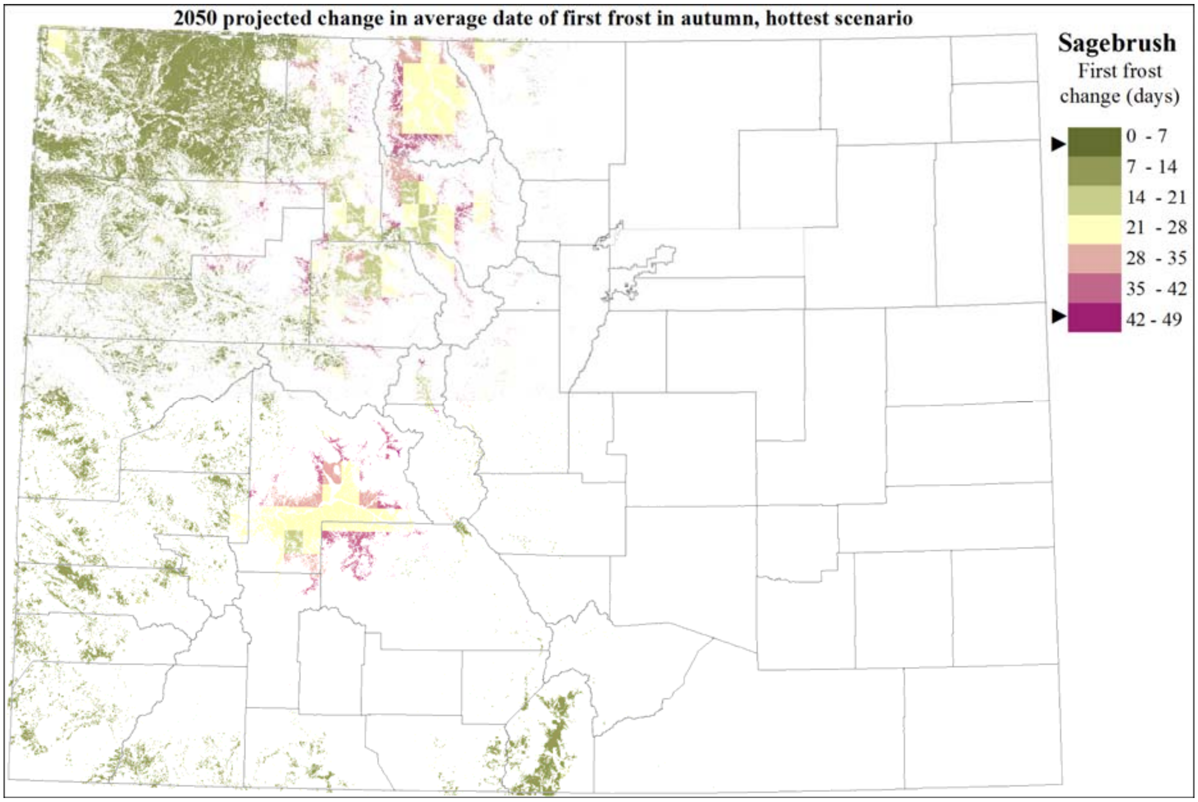
Sagebrush shrublands are ranked as having low vulnerability to the effects of climate change by mid-century under a moderate emissions scenario. The primary factor contributing to this ranking is the projected low exposure to warmer and drier future conditions in the part of Colorado where the greater portion of this habitat is found. The combination of the three big sagebrush subspecies in our analysis collectively gives this habitat type a wide ecological amplitude. Under a more severe emissions scenario, these shrublands would have higher vulnerability, similar to the assessment of Pocewicz et al. (2014) for sagebrush habitats in Wyoming.

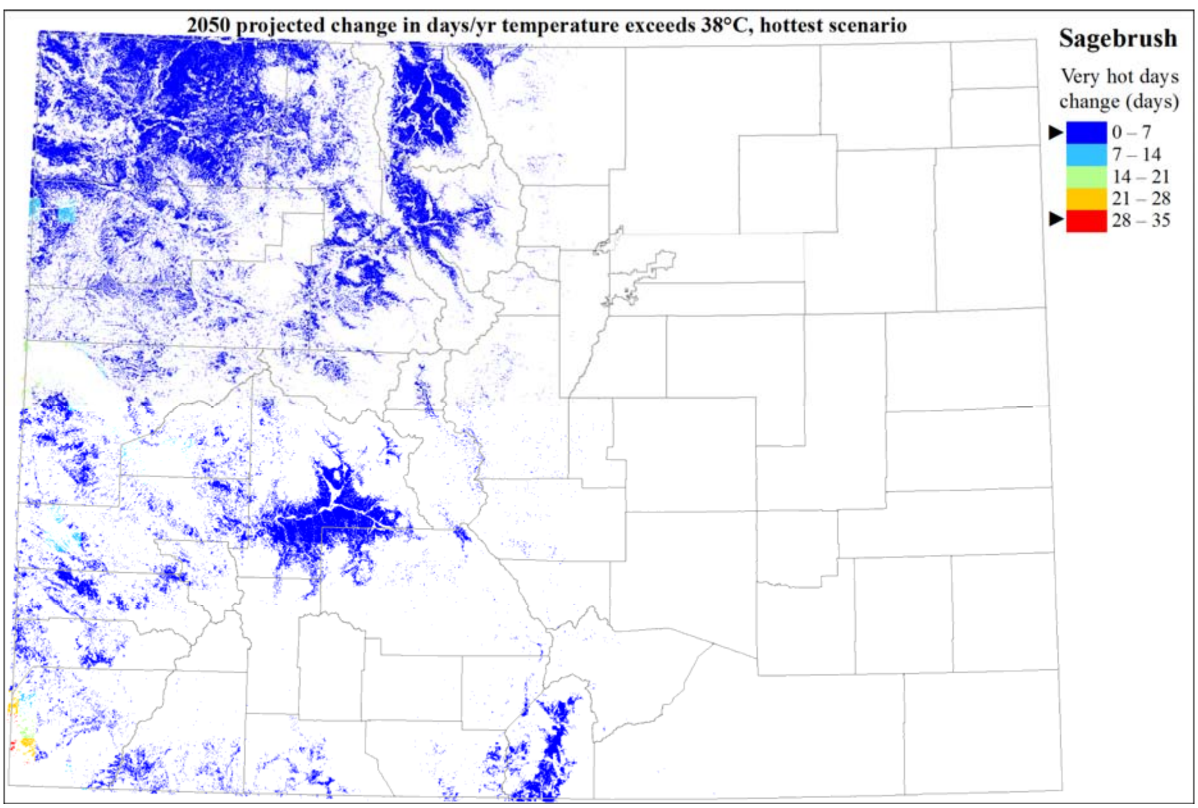
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for sagebrush habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Winter and spring precipitation levels are projected to decrease the most in the southwestern part of the Colorado distribution of sagebrush, while the majority of these shrublands in northwestern Colorado may see little change. Summer precipitation shows the greatest projected decrease in the eastern parts of the habitat distribution, especially in the high intermountain valleys. In portions of the distribution from the Gunnison valley up to North Park, average dates of first fall frost could be shifted 1-4 weeks later than current means. With the exception of the extreme southwest corner of Colorado, sagebrush shrublands in the state may experience only a slight increase in the number of very hot days. These trends tend to indicate that lower elevation sagebrush stands in the southern part of Colorado are most vulnerable.




2050 projected change in total spring precipitation, driest scenario
Sagebrush
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total summer precipitation, driest scenario
Sagebrush
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in average date of first frost in autumn, hottest scenario
Sagebrush
First frost change (days)
0 - 7
7 - 14
14 - 21
21 - 28
28 - 35
35 - 42
42 - 49


2050 projected change in days/yr temperature exceeds 38°C, hottest scenario
Sagebrush
Very hot days change (days)
0 – 7
7 – 14
14 – 21
21 – 28
28 – 35

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SANDSAGE

Climate Influences

This habitat has often been treated as an edaphic variant of eastern plains mixed-grass prairie (Albertson & Weaver 1944, Daley 1972,), or of shortgrass prairie (Ramaley 1939, Sims and Risser 2000). Sand sage (*Artemisia filifolia*) forms extensive open shrublands in sandy soils of Colorado's eastern plains, and is of particular importance for both greater and lesser prairie chicken habitat, as well as for other grassland birds. In eastern Colorado, this system is found in extensive tracts on Quaternary eolian deposits along the South Platte, Arikaree and Republican Rivers, between Big Sandy and Rush Creeks, and along the Arkansas and Cimarron Rivers, where it is contiguous with areas in Kansas and Oklahoma (Comer et al. 2003). During the past 10,000 years, these areas are likely to have fluctuated between active dune fields and stabilized, vegetated dunes, depending on climate and disturbance patterns (Forman et al. 2001). Extended periods of severe drought or other disturbance that results in loss of stabilizing vegetation can quickly lead to soil movement and blowouts that inhibit vegetation re-establishment, and may eventually lead to dramatically different species composition.

Little is known about the tolerance of sand sage for soils other than well-drained sand with a low silt and clay component. Such soils are often "droughty", with reduced water-holding ability, and consequently, the potential for increased water stress to resident plants (Soil Survey Division Staff 1993). Rasmussen and Brotherson (1984) speculated that sand sage is adapted to less fertile soils than species of adjacent grassland communities. Ramaley (1939) indicated that the persistence of sand sage was facilitated by fire and long overgrazing, in the absence of which a site would transition to sand prairie. However, there is no evidence to suggest that, under certain combinations of temperature, precipitation, grazing, and other disturbance, sand sage would be unable to expand onto other soil types.

Sand sage occurrences in southern Colorado have historically experienced a long growing season, low annual precipitation, and seasonal differences in precipitation patterns from north to south (Western Regional Climate Center 2004). North-south gradients in temperature and precipitation on Colorado's eastern plains appear to be reflected in the species composition of sand sage habitat, especially in midgrass species (Daley 1972), which may contribute to variable vulnerability between northern and southern stands.

This habitat is well adapted to sandy soils, and may be able to expand into adjacent areas under warmer, drier conditions, depending on disturbance interactions. Overall condition and composition of these shrublands may change with changing climate.

Exposure and Sensitivity Summary

Sandsage shrublands are projected to experience temperatures warmer than the current range in most of the current distribution, including an increase in number of very hot days. Projected winter and spring precipitation levels are projected to be lower than the driest end of the current range for 15-19% of the distribution, and drought days are projected to increase in additional areas.

Sandsage

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Winter precipitation (M, E)	19%
Spring precipitation (E)	15%
Drought days (M)	29%
Growing degree days - base 0 (L)	84%
Very hot days (L)	87%
Average range shift	46.7%
Rank	H
Exposure-Sensitivity level	High

Resilience Components

Sandsage habitat dominates sandy soils of Colorado's eastern plains, at elevations generally below 5,500 ft. In other states, sand sage is known to occur up to 6, 000 ft. (McWilliams 2003). Sandsage shares the dry and warm climate of shortgrass. Annual average precipitation is on the order of 10-18 inches (25-47 cm), with a mean of 16 in (40 cm). The growing season is generally long, with frequent high temperatures.

Sagebrush species in general have poor dispersal ability, with most seeds landing close to the parent plant (McWilliams 2003). Although sand sage does not reproduce vegetatively, it is able to resprout after fire. Fire extent and intensity are correlated with climate and grazing effects on fuel loads. Fire and grazing are both important disturbance processes for sand sage habitat, and may interact with drought, as well as permitting invasive exotic plant species to establish and spread. A significant portion of this habitat has been converted from midgrass to shortgrass sand sage community, in large part due to long-term continuous grazing by domestic livestock (LANDFIRE 2006).

Adaptive Capacity Summary

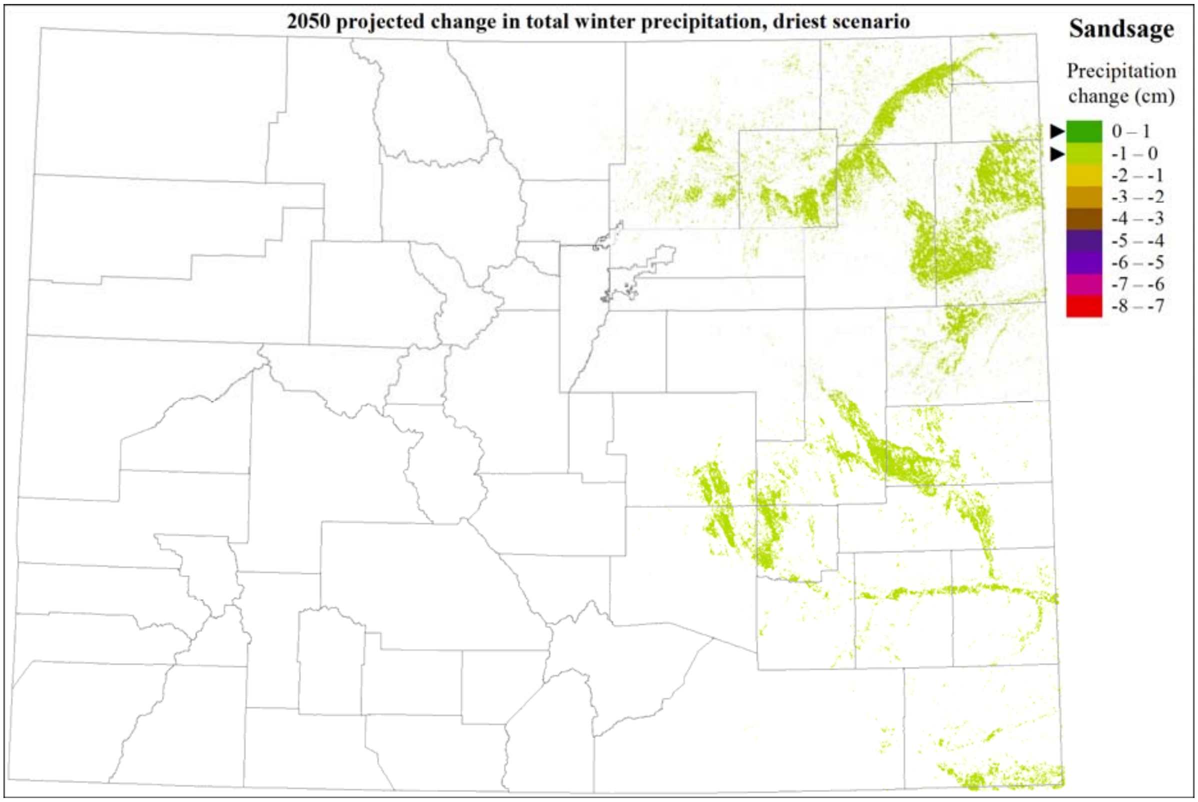
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Sandsage	0.65	1	0.67	1	0.43	0.74	H	High

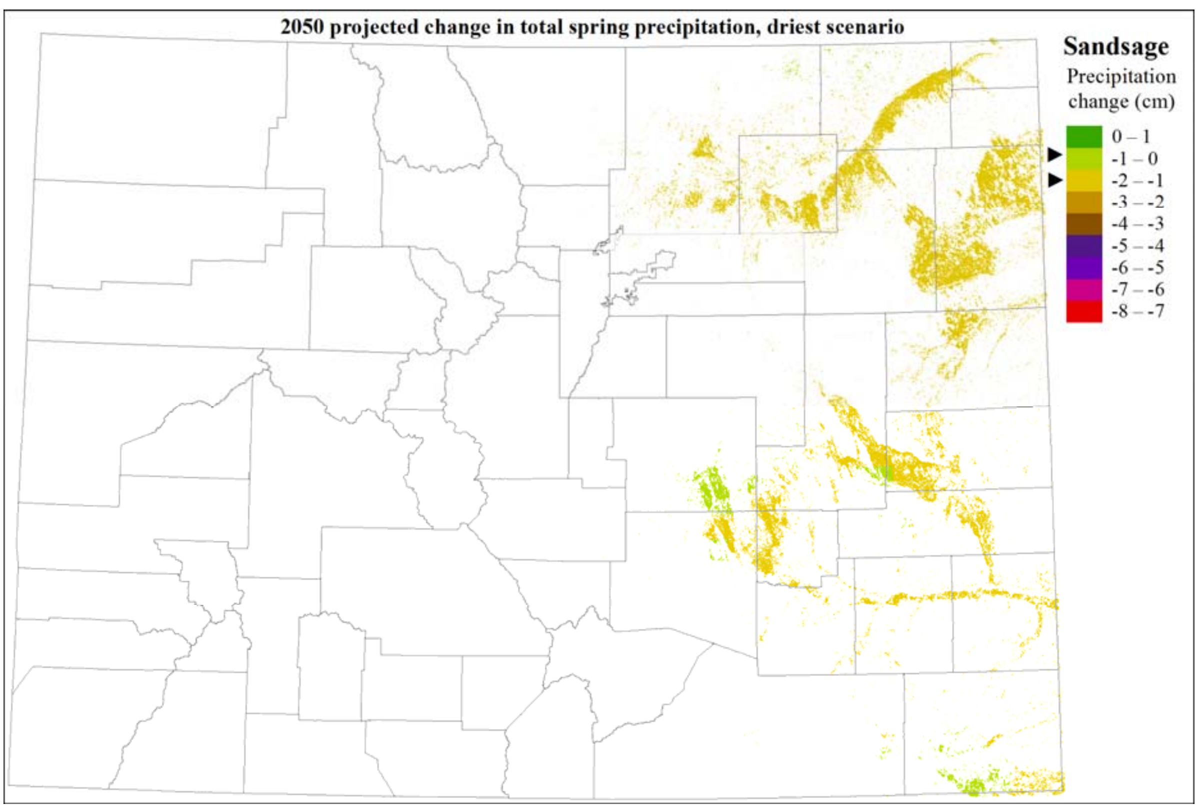
Vulnerability to Climate Change

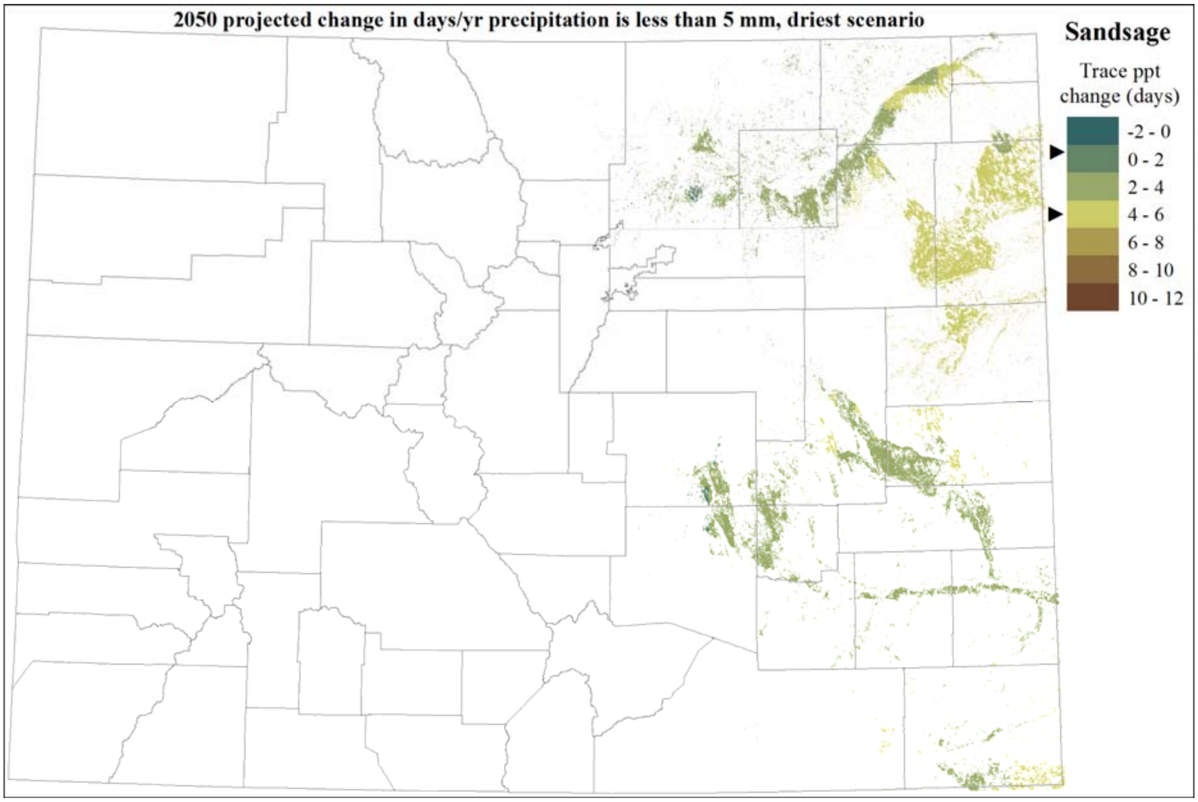
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Sandsage shrubland	High	High	H/H	Moderate

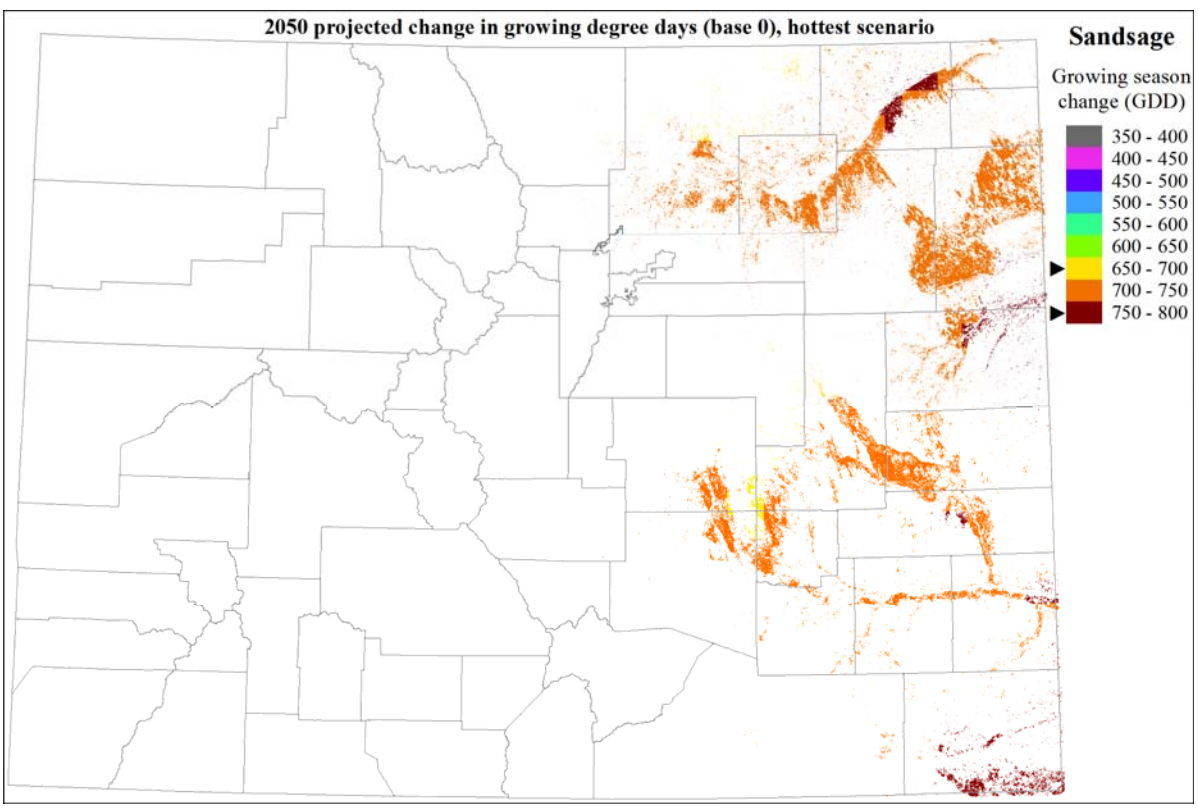
Sandsage shrublands are ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. This ranking is primarily due to the concentration of greatest exposure for all temperature variables on the eastern plains of Colorado, where these habitats are found. In addition, anthropogenic disturbance in these shrublands has reduced the overall landscape condition of the habitat.

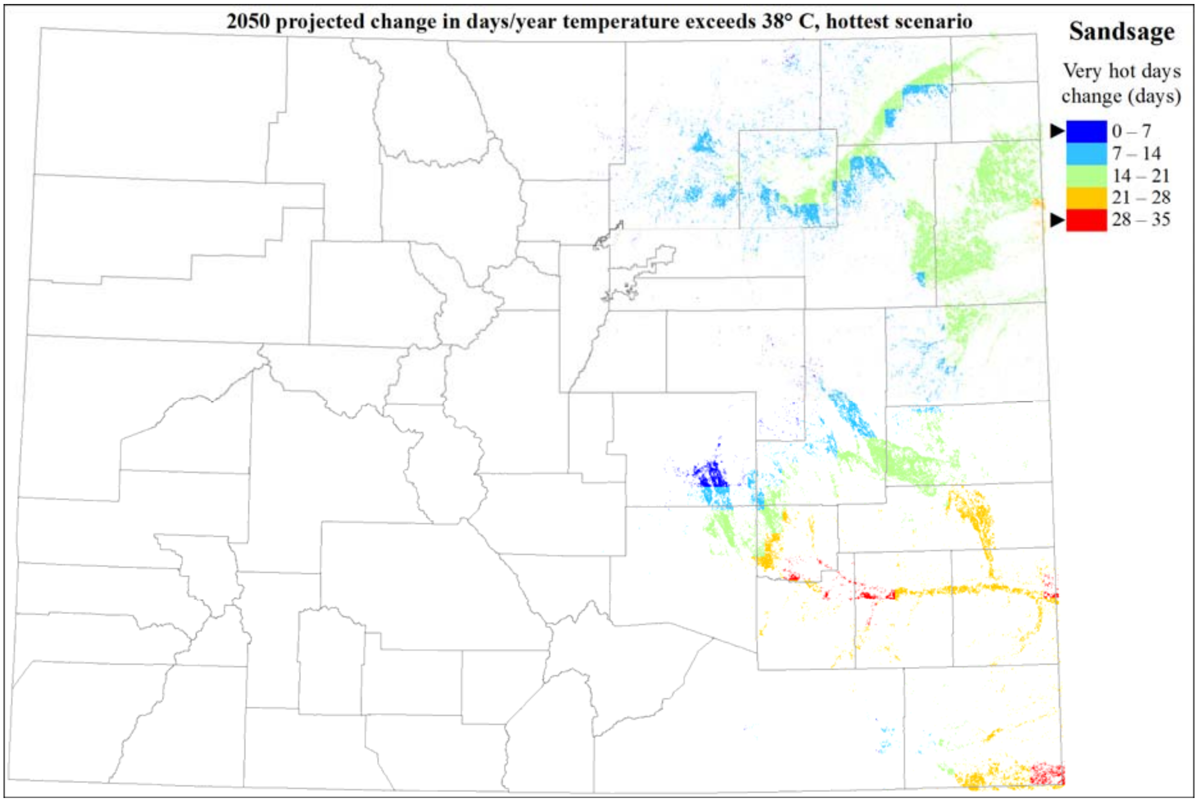
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for sandsage habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Under the driest future projections, decrease in winter precipitation is generally less than1 cm, within the range of these shrublands in Colorado, while the decrease in spring precipitation is greater, at 1-2 cm. Eastern sandsage stands may experience several fewer days of measurable precipitation per year. The greatest projected change for sandsage shrublands in Colorado is in very hot days and growing season length, both of which show a substantial increase, especially in the southeastern part of the state.


2050 projected change in total winter precipitation, driest scenario
Sandsage
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in total spring precipitation, driest scenario
Sandsage
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in days/yr precipitation is less than 5 mm, driest scenario
Sandsage
Trace ppt change (days)
-2 - 0
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12


2050 projected change in growing degree days (base 0), hottest scenario
Sandsage
Growing season change (GDD)
350 - 400
400 - 450
450 - 500
500 - 550
550 - 600
600 - 650
650 - 700
700 - 750
750 - 800



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FOOTHILL AND MOUNTAIN GRASSLAND

Climate Influences

Colorado's non-shortgrass prairie grasslands are highly variable, depending on elevation and latitude. Foothill or piedmont grasslands are found at the extreme western edge of the Great Plains at elevations between 5,250 and 7,200 feet, where increasing elevation and precipitation facilitate the development of mixed to tallgrass associations on certain soils. Montane-subalpine grasslands in the Colorado Rockies are found at elevations of 7,200-10,000 feet, intermixed with stands of spruce-fir, lodgepole, ponderosa, and aspen, or as the matrix community in the large intermountain basin of South Park. Semi-desert grasslands are found primarily on dry plains and mesas in western Colorado at elevations of 4,750-7,600 feet. Our vulnerability analysis divided grasslands into those above and below 7,500 feet, roughly dividing montane-subalpine occurrences from the eastern and western lower elevation grassland types.

Higher elevation grasslands are characterized by cold winters and relatively cool summers, although temperatures are more moderate at lower elevations. Soil texture is important in explaining the existence of montane-subalpine grasslands (Peet 2000). Montane grasslands often occupy the fine-textured alluvial or colluvial soils of valley bottoms, in contrast to the coarse, rocky material of adjacent forested slopes (Peet 2000). Other factors that may explain the absence of trees in this system are soil moisture (too much or too little), competition from established herbaceous species, cold air drainage and frost pockets, high snow accumulation, beaver activity, slow recovery from fire, and snow slides (Daubenmire 1943, Knight 1994, Peet 2000). Where grasslands occur intermixed with forested areas, the less pronounced environmental differences mean that trees are more likely to invade (Turner and Paulsen 1976).

West Slope low-elevation grasslands occur in semi-arid to arid climates with cold temperate conditions. Hot summers and cold winters with freezing temperatures and snow are common. Grasslands of the western valleys receive a significant portion of annual precipitation in July through October during the summer monsoon storms, with the rest falling as snow during the winter and early spring months. Foothill grasslands of the eastern mountain front have a continental climate with both east-west and north-south gradients. Along the western edge of the plains, the Rocky Mountains create a rain shadow to the east. Precipitation rapidly increases with increasing elevation. Severe drought is also a common phenomenon in the Western Great Plains (Borchert 1950, Stockton and Meko 1983, Covitch et al. 1997). Temperature variation in the foothill zone is less than on the plains, with lower summer temperatures and higher winter temperatures producing a climate is more moderate than that for grasslands to the east (Western Regional Climate Center 2004).

Drought and warmer temperatures may change species composition, or allow invasion by drought-tolerant trees/shrubs or invasive species in some areas. Drought can increase extent of bare ground and decrease forb coverage, especially in more xeric grasslands (Debinski et al 2010), which could result in a transformation to a semi-desert grassland type.

Exposure and Sensitivity Summary

Foothill and montane grasslands are projected to experience both summer and winter temperatures that are warmer than the current range in about half of the current distribution, more so in lower elevation grasslands. Although projected winter precipitation levels are generally within the current range, annual precipitation levels are projected to be lower than the driest end of the current range for nearly half of the lower elevation distribution, and drought days are projected to increase in additional areas.

	High elevation grasslands	Low elevation grasslands
Climate variable	**% projected range shift**	
Winter precipitation	0%	1%
Annual precipitation	7%	44%
Drought days	5%	22%
Mean winter temperature	44%	64%
Mean summer temperature	55%	65%
Average range shift	22.1%	39.1%
Rank	M	H
Exposure-Sensitivity level	Moderate	High

Resilience Components

These foothill and montane grasslands are not restricted to high elevations, and are not at the southern edge of their North American distribution in Colorado.

Climatic variation, fire exclusion, and grazing appear to interact with edaphic factors to facilitate or hinder tree invasion in these grasslands (Zier and Baker 2006). The work of Coop and Givnish (2007) in the Jemez Mountains of northern New Mexico suggests that both changing disturbance regimes and climatic factors are linked to tree establishment in some montane grasslands. Increased tree invasion into montane grasslands was apparently linked to higher summer nighttime temperatures, and less frost damage to tree seedlings; this trend could continue under projected future temperature increases. The interaction of multiple factors indicates that management for the maintenance of these montane and subalpine grasslands may be complex.

Floristic composition in grasslands is influenced by both environmental factors and grazing history. Many grassland occurrences are already highly altered from pre-settlement condition. Grazing is generally believed to lead to the replacement of palatable species with less palatable ones more able to withstand grazing pressure (Smith 1967, Paulsen 1975, Brown 1994, but see Stohlgren et al. 1999). Grazing by domestic livestock may act to override or mask whatever natural climatic or edaphic mechanism is responsible for maintaining an occurrence. This habitat is also adapted to grazing and browsing by native herbivores including deer, elk, bison, and pronghorn, as well as burrowing and grazing by small mammals such as gophers, prairie dogs, rabbits, and ground squirrels. Activities of these animals can influence both vegetation structure and soil disturbance, potentially suppressing tree establishment. Periodic drought is common in the range of foothill and semi-desert grasslands, but may not be as great a factor in the vegetation dynamics of this system as in grasslands of the plains.

Adaptive Capacity Summary

	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
High elevation grasslands	0.82	1	0.33	0.67	0.37	0.64	M	Moderate
Low elevation grasslands	0.71	1	0.33	0.67	0.37	0.62	M	Moderate

Vulnerability to Climate Change

Foothill & mountain grassland	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
High elevation	Moderate	Moderate	M/M	Moderate
Low elevation	High	Moderate	H/M	High

Foothill and mountain grasslands of elevations above 7,500 ft. are ranked as moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario, and those below 7,500 ft. have high vulnerability. Primary factors contributing to this ranking are vulnerability of these area to invasive species, and the generally highly disturbed condition of occurrences, both of which are likely to interact with the significant increases in temperature across much of the distribution of the habitat in Colorado to reduce resilience of these habitats.

NOTE: due to the generally small size of montane-foothill grassland occurrences, exposure maps were not produced for this habitat.

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SHORTGRASS PRAIRIE

Climate Influences

Soil moisture level is a key determinant of the distribution of shortgrass prairie habitat; change in precipitation seasonality, amount, or pattern will affect soil moisture. Grasslands generally occur in areas where there is at least one annual dry season and soil water availability is lower than that required for tree growth (Parton et al. 1981, Sims and Risser 2000). Soil water availability acts on both plant water status and nutrient cycling (Sala et al. 1992). This habitat receives most of its annual precipitation during the spring and summer growing season. Daily precipitation amounts are typically quite small (5mm or less), and do not contribute significantly to soil water recharge, which instead is primarily dependent on large but infrequent rainfall events (Parton et al. 1981, Heisler-White et al. 2008). Larger rainfall events permit deeper moisture penetration in the soil profile, and enable an increase in above-ground net primary production (Heisler-White et al. 2008). The dominant shortgrass species blue grama (*Bouteloua gracilis*) is able to respond quickly to very small rainfall events, although this ability is apparently reduced during extended drought periods (Sala and Lauenroth 1982, Sala et al. 1982, Cherwin and Knapp 2012). Nevertheless, blue grama exhibited extensive spread during the drought of the Dustbowl years (Albertson and Weaver 1944). If large rainfall events are more common, the sensitivity of shortgrass prairie is reduced (Cherwin and Knapp 2012).

Grasslands in areas where mean annual temperature is above 10°C are generally dominated by C_4 (warm-season) grass species, which are tolerant of warmer temperatures and more efficient in water use (Sims and Risser 2000). In Colorado, shortgrass prairie has a historic annual mean temperature slightly greater than 10°C, although the range includes slightly cooler annual mean temperatures as well. Although these grasslands are adapted to warm, dry conditions, Alward et al. (1999) found that warming night-time temperatures in spring were detrimental to the growth of blue grama, and instead favored cool-season (C_3) species, both native and exotic. Consequently, the effect of increasing temperatures on shortgrass prairie is difficult to predict.

Warmer and drier conditions would be likely to reduce soil water availability and otherwise have detrimental effects on ecosystem processes, while warmer and wetter conditions could be favorable. Furthermore, changing climate may lead to a shift in the relative abundance and dominance of shortgrass prairie species, giving rise to novel plant communities (Polley et al. 2013). Because woody plants are more responsive to elevated CO_2, and may have tap roots capable of reaching deep soil water (Morgan et al. 2007), an increase of shrubby species (e.g., cholla, yucca, snakeweed, sandsage), or invasive exotic species, especially in areas that are disturbed (for instance, by heavy grazing) may also result.

Exposure and Sensitivity Summary

Shortgrass prairie is projected to experience spring and summer temperatures that are warmer than the current range in the majority of the current distribution. Projected precipitation levels are projected to be lower than the driest end of the current range for nearly half of the lower elevation distribution. An increase in drought days, and fewer days with large precipitation events are projected for a substantial portion of the current distribution as well.

Shortgrass prairie

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Annual precipitation (L)	43%
Days with heavy precipitation (L)	30%
Drought days (M, E, L)	38%
Mean spring temperature (L)	58%
Mean summer temperature (L)	67%
Average range shift	41.2%
Rank	H
Exposure-Sensitivity level	High

Resilience Components

In spite of extensive conversion to agriculture or other uses, shortgrass prairie still forms extensive tracts on the eastern plains of Colorado, at elevations below 6,000 feet. Colorado accounts for a substantial portion of the North American distribution of these grasslands, which extend from Texas to Wyoming. Shortgrass prairie experiences a much drier and warmer climate than most other habitat types in Colorado. Annual average precipitation is on the order of 10-18 inches (25-47 cm), with a mean of 15 in (38 cm), and the growing season is generally long, with frequent high temperatures.

The short grasses that characterize this habitat are extremely drought- and grazing-tolerant. These species evolved with drought and large herbivores and, because of their stature, are relatively resistant to overgrazing. Fire is less important than herbivory in shortgrass habitat; the typically warm and dry climate conditions act to decrease the fuel load and thus the relative fire frequency within the habitat. Historically, fires that did occur were often extensive; fire suppression and grazing have greatly changed this tendency. More frequent occurrence of climate extremes (e.g. very wet conditions followed by very dry conditions) could increase the frequency and extent of grassland wildfires (Polley et al. 2013).

Adaptive Capacity Summary

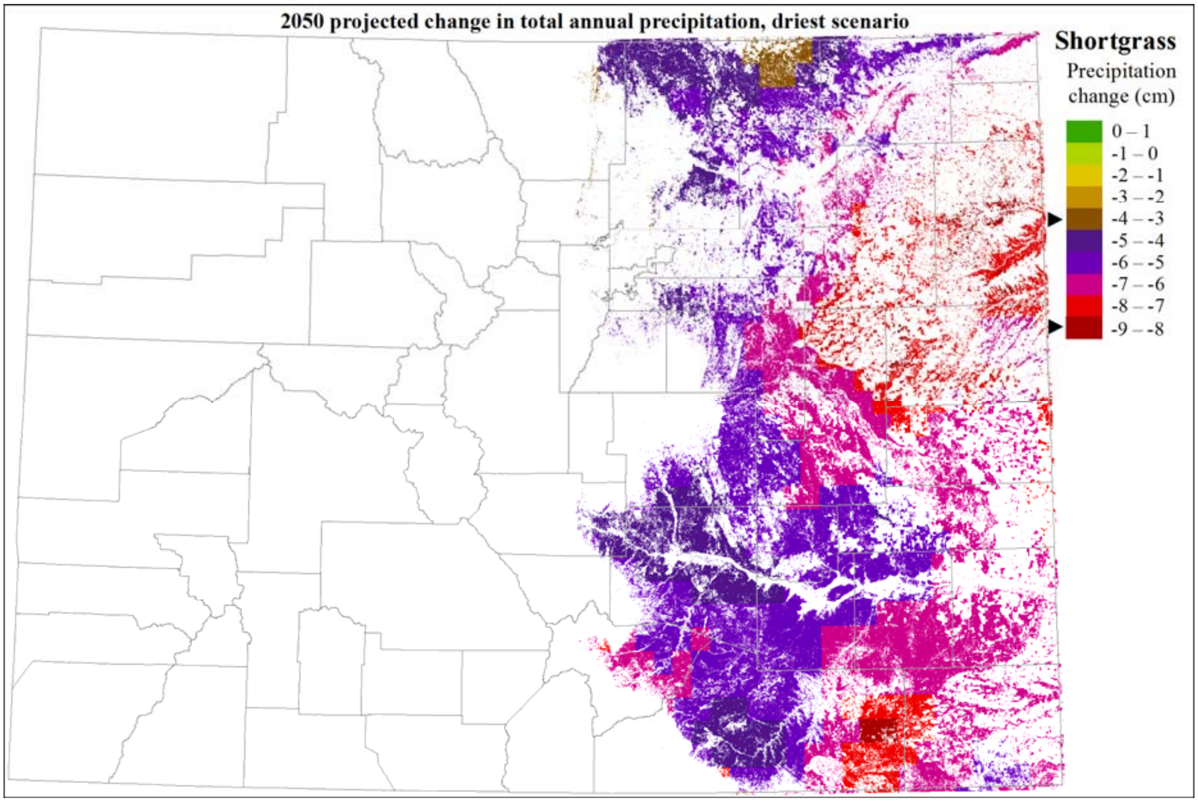
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Shortgrass	0.69	1	0.33	0.67	0.44	0.62	M	Moderate

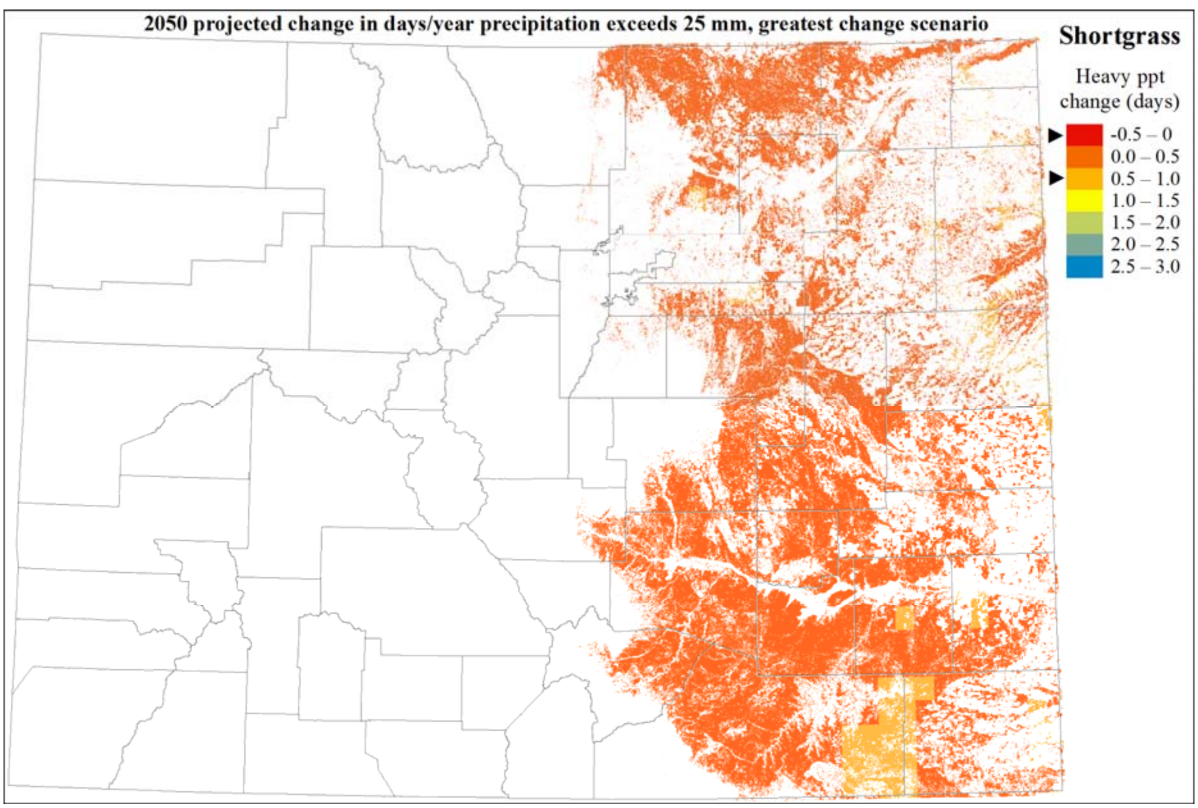
Vulnerability to Climate Change

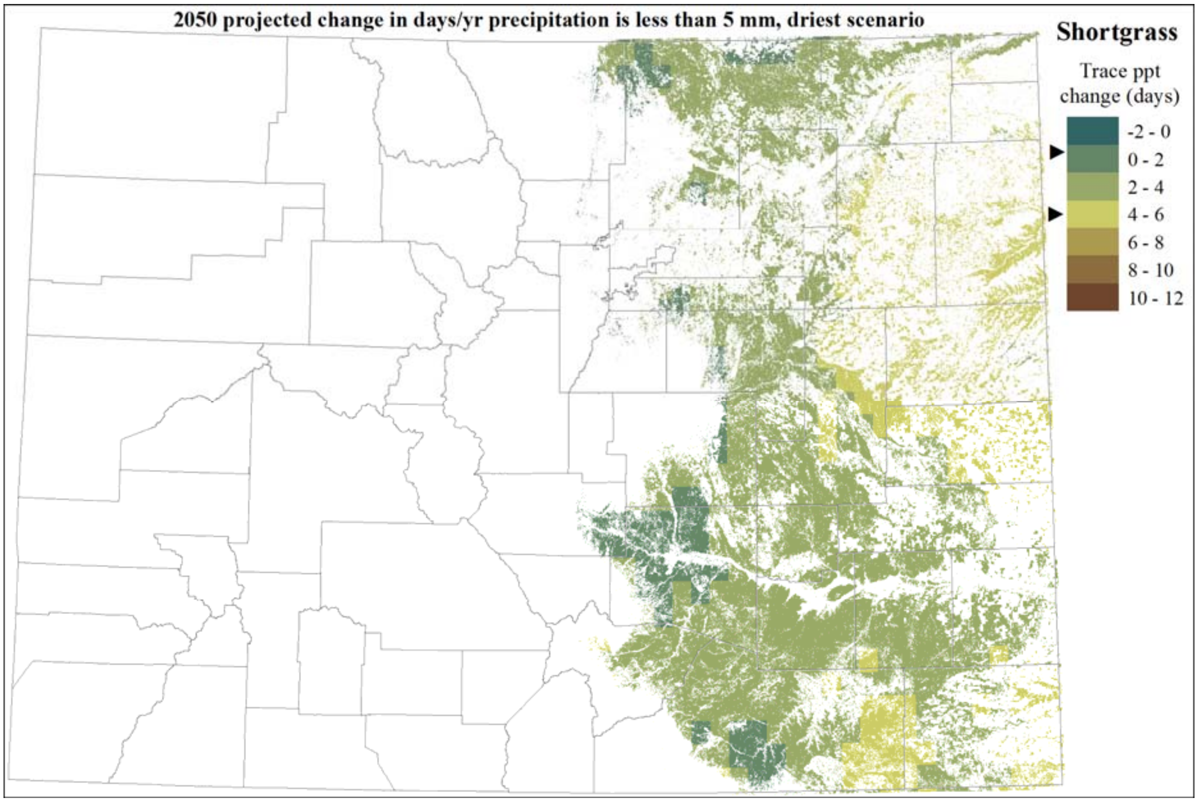
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Shortgrass prairie	High	Moderate	H/M	High

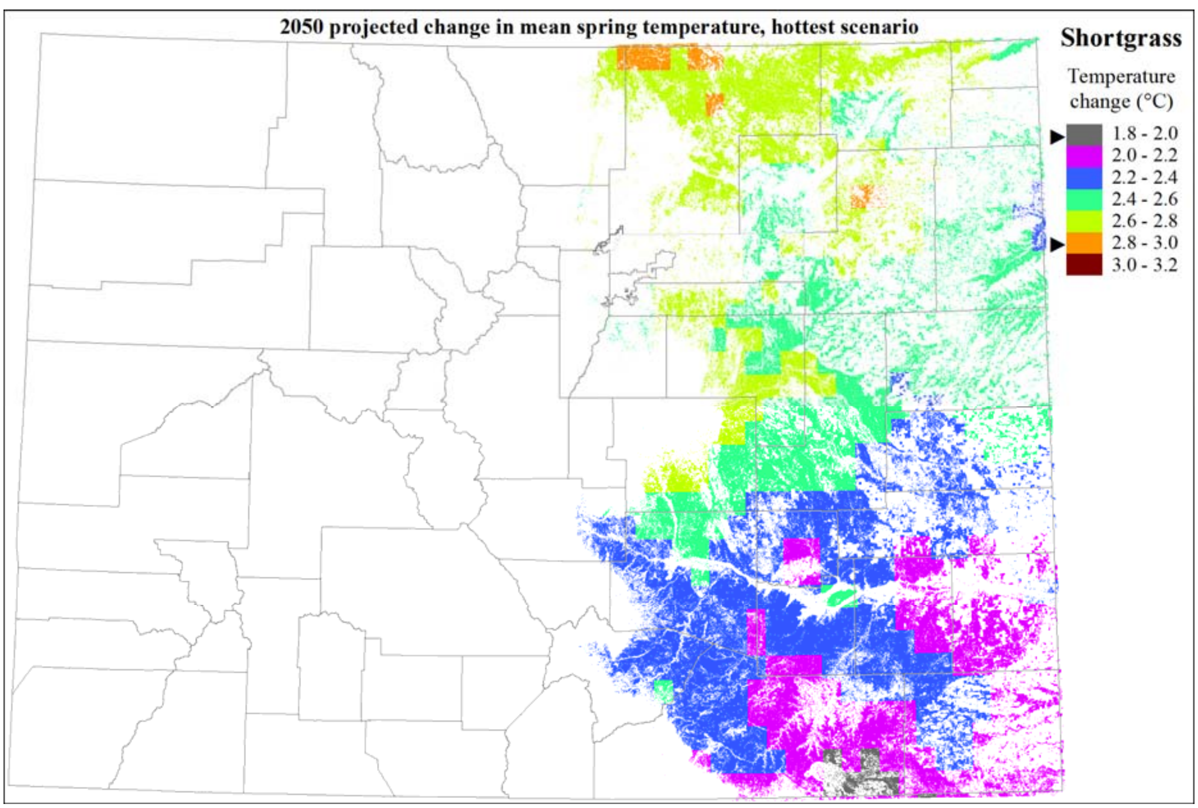
Shortgrass prairie is ranked as having high vulnerability to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the fact that these grasslands are found on the eastern plains of Colorado, where the greatest levels of exposure for all temperature variables occur. In addition, anthropogenic disturbance in these grasslands has reduced the overall landscape condition of the habitat, which is likely to reduce its resilience in the face of increasing frequency of extreme events.

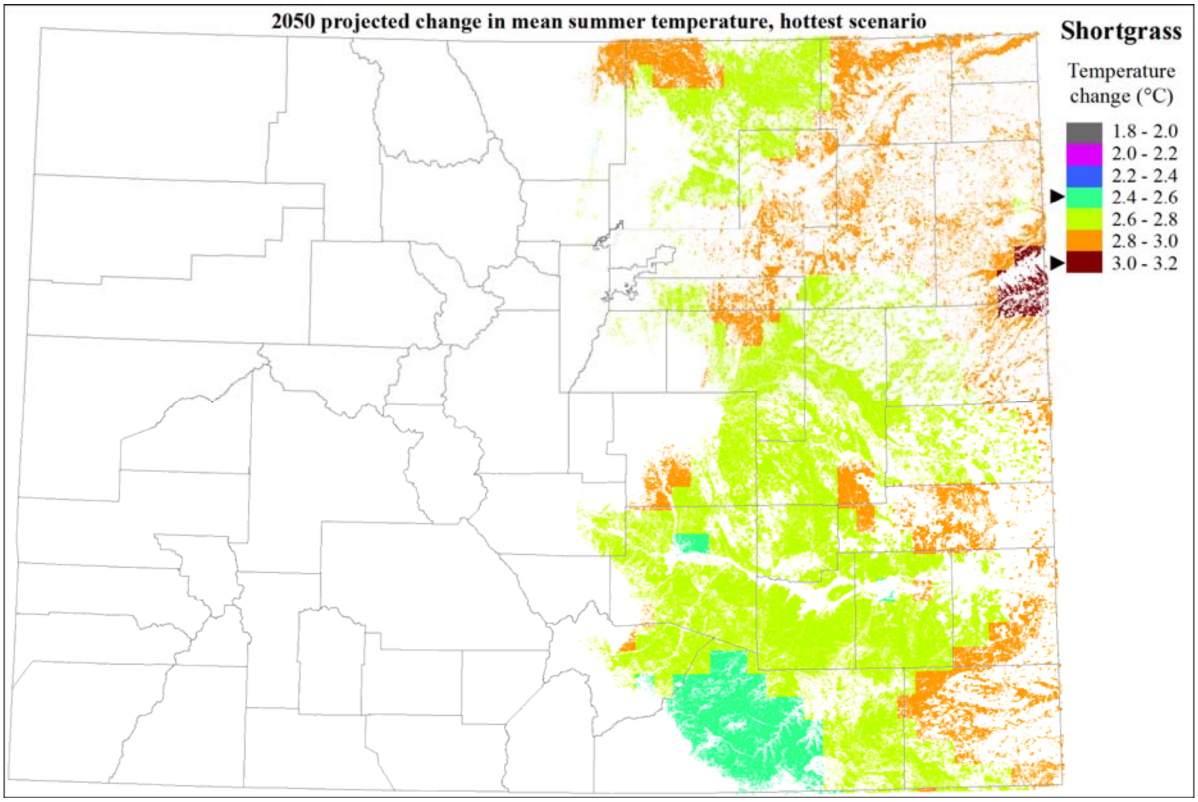
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for shortgrass habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. For the driest projection, annual precipitation could be 4-8 cm less than current levels, with a reduction in heavy precipitation events even under wetter scenarios, and increase in days with little to no measurable precipitation. Spring and summer temperatures are projected to increase by 2.5-3°C in the warmest scenario across the distribution of this habitat, which is likely to increase drought stress for shortgrass prairie.


2050 projected change in total annual precipitation, driest scenario
Shortgrass
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7
-9 – -8


2050 projected change in days/year precipitation exceeds 25 mm, greatest change scenario
Shortgrass
Heavy ppt change (days)
-0.5 – 0
0.0 – 0.5
0.5 – 1.0
1.0 – 1.5
1.5 – 2.0
2.0 – 2.5
2.5 – 3.0


2050 projected change in days/yr precipitation is less than 5 mm, driest scenario
Shortgrass
Trace ppt change (days)
-2 - 0
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12


2050 projected change in mean spring temperature, hottest scenario
Shortgrass
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2



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PLAYAS

Climate Influences

Playas of Colorado's eastern plains are small, shallow, isolated temporary wetlands, each within a closed watershed. In the absence of anthropogenic disturbance, playas receive water only from precipitation and associated runoff, and water is lost through evaporation, transpiration, and infiltration (Haukos and Smith 2003). Wet and dry periods are dependent on local patterns of precipitation and temperature both seasonally and from year to year. In common with the surrounding shortgrass prairie habitat, playas in eastern Colorado receive most of their limited annual precipitation in the form of rain during the period April through September (WRCC 2004). Unmodified playas are normally dry in late winter and early spring (Bolen et al. 1989). Most precipitation events are small (5mm or less), but infrequent heavy rainfall events are characteristic of the region. The biodiversity of a playa in a given year is a product of both current and past conditions that permit the growth of vegetation from the seed bank, and support associated fauna (Haukos and Smith 1993).

Colorado's eastern plains generally experience a large daily range in temperature, and summer temperatures are generally higher than in other areas of the state, or equivalent to the warmest low-elevation areas in southwest Colorado. The warm, dry conditions of late summer facilitate the evaporation of standing water, as well as transpiration by playa vegetation. Extended periods of drought, and attendant dust storms are characteristic of the region (WRCC 2004).

Changes in the amount and timing of precipitation, as well as the effect of increasing temperature on evapotranspiration rates are likely to alter the hydroperiod of individual playas, and, in aggregate, the number and distribution of playas on the landscape (Matthews 2008). Decreases in precipitation are likely to increase fragmentation of playa lakes as a landscape level habitat resource, such that species utilizing these habitats will face increased difficulty in moving between playas (McIntyre et al. 2014, Ruiz et al. 2014).

Exposure and Sensitivity Summary

Projected precipitation levels for playas are generally within the current range. Spring and summer temperatures are projected to be warmer than the current range in more than half of the distribution of this habitat.

Playas

Climate variable	% projected range shift
Spring precipitation	0%
Summer precipitation	0%
Drought days	0%
Mean spring temperature	58%
Mean summer temperature	56%
Average range shift	23%
Rank	M
Exposure-Sensitivity level	Moderate

Resilience Components

Playas in eastern Colorado are not restricted to high elevations, and are not at the southern edge of their range. However, these factors may not be as relevant to determining vulnerability for these small, isolated habitat patches as for larger, more contiguous habitat types. Playas in eastern Colorado occur in a relatively small range of precipitation and growing season conditions. Furthermore, the small size, isolation, and dynamic nature of these habitats means that connectivity and dispersal are critical points of vulnerability in the persistence of these habitats and the species that rely on them.

Increased sedimentation through water erosion of adjacent cultivated lands and active filling of depressional wetlands has been the primary threat to the persistence of playa habitats (Haukos and Smith 2003). Far fewer than 1% of extant playas are without modification, either to the wetland itself, or to its watershed (Johnson et al. 2012). Anthropogenic alterations to hydrology within individual playas include tilling, pit excavation to increase water storage, runoff diversion, and pumping for irrigation. Additional land use practices within the immediate watershed may include crop cultivation, livestock grazing, development, and other practices that increase sediment accumulation in the playa (Luo et al. 1997, Johnson et al. 2012). Impacts to playas from conversion to cropland are significant, and tend to decrease the resilience of the playa habitat. Tilling decreases the ability of a playa depression to maintain natural hydroperiod (Tsai et al. 2007), and increases the chance of colonization by exotic species (Tsai et al. 2012). The highly altered condition of playa habitat is likely to significantly degrade the ability of these wetlands to adapt to climate change.

Adaptive Capacity Summary

	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Playas	0.62	0.00	0.33	0.67	0.57	0.44	L	Low

Vulnerability to Climate Change

	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Playas	Moderate	Low	M/L	High

Playas are ranked as having high vulnerability to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the fact that these isolated wetlands are found on the eastern plains of Colorado, where the greatest levels of exposure for all temperature variables occur. In addition, anthropogenic disturbance in these has reduced the overall landscape condition and connectivity of the habitat, which is likely to reduce its resilience in the face of increasing frequency of extreme events, and generally warmer, drier conditions.

NOTE: due to the generally small size of playa occurrences, exposure maps were not produced for this habitat.

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RIPARIAN WOODLANDS AND SHRUBLANDS

Climate Influences

We assessed the condition of riparian woodlands and shrublands in each of three regions in Colorado, corresponding roughly to ecoregions as defined by The Nature Conservancy (2009, modified from Bailey 1998): the eastern plains (Central Shortgrass Prairie ecoregion); mountains (Southern Rocky Mountain ecoregion); and western plateaus and valleys (Colorado Plateau, Wyoming Basins, and other ecoregions).

Riparian areas of Colorado's eastern plains are primarily associated with intermittently flowing streams of small to moderate size, but also include the larger floodplains of the large snowmelt-fed rivers (South Platte and Arkansas). Smaller streams receive water from precipitation and groundwater inflow, have greater seasonal flow variation than the larger rivers, and have minimal or no flow except during floods (Covich et al. 1997). In mountainous areas of Colorado, riparian areas are much more likely to be associated with perennially flowing streams, and these plant communities are adapted to high water tables and periodic flooding. Runoff and seepage from snowmelt is a primary source of streamflow. Lower elevation riparian areas in western Colorado are adapted to periodic flood disturbance and predominantly arid conditions. Larger streams and rivers are sustained by runoff from mountain areas. Smaller streams are primarily supported by groundwater inflow, or occasional large precipitation events, and are often dry for some portion of the year.

Riparian woodlands and shrublands are adjacent to and affected by surface or ground water of perennial or ephemeral water bodies. They are characterized by intermittent flooding and a seasonally high water table. The close association of riparian areas with streamflow and aquatic habitats means that changing patterns of precipitation and runoff that alter hydrologic regimes are likely to have a direct effect on these habitats (Capon et al. 2013). In addition, the interaction of increased growth due to increased CO_2 concentration, warming-induced drought and heat-stress with potentially reduced streamflows are likely to affect riparian community structure and composition, especially in more arid areas (Perry et al. 2012).

Climate projections for mid-century are generally for warmer and drier outcomes, although precipitation change is more uncertain in direction and magnitude (Lucas et al. 2014). Annual runoff and streamflow are affected by both temperature and precipitation, and effects of future changes in these factors are difficult to separate. Warming temperatures are likely to affect the hydrologic cycle by shifting runoff and peak flows to earlier in the spring, and reducing late summer-early autumn flows (Rood et al. 2008). Riparian vegetation is in part determined by flow levels (Auble et al. 1994). Reduced summer flows are predicted to result in more frequent drought stress for riparian habitats, with a resulting loss or contraction of the habitat (Rood et al. 2008). Warming-induced changes in snowpack and snowmelt timing include earlier spring snowmelt, a shift towards precipitation falling as rain instead of snow in spring and fall, and increased sublimation from the snowpack throughout the season. These changes are expected to have greater impact at lower elevations (Lucas et al. 2014).

Exposure and Sensitivity Summary

Because of the widespread nature and generally wide ecological tolerances of this diverse group of plant communities as a whole, projected temperature and precipitation conditions across the complete current distribution are generally within the current range. Riparian woodlands and shrublands in western Colorado are projected to experience summer temperatures that are warmer than the current range in nearly half of the current distribution. In eastern Colorado, projected precipitation levels are projected to be lower than the driest end of the current range for 15% of the current distribution, and drought days are projected to increase as well.

Riparian woodland and shrubland	West	Mountain	East
Climate variable	**% projected range shift**		
Winter precipitation		0%	
Spring precipitation		0%	15%
Summer precipitation	0%		0%
Fall precipitation	0%		
Days with heavy precipitation		0%	
Drought days			38%
Mean winter temperature		0%	
Mean spring temperature	0%	0%	0%
Mean summer temperature	43%		0%
Very hot days	0%		
Average range shift	9%	0%	11%
Rank	L	L	L
Exposure-Sensitivity level	Low	Low	Low

Resilience Components

Riparian areas have a wide ecological amplitude in Colorado, and are not restricted by elevation or edge-of-range factors. However, the structure and composition of riparian habitats is closely tied to local as well as upstream environmental conditions, and is consequently highly variable from one part of the state to another. Changing climates could have dramatic effects on the component species and arrangement of riparian habitats; the consequences of these changes for habitat function and persistence are little known.

Dominant riparian species are often dependent on periodic flood disturbance for dispersal and regeneration. Altered hydrology due to dams, diversions, and groundwater pumping may interact with warming temperatures and changes in precipitation pattern to alter fluvial regimes. Such changes may increase vulnerability of riparian habitats to invasion by exotic species, especially after extreme events (Capon et al. 2013). Increased frequency and magnitude of drought is likely to have more impact on these habitats than stream warming or wildfire, at least at regional scales (Holsinger et al. 2014). Climate change in water source areas as well as in adjacent habitats could have significant impact on riparian habitats, potentially reducing vegetative cover, and altering species composition.

Adaptive Capacity Summary

Riparian woodland and shrubland	**Range and biophysical envelope**	**Dispersal & growth form**	**Biological stressors**	**Extreme events**	**Landscape condition**	**Resilience - Adaptive capacity score**	**Rank**	**Resilience Level**
West	0.57	0.50	0.33	0.67	0.40	0.50	L	Low
Mountain	0.81	0.50	0.33	0.67	0.69	0.60	M	Moderate
East	0.64	0.50	0.33	0.67	0.44	0.52	M	Moderate

Vulnerability to Climate Change

Riparian woodland & shrubland	**Exposure - Sensitivity**	**Resilience – Adaptive Capacity**	**Combined rank**	**Overall vulnerability to climate change**
West	Low	Low	L/L	Moderate
Mountain	Low	Moderate	L/M	Low
East	Low	Moderate	L/M	Low

Riparian woodland and shrublands of the eastern plains and mountain areas are ranked as having low vulnerability to the effects of climate change by mid-century under a moderate emissions scenario, while those of the western valleys are considered moderately vulnerable. Primary factors contributing to these rankings are the wide ecological amplitude and distribution of riparian habitats throughout Colorado, although the vulnerability of some species assemblages may be higher than is reflected by the collective assessment. The low to moderate resilience ranks reflect the highly altered condition of most of these habitats, and in general, riparian woodlands and shrublands throughout the state should probably be regarded as having some degree of vulnerability to climate change that is not captured by our broad-scale assessment methods.

NOTE: due to the relatively small size of riparian occurrences, exposure maps were not produced for this habitat.

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WETLANDS

Climate Influences

We assessed the condition of non-riparian wetlands in each of three sections of Colorado, corresponding approximately to ecoregions as defined by The Nature Conservancy (2009, modified from Bailey 1998): the eastern plains (Central Shortgrass Prairie ecoregion); mountains (Southern Rocky Mountain ecoregion); and western plateaus and valleys (Colorado Plateau, Wyoming Basins, and other ecoregions).

As considered herein, wetlands are areas characterized by water saturation and hydric soils typically supporting hydrophytic vegetation. Non-riparian wetlands of Colorado's eastern plains and western valleys are primarily marshes, seeps, and springs, and wet meadows. Although natural marshes and wet meadows are primarily found at higher elevations, irrigation practices (direct flood application, irrigation tail waters, elevated groundwater levels, etc.) have greatly increased the incidence of wet meadows on the eastern plains (Sueltenfuss et al. 2013). Playas are considered separately above. Most of the state's wet meadows occur in mountainous areas of Colorado, and marshes are generally less common. Fens are also characteristic of the mountain region.

Effects of climate change on wetlands are expected to be largely mediated through the source of water, either precipitation, groundwater discharge, or, for wetlands associated with riparian areas, surface flow (Winter 2000). Precipitation supported wetlands are thought to be most vulnerable to drier climatic outcomes, but decreasing precipitation would also be likely to lower water table levels and lead to contraction of groundwater-fed wetlands (Winter 2000, Poff et al. 2002). Under wetter conditions, some wetland types may be able to expand or at least maintain current extents. Consideration of the effects of changing precipitation is further complicated by the fact that wetlands may receive water input from the surrounding basin, not just the immediate environs (Gitay et al. 2001).

Temperature affects wetland distribution and function primarily through its effects on rates of chemical, physical and biological processes (Gage and Cooper 2007). Although wetlands are to some extent buffered from the immediate effects of warming on water temperature, warming could increase both plant growth and microbial activity driving decomposition (Fischlin et al. 2007). Temperature is also a driver of evapotranspiration rate, and the water cycle in general (Gitay et al. 2001).

Variation in climatic conditions affects groundwater levels both directly via recharge rates, and indirectly through changes in patterns of groundwater use, especially irrigation

(Taylor et al. 2012). Drier future conditions are likely to result in tighter controls on irrigation seepage, and a consequent reduction in wetland acres supported by this source. Although climate change is expected to have a significant effect on wetlands through changes in the seasonality and variability of precipitation and extreme events (Gitay et al. 2005), changing water use patterns in response to climate change are also likely to play a major role in the future of wetlands (Taylor et al. 2012).

Exposure and Sensitivity Summary

These habitats have a wide distribution in Colorado, and as a whole are generally less exposed than are individual wetland occurrences. In western Colorado, projected summer and fall precipitation are drier than conditions for the current distribution in some areas, and the number of very hot days is likely to increase for about a third of the distribution there. Wetlands in the mountain areas of the state are most likely to see drier than current conditions in the winter and spring. Wetland habitats of the eastern plains are most likely to see summer temperatures warmer than the current range, drier spring and summer, and increased drought days in comparison to the current range.

Wetland	West	Mountain	East
Climate variable	**% projected range shift**		
Winter precipitation		19%	
Spring precipitation		4%	6%
Summer precipitation	14%		12%
Fall precipitation	6%		
Days with heavy precipitation		0%	
Drought days			29%
Mean winter temperature		0%	
Mean spring temperature	0%	0%	0%
Mean summer temperature	0%		67%
Very hot days	32%		
Average range shift	10%	5%	23%
Rank	L	L	M
Exposure-Sensitivity level	Low	Low	Moderate

Resilience Components

Wetlands have a wide ecological amplitude in Colorado, and are not restricted by elevation or edge-of-range factors. The potential aggregation of basinwide effects into wetland areas increases the chance for changes to have an impact over considerable distances. Changing climates could have dramatic effects on the component species and hydrologic cycles of wetlands; the consequences of these changes for habitat function and persistence are likely to be significant. Because many wetlands are small and relatively isolated within the landscape, habitat connectivity and species dispersal are a point of vulnerability.

Wetland habitats have been heavily impacted by anthropogenic activities, especially water management (Gage and Cooper 2007). Altered hydrology due to dams, diversions, and groundwater pumping may interact with warming temperatures and changes in precipitation pattern to alter groundwater recharge rates, and lead to drying or contraction of wetlands. Impacted wetlands may be more vulnerable to invasion by exotic species. Increased frequency and magnitude of drought is likely to have significant impact on these habitats. Climate change in water source areas as well as in adjacent habitats could have significant impact on wetlands.

Adaptive Capacity Summary

Wetlands	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
West	0.69	0.50	0.33	0.67	0.41	0.52	M	Moderate
Mountain	0.90	0.50	0.33	0.67	0.67	0.61	M	Moderate
East	0.66	0.50	0.33	0.67	0.43	0.52	M	Moderate

Vulnerability to Climate Change

Wetlands	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
West	Low	Moderate	L/M	Low
Mountain	Low	Moderate	L/M	Low
East	Moderate	Moderate	M/M	Moderate

Wetland habitats of the western valleys and mountain areas are ranked as having low vulnerability to the effects of climate change by mid-century under a moderate emissions scenario, while those of the eastern plains are considered moderately vulnerable. Primary factors contributing to these rankings are the wide ecological amplitude and distribution of wetland habitats throughout Colorado, although the vulnerability of some species assemblages may be higher than is reflected by the collective assessment. The moderate resilience ranks reflect the highly altered condition of most of these habitats, and in general, wetlands throughout the state should probably be regarded as having some degree of vulnerability to climate change that is not captured by our broad-scale assessment methods.

NOTE: due to the generally small size of wetland occurrences, exposure maps were not produced for this habitat.

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ALPINE

Climate Influences

Snowpack is a crucial component of alpine ecosystems, and depends on both precipitation amounts and winter-spring temperature (Williams et al. 2002). Vegetation in alpine areas is controlled by patterns of snow retention, wind desiccation, permafrost, and a short growing season (Greenland and Losleben 2001). Dryer areas are often characterized by a dense cover of low-growing, perennial graminoids and forbs. Rhizomatous, sod-forming sedges are the dominant graminoids, and prostrate and mat-forming plants with thick rootstocks or taproots characterize the forbs. Low-growing shrublands characterized by an intermittent layer of snow willow or dwarf-shrubs less than 0.5 m in height, with a mixture of forbs and graminoids (especially sedges) are typically is found in areas of level or concave glacial topography, with late-lying snow and subirrigation from surrounding slopes.

The length of the growing season is particularly important for the alpine zone, and for the transition zone between alpine and forest (treeline). Alpine areas have the fewest growing degree days and lowest potential evapotranspiration of any habitat in Colorado. Treeline-controlling factors operate at different scales, ranging from the microsite to the continental (Holtmeier and Broll 2005). On a global or continental scale, there is general agreement that temperature is a primary determinant of treeline. At this scale, the distribution of alpine ecosystems is determined by the number of days that are warm enough for alpine plant growth, but not sufficient for tree growth. Other alpine conditions that maintain treeless vegetation at high elevations include lack of soil development, persistent snowpack, steep slopes, wind, and dense turf that restricts tree seedling establishment and survival within the treeline ecotone (Moir et al. 2003, Smith et al. 2003, Holtmeier and Broll 2005).

On the basis of historic evidence, treeline is generally expected to migrate to higher elevations as temperatures warm, as permitted by local microsite conditions (Smith et al. 2003, Richardson and Friedland 2009, Grafius et al. 2012). It is unlikely that alpine species would be able to move to other alpine areas. In the short-term with warmer temperatures, alpine areas may be able to persist, especially in areas where it is difficult for trees to advance upslope. The slow growth of woody species and rarity of recruitment events may delay the conversion of alpine areas to forest for 50-100+ after climatic conditions have become suitable for tree growth (Körner 2012). Thus, alpine ecosystems may persist for a while beyond mid-century, but are likely to eventually largely disappear from Colorado in the long run.

Exposure and Sensitivity Summary

Alpine habitats are projected to experience temperatures warmer than the current range in more than half of their current distribution. Projected winter and spring precipitation levels are generally within the range of the current distribution.

Alpine

Climate variable (sources: M=model, E = expert review, L = literature review)	**% projected range shift**
Winter precipitation (M, L)	0%
Spring precipitation (M)	4%
Days with heavy precipitation (M, L)	0%
Mean summer temperature (M, L)	56%
Growing degree days - base 0 (L)	51%
Average range shift	22.1%
Rank	M
Exposure-Sensitivity level	Moderate

Resilience Components

Elevations of alpine habitats in Colorado range from about 11,000 to over 14,000 ft., with a mean of about 12,000 ft. Alpine habitats are restricted to high elevations, and are also near the southern extent of their continental range in Colorado. Statewide, the annual average precipitation range is about 20-60 in (50-150 cm) with a mean of 36 in (92.5 cm). Alpine growing seasons are the shortest of any habitat in Colorado.

Alpine environments are generally not susceptible to outbreaks of pest species or disease, but may have some slight vulnerability to invasive plant species such as yellow toadflax. These treeless environments are not vulnerable to fire, but could become so if trees are able to establish. Xeric alpine environments are already subject to extreme conditions, but the more mesic areas are vulnerable to drought and changes in snowmelt timing. Even under increased snowpack, warmer temperatures are likely to alter patterns of snowmelt, and may reduce available moisture. These changes are likely to result in shifts in species composition, perhaps with an increase in shrubs on xeric tundra. With warming temperatures and earlier snowmelt, however, elk may be able to move into alpine areas earlier and stay longer, thereby increasing stress on alpine willow communities (Zeigenfuss et al. 2011).

Alpine habitats are also indirectly affected by both drought and land-use practices in upwind areas that lead to dust emissions. When wind-blown dust is deposited on mountain snowpack, the resulting darkening of the snow allows increased absorption of solar radiant energy, and earlier melting than under dust free conditions. Unlike warming temperatures, which advance both snowmelt timing and growing season onset for alpine vegetation, the effect of dust deposition on mountain snowpack is also a source of earlier snowmelt, and is not directly linked to seasonal warming (Steltzer et al. 2009). Although dust deposition may be a significant contributor to soil development in some areas (Lawrence et al. 2011), it can increase evapotranspiration and decrease annual runoff flows (Deems et al. 2013). Changes in soil moisture levels due to earlier snowmelt may interact with other climate change effects to produce changes in species composition and structure of alpine habitats.

Adaptive Capacity Summary

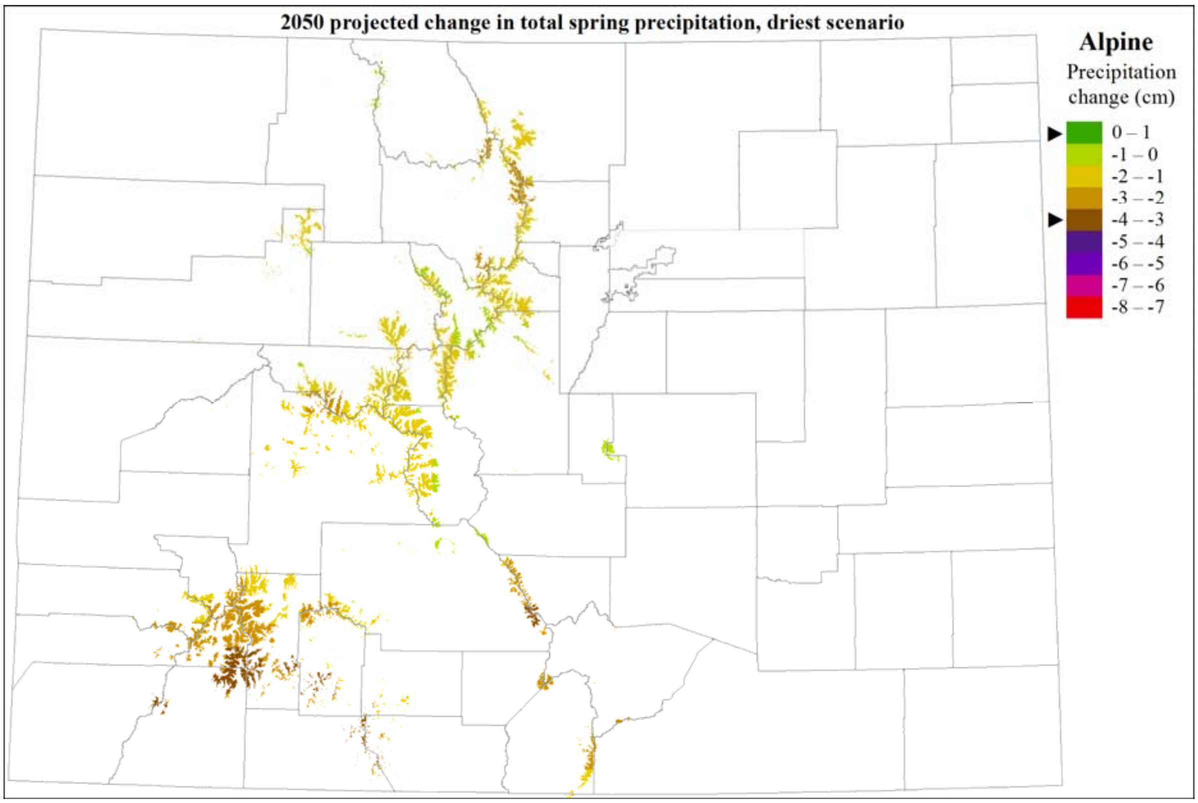
	Range and biophysical envelope	Dispersal & growth form	Biological stressors	Extreme events	Landscape condition	Resilience - Adaptive capacity score	Rank	Resilience Level
Alpine	0.32	0.5	0.67	0.67	0.98	0.61	M	Moderate

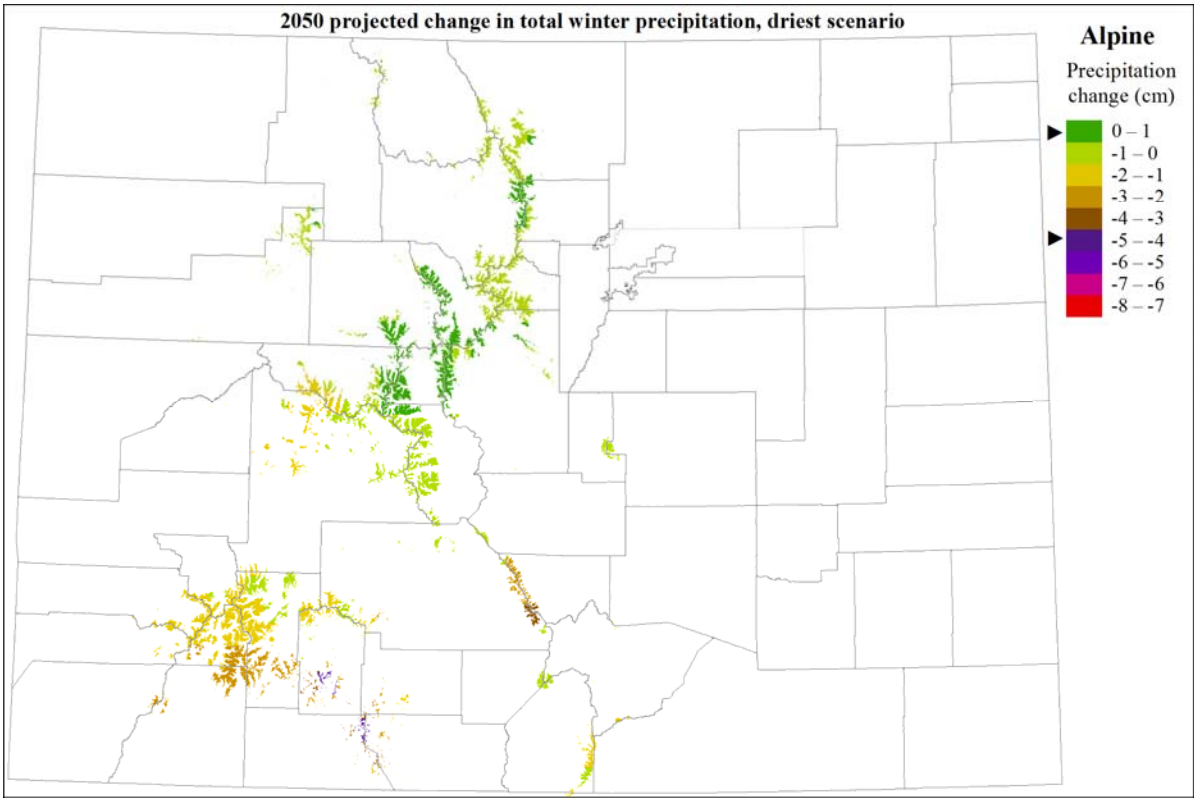
Vulnerability to Climate Change

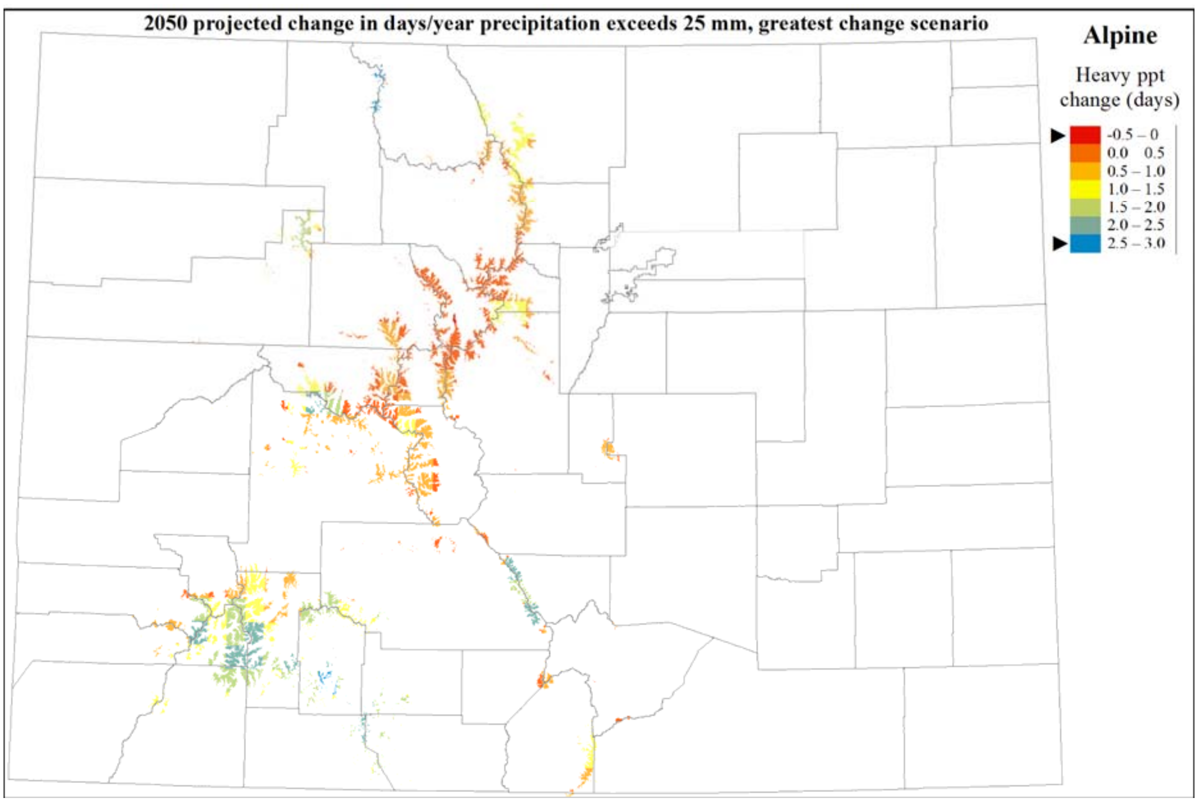
	Exposure - Sensitivity	Resilience – Adaptive Capacity	Combined rank	Overall vulnerability to climate change
Alpine	Moderate	Moderate	M/M	Moderate

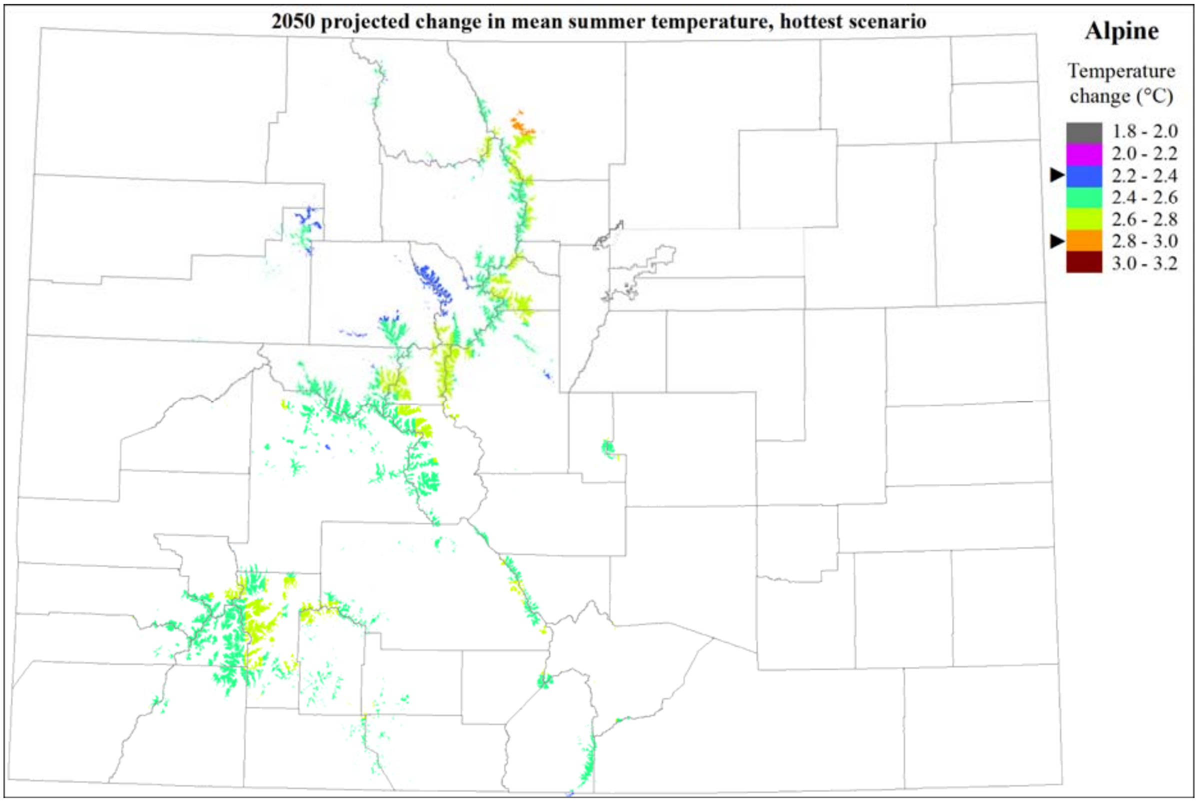
Alpine habitats are ranked moderately vulnerable to the effects of climate change by mid-century under a moderate emissions scenario. Primary factors contributing to this ranking are the fact that these habitats are restricted to the highest elevations of Colorado, and consequently have a narrow biophysical envelope. Many of the constituent species are at the southern edge of their distribution in Colorado. Under a longer-term evaluation frame, vulnerability of this habitat is expected to be greater.

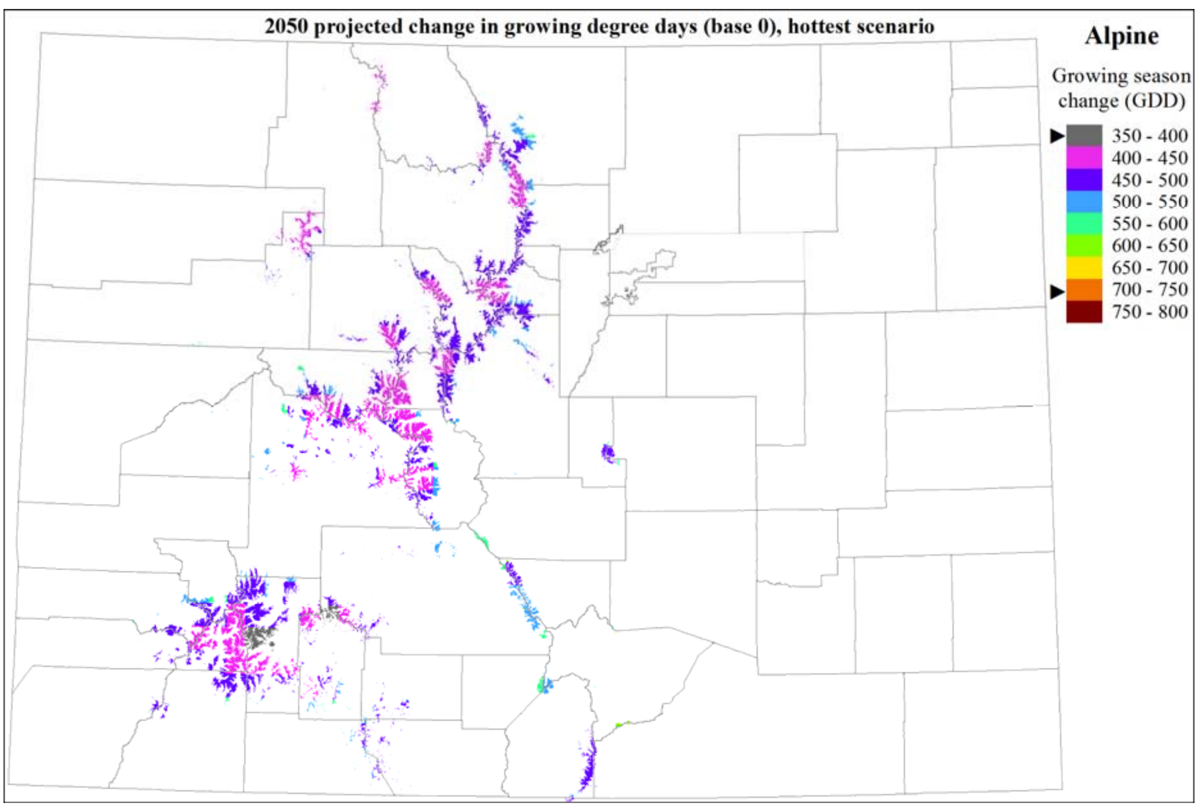
Maps below illustrate the spatial pattern of exposure under the worst case scenario for the five climate variables assessed for alpine habitats. Legend pointers indicate the range of change for this habitat within the statewide extent of change. Alpine areas in the San Juan Mountains are generally most exposed to drier conditions. Under a wetter scenario, however, some parts the southern mountains may experience an increase in large precipitation events. Temperature patterns are less clear; all areas are projected to undergo warming to some degree, although to a lesser extent than is projected for lower elevation habitats.




2050 projected change in total winter precipitation, driest scenario
Alpine
Precipitation change (cm)
0 – 1
-1 – 0
-2 – -1
-3 – -2
-4 – -3
-5 – -4
-6 – -5
-7 – -6
-8 – -7


2050 projected change in days/year precipitation exceeds 25 mm, greatest change scenario
Alpine
Heavy ppt change (days)
-0.5 – 0
0.0 – 0.5
0.5 – 1.0
1.0 – 1.5
1.5 – 2.0
2.0 – 2.5
2.5 – 3.0


2050 projected change in mean summer temperature, hottest scenario
Alpine
Temperature change (°C)
1.8 - 2.0
2.0 - 2.2
2.2 - 2.4
2.4 - 2.6
2.6 - 2.8
2.8 - 3.0
3.0 - 3.2


2050 projected change in growing degree days (base 0), hottest scenario
Alpine
Growing season change (GDD)
350 - 400
400 - 450
450 - 500
500 - 550
550 - 600
600 - 650
650 - 700
700 - 750
750 - 800

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