



San Juan / Tres Rios Climate Change Ecosystem Vulnerability Assessment



October 2014

CNHP's mission is to preserve the natural diversity of life by contributing the essential scientific foundation that leads to lasting conservation of Colorado's biological wealth.

Colorado Natural Heritage Program

Warner College of Natural Resources
Colorado State University
1475 Campus Delivery
Fort Collins, CO 80523
(970) 491-7331

Report Prepared for:
San Juan National Forest

Recommended Citation:

Decker, K. and R. Rondeau. 2014. San Juan / Tres Rios Climate Change Ecosystem Vulnerability Assessment. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado.

Front Cover: San Juan landscapes. © Colorado Natural Heritage Program

San Juan / Tres Rios Climate Change Ecosystem Vulnerability Assessment

Karin Decker and Renée Rondeau

Colorado Natural Heritage Program
Warner College of Natural Resources

Colorado State University
Fort Collins, Colorado 80523-1475



October 2014

Table of Contents

INTRODUCTION	1
Climate change in the San Juan / Tres Rios	1
Study area	2
Terrestrial Ecosystem Responses to Climate Change	3
METHODS.....	5
Components of vulnerability.....	5
San Juan and Tres Rios Terrestrial Ecosystems.....	5
RESULTS	11
Elevation range	11
Bioclimatic envelope.....	12
Biological stressors.....	14
Intrinsic dispersal rate.....	15
Extreme events	15
Phenologic change	15
Non-climate abiotic stressors	16
Potential biome shifts	16
Vulnerability summary.....	17
Table.....	20
TERRESTRIAL ECOSYSTEM VULNERABILITY ASSESSMENT SUMMARIES	22
ALPINE – Herbaceous and Shrubland	23
SPRUCE-FIR FORESTS	27
MONTANE GRASSLAND	33
ASPEN.....	37

MIXED CONIFER – Cool, moist & Warm, dry.....	42
OAK SHRUBLAND & MIXED MOUNTAIN SHRUBLAND.....	48
PONDEROSA PINE	53
PINYON-JUNIPER.....	57
SAGEBRUSH.....	63
DESERT GRASSLAND.....	66
DESERT SHRUBLAND	69
RIPARIAN / WETLAND / FEN	72
REFERENCES.....	76

List of Figures

Figure 1. Seasonal projected temperature (a) and precipitation (b) changes by mid 21st century (2050; centered around 2035-2064 period) for southwest Colorado.	2
Figure 2. Land ownership/management in the San Juan / Tres Rios.	3
Figure 3. Key components of vulnerability (adapted from Glick et al. 2011).	5
Figure 4. Major ecosystems in the San Juan / Tres Rios, developed from San Juan NF and SWReGAP mapping. Note that most wetlands and riparian areas do not show up on this map due to the small areas that they occupy.	7
Figure 5. Area of ecosystems mapped at various elevations in San Juan / Tres Rios.	11
Figure 6. Elevation zones for San Juan / Tres Rios terrestrial ecosystems. Boxes represent the middle quartiles, while whiskers show the entire range.	12
Figure 7. Bioclimatic envelope as represented by annual precipitation and growing degree days for ecosystems in the San Juan / Tres Rios. Error bars represent the 10-90% range around the mean.	13
Figure 8. Mean January and July temperature ranges for ecosystems in the San Juan / Tres Rios. Boxes represent the middle quartiles, while whiskers show the 10-90% range.	13
Figure 9. Area within temperature ranges for current and 2050.	14
Figure 10. Biotic communities of the recent past (Brown et al. 1998) in the San Juan / Tres Rios.	16
Figure 11. Biotic communities of 2060 consensus model (Rehfeldt et al. 2012).	17
Figure 12. Vulnerability and confidence scores for terrestrial ecosystems in the San Juan / Tres Rios. The vulnerability scores range from low (expected to greatly increase) through medium (presumed stable) to high (most vulnerable) - see Table 3 for definitions. The confidence score represents our confidence in the overall vulnerability score.	19
Figure 13. Predicted suitable habitat for subalpine fir under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	31
Figure 14. Predicted suitable habitat for Englemann spruce under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	32
Figure 15. Predicted suitable habitat for quaking aspen under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	41
Figure 16. Predicted suitable habitat for Douglas fir current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	45
Figure 17. Predicted suitable habitat for white fir current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	46
Figure 18. Predicted suitable habitat for blue spruce current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	47
Figure 19. Predicted suitable habitat for Gambel oak (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	52
Figure 20. Predicted suitable habitat for ponderosa pine current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	56
Figure 21. Predicted suitable habitat for pinyon pine current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	60
Figure 22. Predicted suitable habitat for Rocky Mountain juniper current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).	61

Figure 23. Predicted suitable habitat for Utah juniper current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).....62

Figure 24. Wetlands that have been mapped in the San Juan / Tres Rios (extent exaggerated for display). Not all areas have been thoroughly mapped.73

List of Tables

Table 1. Projected changes (relative to 1971-2000) by mid 21st century (2050; centered around 2035-2064 period) for southwest Colorado..... 1

Table 2. Surface ownership/management in study area.2

Table 3. Terrestrial ecosystems evaluated.6

Table 4. Ecosystem Vulnerability Scoring System (adapted from Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife, 2010).....10

Table 5. Vulnerability and confidence scores for terrestrial ecosystems in the San Juan / Tres Rios for 2040-2060 timeframe. 17

Table 6. Factors contributing to each ecosystem’s comparative vulnerability in the San Juan / Tres Rios.20

Introduction

Climate change in the San Juan Mountain region

The San Juan Mountain region has experienced a rapid increase in both maximum and minimum temperature since 1990 (Rangwala and Miller 2010), and this trend is expected to continue during the 21st century (Rangwala et al. 2012). Projections based on NARCCAP regional climate models (Mearns et al. 2007, 2012) for change in temperature and precipitation in southwest Colorado (approximately equivalent to the San Juan Public Lands region) are summarized in Table 1.

Table 1. Projected changes (relative to 1971-2000) by mid-21st century (2050; centered around 2035-2064 period) for southwest Colorado.

Projected changes by mid-21st century*	Mean	10th	50th	90th
Change in annual min. temperature (°F)**	4.56	2.63	4.59	6.15
Change in annual avg. temperature (°F)	4.60	2.68	4.68	6.29
Change in annual max. temperature (°F)	4.81	2.52	4.59	6.82
Change in annual precipitation (%)	0.46	-7.42	1.41	6.85

*Projections are based on equal representation from RCP 4.5 & 8.5 concentration pathways, using 66 to 72 models. A single model run was selected from each "parent" modelling group. Data provided by Imtiaz Rangwala.

**A temperature interval of 1 °F is equal to an interval of 5/9 degrees Celsius.

Projected changes summarized above indicate increased minimum, average, and maximum temperatures of anywhere from about 2.5-6.8 °F, with mean increases of about 4.5 °F. Furthermore, temperature increases are projected for all seasons (Figure 1a). Winter minimum temperatures are projected to have greater increases than winter maximum temperatures, but in all other seasons the greatest increases are projected in maximum temperatures, and the least in minimum temperatures. Ranges of projected increase for all seasons are broadly overlapping. Previous NARCCAP regional climate model analysis under a high emissions (A2) scenario (Kunkel et al. 2013) indicates that, in addition to projected increases in minimum, average, and maximum temperatures, the mid-century is projected to have a fewer very cold days (minimum <10 °F), fewer days below freezing, and a longer freeze-free season, with effects projected to be greater at higher elevations across the southwestern United States. While very hot days (maximum > 95 °F) are not projected to increase at the higher elevations, as altitude decreases, more very hot days, as well as more consecutive very hot days are projected (Kunkel et al. 2013).

Mean projected precipitation changes are generally less certain than those for temperature, and may not be outside the range of historic variability, at least by mid-century. Previous NARCCAP regional climate model analysis under a high emissions (A2) scenario (Kunkel et al. 2013) indicated for Colorado a generally northeast-southwest gradient in precipitation change

whereby the largest decreases are projected in areas further south. Seasonal increases (winter-spring) are generally greatest in northern and eastern portions of the state (Kunkel et al. 2013). Seasonal projected percent changes in precipitation are on average greatest for winter (Figure 1b), while summer is projected to have decreased precipitation on average. However, ranges for all seasons include both increased and decreased precipitation.

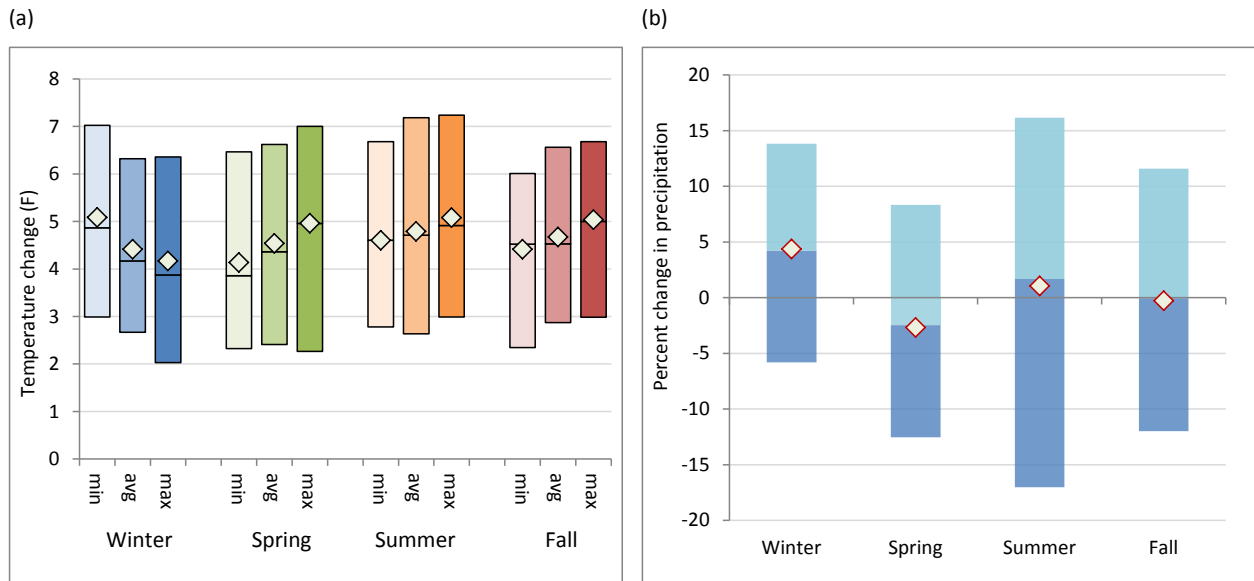


Figure 1. Seasonal projected temperature (a) and precipitation (b) changes by mid-21st century (2050; centered around 2035-2064 period) for southwest Colorado.

The bottom of each bar represents the 10th percentile, the middle line is the 50th, and the top of the box is the 90th. Mean projected change is represented by open diamonds. For each season, change in minimum, average, and maximum temperatures are shown in (a). Seasons are: winter=DJF, spring=MAM, summer=JJA, and fall=SON. Data provided by Imtiaz Rangwala.

Study area

The San Juan / Tres Rios study area includes portions of nine counties covering nearly 5 million acres in southwestern Colorado. The area represents the Colorado portion of the San Juan River, and the southern half of the Upper Colorado-Dolores Rivers HUC4 basins. Primary population centers include Durango (pop. 16,887), Cortez (pop. 8,482), Bayfield (pop. 2,333) Pagosa Springs (pop. 1,727), and Mancos (pop. 1,336). The majority of the area's population lives in smaller towns or in unincorporated areas. Surface ownership (Figure 2, Table 2) is dominated by federal, state, and tribal entities, which account for about 70% of acreage within the study area. Primary economic activities in the area are farming/ranching, logging, energy resource extraction, recreation, and tourism.

Table 2. Surface ownership/management in study area.

Owner/Manager	Acres
USFS	1,865,332
BLM	674,123
NPS	53,937
State	86,174
Tribal	769,510
Other (incl. private)	1,477,914
Total	4,926,990

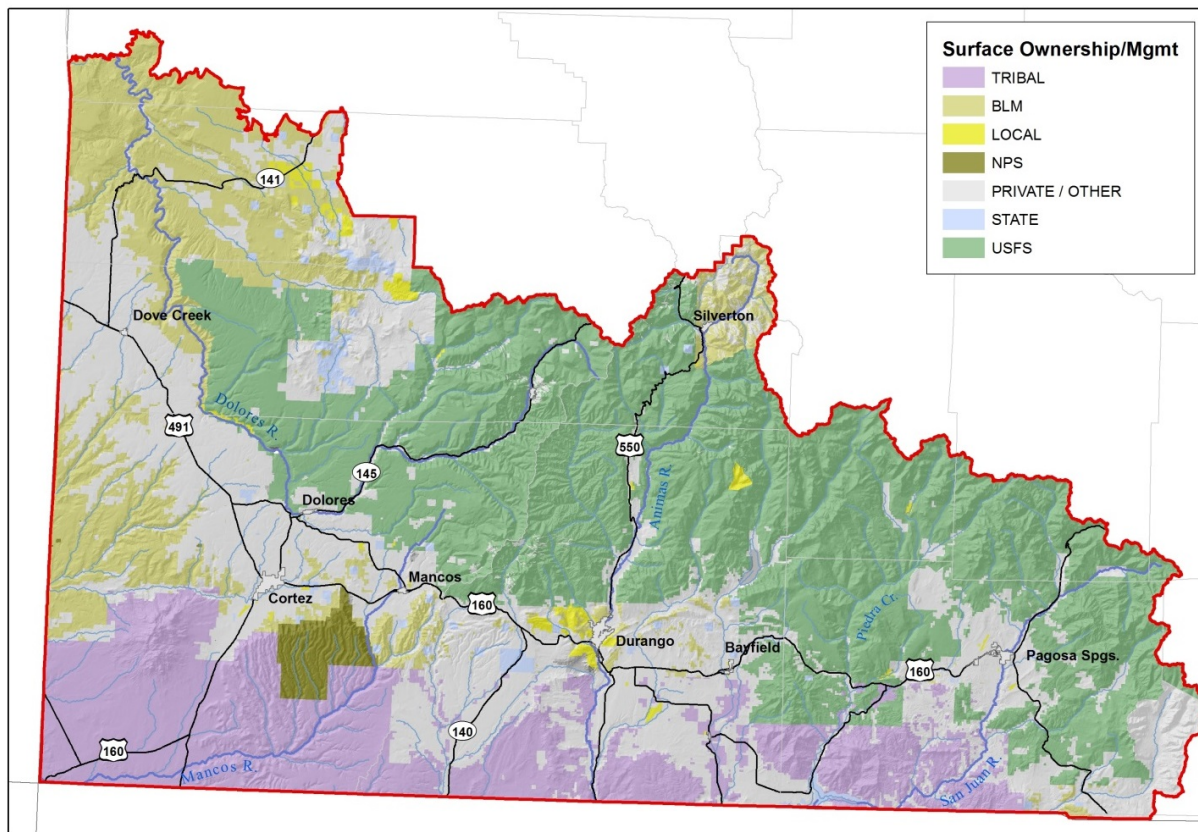


Figure 2. Land ownership/management in the San Juan / Tres Rios (USFS 2005).

Terrestrial Ecosystem Responses to Climate Change

On the continental scale, climate (i.e. patterns of temperature and precipitation) is the primary determinant for the overall geographic ranges of plant species and vegetation patterns (Woodward 1987, Prentice et al. 1992, Neilson 1995). Geologic studies reveal that the geographic locations and extents of plant species have changed greatly as climate has varied in the past (Huntley and Webb 1998). Species rather than plant communities move in response to climate changes (Betancourt 2004). Numerous publications have attempted to correlate geographic patterns of vegetation and climate to predict the broad physiognomic vegetation types known as plant formations, or biomes, i.e., Koppen (1936) and Holdridge (1947). The Koppen scheme has recently been improved by Guetter & Kutzback (1990) and the Holdridge scheme by K. C. Prentice (1990). Neilson (1995) and Prentice et al. (1992) developed predictive models that had a high degree of accuracy for predicting vegetation within North America and globally.

The prediction of potential plant distribution under future climate conditions is based on the ecological principle that the presence of a species on the landscape is controlled by a variety of biotic and abiotic factors, in the context of biogeographic and evolutionary history. Biotic interactions (e.g., competition, predation, parasitism, etc.) together with climate and other abiotic components act to influence the spatial arrangement of species at local, regional, and

continental scales. Temperature, water, carbon dioxide, nutrients, and disturbance regimes are primary abiotic constraints controlling ecosystem processes and species distributions (Woodward 1987, Eamus and Jarvis 1989, Stephenson 1990, Neilson et al. 1992). Water balance, or the difference between precipitation inputs and water loss in the form of evapotranspiration, runoff, and deep drainage, is a primary determinant of terrestrial vegetation distribution in the U.S. (Woodward 1987, Stephenson 1990, Nielson et al. 1992, Nielson 1995).

Because complete and accurate knowledge of driving factors and history is rarely, if ever, available, we rely on correlative models that relate observed species distribution with past and recent levels of climatic variables. The predictive process is further constrained by our inability to measure such variables accurately on a continuous spatial or temporal scale. As a result, modeling variables are usually an approximation of the environmental factors that control species distribution, using available data that is likely only a surrogate for the actual controlling factors. Furthermore, because the rate of vegetation response to environmental shifts is likely to be lower than the rate of climate change itself, predictive models are more useful in identifying the future location of suitable habitat for a species than in predicting the actual ground cover at a specific time in a particular location. In spite of these limitations, we chose to incorporate the results of predictive species distribution modeling into our vulnerability analysis.

Some frequently used climatic parameters for predicting plant distribution include: 1) mean temperature of coldest month, 2) mean temperature of warmest month, 3) annual or growing season precipitation, 4) growing degree days, and 5) a moisture index such as actual evaporation/potential evaporation. Thompson et al. (2000) developed relations between these climatic parameters and distributions of important trees and shrubs that provide us with temperature, precipitation, and moisture tolerances for many of the dominant plants in North America. These values for characteristic ecosystem species are included in the following analysis as a reference point for conditions under which the present distribution of that ecosystem is found. In addition, we include predicted climate profiles for the 10 year period centered around 2060 under an A1B for a number of the dominant species (Crookston et al. 2010). Finally, although we can estimate the climatic requirements of a given species, and extrapolate from that estimate the eventual distribution of an ecosystem, it is more difficult to predict vegetation dynamics that are the result of disturbance events or ecological processes (e.g., drought, fire, snowmelt, herbivory, insect outbreaks, etc.). These factors are addressed narratively, and evaluated through expert elicitation.

Methods

Components of vulnerability

In *Scanning the Conservation Horizon: a Guide to Climate Change Vulnerability Assessment* (Glick et al. 2011) the authors present a generalized but detailed guide to the key components needed to assess the sensitivity, exposure, and adaptive capacity of species or ecosystems with regard to climate change (Figure 3). *Exposure* (how much change the species or ecosystem is likely to experience) and *Sensitivity* (how likely the species or ecosystem is to be affected) combine to produce a species- or ecosystem-specific potential impact from climate change. Potential impacts can be mitigated by *Adaptive Capacity*, perhaps through direct intervention, or by taking advantage of inherent adaptive qualities of the species or ecosystem. The combination of potential impact and our adaptive responses to it produces a particular level of *Vulnerability*. Our vulnerability analysis attempts to address these key components.

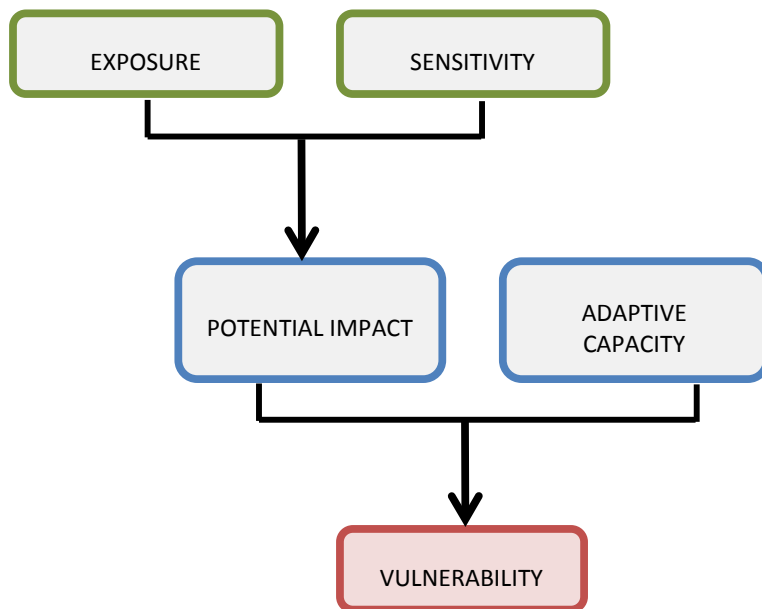


Figure 3. Key components of vulnerability (adapted from Glick et al. 2011).

San Juan and Tres Rios Terrestrial Ecosystems

Ecosystems (for the purposes of this report we use the term ecosystems broadly to represent ecological systems and/or habitats) evaluated represent the majority of the San Juan / Tres Rios landscape and were adapted from mapping provided by San Juan NF, in combination with Southwest ReGAP (USGS 2004). Fourteen upland types and three wetland/riparian ecosystems are included (Table 3, Figure 4).

Table 3. Terrestrial ecosystems evaluated.

Terrestrial ecosystem	Acres in San Juan / Tres Rios	USFS	BLM
Alpine, herbaceous	114,296	88,445	12,402
Alpine, shrubland	76,361	68,808	2,063
Spruce-fir	534,681	497,646	10,970
Aspen & aspen/mixed conifer	352,408	291,304	5,137
Mixed conifer, cool-moist	152,359	131,759	3,566
Mixed conifer, warm-dry	147,143	107,735	8,053
Montane grassland	246,110	123,643	6,928
Mixed mountain shrubland	108,852	49,556	25,058
Oak shrubland	368,912	137,345	25,112
Ponderosa	514,851	241,307	14,196
Pinyon-juniper	930,075	36,193	282,190
Sagebrush	308,793	13,823	93,690
Desert grassland	133,419	3,852	36,017
Desert shrubland	238,278	26	57,331
Riparian	88,610	24,388	8,638
Wetland	Not mapped		
Fen	Not mapped		

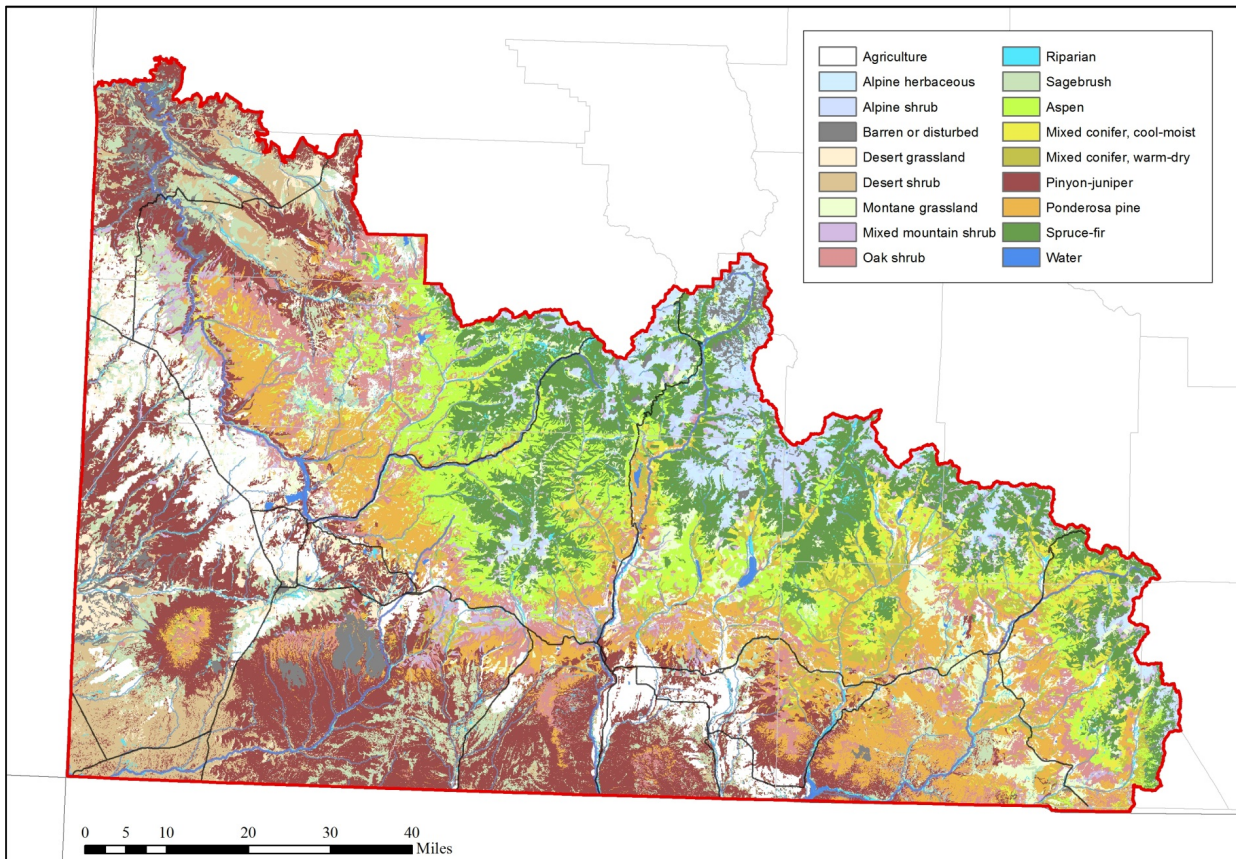


Figure 4. Major ecosystems in the San Juan / Tres Rios, developed from San Juan Public Lands (2008) and SWReGAP (USGS 2004) mapping. Note that most wetlands and riparian areas do not show up on this map due to the small areas that they occupy

DRAFT

A list of important ecosystem variables or factors that should be considered when evaluating climate change impacts was adapted from Manomet Center for Conservation Science and Massachusetts Division of Fish and Wildlife (MCCS and MAFW 2010). An ecosystem vulnerability scoring system adapted from Manomet was also developed (see below). This provides a framework for evaluating the comparative vulnerabilities of San Juan / Tres Rios ecosystems. Confidence levels were assessed using a three-point scoring system to capture the level of confidence in assigning the vulnerability score.

Our major questions were:

1. How vulnerable are terrestrial ecosystems to substantial climate change induced responses and why?
2. What degree of confidence can be assigned to the above predictions?

To answer these questions, Colorado Natural Heritage Program ecologists developed basic descriptive climatic information about the current or recent past for each ecosystem as represented in the San Juan / Tres Rios area and used Cozzetto et al (2011) climate scenarios for mid-21st century to assess the vulnerabilities. In order to compare species climatic parameters we used Thompson et al. (2000) ranges (10-90%) for North America and means for San Juan / Tres Rios ecosystems. Thompson et al. (2000) provided growing degree days calculated on a base of 5°C; we were unable to match this, and provide growing degree days calculated on base 0°C instead.

The following factors, adapted from the MCCS and MAFW (2010) were considered in the assessment of each terrestrial ecosystem. We ranked important factors for each ecosystem, then applied best professional judgment in combination with expert review to establish a logical estimate of the vulnerability of each ecosystem. That is, there was no algorithm used for the overall vulnerability score. See Table 4 for scoring system.

- **Elevation**
Current elevation range of the ecosystem. Suitable conditions for ecosystems at upper elevations may be eliminated.
- **Bioclimatic envelope**
Current temperature and precipitation ranges for the ecosystem, and relative width of bioclimatic envelope as measured by temperature and precipitation related variables. Ecosystems with narrow bioclimatic envelopes may be more vulnerable to climate change.
- **Vulnerability to increased attack by biological stressors (e.g., grazers and browsers, pests, invasives, pathogens)**
Which biological stressors 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. Ecosystems that are currently vulnerable to these stressors may become more so under climate change.

- **Intrinsic dispersal rate**
Do the component species and plant communities of a particular ecosystem have the ability to shift their ranges in response to climate change relatively quickly? What characteristics, such as, seed-dispersal capability, vegetative growth rates, stress-tolerance etc. may enable component species to adapt to shifting climatic regimes relatively quickly? What obstacles are present that reduce or prevent shift in ranges in response to climate change by preventing migration/dispersal of the component species?
- **Vulnerability to increased frequency or intensity of extreme events (fire, drought, windstorms, floods)**
Does the ecosystem have characteristics 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.
- **Vulnerability to phenologic change**
How will changes in the timing of annual events such as snow melt, run-off, growing season etc. affect the life cycle events of component species in each ecosystem?
Changes in the timing of climate driven events may favor some species over others.
- **Likely future impacts of non-climate stressors**
Because future adaptation to climate change may focus largely on enhancing ecosystems/habitat resilience it is important to identify non-climate stressors that may be mitigated for each ecosystem. Non-climate stressors include environmental contaminants, anthropogenic disturbance, habitat fragmentation and destruction, etc.

Table 4. Ecosystem Vulnerability Scoring System (adapted from Manomet Center for Conservation Sciences and Massachusetts Division of Fisheries and Wildlife, 2010).

Score	Interpretation
Extremely Vulnerable	Ecosystem at risk of being eliminated from the San Juan / Tres Rios area as a result of climate change
Highly Vulnerable	Majority of ecosystem at risk of being eliminated (i.e., >50% loss) as a result of climate change, but unlikely to be eradicated entirely. Species composition or structure likely to be highly altered.
Moderately Vulnerable	Extent of ecosystem at risk of being moderately reduced (<50% loss) as a result of climate change.
Presumed Stable	Extent of ecosystem may not change appreciably under climate change, however, any given stand may be at risk while new stands are established.
Slight Increase	Ecosystem may become established within the basin from areas outside.
Moderate Increase	Extent of ecosystem may expand moderately (<50% gain) as a result of climate change.
Greatly Increase	Ecosystem may expand greatly (>50% gain) as a result of climate change.
Unknown	Vulnerability of ecosystem under climate change is uncertain

Current Condition Definitions:

Condition assignments are based on previous work that evaluated the status of Colorado’s ecosystems on a statewide basis (Rondeau et al. 2011), adjusted to reflect knowledge of San Juan/Tres Rios conditions contributed by local land management agency staff as needed.

Very good – system can maintain itself, ecologically functioning and desired condition

Good – Desired condition, needs management to be maintained

Fair – Degraded condition

Poor – Very degraded condition, will be lost if action is not taken soon

Confidence Definitions:

Confidence assignments are based on a qualitative synthesis of the literature and expert opinion. Confidence ranges from high (trends seem clear, evidence supports conclusions), through medium (some evidence supports conclusions) to low (trends are unclear, evidence is lacking).

Results

Elevation range

Ecosystem elevations in the study area range from about 4,600 ft to nearly 14,000 ft (Figure 5). The extreme highest elevations are non-vegetated. The majority of the area lies below 8,500 ft. Low elevations are occupied by semi-desert ecosystems dominated by species adapted to lower precipitation and warm conditions. A number of montane to sub-alpine ecosystems are clustered together at middle elevations from about 7,000-10,000 ft. At higher elevations, subalpine forest and alpine vegetation occupy fairly distinct elevational zones.

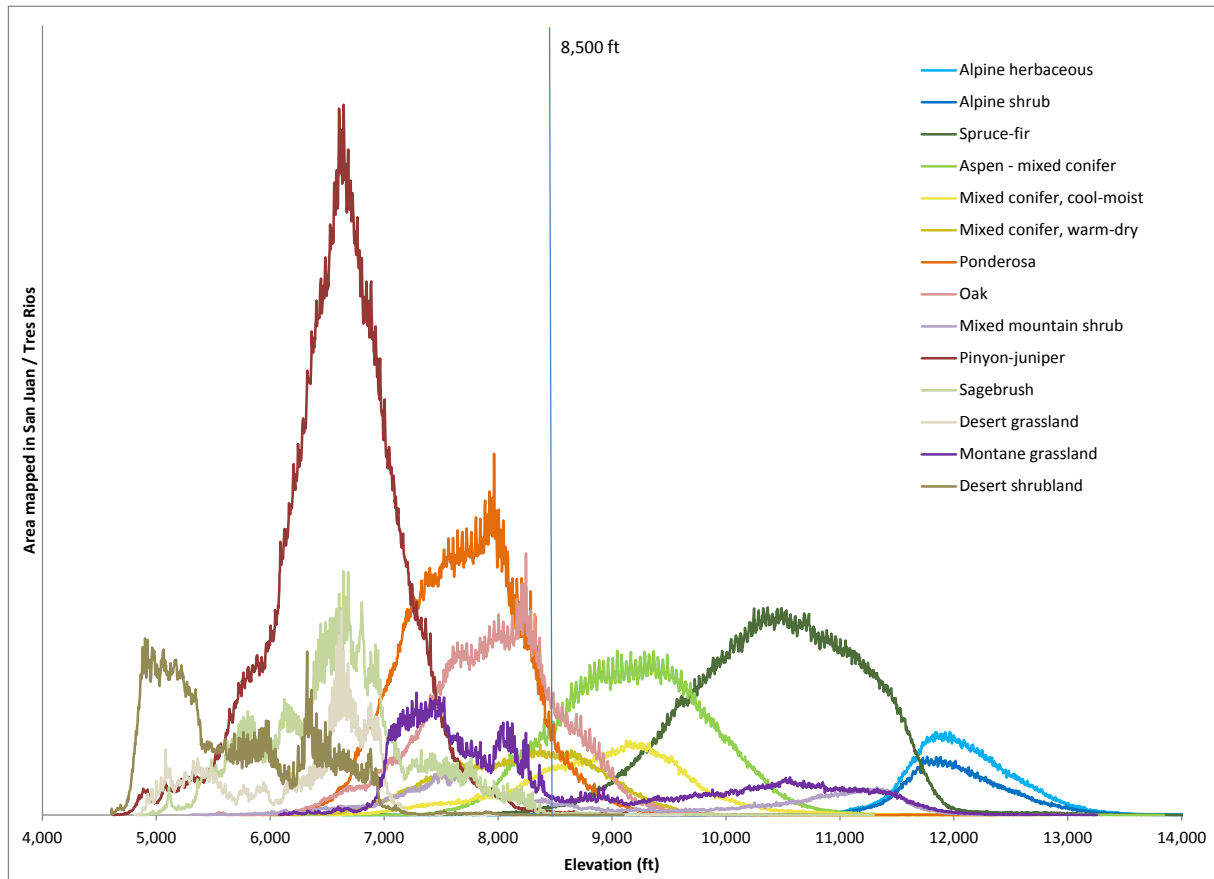


Figure 5. Area of ecosystems mapped at various elevations in San Juan / Tres Rios.

Mixed mountain shrubland and montane grassland have very wide elevational ranges in the study area (Figure 6), however it is likely that higher elevation species composition is distinctly different from lower elevation species composition for both of these types. The narrowest elevational ranges are those occupied by the high elevation alpine ecosystems and the lower elevation woodlands, pinyon-juniper and ponderosa. The alpine ecosystems are most likely to be restricted by the availability of suitable elevation habitat under changing climatic conditions. Although pinyon-juniper and ponderosa currently occupy a narrow elevational range within the study area, there is significant acreage that lies within

this elevation zone. Most ecosystem elevation ranges show considerable overlap, with the exception of spruce-fir and the combined alpine types.

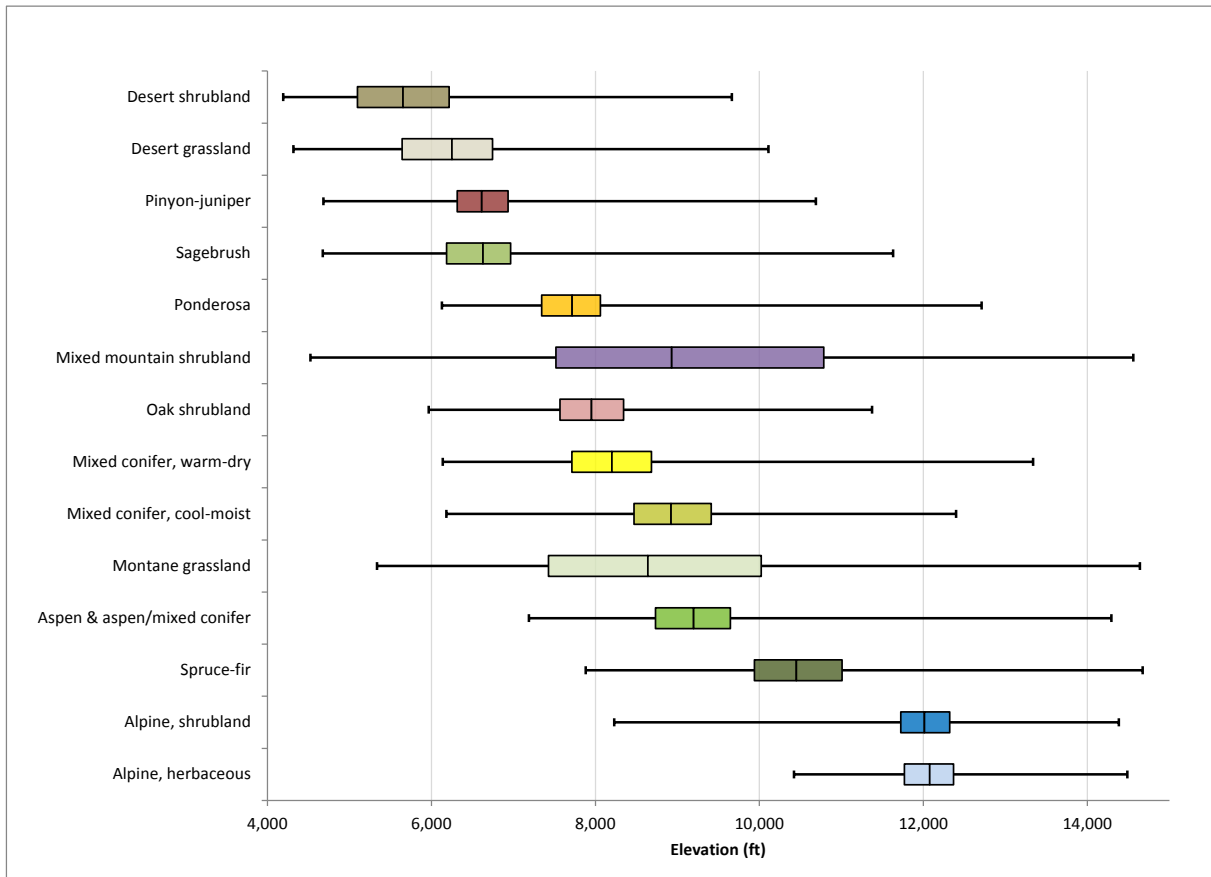


Figure 6. Elevation zones for San Juan / Tres Rios terrestrial ecosystems. Boxes represent the middle quartiles, while whiskers show the entire range.

Bioclimatic envelope

Temperature and precipitation variables were used to characterize the current bioclimatic envelope for each of the 14 terrestrial ecosystems. A combined precipitation and growing season space is shown for each ecosystem in Figure 7. Because precipitation and temperature are highly correlated with elevation, patterns are similar to those shown under elevation range above. Desert shrubland occupies the driest, warmest bioclimatic envelope. Pinyon-juniper woodland and sagebrush shrubland are closely related in bioclimatic space, and show substantial overlap with desert grassland. Ponderosa woodland and oak shrubland essentially share the same bioclimate envelope, at the warmer, drier end of the middle group whose center is defined by mixed mountain shrubland and montane grassland. Aspen and cool-moist mixed conifer occupy the cooler, wetter end of this group. The coldest, wettest environments are occupied by alpine types, with spruce-fir forest intermediate between the middle group and these habitats.

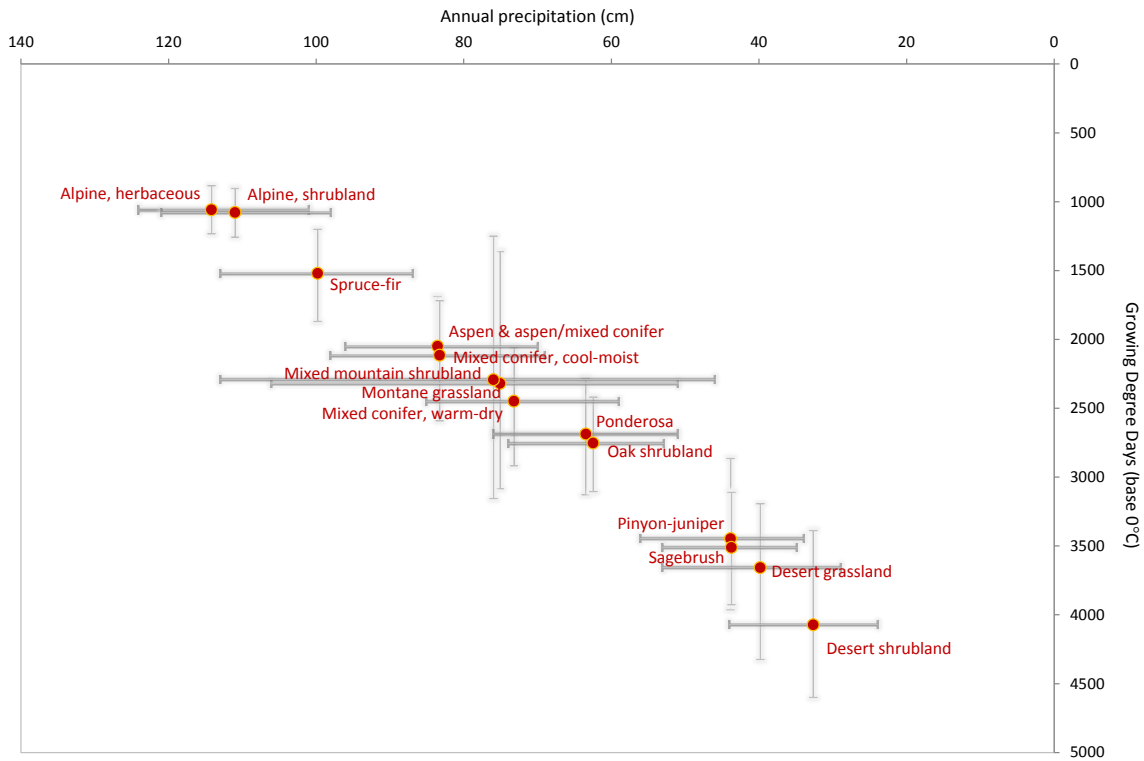


Figure 7. Bioclimatic envelope as represented by annual precipitation and growing degree days for ecosystems in the San Juan / Tres Rios. Error bars represent the 10-90% range around the mean.

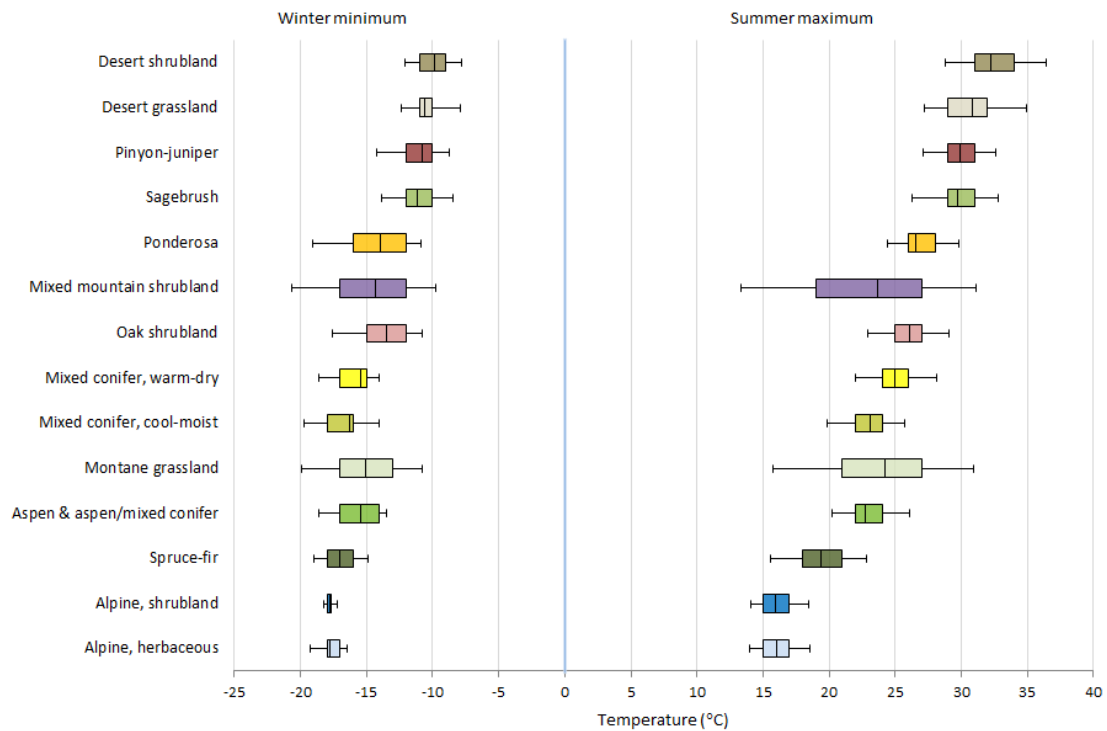


Figure 8. Minimum winter and maximum summer temperature ranges for ecosystems in the San Juan / Tres Rios. Boxes represent the middle quartiles, while whiskers show the 10-90% range.

Bioclimatic envelopes are narrowest for the two alpine ecosystems, and for the lower elevation woodlands (ponderosa and pinyon-juniper). Oak shrubland and sagebrush shrubland are comparatively narrow as well.

Current mean temperature ranges for coldest (January) and warmest (July) months for each ecosystem are shown in Figure 8, and illustrate the same relationship to elevation as do the other climate variables. The geographic area currently occupied by each ecosystem in the San Juan / Tres Rios is likely to experience a shift toward warmer temperatures, with the result that bioclimatic envelopes will shift toward higher elevations. The acreage that falls within a particular temperature range will be reduced for cooler temperatures and increased for warmer temperatures (Figure 9). In the absence of mitigating circumstances or other non-climatic factors controlling ecosystem distribution, the climate envelope of the current substantial area occupied by pinyon-juniper will shift toward a temperature zone currently occupied by desert shrubland, and the temperature zone currently occupied by alpine types will be eliminated.

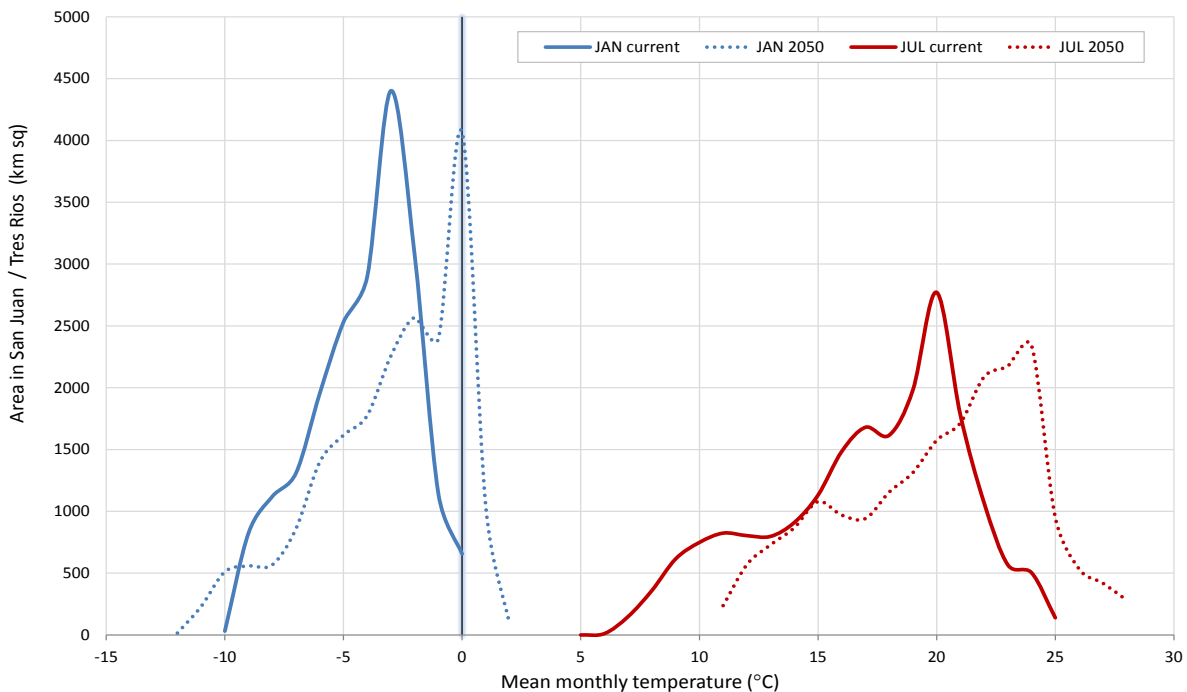


Figure 9. Area within temperature ranges for current and 2050.

Biological stressors

Biological stressors in the San Juan / Tres Rios include forest pests and pathogens, invasive species, domestic livestock grazing, and changes in patterns of native ungulate herbivory.

Native insects that cause tree damage and mortality in the area include bark beetles (*Dendroctonus* spp., *Ips* spp.), western spruce budworm (*Choristoneura occidentalis*), and tent caterpillars (*Malacosoma* spp.). Armillaria root disease is a significant cause of mortality in conifer species.

Exotic invasive plant species with the potential to alter ecosystem functioning that are widespread in the San Juan / Tres Rios include Russian knapweed (*Acroptilon repens*), cheatgrass (*Bromus tectorum*), and tamarisk (*Tamarix ramosissima*). Canada thistle (*Cirsium arvense*) is also widespread, and other, less prevalent problem species include oxeye daisy (*Leucanthemum vulgare*) and yellow toadflax (*Linaria vulgaris*). Mountain grasslands, low elevation shrubland, and riparian/wetland ecosystems are most affected.

Intrinsic dispersal rate

Most characteristic species of San Juan / Tres Rios ecosystems do not produce large numbers of seedlings or spread quickly via vegetative growth. With the exception of aspen and Gambel oak, forest and woodland tree species in particular are typically slow growing, with limited dispersal ability. However, Redmond and Barger (2013) found that in the presence of suitable microsites for seedling establishment, even areas of severe tree mortality are able to regenerate through seedling growth (advance regeneration). Shrub and grass-dominated ecosystems are somewhat better adapted to spread into available habitat through relatively rapid vegetative growth. Barriers to ecosystem movement in the study area are primarily those due to elevational gradients or habitat fragmentation, although soil type is likely to influence dispersal and establishment patterns through variable water-holding capacity.

Extreme events

Extreme events that may increase in frequency and/or severity under changing climatic conditions include drought, wildfire, windstorms, and flooding/erosion.

Prolonged drought has been a periodic influence in the San Juan / Tres Rios area. Ecosystems of lower elevations are already generally drought tolerant, although species composition within an ecosystem is likely to shift with changing climate patterns. For instance, the greater drought tolerance of juniper in comparison with pinyon pine (Breshears et al. 2008) has implications for the relative dominance of these two species in pinyon-juniper ecosystems. Anderegg et al. (2013) link the recent widespread aspen die-off to severe moisture stress due to a combination of low snowpack and early snowmelt followed by a prolonged dry period during the 2002 drought. Increasing drought severity in the future is likely to continue this effect. Furthermore, drought is typically an inciting factor for stand-replacing events such as fire or insect outbreak (DeRose and Long 2012).

After a century of low fire frequency, the severity, frequency, and extent of wildfires in the San Juan / Tres Rios are expected to increase in the future as climate conditions change and interact with anthropogenic disturbances (Grissino-Mayer et al. 2004). Nine large fires or fire complexes have burned a total greater than 291,000 acres in southwestern Colorado in the period since 2000, which tends to support this expectation.

Phenologic change

Phenology, or the relationship between climatic conditions and periodic events in the lifecycle of particular species, has already been shown to be changing with changing climate (Inouye 2008, Calinger et al. 2013). For ecosystems, important periodic events include the timing of snowmelt and runoff, the form of precipitation (rain vs snow), and patterns of first and last frost. Although most of the dominant species in ecosystems

considered here are wind pollinated, there is a potential for the effect of changing phenology on pollinators or dispersers to have an impact on the distribution of some species.

Non-climate abiotic stressors

Anthropogenic disturbance in the San Juan / Tres Rios area includes habitat fragmentation and conversion, primarily from agricultural use, but also due to residential and recreational development. Lower elevations within the San Juan Basin have been subjected to extensive energy resource development, while higher elevations have undergone mining, livestock grazing, logging, fire suppression, and increasing recreational use, both motorized and non-motorized. Population levels in the area are generally stable or slightly decreasing. Future stressors are likely to be tied to continued effects of habitat fragmentation.

Potential biome shifts

Rehfeldt et al. (2012) modeled the North American biomes of Brown et al. (1998) for future climate scenarios. Within the San Juan / Tres Rios, recent past conditions are suitable for seven 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, and desert shrubland as assessed herein (Figure 10).

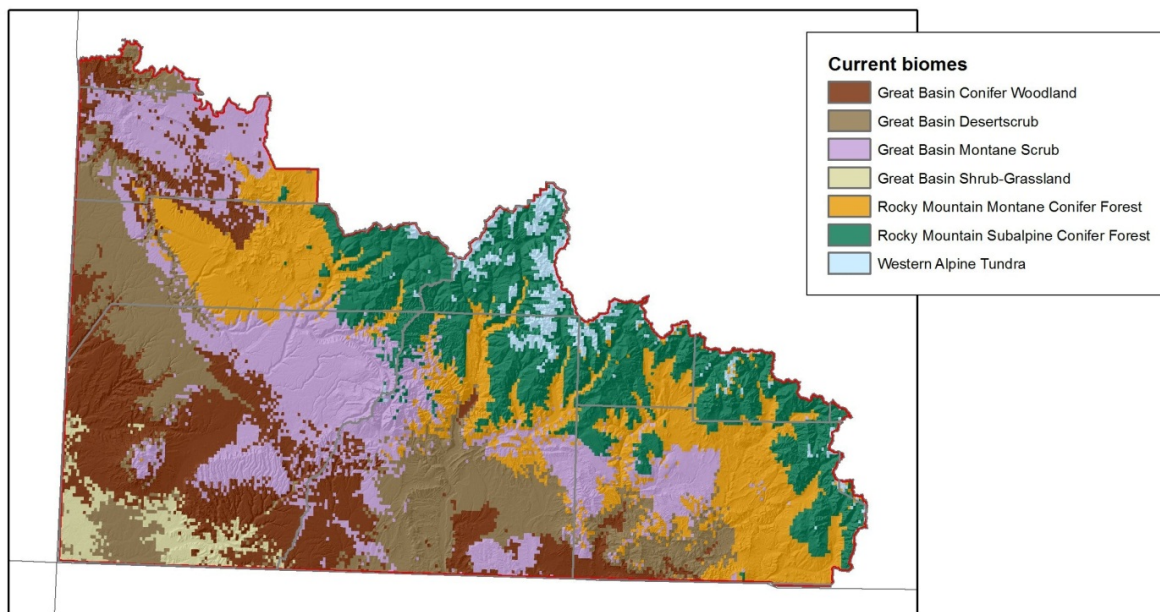


Figure 10. Biotic communities of the recent past (Brown et al. 1998) in the San Juan / Tres Rios.

As predicted by the model consensus for 2060 (Figure 11), biomes in the study area are expected to shift such that areas suitable for alpine are eliminated in favor of a reduced area favorable to spruce-fir, together with a potential for novel combinations of conifers at elevations previously dominated by these subalpine forests. The zone suitable for the

various conifer and aspen types is predicted to expand substantially, potentially eliminating much area currently occupied by oak-mixed mountain shrubland. Conditions suitable for desert shrubland also are predicted to expand considerably into areas currently occupied by sagebrush-grassland (or agriculture). Naturally, other biophysical constraints such as soils, topography, and disturbance regimes could delay or prevent these shifts from occurring in many places.

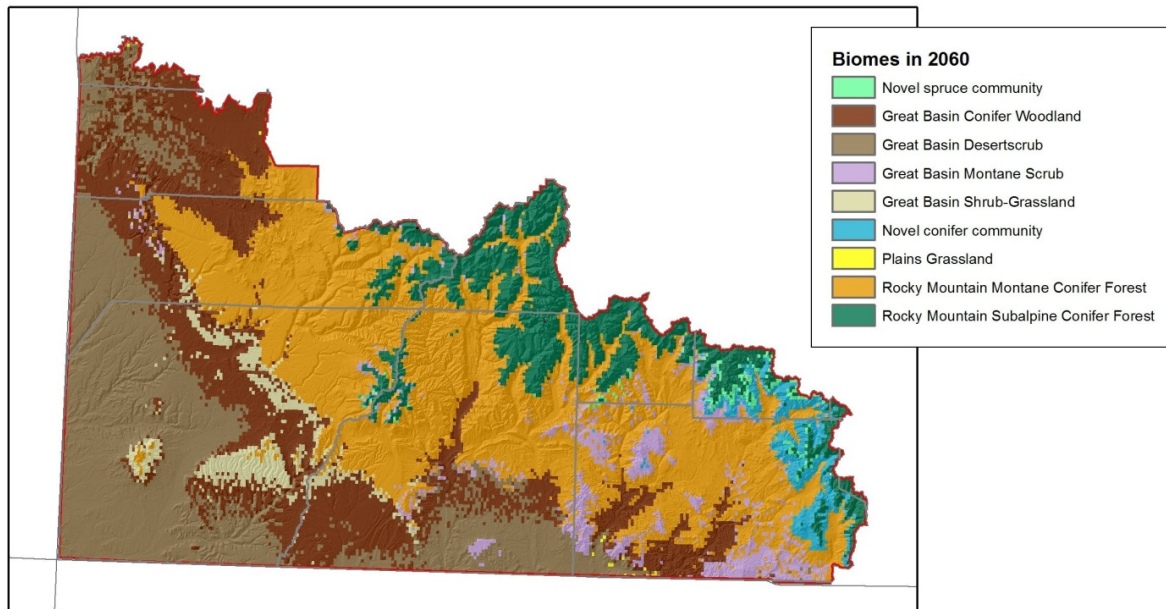


Figure 11. Biotic communities of 2060 consensus model (Rehfeldt et al. 2012).

Vulnerability summary

Vulnerability of the 14 terrestrial ecosystems assessed ranged from highly vulnerable to moderately increase (Table 5); confidence in these ratings was high to low. In general the ecosystems at the highest elevations were more vulnerable than ecosystems at low elevations, with the exception of desert grassland.

Table 5. Vulnerability and confidence scores for terrestrial ecosystems in the San Juan / Tres Rios for 2040-2060 timeframe.

Ecosystem	Vulnerability Score	Current Condition	Confidence in Score
Alpine, herbaceous	Highly Vulnerable	Very good	High
Alpine, shrubland	Moderately Vulnerable	Very good	Medium
Spruce-fir	Moderately Vulnerable	Good	Medium
Montane grassland	Presumed Stable	Good	Low
Aspen & aspen/mixed conifer	Presumed Stable	Fair to Good	Medium

Mixed conifer, cool-moist	Presumed Stable	Good	Low
Mixed conifer, warm-dry	Presumed Stable to Slight Increase	Good	Low
Mixed mountain shrubland	Presumed Stable	Good	Medium
Oak shrubland	Presumed Stable	Good	High
Ponderosa	Presumed Stable	Good	Medium
Pinyon-juniper	Moderately Vulnerable	Fair to Good	Low
Sagebrush	Moderately Vulnerable	Fair to Good	Low
Desert grassland	Highly Vulnerable	Poor to Fair	Low
Desert shrubland	Moderate Increase	Fair to Good	High
Riparian/Wetland High elev	Moderately Vulnerable	Very good	Medium
Fen (Low to high elev)	Moderately Vulnerable	Very good	Medium
Riparian/Wetland Low elev	Highly Vulnerable	Fair	Low
Current Condition Definitions for Upland and Riparian Ecosystems: Very good – system can maintain itself, ecologically functioning and desired condition Good – Desired condition, needs management to be maintained Fair – Degraded condition Poor – Very degraded condition, will be lost if action is not taken soon			

Only three ecosystems (alpine herbaceous, desert grassland, and low elevation riparian/wetland) were rated highly vulnerable. Alpine types are restricted to the highest elevations; there is low probability that species that make up this system will re-colonize other areas. Desert grassland has already been highly altered and fragmented in the study area, and is vulnerable to encroachment by shrubs. Riparian areas and wetlands of lower elevations are generally highly modified, and vulnerable to increasing drought.

Three terrestrial ecosystems (spruce-fir, pinyon-juniper, and sagebrush) were rated moderately vulnerable. Spruce fir is vulnerable because increased droughts may increase mortality by spruce beetle, fir engraver, armillaria root disease, and budworm, and predicted increase in fire may reduce acreage. In addition, lower elevation spruce fir may be most vulnerable. Pinyon-juniper woodland vulnerability is also driven by increased drought that leads to increased pest attacks and wildfire. Sagebrush in the San Juan / Tres Rios is near the edge of its range and occurs in smaller patches than elsewhere. Although it is adapted to arid environments, it is vulnerable to increased fire under warmer, drier conditions, and to displacement by other shrub species that may be able to colonize sagebrush stands under future climate conditions.

Six ecosystems (aspen, both mixed conifer types, montane grassland, mixed mountain shrubland, oak shrubland, and ponderosa) were rated 'presumed stable'. All of these

ecosystems occupy the broad middle zone of the study area, and have more-or-less overlapping bioclimatic envelopes. The future distribution and relative degree of change for all of these ecosystems is highly uncertain, however, the interaction of local conditions with broad climatic trajectories is likely to produce observable change in these ecosystems. Ecosystems within this zone are likely to develop novel species combinations or altered dominance within current types.

One ecosystem (desert shrubland) was rated ‘moderate increase’ meaning that conditions may be more favorable for these shrublands in the future compared to the recent past.

Individual factor ratings are given in Table 6. Detailed vulnerability assessments for each of the assessed ecosystems occurring in the San Juan / Tres Rios are provided below. A plot of overall vulnerability ratings vs. confidence scores summarizes the upland results (Figure 12).

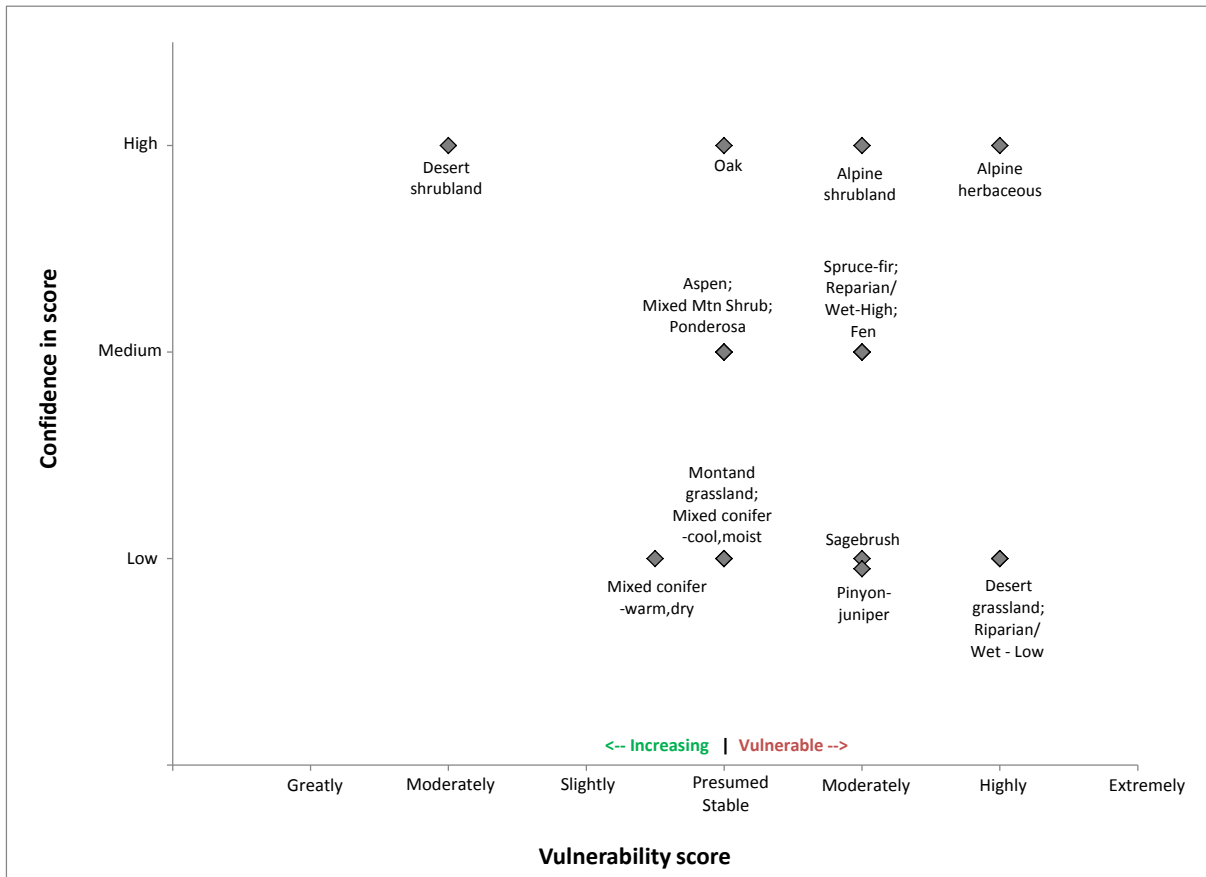


Figure 12. Vulnerability and confidence scores for terrestrial ecosystems in the San Juan / Tres Rios. The vulnerability scores range from low (expected to greatly increase) through medium (presumed stable) to high (most vulnerable) - see Table 3 for definitions. The confidence score represents our confidence in the overall vulnerability score.

DRAFT

Table 6. Factors contributing to each ecosystem’s comparative vulnerability in the San Juan / Tres Rios.

High critical factor for identifying the reaction of this system to expected climate change
 Medium moderate factor for identifying the reaction of this system to expected climate change
 Low some effect, but not a major factor for identifying the reaction of this system to expected climate change
 “-” not an important factor

Ecosystem	Vulnerability Score	Restricted to high elevation or at edge of range	Narrow bioclimatic envelope	Biological stressors			Extreme events			Timing of snowmelt and/or Phenologic change	Non-climate abiotic stressors
				Increased pest attacks	Increased grazing or browsing	Increased invasive species and/or encroachment by natives	Poor dispersal and/or barriers	Fire	Drought		
Alpine, herbaceous	Highly Vulnerable	High	Medium	-	Low	Medium	High	-	Low	Medium	-
Alpine, shrubland	Moderately Vulnerable	High	Medium	-	-	Medium	High	-	Low	Medium	-
Spruce-fir	Moderately Vulnerable	-	-	High	-	-	-	Medium	Medium	Medium	-
Montane grassland	Presumed Stable	-	-	-	Low	Low	-	Low	Low	Medium	-
Aspen	Presumed Stable	-	-	Low	Medium	-	-	-	High (low elevations)	Medium	-
Mixed conifer, cool-moist	Presumed Stable	-	-	Medium	-	-	-	Medium	Medium	-	-
Mixed conifer, warm-dry	Presumed Stable to Slight Increase	-	-	Low	-	-	-	Low	Low	-	-
Mixed mountain shrubland	Presumed Stable	-	-	-	Medium	-	-	-	Low	-	-
Oak shrubland	Presumed Stable	-	Low	Low	Medium	-	-	-	Low	Low	-

Ecosystem	Vulnerability Score	Restricted to high elevation or at edge of range	Narrow bioclimatic envelope	Biological stressors			Extreme events			Timing of snowmelt and/or Phenologic change	Non-climate abiotic stressors
				Increased pest attacks	Increased grazing or browsing	Increased invasive species and/or encroachment by natives	Poor dispersal and/or barriers	Fire	Drought		
Ponderosa	Presumed Stable	-	Low	Medium	Low	Low	-	Medium	Low	-	-
Pinyon-juniper	Moderately Vulnerable	-	Low	High	-	-	Medium	Medium	Medium	-	Low
Sagebrush	Moderately Vulnerable	-	Low	-	Low	Medium	-	Medium	Medium	Low	Medium
Desert grassland	Highly Vulnerable	-	-	-	Low	High	-	-	High	-	High
Desert shrubland	Moderate Increase	-	-	-	-	Low	-	-	Low	-	Low
Riparian / Wetland High-elevation	Moderately Vulnerable	Low	-	-	Medium	Medium	-	-	Medium	Medium	Low
Fen	Moderately Vulnerable	Medium	Low	-	-	Medium	High	-	Medium	Low	Low
Riparian / Wetland Mid- to Low-elevation	Highly Vulnerable	-	-	-	Medium	High	-	-	High	High	High

Terrestrial Ecosystem Vulnerability Assessment Summaries

- 1. Alpine - herbaceous**
- 2. Alpine - shrub**
- 3. Spruce-fir**
- 4. Mixed conifer, cool-moist**
- 5. Mixed conifer, warm-dry**
- 6. Aspen and aspen/mixed conifer**
- 7. Ponderosa pine**
- 8. Pinyon-juniper**
- 9. Oak shrubland**
- 10. Mixed mountain shrubland**
- 11. Sagebrush shrubland**
- 12. Montane grassland**
- 13. Desert shrubland**
- 14. Desert grassland**
- 15. Riparian**
- 16. Wetland**
- 17. Fen**

ALPINE – Herbaceous and Shrubland

Alpine vegetation is found at the highest elevations, usually above 11,000 feet where the long winters, abundant snowfall, high winds, and short summers create an environment too harsh for permanent human habitation. Vegetation in these areas is controlled by snow retention, wind desiccation, permafrost, and a short growing season. Areas dominated by herbaceous cover may be dry tundra, cushion-plant dominated fellfield, or wet meadows. Shrub-dominated areas are characterized by ericaceous dwarf-shrubs or dwarf willows.

Characteristic species: Ptarmigan, Brown-capped rosy finch, American pipits, Lincoln's sparrow, White-crowned sparrow, Wilson's warbler, McGillivray's warbler, Fox sparrow, Boreal toad, Bighorn sheep, Pika, Marmot, and Elk.

Current condition **Very Good**

Exposure Warming trend expected across entire ecosystem range, maximum summer temperatures may increase more in the eastern portion where this ecosystem is concentrated. Precipitation patterns change but probably no substantial decrease.

Sensitivity An increase in the growing season, i.e., warmer summertime temperatures, will allow shrubs and trees to encroach on alpine. Warmer temperatures that alter patterns of snowmelt may expose plants to more frost damage, and/or reduce available moisture.

Adaptive capacity Poor, no higher elevation areas are available.

Vulnerability Herbaceous: **Highly vulnerable**
Shrubland: **Moderately vulnerable**

Confidence **High**

Literature study supports the eventual disappearance of these ecosystems; the timeframe is uncertain, but the rate of change is likely to be gradual.

Alpine shrubland typically is found in areas of level or concave glacial topography, with late-lying snow and subirrigation from surrounding slopes. Vegetation in these areas is controlled by patterns of snow retention, wind desiccation, permafrost, and a short growing season. These moist but well-drained areas have developed relatively stable soils that are strongly acidic, often with substantial peat layers. Alpine shrublands are characterized by an intermittent layer of snow willow or ericaceous dwarf-shrubs less than 0.5 m in height, with a mixture of forbs and graminoids, especially sedges.

Elevations of alpine herbaceous and shrubland communities range from about 11,000 to over 14,000 ft, with a mean of about 12,000 ft. The elevation range of alpine communities

overlaps with the upper end of spruce-fir forest, montane grassland, and mixed mountain shrubland. Annual average precipitation range is about 35-51 in (90-130 cm) for both types combined, with a mean of 44 in (112 cm).

Alpine herbaceous Alpine shrub	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Ecosystem in SJTR	-9 to -8	7 to 10	100 - 125	1200 - 1870	0.84 – 0.90
Ecosystem on USFS/BLM					
Weather Stations					
Beartown SNOTEL (11,600 ft.)	-9	10	107		
Wolf Creek Summit SNOTEL (11,000 ft)	-8	11	127		

The length of the growing season is particularly important for the alpine and subalpine zones, and for the transition zone between alpine and forest (treeline). Alpine areas have the fewest growing degree days and lowest potential evapo-transpiration of any ecosystem in the San Juan / Tres Rios. 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). If the alpine summer mean temperatures increase 5.8 – 7.3°F (3- 4°C), as modeled by Cozzetto et al. (2011), treeline could move upslope to elevations near 13,000 ft, leaving very little area suitable for alpine ecosystems. We may eventually see treeline increase to approximately 1,970 ft (600 m) higher than it is today. It is unlikely that alpine species would be able to move to other high elevation areas. 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. A gradual shift towards dominance of subalpine species could change the composition of these areas.

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, and a change in dominant shrub species. 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). Populations of characteristic alpine species such as American pika (*Ochotona princeps*) and white-tailed ptarmigan (*Lagopus leucurus*) are likely to decrease under warmer conditions, especially in areas that are impacted by other stressors (Erb et al. 2014).

Vulnerability Factor	Rating	Comments
Restricted to high elevation	High	Already at highest elevation in the area.
Narrow bioclimatic envelope	Medium	Relatively narrow within the study area.
Vulnerable to increased pest attacks	-	Not a concern.
Vulnerable to increased grazing/browsing	Low (herbaceous)	Elk should be monitored.
Vulnerable to increased invasive species and encroachments from natives	Medium	Invasives and encroachment by trees and shrubs are likely, especially up to 13,000 feet. Increase in growing degree days will favor trees and shrubs. Yellow toadflax and oxeye daisy are potential weeds.
Barriers to dispersal	High	No higher areas available and low probability of recolonizing other areas since they are widely scattered (isolated mountain tops separated by lower elevation habitats); alpine species don't tend to colonize after disturbance. Species composition is likely to change.
Vulnerable to fire	-	Not a concern.
Vulnerable to drought	Low	Minor effects expected.
Vulnerable to timing of snowmelt	-	Snowmelt change at high elevations not expected to be dramatically different.
Vulnerable to phenologic change	Medium	Timing of pollinators and flowering may be mismatched; earlier flowering yet late frosts may

Vulnerability Factor	Rating	Comments
		decrease seed production.
Non-climate abiotic stressors	-	Generally in very good condition with little fragmentation. An increase of dust deposition on snow could advance snowmelt timing in some years.

SPRUCE-FIR FORESTS

These high elevation forests form the matrix of the sub-alpine zone at elevations of 9,500 to 11,500 feet. They are characterized by dense stands of Engelmann spruce and subalpine fir. This is one of the few Colorado forest types that is not fire-adapted - the typical fire return frequency is around 400 years. Areas with spruce-fir forest typically receive a lot of precipitation in the form of snowfall and frequent summer showers, but droughts can occur. During drought periods the stressed trees become susceptible to spruce-bud worm outbreaks, which can kill entire hillsides of trees in one summer. In the early 20th century, much of Colorado's old-growth spruce fir was cut for timber.

Characteristic species: Boreal owl, Three-toed woodpecker, Gray jay, Pine grosbeak (breeds only in Spruce-fir), pine marten, lynx

Current condition	Good
Exposure	Warming trend expected across entire ecosystem range, maximum summer temperatures may increase more in the eastern portion. Precipitation patterns change but probably no substantial decrease. Lower elevations most exposed.
Sensitivity	Increased drought may drive fires and insect outbreaks.
Adaptive capacity	An extended growing season may allow this ecosystem to slowly move into areas currently above treeline.
Vulnerability	Moderately Vulnerable
Confidence	Medium Uncertainty regarding the degree of impact from insect outbreaks and fire events, however, the Pagosa Ranger District and the adjacent Rio Grande NF recently experienced 85% die back of mature spruce trees.

Spruce-fir forests in the San Juan / Tres Rios have a wide elevational range, extending from about 8,900 ft up to over 12,000 ft. This forest type is widespread in the San Juan mountains at the northern edge of the area, overlapping with alpine at its upper end, and with aspen and mixed conifer forests at lower elevations.

In the San Juan Mountains, forested areas are restricted to relatively wet and cool areas; spruce-fir forest dominates the wettest and coolest habitats below treeline. The annual average precipitation is slightly lower than for alpine with a range of 31.8-46.8 in. (81-119 cm) with a mean of 39.3 (100 cm).

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, Smith et al. 2003, Holtmeier and Broll 2005). 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).

In the San Juan mountains, 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 where such dispersal is not otherwise constrained. Since spruce-fir may be able to tolerate warmer summer temperatures, the lower extent of this habitat type may be able to remain at current levels for some time, if soil moisture remains adequate. There is some indication that Engelmann spruce germinates faster at relatively low temperatures (Smith 1985), giving it a competitive advantage over less cold-tolerant species under moist conditions. 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.

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). 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 (Rocheffort et al. 1994).

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. Insect and disease outbreaks are typically associated with droughts, thus, the

combination of increased fire and insect risks means that the spruce-fir forest are vulnerable to changes by 2050.

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. Under 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 or conversion to aspen in spruce-fir forests, at least in the short term, and depending on local site conditions.

The climate-based models of Crookston et al. (2010) shown below indicate a changed distribution of suitable habitat for spruce-fir forest by 2060, especially in the eastern portion of the San Juan / Tres Rios area, generally in agreement with our vulnerability ranking, although effects may take longer to become evident.

Spruce-fir	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0(°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Abies lasiocarpa</i>	-23 to -6	11 to 16	36 – 125		0.5 – 0.98
<i>Picea engelmannii</i>	-13 to -5	10 to 17	44 – 120		0.52 – 0.97
Ecosystem in SJTR	-9 to -6	9 to 13	87-113	1200 - 1870	0.77-0.88
Ecosystem on USFS/BLM					
Weather Stations					
Silverton (9,720 ft)	-9	13	62	1631	
El Diente Peak SNOTEL (10,000 ft)	-7	12	83		
Molas Lake SNOTEL (10,500 ft)	-8	11	78		
Wolf Creek Pass 1E (10,640 ft)	-8	12	115	1308	
Wolf Creek Summit SNOTEL (11,000 ft)	-8	11	127		

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 8,900-13,400 ft (mean 10,450 ft) in SJTR.
Narrow bioclimatic envelope	-	Not a concern. Well defined envelope below alpine and above other conifers and aspen.
Vulnerable to increased pest attacks	High	Interaction with drought and warmer temperatures likely to increase vulnerability.

Vulnerable to increased grazing/browsing	-	Not a concern.
Vulnerable to increased invasive species and encroachments from natives	-	In some areas novel combinations of conifers may establish, especially within the given time frame.
Barriers to dispersal	-	None known, but regeneration may be low after large fire events. Some trees are likely to remain after extensive insect outbreaks.
Vulnerable to fire	Medium	Under drought conditions and with earlier snow melt, lower elevation fires are more likely to move into spruce-fir. It is unclear if these forests can come back as spruce-fir after a large fire. In some areas novel combinations may occur.
Vulnerable to drought	Medium	More drought expected. Drought drives vulnerability to fire and insect outbreaks.
Vulnerable to timing of snowmelt	Medium	May be vulnerable at the end of summer; if earlier melt results in lower moisture availability at end of growing season.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	-	Generally in very good condition with little fragmentation.

Abies lasiocarpa

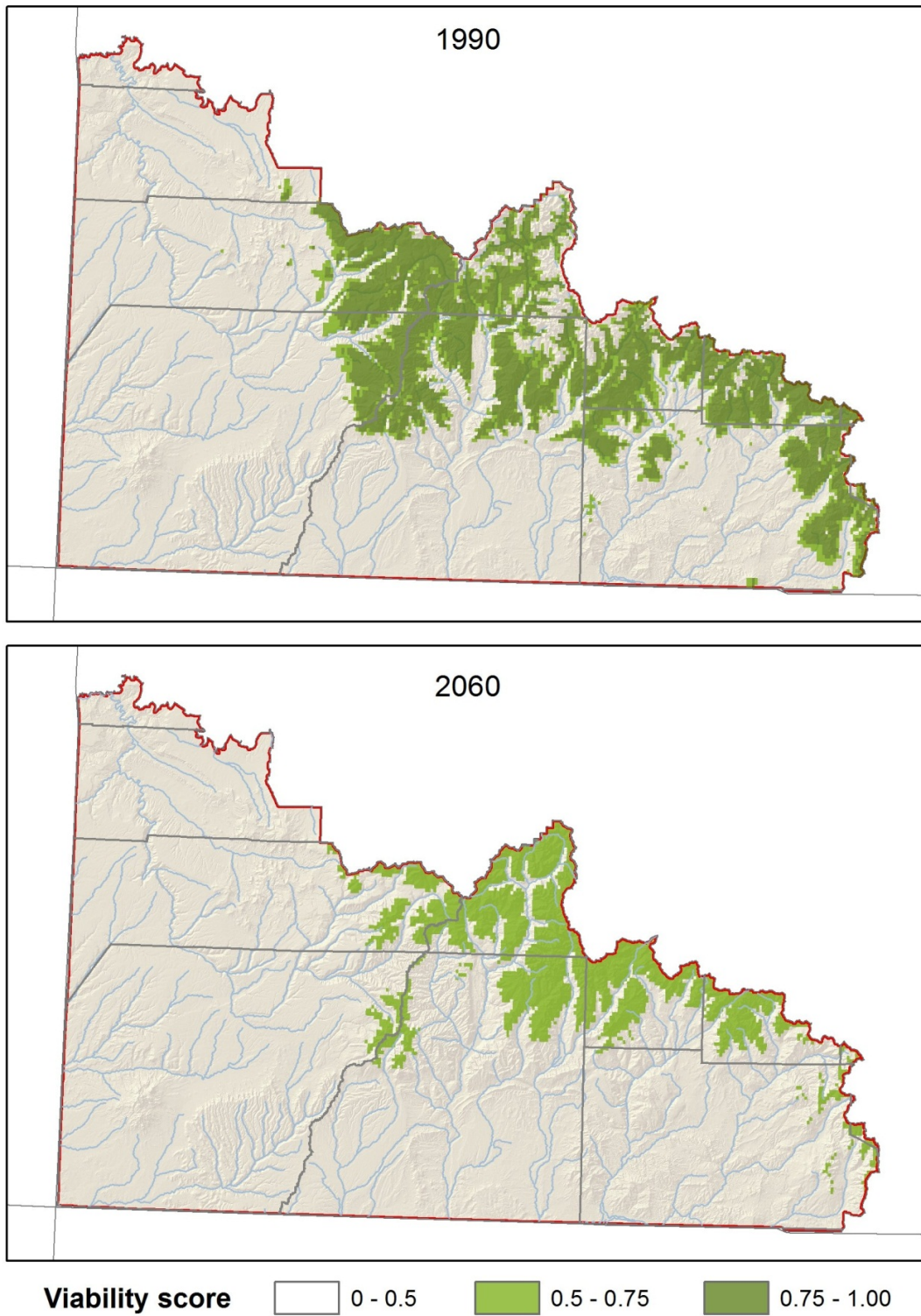


Figure 13. Predicted suitable habitat for subalpine fir under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

Picea engelmannii

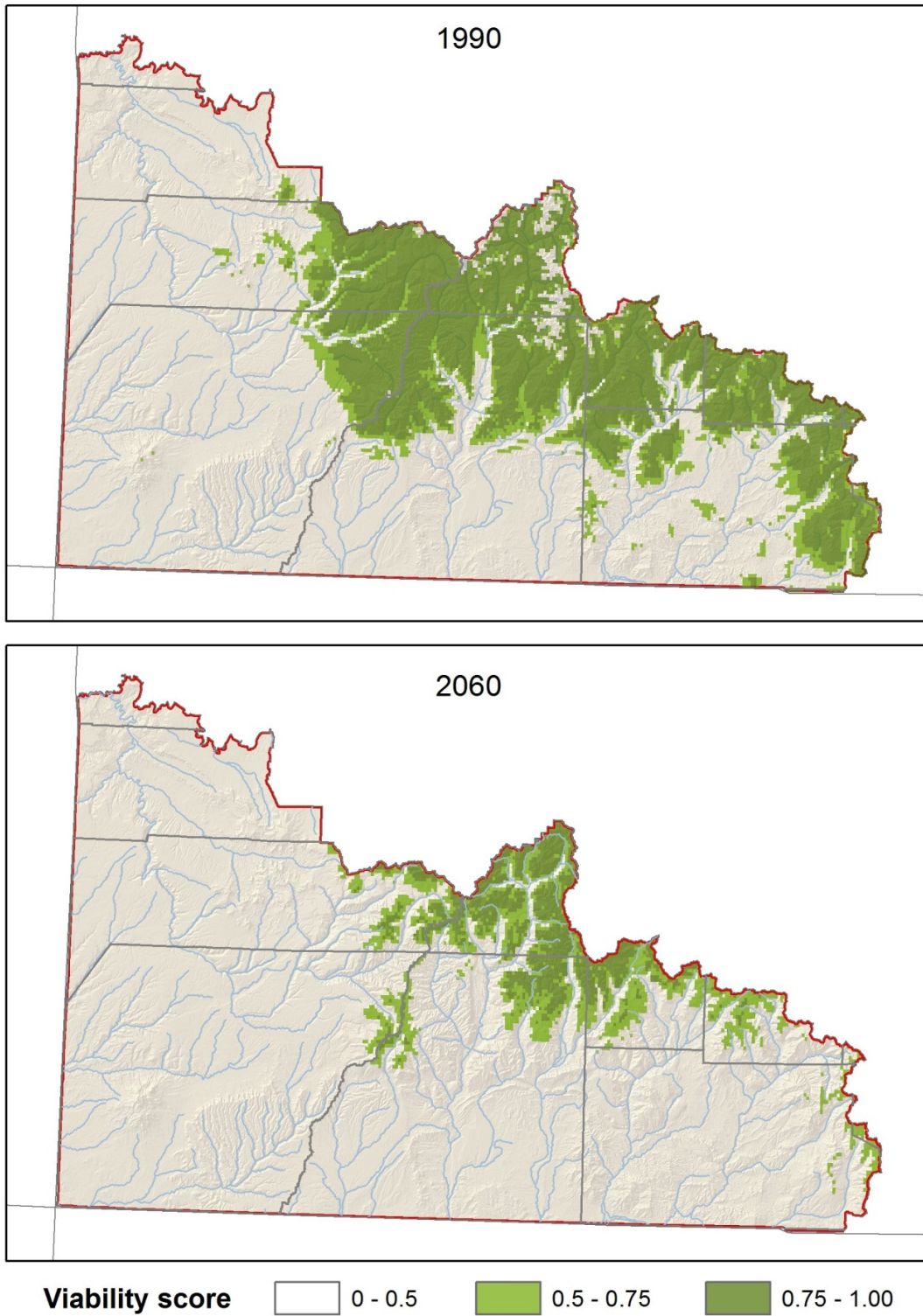


Figure 14. Predicted suitable habitat for Engelmann spruce under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

MONTANE GRASSLAND

Montane to subalpine grasslands in the San Juan Mountains are found at elevations of 7,000-12,000 feet, intermixed with stands of spruce-fir, ponderosa, and aspen forests, as park-like openings that vary in size from a few to several thousand acres. Lower elevation montane grasslands are more xeric, while upper montane or subalpine grasslands are more mesic. Typical species include Thurber's fescue, elk sedge, western wheat grass, mountain muhly, indian rice grass, squirrel tail, blue grama, oatgrass, and others. Trees and shrubs are generally sparse or absent, but occasional individuals from the surrounding communities may occur. In general, these grasslands experience long winters, deep snow, and short growing seasons.

Characteristic species: *Western meadowlark, Vesper sparrow, Gunnison's prairie dog, Burrowing owls*

Current condition	Good
Exposure	Warming trend expected across entire ecosystem range. Lower elevation types are most exposed.
Sensitivity	Change in precipitation patterns could facilitate encroachment by woody species in some areas, although increased fire may offset this trend.
Adaptive capacity	Species diversity may enable these communities to respond more quickly to changes than adjacent forest types.
Vulnerability	Presumed stable to slightly vulnerable at lower elevations
Confidence	Low

The general climate in the range of this ecological system is typically montane to subalpine, characterized by cold winters and relatively cool summers, although temperatures are more moderate at lower elevations. Montane grasslands in the San Juan / Tres Rios have a wide elevational range, from 7,000 to around 12,000 ft, and a mean of 8,640 feet.

Associations are variable depending on site factors such as slope, aspect, precipitation, etc., but generally lower elevation montane grasslands are more xeric and dominated by *Muhlenbergia* spp., *Pseudoroegneria spicata*, *Festuca arizonica*, and *Festuca idahoensis*, while upper montane or subalpine grasslands are more mesic and may be dominated by *Festuca thurberi* or *Danthonia intermedia*. *Danthonia parryi* is found across most of the elevational range of this system. In the San Juan Mountains of southwestern Colorado, these grasslands are dominated by *Festuca thurberi* and other large bunch grasses (Jamieson et al. 1996).

The geology of the Southern Rocky Mountains is extremely complex, therefore, soils are also highly variable, depending on the parent materials from which they were derived and the conditions under which they developed. Soil texture is important in explaining the existence of montane-subalpine grasslands (Peet 2000). These 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).

The most extensive montane grasslands in the area are in the vicinity of Pagosa Springs, on the western and southern flanks of the San Juan Mountains. Annual precipitation range is 17-47 in (43-120 cm) with a mean of 29.5 in (75 cm) in the San Juan / Tres Rios, and the majority of this falls as snow. Snow cover in some areas can last from October to May, and serves to insulate the plants beneath from periodic subzero temperatures. Other areas are kept free from snow by wind. Rapid spring snowmelt usually saturates the soil, and, when temperatures rise plant growth is rapid. Xeric montane grasslands, accounting for about 60% of this type in the study area, are generally found below 8,000 to 8,500 feet, with mean annual precipitation of 23.9 in., while mesic types above 8,500 ft. average 38.5 in (97 cm) annually.

A variety of factors, including fire, wind, cold-air drainage, climatic variation, soil properties, competition, and grazing have been proposed as mechanisms that maintain open grasslands and parks in forest surroundings. Observations and repeat photography studies in sites throughout the southern Rocky Mountains indicate that trees do invade open areas, but that the mechanisms responsible for this trend may differ from site to site. In the San Juan Mountains, Zier and Baker (2006) also found that the probability of tree invasion varied with forest type. 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). In the Gunnison Basin, Schauer et al. (1998) identified seedling mortality as the primary factor preventing invasions of Engelmann spruce, but did not determine if this was due to competition from established grassland plants, or to edaphic conditions.

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 grasslands was apparently linked to higher summer nighttime temperatures, and less frost damage to tree seedlings; this trend would continue under projected future temperature increases. Pocket gophers (*Thomomys* spp.) are a widespread source of disturbance in montane-subalpine grasslands. The activities of these burrowing mammals result in increased aeration, mixing of soil, and infiltration of water, and are an important component of normal soil formation and erosion (Ellison 1946). In addition, Cantor and Whitham (1989) found that below-ground herbivory of pocket gophers restricted establishment of aspen to rocky areas in Arizona mountain meadows. The interaction of multiple factors indicates that management for the maintenance of these montane and subalpine grasslands may be complex.

Drought and warmer temperatures may change species composition, or allow invasion by 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).

Floristic composition in these 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 a grassland occurrence. This system is also naturally adapted to grazing and browsing by native herbivores including deer, elk, bison, and pronghorn, as well as burrowing and grazing by small mammals. A cessation or reduction of grazing, in combination with favorable future climatic conditions could favor increased tree establishment in montane grasslands. Likewise, continued grazing could counteract tree invasions under projected future warming conditions.

Montane grassland High and low	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species					
<i>Festuca thurberi</i>	-10 to 14 total range		46 -76	Frost free 2 months	
<i>Festuca arizonica</i>	-11 to 6, mean -3	10 to 27, mean 18	510 mm avg <360 mm avg	153 ff days	
<i>Muhlenbergia</i> spp.					
Ecosystem in SJTR					
Above 8,500 ft.	-8 to -5	9 to 15	81 - 113	1215 - 2170	0.70 – 0.88
Below 8,500 ft.	-5 to -3	16 to 19	43 - 73	2415 - 3150	0.50 – 0.72
Ecosystem on USFS/BLM					
Weather Stations					
Pagosa Spgs. (7,110 ft)	-7	18	55	2963	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 6,550-12,000 ft (mean 8,640 ft) in the SJTR.
Narrow bioclimatic envelope	-	Wide bioclimatic span: xeric types at lower elevation, and mesic types at higher altitudes.
Vulnerable to increased pest attacks	-	Not a concern.

Vulnerability Factor	Rating	Comments
Vulnerable to increased grazing/browsing	Low	Variable effects possible, may facilitate or decrease tree growth
Vulnerable to increased invasive species and encroachments from natives	Low	Shrub or tree encroachment may occur in some areas.
Barriers to dispersal	-	None known.
Vulnerable to fire	Low	Vulnerability may depend on soil type.
Vulnerable to drought	Low	Xeric locations more vulnerable.
Vulnerable to timing of snowmelt	Medium	Patterns of snow deposition and meltoff may influence local species composition.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	-	Current impacts are low.

ASPEN

Aspen forests are quite common in the San Juan Mountains. These upland forests are dominated by quaking aspen, or mixed aspen and conifer, and range in elevation from about 7,500 to 10,500 feet. They usually occur as a mosaic of many plant associations and may be surrounded by a diverse array of other systems, including grasslands, wetlands, coniferous forests, etc. Aspen forests are one of our most species-rich ecosystems. Most of the plant and animal species that inhabit aspen forests are relatively abundant and not of significant conservation concern.

Characteristic species: Warbling vireo, Red-naped sapsucker, House wren, Goshawk, Hairy woodpecker

Current condition	Fair to Good Depends on elevation
Exposure	Warming trend expected across entire ecosystem range, maximum summer temperatures may increase more in the eastern portion. Precipitation patterns change but no substantial decrease expected. Lower elevations and southwestern facing slopes are more exposed.
Sensitivity	Decreasing precipitation and increased temperatures is likely to stress stands at lower elevations and southwestern facing slopes.
Adaptive capacity	Vegetative reproduction allows this ecosystem to colonize disturbed areas relatively quickly.
Vulnerability	Presumed Stable (except at lowest elevations)
Confidence	Medium

Quaking aspen has the largest distribution of any tree native to North America (Little 1971). The range of this species has expanded dramatically since the end of the last glacial maximum, during which the greater part of its range was covered by the Cordilleran and Laurentide ice sheets. Quaking aspen is able to grow on a wide variety of sites, both dry and mesic (Mueggler 1988). Climatic conditions, in particular minimum winter temperatures and annual precipitation amounts are variable over the range of the species (Howard 1996). In general, quaking aspen is found where annual precipitation exceeds evapotranspiration, and the lower limit of its range coincides with a mean annual temperature of about 7°C (Perala 1990). In the central Rocky Mountains, quaking aspen distribution is highly correlated with elevation, due to its influence on temperature and precipitation patterns.

In the San Juan / Tres Rios, aspen distribution is primarily dictated by fire frequency and severity within the bioclimatic envelope (Romme et al. 1996). Aspen forests are generally found within the lower range of spruce-fir forests, and are often adjacent to mixed-conifer and ponderosa pine forest, or montane shrubland and grasslands. Elevations are mostly between 8,000 and 10,500 ft. (mean 9,200 ft), broadly overlapping the range of mixed-conifer and the lower portion of spruce-fir. The majority of stands (85%) are above 8,500 ft. Annual precipitation range of 15.7-42.9 in (63-102 cm), and mean of 22.8 in (83.5 cm)

are similar to that of cool-moist mixed conifer. Aspens are sensitive to moisture availability; Rocky Mountain stands generally occur where annual precipitation is greater than 14.9 in (38 cm) per year (Morelli and Carr 2011) and summer temperatures are moderate.

Aspen is extremely shade intolerant, and able to establish quickly over a disturbed open area due to its ability to reproduce by vegetative sprouting (Howard 1996). The tufted seed capsules produced by mature aspen trees are amenable to wind dispersal over a considerable distance. Although quaking aspen establishment from seed is common in Alaska, northern Canada and eastern North America, this is less true in the western US, probably because germinated seedlings do not receive sufficient moisture for survival (Kay 1993). There is conflicting evidence for the frequency of seedling establishment in the western US, however, and quaking aspen may establish from seed more frequently than previously thought (Howard 1996, Romme et al. 1997).

There is some evidence for synchronous aspen stand establishment events over a large area of the intermountain west. Kaye (2011) identified two peak periods of establishment via sexual reproduction, the first in the period 1870-1890, and the other in 1970-1980. She speculates that the earlier establishment event may be the legacy of the last large fire events before widespread fire suppression in the intermountain west. The second establishment peak corresponds with improved moisture conditions due to a shift in the Pacific Decadal Oscillation and the Atlantic Multidecadal Oscillation. Elliot and Baker (2004) found that aspen stands in the San Juan Mountains are regenerating and increasing in density. Furthermore, they believe that aspen increase at treeline is occurring as a result of establishment from seed.

Although aspen is not fire tolerant, it is highly competitive in burned areas if other conditions are suitable. Monitoring the response of aspen stands in the area of the 2002 Missionary Ridge fire near Durango may give an indication of the future of aspen forests in southwest Colorado. Aspen clones survive in the understory of cool, moist mixed conifer and low elevation spruce-fir, and can respond quickly to disturbances. However, Morelli and Carr (2011) predict an uncertain future for aspen in the West, where increased drought, ozone, and insect outbreaks can interact with carbon dioxide fertilization and warmer soils, resulting in unknown cumulative effects.

Vulnerability of aspen to pathogens and herbivores, and subsequent aspen mortality may be increased by climate change if drought and warmer conditions increase environmental stress (Morelli and Carr 2011). Heavy grazing by elk in combination with drought appears to be leading to decline in some areas (Morelli and Carr 2011). Stress from grazing could be mitigated by management actions. Canker infections, gypsy moth, and forest tent caterpillar outbreaks are tightly associated with drier and warmer conditions (Cryer and Murray 1992, Johnston 2001, Logan 2008, Hogg et al. 2002).

Aspens have increased susceptibility to episodic decline at lower elevations, under warm and dry conditions (Worrall et al. 2008). This aspen dieback (sometimes called Sudden Aspen Decline) appears to be related to drought stress, and is typically greatest on the hotter and drier slopes, which are usually at the lowest elevations of a stand (Rehfeldt et al. 2009). Stands may undergo thinning, but then recover. Increasing drought with climate

change is believed to be the primary vulnerability of this ecosystem (Worrall et al. 2013), and substantial loss of this type can be expected. The effects of drought are likely to interact with other stressors such as outbreaks of pests and disease, snowmelt timing, and ungulate herbivory.

Although the climate-based model of Crookston et al. (2010) shown below project a substantial decrease in aspen acreage for the San Juan area, our analysis concludes that, when the ability of these forests to take advantage of disturbance is considered, aspen is primarily vulnerable at lower elevations in the study area.

Aspen and aspen/mixed-conifer High and low	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Populus tremuloides</i>	-28 to -6	13 to 21	33 - 106		0.50 - 0.99
<i>Pseudotsuga menziesii</i>	-12 to 5	11 to 20	41 - 162		0.51 - 0.96
<i>Abies concolor</i>	-9 to 3	13 to 22	37 to 119		0.49 - 0.87
Ecosystem in SJTR					
Above 8,500 ft.	-7 to -5	12 to 15	74 - 97	1660 - 2285	0.68 - 0.84
Below 8,500 ft.	-6 to -4	15 to 17	60 - 80	2235 - 2630	0.62 - 0.79
Ecosystem on USFS/BLM					
Weather Stations					
Rico (8,780 ft)	-6	14	67	2040	
Silverton (9,720 ft)	-9	13	62	1631	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. The majority of stands are from 8,500-10,970 ft (mean 9,200 ft) in the SJTR.
Narrow bioclimatic envelope	-	A very widespread North American species.
Vulnerable to increased pest attacks	Low	Droughts increase vulnerability to pest and pathogen outbreaks.
Vulnerable to increased grazing/browsing	Medium	Intense grazing/browsing is known to degrade aspen stands. If a stand is stressed from climate, especially drought, then the stand will be less resistant to grazing/browsing pressures
Vulnerable to increased invasive species and encroachments from natives	-	Although climate change may increase invasive species, it is not believed to be a significant factor.

Vulnerability Factor	Rating	Comments
Barriers to dispersal	-	No major barriers.
Vulnerable to fire	-	Aspens have been found to be 200 times less likely to burn than spruce-fir stands (Bigler et al. 2005)
Vulnerable to drought	High (low elevations)	The 2002 drought killed some aspen stems; a prolonged drought could reduce aspen stands; those stands that are currently in mesic zones will probably fare better. Aspens may adapt by moving up in elevation.
Vulnerable to timing of snowmelt	Medium	Earlier snowmelt may lead to end-of-growing season drought stress.
Vulnerable to phenologic change	-	Although aspen growth could benefit from a longer growing season, the effects would depend in part on the timing of snowmelt replenishment of soil moisture.
Non-climate abiotic stressors	-	Generally in good condition, but with some fragmentation.

Populus tremuloides

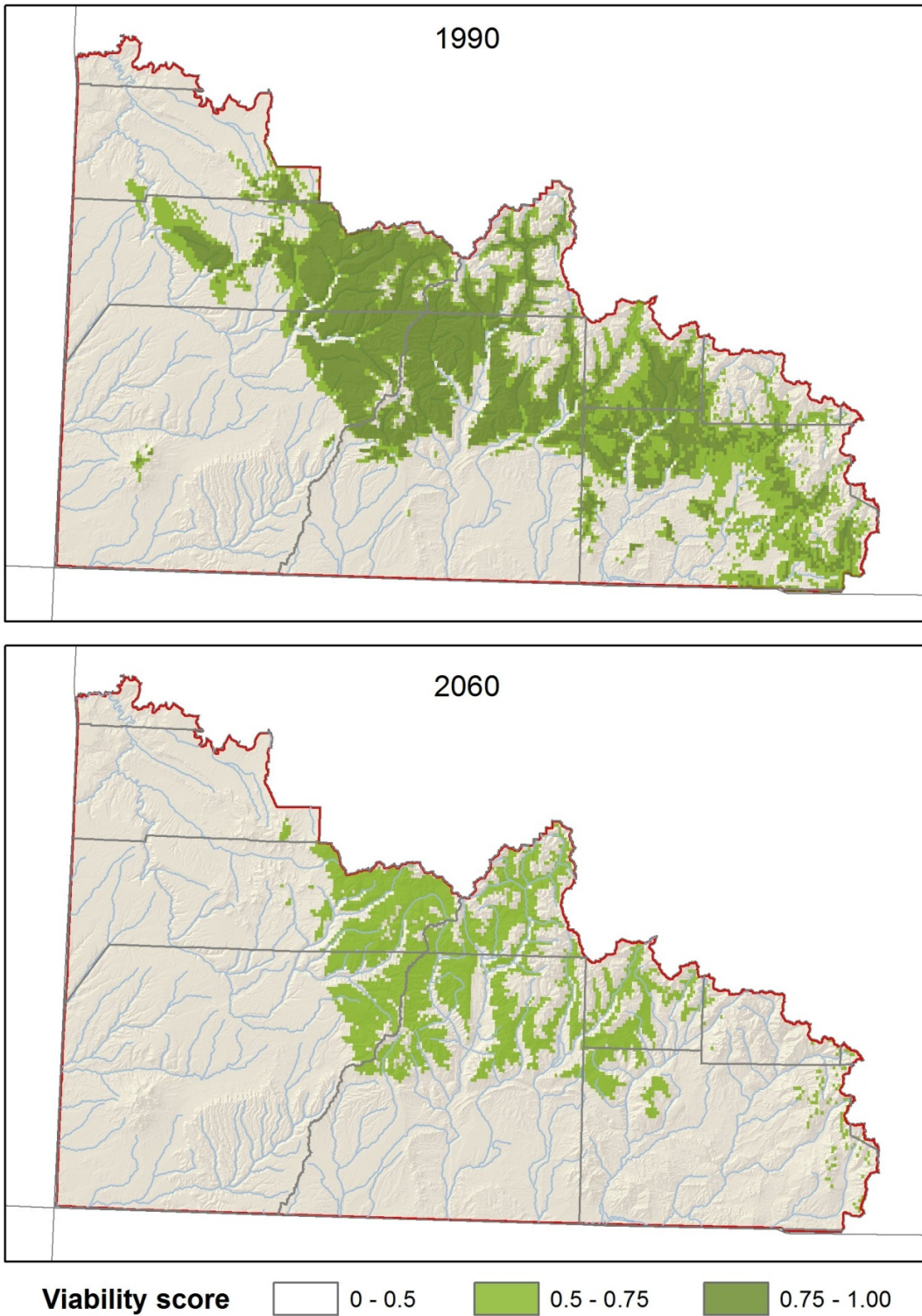


Figure 15. Predicted suitable habitat for quaking aspen under current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

MIXED CONIFER – Cool, moist & Warm, dry

In Colorado mixed-conifer forests occur on all aspects at elevations ranging from 4,000 to 10,800 feet. Douglas-fir and white fir are the most common dominant trees, but many different conifer species may be present, and stands may be intermixed with other forest types dominated by ponderosa pine or aspen. Douglas-fir stands are characteristic of drier sites, often with ponderosa pine. More mesic stands are found in cool ravines and on north-facing slopes, and are likely to be dominated by white fir with blue spruce or quaking aspen stands. Natural fire processes in this system are highly variable in both return interval and severity. Fire in cool, moist stands is infrequent, and the understory may be quite diverse.

Characteristic species: Ruby-crowned kinglet, Hermit Thrush, Hammond's FC, Williamson's sapsucker, Yellow-rumped warbler, Pine siskin, Red-breasted nuthatch, Townsend's solitaire, Western Tanager, Brown creeper, Cassin's finch, Red crossbill, Olive-sided flycatcher, Mountain chickadee, Juncos, Snowshoe hare, Lynx, Pine marten, Goshawk

Current condition	Good
Exposure	Warming trend expected across entire ecosystem range, maximum summer temperatures may increase more in the eastern portion, where these forests are more prevalent. Precipitation patterns change but probably no substantial decrease. Lower elevation and warm-dry types are most exposed, especially below 8,500 ft.
Sensitivity	Increased drought may drive fires and insect outbreaks. Relative proportions of component species may change.
Adaptive capacity	Highly variable species composition may endow this ecosystem with ability to persist under variable climate conditions.
Vulnerability	Cool-moist: Presumed stable Warm-dry: Presumed stable to Slight increase
Confidence	Low The ecotonal nature of this type makes it difficult to evaluate. Novel combinations may occur.

Mixed conifer forests in the San Juan / Tres Rios are generally between the elevations of about 7,500 ft. and 10,300 ft., where they are often adjacent to ponderosa, aspen or spruce-fir forest. Average elevation of cool-moist mixed conifer stands is slightly higher (8,920 ft.) than that of warm-dry stands (8,200 ft.). These mixed-species forests may include Douglas-fir, ponderosa pine, white fir, aspen, blue spruce, Engelmann spruce, subalpine fir, and limber pine, which reaches the southern limit of its distribution in the San Juan mountains. Stands are often in the transitional ecotone area between other forest types. Warm-dry sites are characterized by Douglas-fir, often with ponderosa pine and Gambel oak. Cool-moist stands are found in mesic ravines and on north-facing slopes, and are likely to be dominated by Douglas fir, white fir, blue spruce and some quaking aspen.

Cool-moist mixed conifer has an average annual precipitation range of 21.6-41.3 in (55-105 cm) with a mean of 32.7 in (83 cm). Annual averages for warm-dry mixed conifer stands range from 20.8 to 35.4 in (53-90 cm), with a mean of 28.8 in (73 cm). Growing degree days for mixed conifer stands are generally similar to those of aspen stands.

The similar environmental tolerances of mixed-conifer and aspen forest means that the two habitat types are somewhat intermixed in many areas. These forests appear to represent a biophysical space where a number of different overstory species can become established and grow together. Local conditions, biogeographic history, and competitive interactions over many decades are prime determinants of stand composition.

Although cool moist mixed-conifer forests are generally warmer and drier than spruce-fir forests, these stands are often in relatively cool-moist environments where fires were historically infrequent with mixed severity. When stands are severely burned, aspen often resprouts. Warm-dry mixed conifer forests had a historic fire-regime that was more frequent, with mixed severity. In areas with high severity burns, aspen or Gambel oak resprouts and dominates the site for a relatively long period of time.

The ecotonal nature of mixed conifer stands increases the difficulty of interpreting their vulnerability to climate change, and their capacity to move into new areas. Changing climate conditions are likely to alter the relative dominance of overstory species, overall species composition and relative cover, especially through the action of fire, insect outbreak, and drought. The diversity of species within this type, however, is expected to increase its flexibility in the face of climate change. Outcomes for particular stands are likely to depend on current composition and location. Drought and disturbance tolerant species will be favored over drought vulnerable species. Species such as blue spruce that are infrequent and have a narrow bioclimatic envelope are likely to decline or move up in elevation. Abundant species that have a wide bioclimatic envelope such as Gambel oak and aspen are likely to increase. Current stands of warm, dry mixed conifer below 8,500 ft may be at higher risk or may convert to pure ponderosa pine stands as future precipitation scenarios favor rain rather than snow. Upward migration into new areas may be possible.

The climate-based models of Crookston et al. (2010) shown below indicate a potential increase of habitat for Douglas fir and white fir in some areas of the San Juan / Tres Rios, while habitat suitable for the more mesic blue spruce could be largely eliminated. When other factors are taken into account, this is generally in agreement with our vulnerability estimate.

Mixed conifer cool-moist & warm-dry	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Pseudotsuga menziesii</i>	-12 to 5	11 to 20	41 - 162		0.51 - 0.96
<i>Abies concolor</i>	-9 to 3	13 to 22	37 to 119		0.49 - 0.87
<i>Picea pungens</i>	-11 to -5	10 to 20	34 - 82		0.45 - 0.90
Ecosystem in SJTR					

Cool-moist	-7 to -4	12 to 16	69 - 98	1720 - 2590	0.65 - 0.84
Warm-dry	-6 to -4	14 to 18	59 - 85	2060 - 3130	0.59 - 0.74
Ecosystem on USFS/BLM					
Weather Stations					
Rico (8,780 ft)	-6	14	67	2040	
Silverton (9,720 ft)	-9	13	62	1631	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 6,600 – 10,950 ft (mean 8,780 ft) in SJTR.
Narrow bioclimatic envelope	-	Narrower for cool-moist types.
Vulnerable to increased pest attacks	Medium/ Low	Outbreaks may alter composition.
Vulnerable to increased grazing/browsing	-	Not a concern.
Vulnerable to increased invasive species and encroachments from natives	-	May be replaced by ponderosa at lowest elevations.
Barriers to dispersal	-	None known, may be able to move into areas currently dominated by aspen or lower elevation spruce-fir.
Vulnerable to fire	Medium/ Low	Mixed regime fires may alter composition.
Vulnerable to drought	Medium/ Low	May be eliminated at lowest and driest elevations.
Vulnerable to timing of snowmelt	-	Not a concern.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	-	Generally in good condition, but with some fragmentation.

Pseudotsuga menziesii

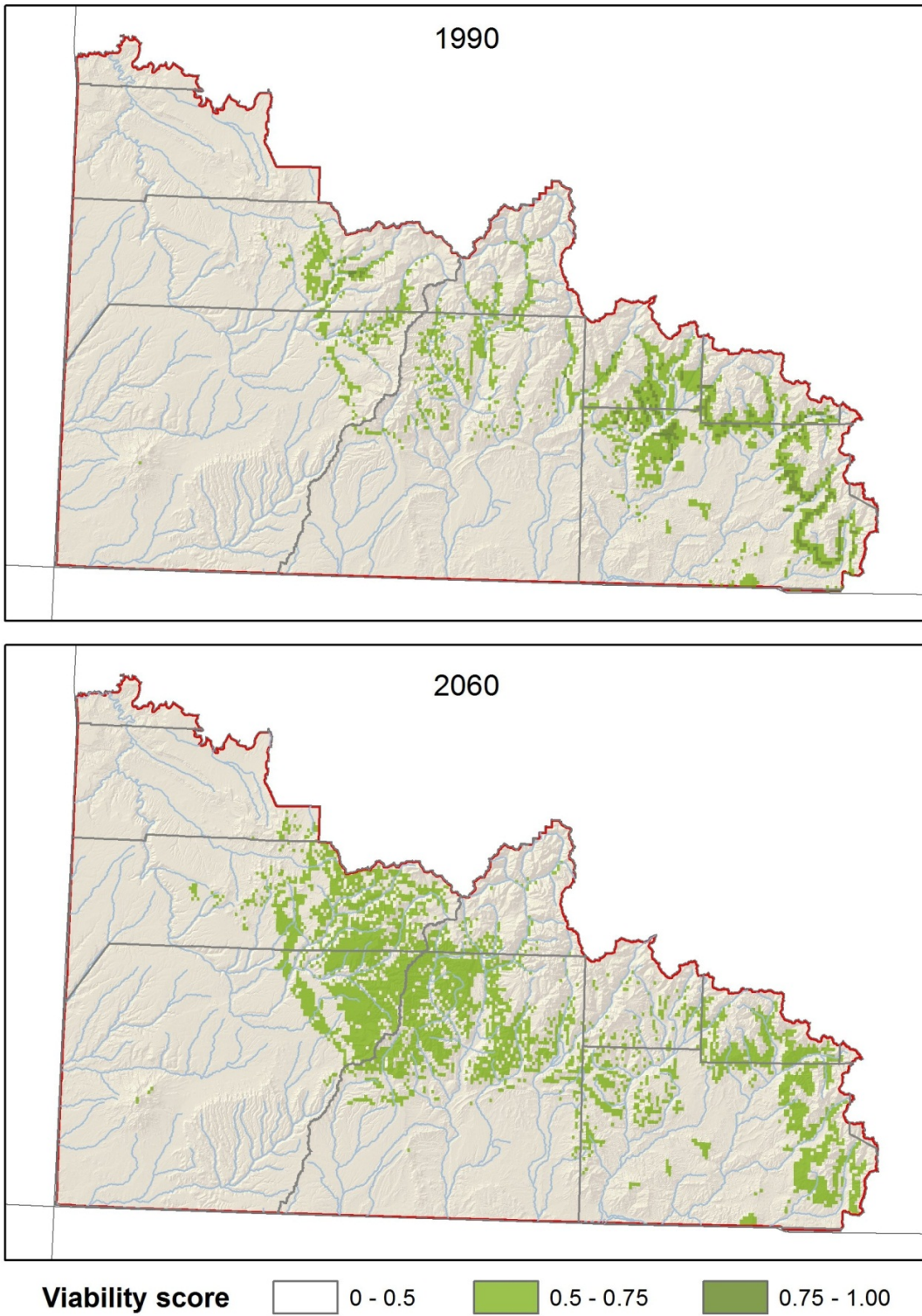


Figure 16. Predicted suitable habitat for Douglas fir current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

Abies concolor

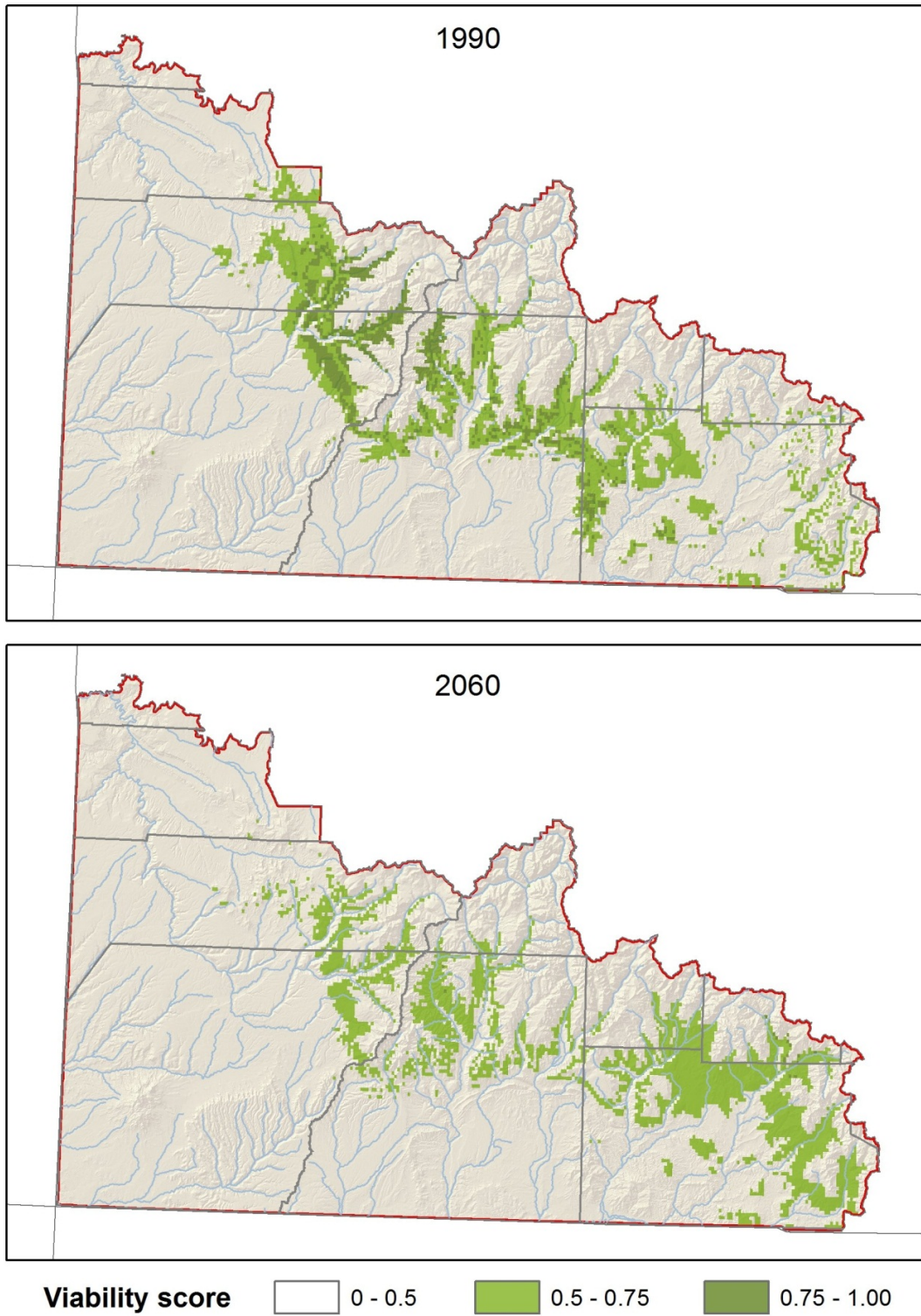


Figure 17. Predicted suitable habitat for white fir current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

Picea pungens

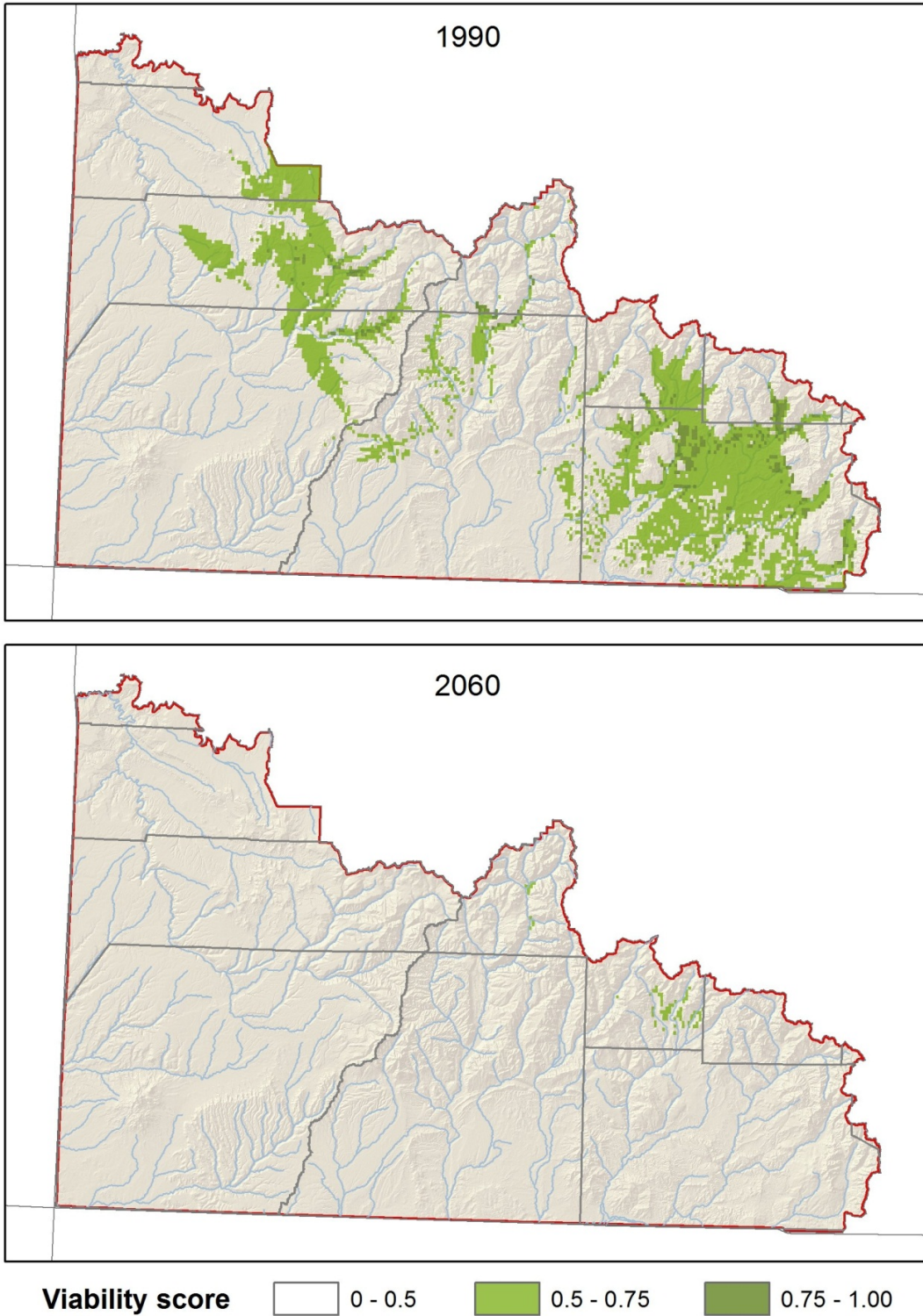


Figure 18. Predicted suitable habitat for blue spruce current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

OAK SHRUBLAND & MIXED MOUNTAIN SHRUBLAND

In Colorado, oak and mixed mountain shrublands are most common on the west slope, where they form extensive bands on the lower mountain slopes, plateaus, and dry foothills. Gambel oak is dominant in many stands, and often intermixed with stands dominated by other montane shrubs, such as serviceberry, mountain mahogany, antelope bitterbrush, big sagebrush, chokecherry, fendler bush, skunkbush, and snowberry. Both shrubland types may form dense thickets, or occur as open shrublands with an herbaceous understory. Although this is a shrub-dominated system, some trees may be present. Fire typically plays an important role in this system, causing shrub die-back in some areas, promoting stump sprouting of the shrubs in other areas, and reducing tree sprouting.

Characteristic species: Spotted towhee, Virginia warblers, Green-tailed towhee, Blue-gray gnatcatcher, Turkey, Black bear, Deer, Elk, Mountain Lion, few rare plants.

Current condition	Good
Exposure	Warming trend expected across entire ecosystem range, with winter daily maximum temperatures increasing the most within the distribution of this ecosystem. Precipitation changes uncertain, but may be greatest in some parts of the distribution of this ecosystem.
Sensitivity	Increased drought may drive fires and insect outbreaks. Relative proportions of component species may change. Late frosts and drought reduce productivity.
Adaptive capacity	Sprouting ability of most component species enhances recovery from disturbance. Variable species composition of mountain shrubland types may increase adaptive capacity of ecosystem as a whole. Likely to become dominant in stands where it is currently subdominant, especially after fire events.
Vulnerability	Presumed stable
Confidence	Medium

Oak and mixed mountain shrublands are widespread in the San Juan / Tres Rios at elevations from about 6,000- 9,500 feet, dominating a zone between pinyon-juniper at lower elevations and ponderosa pine forest at higher elevations. Stands dominated by Gambel oak are more common, but are completely interspersed with stands dominated by other shrub species, especially serviceberry with mahogany at higher elevations. Mixed mountain shrubland is somewhat imprecisely mapped in the San Juan / Tres Rios; at the highest elevations, mountain “shrublands” are stands of willows, short-statured aspen, and dwarfed spruce-fir (krummholz). Average annual precipitation for oak shrubland is 17.7-32.3 in (45-82 cm), with a mean of 24.9 in (63.4 cm). Precipitation amounts for mixed mountain shrubland are probably slightly higher.

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 systems 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 conditions of low fire frequency, vulnerable newly sprouted stems are able to persist, and form dense thickets.

In general, the upper and lower elevational limits of Gambel oak 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 (Harper et al. 1985).

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*), buckbrush (*Purshia tridentata*), wild crab apple (*Peraphyllum ramosissimum*), snowberry (*Symphoricarpos* spp.), and serviceberry (*Amelanchier* spp.), and chokecherry (*Prunus virginiana*). 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). In higher mountain shrub communities, fire return intervals were 20-30 years. 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 general, stands of these deciduous shrublands in the San Juan / Tres Rios are thought to not be vulnerable to climate change. Oak shrublands in the study area are well within the central portion of the species' distribution. 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. Insect pests and affecting Gambel oak include the wood borer (*Agrilus quercicola*) and the oak leafroller (*Archips semifera*). The western tent caterpillar (*Malacosoma californicum*) is a common defoliator of shrub species. Large outbreaks of these insects have historically been infrequent in Colorado oak and mixed mountain shrublands (USDA Forest Service 2010). 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.

Oak and mixed mountain shrublands are important habitat for wildlife, especially mule deer, turkey, and black bear (Jester et al. 2012). Calorie-rich acorns are an important food source for both bears and turkeys. Although oaks are most likely to do well under climate change, droughts may reduce the frequency of establishment through seedling recruitment by reducing seedling survival (Neilson and Wullstein 1983). The larger acorn-producing stems also appear to be more vulnerable to drought induced mortality. Because oak is generally unpalatable to cattle, livestock grazing can facilitate the increase of oak cover at

the expense of understory grasses (Mandany and West 1983). Native mule deer, however, browse oak and mixed mountain shrub species during most seasons (Kufeld et al. 1973).

The climate-based models of Crookston et al. (2010) for Gambel oak shown below indicate a moderate reduction in area suitable for the species by 2060. Our analysis concludes that, when the ability of these shrubs to persist under disturbance is considered, oak is likely to remain generally in the study area at least for the period up to mid-century.

Oak & Mixed mountain shrub	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Quercus gambelii</i>	-9 to 2	14 to 24	24 – 65		0.32 – 0.83
<i>Amelanchier utahensis</i>	-10 to 0	13 to 23	26 – 68		0.37 – 0.84
<i>Amelanchier alnifolia</i>	-25 to -5	12 to 21	34 - 107		0.50 – 0.94
Ecosystem in SJTR					
Oak	-5 to -3	15 to 19	51 - 76	2280 - 3130	0.51 - 0.74
Mixed mountain shrub*	-8 to -3	10 to 19	46 - 113	1250 - 3155	0.49 - 0.87
Ecosystem on USFS/BLM					
Weather Stations					
Durango (6,600 ft)	-4	20	48		
Pagosa Spgs. (7,110 ft)	-7	18	55		
Ft. Lewis (7,600 ft)	-5	18	45		

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 5,400-9,500 ft (generally below 12,000 ft) in the SJTR.
Narrow bioclimatic envelope	Low (Oak)	Demonstrated limiting combination of temperature and moisture stress.
Vulnerable to increased pest attacks	Low (Oak)	Infestations of defoliating insects are sporadic, but could increase with changing climate.
Vulnerable to increased grazing/browsing	Medium	Interaction with increased fire frequency could increase mule deer browsing.
Vulnerable to increased invasive species and encroachments from natives	Medium (mixed shrub)	Lower elevation areas are vulnerable to cheatgrass and knapweed invasion.
Barriers to dispersal	-	None known, although oak seedling recruitment is

		currently sporadic at edge of range.
Vulnerable to fire	-	Most species able to regenerate post-fire.
Vulnerable to drought	Low	Seedlings and older stems most vulnerable to drought.
Vulnerable to timing of snowmelt	Low (Oak)	Early snowmelt could increase late growing season moisture stress.
Vulnerable to phenologic change	-	Not a concern. Earlier average dates of last spring frost would benefit oak.
Non-climate abiotic stressors	-	In good condition, with limited fragmentation.

Quercus gambelii

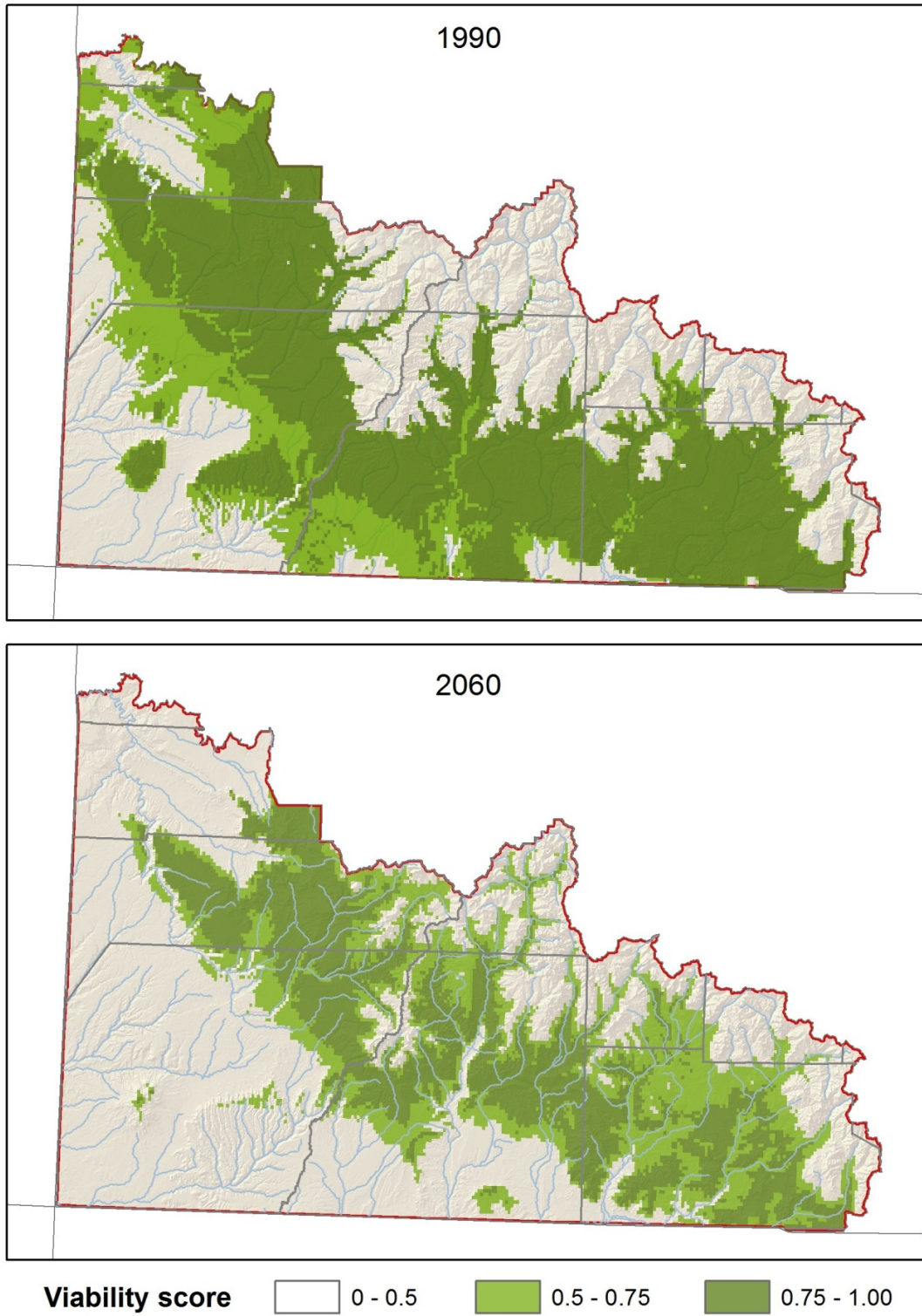


Figure 19. Predicted suitable habitat for Gambel oak (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

PONDEROSA PINE

In the San Juan / Tres Rios these matrix-forming forests occur at the lower treeline transition between pinyon-juniper woodlands, grasslands or shrublands and the more mesic coniferous forests above. Healthy ponderosa pine forests often consist of clumps of even-aged trees of various ages with an open fire tolerant grassy understory, or an understory of Gambel oak/mountain shrubland. Frequent, low-intensity ground fires are typical in these forests. In stands where the natural fire regime still occurs, shrubs, understory trees and downed logs are less frequent. A century of human development and fire suppression has resulted in a higher density of ponderosa pine trees in many areas.

Characteristic species: *Pygmy nuthatch, Western bluebird, Abert's squirrel, Flammulated owl*

Current condition	Good
Exposure	Warming trend expected across entire ecosystem range, with winter daily maximum temperatures increasing the most within the distribution of this ecosystem. Precipitation changes uncertain, but may be greatest in some parts of the distribution of this ecosystem.
Sensitivity	Increased drought may drive fires and insect outbreaks. Relative proportions of component species may change.
Adaptive capacity	Well adapted to warm, dry conditions, and able to establish on a variety of substrates, especially if precipitation not drastically changed. More fire tolerant than some other forest types.
Vulnerability	Presumed Stable
Confidence	Medium

Ponderosa pine forms a broad zone of coniferous forest along the southern flank of the San Juan Mountains in the San Juan / Tres Rios, generally at elevations between 6,750 and 8,750 (mean 7,715 ft). Nearly all (94%) ponderosa stands in the area are below 8,500 ft. At the upper elevation, ponderosa pine will be mixed with Douglas fir and white fir. At lower elevations, Rocky Mountain juniper may be present. Annual precipitation is similar to that for warm-dry mixed conifer and oak shrubland, with a range of 18.9- 35.8 in (48-91 cm) and a mean of 24.5 in (62.5 cm). Stands above 8,500 ft are cooler and wetter, with mean annual precipitation of 30.7 in (78 cm), compared to 24.2 in (61.5 cm) for lower elevation stands.

Ponderosa pine is able to tolerate fairly warm temperatures (including annual extremes up to 110°F), but soil moisture are likely to limit growth under dry conditions (Oliver and Ryker 1990). Although seeds are typically not dispersed very far, ponderosa pine is often present in warm-dry mixed conifer stands; these areas may provide a seed bank for

regeneration or a shift to ponderosa pine. Optimal germination and establishment conditions occur when temperatures are above 50°F and monthly precipitation is greater than 1 inch (Shepperd and Battaglia 2002). 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.

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 if it restores some pre-settlement conditions (Covington and Moore 1994). These forests are susceptible to outbreaks of the mountain pine beetle and mistletoe infestations, all of which may be exacerbated by increased drought. Impacts of native grazers or domestic livestock could also alter understory structure and composition, and have the potential to negatively impact soil stability (Allen et al. 2002). While ponderosa pine forests may be able to expand upwards in elevation or remain in the same vicinity if precipitation doesn't drastically change, the density of some stands may decrease due to a reduction in available soil moisture. Stands of lower elevations and southwestern-facing slopes are most likely to experience reduced extent of ponderosa pine forests, with the potential for replacement by grassland, shrubland or pinyon-juniper woodland.

The climate-based model of Crookston et al. (2010) shown below indicate a changed distribution of suitable habitat for ponderosa pine by 2060, especially in the eastern portion of the San Juan / Tres Rios area. Because acreage suitable for ponderosa may actually increase in some areas, we conclude that this ecosystem is likely to be stable in the period up to the mid-century.

Ponderosa High and low	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Pinus ponderosa</i>	-9 to 7	14 to 23	33 - 108		0.44 - 0.88
Ecosystem in SJTR					
Above 8,500 ft.	-6 to -4	14 to 16	67 - 87	2010 - 2480	0.64 – 0.83
Below 8,500 ft.	-5 to -3	16 to 19	52 - 72	2465 - 3110	0.52 – 0.70
Ecosystem on USFS/BLM					
Weather Stations					
Durango (6,600 ft)	-4	20	48	3799	
Mancos (6,910 ft)	-3	20	43	3764	

Pagosa Spgs. (7,110 ft)	-7	18	55	2963	
Ft. Lewis (7,600 ft)	-5	18	45	3179	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 6,500-8,750 ft (mean 7,715 ft) in the SJTR.
Narrow bioclimatic envelope	Low	Soil moisture may limit expansion.
Vulnerable to increased pest attacks	Medium	Outbreaks may be facilitated by drought.
Vulnerable to increased grazing/browsing	Low	Grazing may impact soil stability and increase the presence of exotic species in the understory.
Vulnerable to increased invasive species and encroachments from natives	Low	Weed encroachment is a concern and can change fire frequency.
Barriers to dispersal	-	None known.
Vulnerable to fire	Medium	Adapted to variable intensity fire regime.
Vulnerable to drought	Low	Increased drought increases fire vulnerability.
Vulnerable to timing of snowmelt	-	Not especially vulnerable to changes in snowmelt as most of the current precipitation is in the form of rain.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	-	Energy development is a factor in fragmentation of these forests in southern Colorado.

Pinus ponderosa

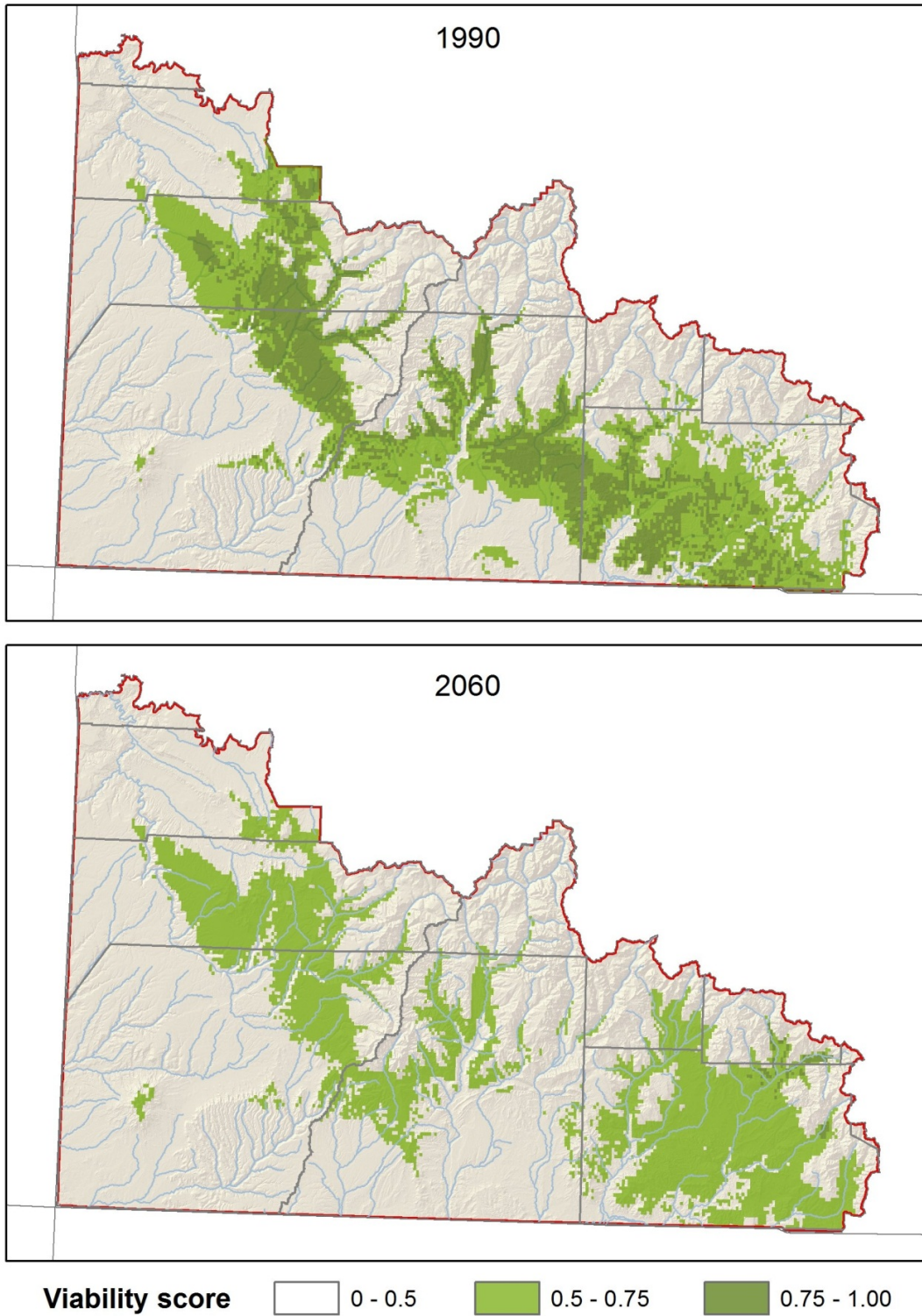


Figure 20. Predicted suitable habitat for ponderosa pine current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

PINYON-JUNIPER

This is the characteristic system of Colorado's western mesas and valleys, where it is typically found at lower elevations (ranging from 4,900 - 8,000 ft) on dry mountains and foothills. Pinyon pine and Utah, one seed, or Rocky Mountain juniper form the canopy. These woodlands often occur in a mosaic with other systems, including sagebrush, oak, and semi-desert shrublands. The understory is highly variable, and may be shrubby, grassy, sparsely vegetated, or rocky. Severe climatic events occurring during the growing season, such as frosts and drought, are thought to limit the distribution of pinyon-juniper systems to the relatively narrow altitudinal belts that they occupy.

Characteristic species: *Plumbeous vireo* – (*Gray flycatcher, black-throated gray warbler, Bushtit, Pinyon Jay*)

Current condition	Fair to Good
Exposure	Warming trend expected across entire ecosystem range, with winter daily maximum temperatures increasing the most within the distribution of this ecosystem. Precipitation changes uncertain, but may be greatest in some parts of the distribution of this ecosystem.
Sensitivity	Many stressors to pinyon-juniper woodland are exacerbated by warming temperatures.
Adaptive capacity	Pinyon and juniper have large ecological amplitudes, and have previously been successful in expanding into extensive areas of the southwest. Juniper appears to be more resistant to drought.
Vulnerability	Moderately vulnerable
Confidence	Low

Pinyon-juniper forms the characteristic woodland of warm, dry lower elevations in the San Juan / Tres Rios, and this type occupies substantial acreage. Stands are generally a mix of pinyon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*). In lower elevations, one-seed juniper (*J. monosperma*) may dominate, and at upper elevations Rocky Mountain juniper (*J. scopulorum*) can dominate in stands mixing with ponderosa pine. Elevations are generally between 5,400 and 7,650 ft, with a mean of about 6,600 ft. Annual precipitation is 11.8-23.6 in (30-60 cm), with a mean of 17.2 in (43.7 cm), similar to sagebrush shrubland.

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 across the landscape that may be naturally resilient.

Barger et al. (2009) found that pinyon 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. 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 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).

Extended drought can also 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 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. Juniper 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 reestablished. It is not known why trees have not been successful in these areas, which are now occupied by shrubland (Floyd et al. 2000).

The climate-based models of Crookston et al. (2010) shown below project a substantial reduction in area suitable for pinyon pine in the San Juan / Tres Rios area, and a slight decline for juniper species by 2060, generally in agreement with our assessment that these woodlands are moderately vulnerable and could eventually become dominated by juniper.

Pinyon-juniper	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Pinus edulis</i>	-7 to 2	18 to 23	22 - 46		0.29 – 0.68
<i>Juniperus osteosperma</i>	-8 to 1	17 to 24	18 - 50		0.26 – 0.65
<i>Juniperus scopulorum</i>	-12 to -2	11 to 21	31 - 92		0.42 – 0.93
Ecosystem in SJTR	-1 to -3	19 to 22	35 - 53	3110 - 3925	0.36 – 0.55
Ecosystem on USFS/BLM					
Weather Stations					

Durango (6,600 ft)	-4	20	48	3799	
Mancos (6,910 ft)	-3	20	43	3764	
Mesa Verde NP (7,110 ft)	-2	22	46	4668	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 5,000- 8,000 ft (mean 6,610 ft) in the SJTR.
Narrow bioclimatic envelope	Low	Relatively narrow in study area.
Vulnerable to increased pest attacks	High	Mediated by increased drought
Vulnerable to increased grazing/browsing	-	Not a concern.
Vulnerable to increased invasive species and encroachments from natives	-	Invasive annual grass in understory may change fire patterns somewhat.
Barriers to dispersal	Medium	Very slow migration into new areas, but able to establish seedlings in suitable microsites.
Vulnerable to fire	Medium	Driven by increased drought.
Vulnerable to drought	Medium	Drought may alter species composition.
Vulnerable to timing of snowmelt	-	Unknown.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	Low	Energy and exurban development have contributed to fragmentation.

Pinus edulis

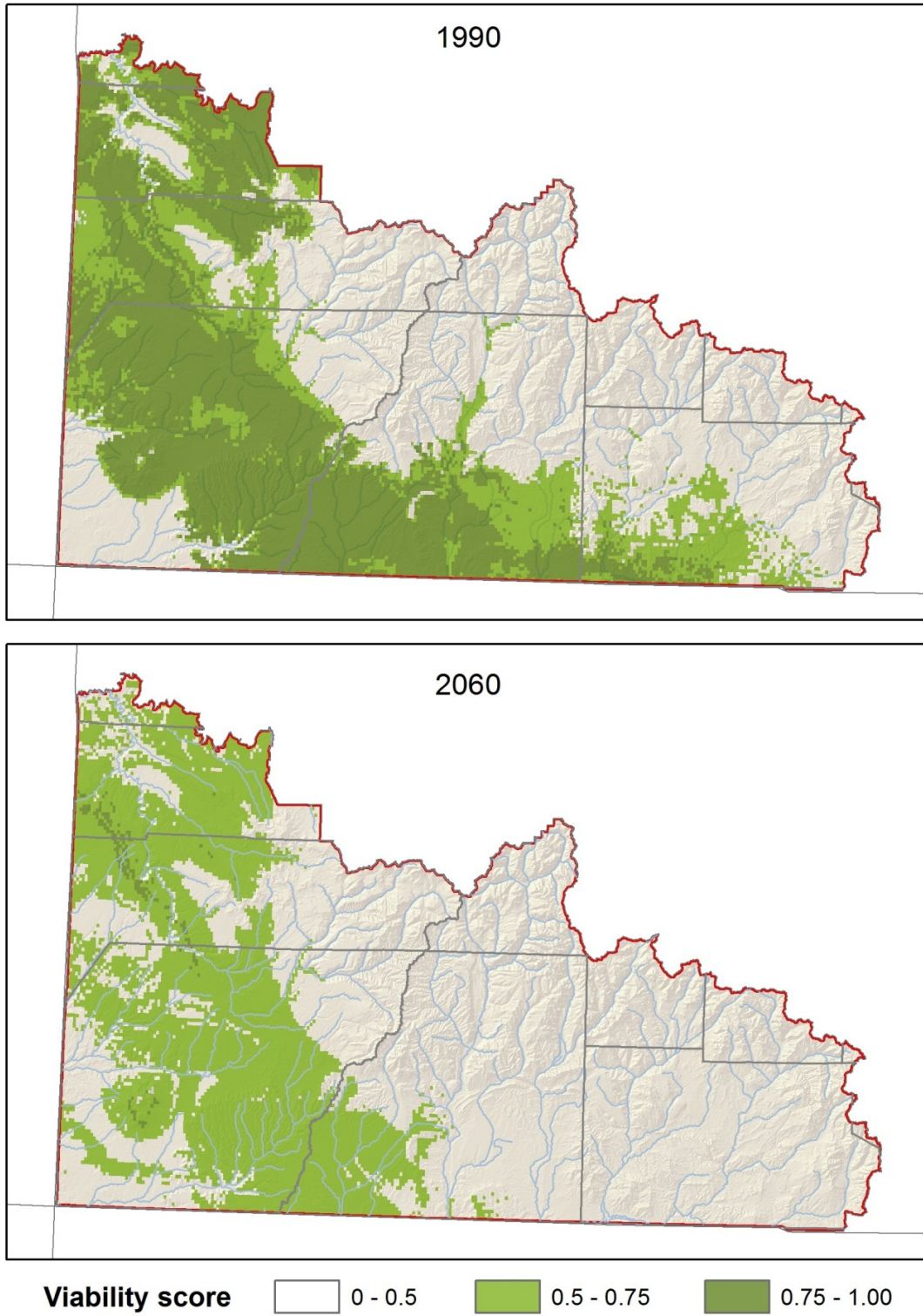


Figure 21. Predicted suitable habitat for pinyon pine current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

Juniperus scopulorum

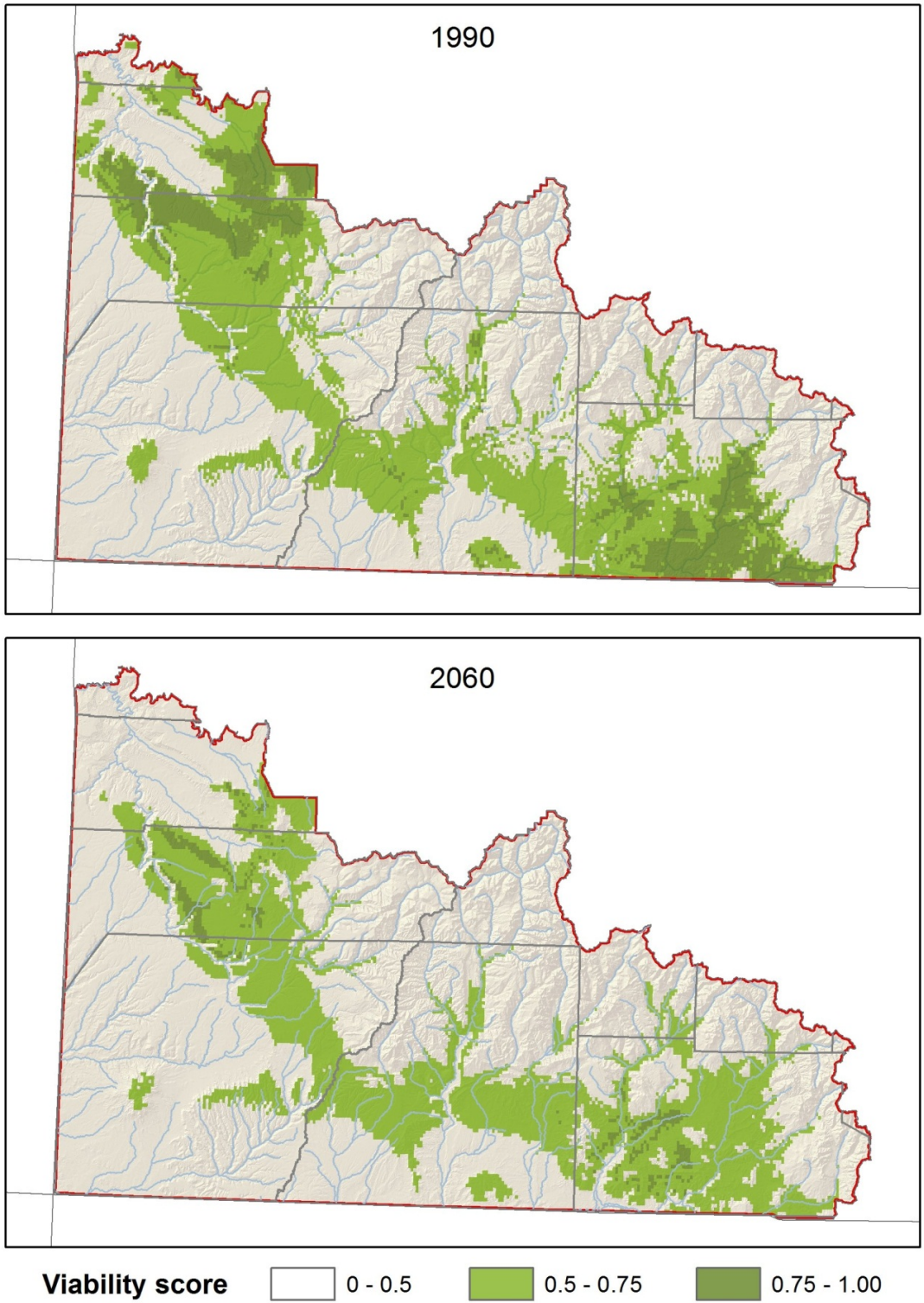


Figure 22. Predicted suitable habitat for Rocky Mountain juniper current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

Juniperus osteosperma

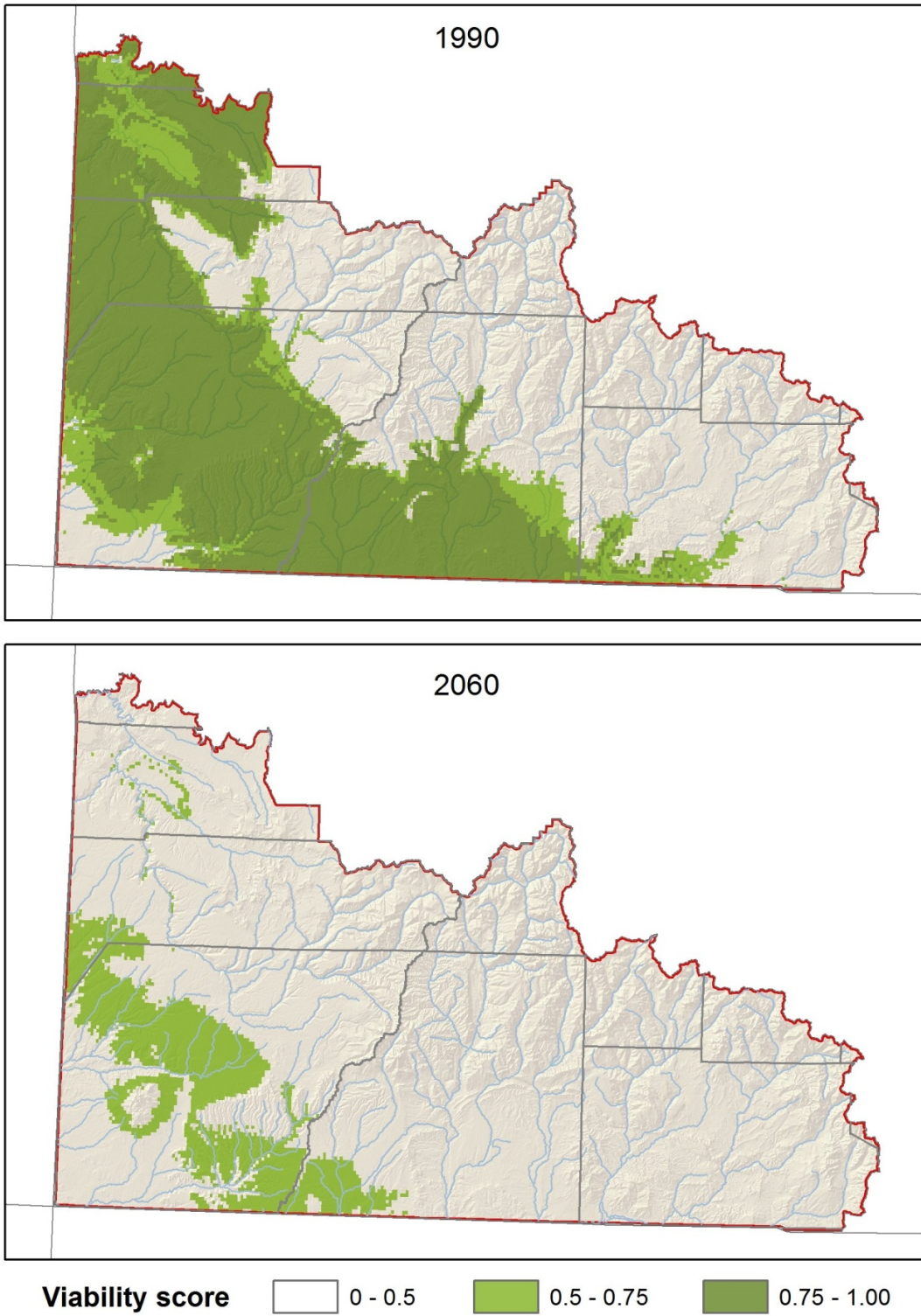


Figure 23. Predicted suitable habitat for Utah juniper current (to 1990) and future (2060) conditions as modeled under CGCM3 GCM, A2 scenario (Crookston et al. 2010).

SAGEBRUSH

Sagebrush shrublands occur throughout much of the western United States, where they are typically found in broad basins between mountain ranges, on plains and foothills. In western Colorado these shrublands are at the southeastern edge of the current ecosystem distribution (they are far more extensive in Nevada and Wyoming). Big sagebrush (*Artemisia tridentata* ssp. *tridentata*) shrublands are characterized by stands of taller sagebrush species with a significant herbaceous understory, and are generally found at elevations from 5,000 to 7,500 feet. The presence of the taller sagebrush species distinguishes these shrublands from the often adjacent montane sagebrush shrublands. Montane sagebrush stands in Colorado are found at elevations from 7,000 to 10,000 feet, typically on deep-soiled to stony flats, ridges, nearly flat ridgetops, and mountain slopes. These montane shrublands have a fairly dense canopy usually dominated by *Artemisia tridentata* ssp. *vaseyana* and a well-vegetated understory of grasses and forbs.

Characteristic species: Brewer's sparrow, Sage sparrow, Sage thrasher, Green-tailed towhee, Gunnison sage grouse, Gunnison's prairie dogs, Pronghorn

Current condition	Fair to Good
Exposure	Temperature increase predicted for entire distribution of this ecosystem. Precipitation change unclear.
Sensitivity	Seasonal timing of precipitation is important. Summer moisture stress may be limiting. Increased drought may increase fire frequency/severity. Increasing temperature may allow the invasion of frost-sensitive shrub species.
Adaptive capacity	Unknown
Vulnerability	Moderately vulnerable
Confidence	Low

The climate envelope of sagebrush shrublands in the San Juan / Tres Rios is broadly similar to that of pinyon-juniper woodlands, and the two types are widely interspersed. These shrublands are most prevalent in the lower elevations around Mesa Verde west to Ignacio, in the vicinity of Sleeping Ute mountain, and in the salt anticline valleys to the north of Dove Creek. Elevations range from 5,400 to 8,000 ft, with a mean of 6,630 ft. Stands are also often intermingled with desert shrubland or grassland. Precipitation for this type is similar to pinyon-juniper, with an annual range of 12.2-25.2 in (31-64 cm) and a mean of 17.2 in (43.8 cm).

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 CO₂ 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.

Because these are shrublands of lower elevations, they are not expected to be limited by a requirement for cooler, high elevation habitat. 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). 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. Warmer, drier sites (typically found at lower elevations) are more invasible by cheatgrass (Chambers et al. 2007). There is a moderate potential for invasion by knapweed species, oxeye daisy, leafy spurge, and yellow toadflax under changing climatic conditions, and a potential for changing fire dynamics to affect the ecosystem. There is no information on the vulnerability of this ecosystem in Colorado to insect or disease outbreak, although severe outbreaks of the sagebrush-defoliating moth *Aroga websteri* have been recorded further west in the Great Basin (Bentz et al. 2008). Grazing by large ungulates (both wildlife and domestic livestock) can change the structure and nutrient cycling of sagebrush shrublands (Manier and Hobbs 2007), but the interaction of grazing with other disturbances such as fire and invasive species under changing climatic conditions appears complex (e.g. Davies et al. 2009) and not well studied in Colorado.

Although sagebrush tolerates dry conditions and fairly cool temperatures it is not fire adapted, and is likely to be severely impacted by intense fires that enhance wind erosion and eliminate the seed bank (Schlaepfer et al. 2014). Increased fire frequency and severity in these shrublands could result increasing area dominated by exotic grasses, especially cheatgrass (D'Antonio and Vitousek 1992, Shinneman and Baker 2009).

Sagebrush	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Species in N. America (Thompson et al. 2000)					
<i>Artemisia tridentata</i>	-10 to -1	16 to 23	20 - 55		0.27 - 0.64
Ecosystem in SJTR	-4 to -1	18 to 22	34-56	2860 - 3960	0.37 - 0.62
Ecosystem on USFS/BLM					
Weather Stations					
Cortez (6,210 ft)	-3	22	33	4506	
Ignacio (6,420 ft)	-5	20	37	3796	

Yellow Jacket (6,860 ft)	-3	22	40	4341	
--------------------------	----	----	----	------	--

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 4,980-8,700 ft (mean 6,630 ft) in the SJTR.
Narrow bioclimatic envelope	Low	This ecosystem in the San Juan / Tres Rios is near the southeastern edge of the species range.
Vulnerable to increased pest attacks	-	Not a concern.
Vulnerable to increased grazing/browsing	Low	Potential changes in structure and function .
Vulnerable to increased invasive species and encroachments from natives	Medium	Invasion by exotic understory species, and by native tree species.
Barriers to dispersal	-	None known.
Vulnerable to fire	Medium	Not fire adapted, increased fire severity and frequency could drastically alter this ecosystem.
Vulnerable to drought	Medium	Most vulnerable on shallower soils.
Vulnerable to timing of snowmelt	Low	Most vulnerable at higher elevations.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	Medium	Habitat fragmentation by agriculture, energy development and exurban development.

DESERT GRASSLAND

The driest grasslands of the intermountain western U.S. occur on xeric sites on a variety of landforms, including swales, playas, mesas, alluvial flats, and plains where it is often found as large patches in mosaics with shrubland systems dominated by sagebrush, saltbush, blackbrush, mormon-tea, and other shrub species. Colorado's semi-desert grasslands are found primarily on dry plains and mesas of the west slope at elevations of 4,750-7,600 feet. These grasslands are typically dominated by drought-resistant perennial bunch grasses such as bluebunch wheatgrass, blue grama, galleta grass, and needle-and-thread, and may include scattered shrubs.

Characteristic species: Prairie dogs, burrowing owls, and small ground dwelling mammals

Current condition	Poor to Fair
Exposure	Temperature increases predicted to be greatest within the distribution of this ecosystem. Precipitation may decrease in summer.
Sensitivity	Unknown.
Adaptive capacity	Well adapted to warm, dry conditions, but already heavily impacted in many areas, which may decrease resilience.
Vulnerability	Highly vulnerable
Confidence	Low

Areas that previously supported desert grasslands in the San Juan / Tres Rios have been largely converted to agricultural use. Scattered grass-dominated stands remain in elevations below 7,000 ft, where they are often intermixed with shrubland or shrub-steppe. Typical dominant grass species are bluebunch wheatgrass (*Pseudoroegneria spicata*), blue grama (*Bouteloua gracilis*), James' galleta (*Pleuraphis jamesii*), and needle and thread (*Hesperostipa comata*). Grasslands at higher elevations are primarily montane types, discussed above. Annual precipitation is 10.6-23.2 in (27-59 cm) with a mean of 15.68 in (39.8 cm), slightly higher than that of desert shrublands. The climate range of these grasslands is similar to that of desert shrublands, but with somewhat cooler summer and winter temperatures.

Precipitation and temperature patterns apparently contribute to some grassland processes. Desert grassland species are generally drought tolerant (Dick-Peddie 1993). Desert grasslands are the driest of North American grasslands, and experience the longest growing season. Soils are typically aridisols, which are dry for most of the year, even during the growing season, and there is little infiltration of water into the soil (Sims and Risser 2000). Changes in the timing and amount of precipitation can affect the structure and persistence of grasslands. With their comparatively shallower root systems, grasses have an advantage over shrubs on shallow, poorly drained soils, whereas shrubs are favored on deeper soils where winter precipitation can penetrate deeply into the soil. Because shrubs are C₃ plants with higher cool-season activity (Asner and Heidebrecht 2005) they are able

to utilize winter precipitation to a greater extent than are warm-season grasses. Sims and Risser (2000) report that a mean annual temperature of 10°C is a threshold between grasslands dominated by cool-season (C₃) grasses and those dominated by warm-season (C₄) species. However, Munson et al. (2011) report a decline in perennial vegetation cover in grasslands of the Colorado Plateau with increases in temperature.

Remnant stands of desert grasslands have been highly altered by livestock grazing, and it is likely that grasslands formerly occupied some sites that are now covered by pinyon-juniper or shrubland (Dick-Peddie 1993). Grazing by domestic livestock can also influence the relative proportion of cool- vs. warm-season grasses, or favor the increase of woody shrub species.

These grasslands are vulnerable to invasion by exotic species, particularly cheatgrass. Extended drought can lead to widespread mortality of perennial grasses and allow the invasion of cheatgrass. Although frequent fires in grasslands may have been common historically, the introduction of cheatgrass has altered the dynamics of the system, and fire often results in cheatgrass dominance. Once overtaken by cheatgrass, more frequent fires are encouraged by the dry flammable material, leading to further domination by cheatgrass. Even a few cheatgrass plants in a stand will produce enough seed to dominate the stand within a few years after fire.

Desert grassland	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Ecosystem in SJTR	-3 to 0	19 to 24	29 - 53	3190 - 4325	0.31 - 0.58
Ecosystem on USFS/BLM					
Weather Stations					
Cortez (6,210 ft)	-3	22	33	4506	
Yellow Jacket (6,860 ft)	-3	22	40	4341	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	These are grasslands of lower elevations.
Narrow bioclimatic envelope	-	Not a concern.
Vulnerable to increased pest attacks	-	No information available.
Vulnerable to increased grazing/browsing	Low	Grazing may alter species composition, or encourage conversion to shrubland, but is not likely to increase dramatically under climate change.

Vulnerability Factor	Rating	Comments
Vulnerable to increased invasive species and encroachments from natives	High	Cheatgrass invasion is the primary threat.
Barriers to dispersal	-	None known.
Vulnerable to fire	-	Increased cover of cheatgrass could alter fire frequency.
Vulnerable to drought	High	Extended drought reduces vegetation cover and may facilitate cheatgrass invasion. Areas of deeper soils may convert to shrubland.
Vulnerable to timing of snowmelt	-	Unknown.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	High	These grasslands are highly fragmented and altered.

DESERT SHRUBLAND

Desert shrubland communities occur throughout the intermountain western U.S., and are typically open-canopied shrublands dominated by saltbush species or other shrubs tolerant of saline or alkaline soils typically derived from marine shales, siltstones and clay. These sparse to moderately dense low-growing shrublands are widespread at lower elevations in Colorado's western valleys. These shrublands occur primarily between 4,500 and 7,000 feet, although shrub-steppe may extend up to 9,500 feet in some areas. Grasses and forbs are generally sparse except in steppe areas transitional with grassland, and dominated by species tolerant of harsh soils. Some areas are essentially barren, or very sparsely vegetated. Pinyon-juniper woodlands and sagebrush shrublands commonly are adjacent at the upper elevations. Climate is generally arid or semi-arid with extreme temperature differences between summer and winter.

Characteristic species: Rare plant species, Loggerhead shrike, Ferruginous Hawk (wintering)

Current condition	Fair to Good
Exposure	Temperature increases predicted to be greatest within the distribution of this ecosystem. Precipitation may decrease in summer.
Sensitivity	Unknown.
Adaptive capacity	Well adapted to warmer, drier conditions. Dominant species may be able to utilize both groundwater and precipitation.
Vulnerability	Moderate increase
Confidence	High

Desert shrublands in the San Juan / Tres Rios area are generally restricted to elevations below 7,000 ft, and are most extensive in the southwestern corner of Colorado on Ute Mountain Ute tribal lands, and on valley floors of the salt anticlines (Disappointment Valley, Paradox Valley, and Dry Creek Basin) to the north. Saltbush and greasewood are typical dominant species. This is typically a system of extreme climatic conditions, with warm to hot summers and freezing winters. Annual precipitation is 8.6 - 20.1 in (22-51 cm) with a mean of 12.8 in (33 cm). The climate range of these shrublands is similar to that of desert grasslands, but with lower mean annual precipitation, and generally warmer winter and summer temperatures.

Munson et al. (2011) found decreased canopy cover in *Atriplex* shrublands with increasing temperature, which they attributed to increased evaporation and reduced water availability in the shale-derived soils. Thus, although these shrublands may be able to tolerate higher temperatures only when precipitation is adequate. However, in some semi-arid and arid systems, temporal variation in water availability may create positive feedbacks that facilitate encroachment of C3 woody plant species into areas formerly dominated by C4 grasses. Other desert shrub species with deeper root systems (e.g., blackbrush, greasewood, mormon tea, sagebrush) are better adapted to expand into grassy

areas than relatively shallow-rooted *Atriplex* species (Munson et al. 2011). Further differentiation between shrub species in the ability to utilize rainfall during particular seasons (Lin et al. 1996) may lead to changes in species composition in these shrublands. Shadscale saltbush (*A. confertifolia*) and other desert shrubs are typically dependent on spring soil moisture for growth, and have low metabolic activity during summer as the soil dries (Mata-González et al. 2014).

Where substrates are shallow fine-textured soils developed from shale or alluvium the naturally sparse plant cover makes these shrublands especially vulnerable to water and wind erosion, especially if vegetation has been depleted by grazing or disturbances, including fire. Historically, salt desert shrublands had low fire frequency (Simonin 2001). Desert shrublands typically have low fuel mass and low soil moisture, which tends to mitigate fire impacts (Allen et al. 2011). In the Great Basin, cheatgrass has demonstrably increased fire activity in sagebrush shrublands (Balch et al. 2013), but less is known about fire-sensitivity of these saline desert types. Fire tolerance of *Atriplex* species is varied; most surviving individuals are able to resprout. Fourwing saltbush (*Atriplex canescens*) in New Mexico had severe mortality from fire (62% killed), but surviving shrubs quickly resprouted and eventually recovered prefire stature (Parmenter 2008). Many of the dominant shrubs are palatable to domestic livestock.

Desert shrubland	Mean January temperature (°C)	Mean July temperature (°C)	Annual Precipitation (cm)	Growing Degree Days 0 (°C) base	Moisture Index (AET/PET)
Ecosystem in SJTR	-3 to 0	20 to 25	24 - 44	3390 - 4600	0.25 - 0.48
Ecosystem on USFS/BLM					
Weather Stations					
Cortez (6,210 ft)	-3	22	33	4506	

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern. Currently found from 4,750-7,500 ft (mean 5,650 ft) in the SJTR.
Narrow bioclimatic envelope	-	Not a concern.
Vulnerable to increased pest attacks	-	No information available.
Vulnerable to increased grazing/browsing	-	Grazing could be an added stress.
Vulnerable to increased invasive species and encroachments from	Low	Invasive exotic plant species of concern are Russian knapweed and cheatgrass.

Vulnerability Factor	Rating	Comments
natives		
Barriers to dispersal	-	None known.
Vulnerable to fire	-	Not a concern unless significant cover of cheatgrass is present to carry fire.
Vulnerable to drought	Low	Primarily on fine-textured, alkaline soils.
Vulnerable to timing of snowmelt	-	Unknown.
Vulnerable to phenologic change	-	Not a concern.
Non-climate abiotic stressors	Low	Habitat fragmentation by energy development.

RIPARIAN / WETLAND / FEN

Riparian and wetland areas are found at all elevations. Smaller (1st and 2nd order) streams at higher elevations include upper montane, alpine and subalpine riparian, generally found above 8,500 ft. Vegetation is riparian shrublands occurring as narrow bands of shrubs lining streambanks and alluvial terraces in narrow to wide, low-gradient valley bottoms and floodplains with sinuous stream channels. Many of the plant associations found within this system are associated with beaver activity. This system often occurs as a mosaic of multiple communities that are shrub- and herb-dominated and includes above-treeline, willow-dominated, snowmelt-fed basins that feed into streams. High-elevation, groundwater-dependent wetlands include fens, seeps and springs, and other wetlands above about 9,000 ft that are not strongly associated with stream systems. At montane elevations from about 7,500 to 9,000 ft, riparian areas consist of seasonally flooded forests and woodlands where snowmelt moisture in may create shallow water tables or seeps for a portion of the growing season. At lower montane elevations and below, riparian areas are typically a mosaic of multiple communities that may be tree-dominated with a diverse shrub component. These areas are dependent on a natural hydrologic regime, especially annual to episodic flooding. Occurrences are found within the flood zone of rivers, on islands, sand or cobble bars, and immediate streambanks.). Other wetlands, not always associated with streams and riparian areas include perennial and intermittent riverine wetlands, wet meadows, emergent, forested, scrub-shrub, and other wetland types.

Characteristic species: Boreal toad

Current condition	Very good at higher elevations to fair in low elevations
Exposure	Warming trend across the entire range of the ecosystem. Decreased precipitation in some areas.
Sensitivity	Most sensitive to reduction in water availability. Highest elevation species may have more sensitivity to increased temperature.
Adaptive capacity	Wide ecological amplitude. The typically small size of occurrences may make it easier to implement mitigation projects.
Vulnerability	High elevation riparian/wetland: Moderately vulnerable Fens: Moderately vulnerable Lower elevation riparian/wetland: Highly vulnerable
Confidence	Medium

In the San Juan / Tres Rios, riparian and wetland ecosystems (Figure 24) include groundwater-fed fens, surface runoff dependent wetlands, and riparian areas of both high and low elevations. At montane and lower elevations (below about 8,500 ft), major stream and rivers in the study area are often highly modified by dams and diversions. The major impoundments in the area are McPhee, Vallecito, Lemon, Williams, and Navajo reservoirs. Dams and other diversions alter the natural hydrograph, modifying or reducing annual

peak flows in many lower elevation tributaries. Water withdrawal for irrigation also alters groundwater levels and patterns of recharge, with consequent effects on associated riparian and wetland ecosystems.

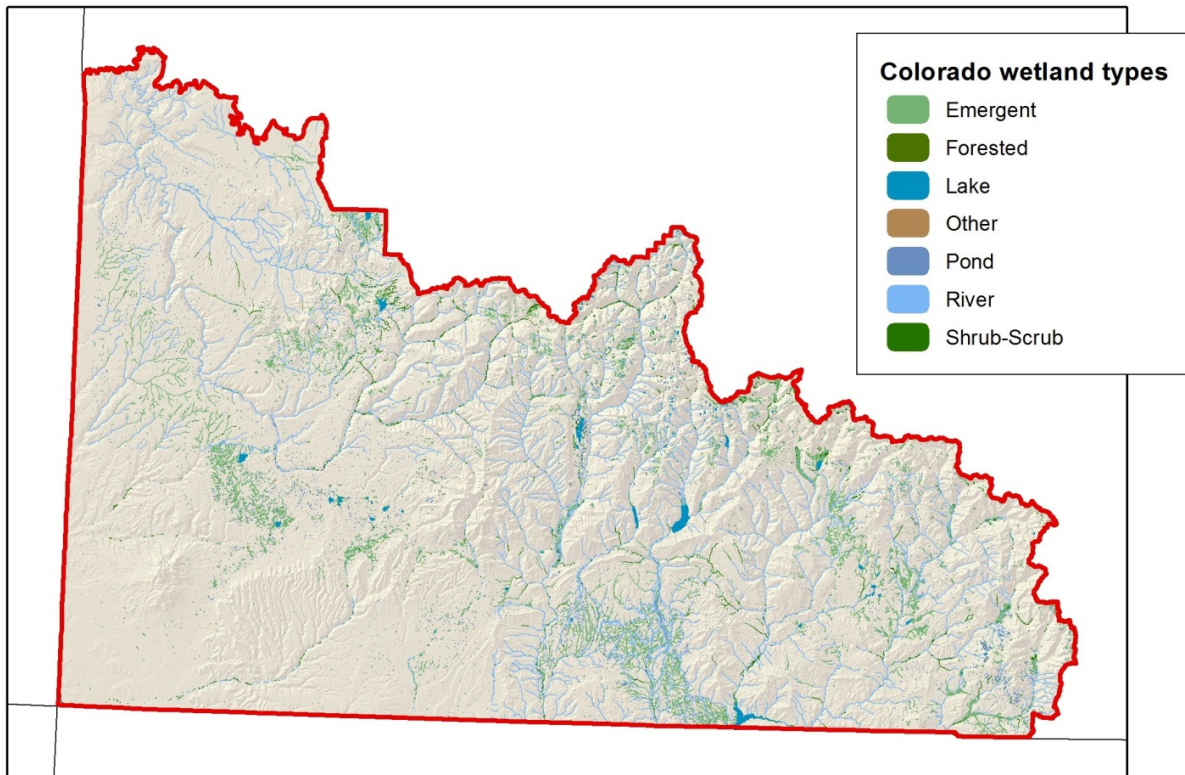


Figure 24. Wetlands that have been mapped in the San Juan / Tres Rios (extent exaggerated for display). Not all areas have been thoroughly mapped.

The structure and species composition of riparian areas is closely tied to elevation, slope, and annual patterns of snowmelt and runoff, as well as periodic flooding produced by extreme storm events. The upper montane streams are dominated by narrowleaf cottonwood, thinleaf alder, mountain ash, and coyote willow. Low elevation rivers have riparian areas dominated by Fremont cottonwood, coyote willow, and tamarisk. Native cottonwood and willow species are adapted to flooding and also have some physiological mechanisms to cope with drought stress (Amlin and Rood 2002, Rood et al. 2003). However, riparian species are generally dependent on shallow alluvial groundwater in the rooting zone; abrupt or prolonged reductions in this source of moisture can have a severe impact on the persistence of riparian vegetation. Peak flow timing can affect the structure and composition of riparian vegetation through its action on seed dispersal and sediment movement (Perry et al. 2012). Although snowmelt timing has already become detectably earlier in southwestern Colorado (Clow 2010), it is not known how this trend will affect the composition and persistence of riparian vegetation. As a consequence of earlier peak flows, low flows are longer and lower during the summer, which could affect riparian vegetation by lowering the water table, resulting in water stress for some species. The projected increase in extreme storm events would cause more scouring of stream banks.

Riparian communities at lower elevations in the San Juan / Tres Rios have already been affected by the invasion of non-native shrub species (especially tamarisk), and future conditions are expected to be favorable for tamarisk to persist (Bradley et al. 2009). High elevation areas are currently generally free of invasive exotic plants. Grazing by domestic livestock is also a stressor for many riparian areas at all except the highest elevations.

Wetlands are defined in law as “an area typically flooded or saturated with sufficient frequency and/or duration, with surface water or groundwater, that these areas support mostly vegetation adapted for growth in soils that are saturated under normal circumstances” (40 CFR 230). Not all wetlands are associated with streams and riparian areas. Within the San Juan / Tres Rios, wetlands include perennial and intermittent riverine wetlands, wet meadows, emergent, forested, scrub-shrub, and other wetland types. Wetlands may include bog birch, sedge, rushes, cattails and bullrush. Wetlands are also variable in the seasonal extent and duration of flooding. In the San Juan / Tres Rios, fens (peatlands supported by groundwater input, and not completely dependent on precipitation) are an important component of subalpine wetlands (Chimner et al. 2010). Both temperature and precipitation can affect the presence and extent of wetlands on the landscape. Warmer, drier conditions are likely to lead to lower groundwater levels, at least during certain seasons, and can have a negative impact on these ecosystems. Earlier spring run-off would result in drying conditions by late summer, possibly reducing the size of existing wetlands. Similarly, wetlands currently supported by late-melting snowfields are likely to dry sooner than under current conditions.

Other wetland stressors include roads, development (especially recreational), diversions, and dewatering. For higher elevation wetlands, invasive species and grazing are minor impacts (Chimner et al. 2010). Although fire has often not been considered an important disturbance in wetland and riparian areas, recent evidence suggests that fires in most types of adjacent upland vegetation are likely to burn into these habitats as well (Charron and Johnson 2006, Stromberg and Rychener 2010).

Vulnerability Factor	Rating	Comments
Restricted to high elevation	-	Not a concern.
Narrow bioclimatic envelope	Low	Community types highly variable across the entire bioclimatic envelope. Some type are more vulnerable.
Vulnerable to increased pest attacks	-	Unknown.
Vulnerable to increased grazing/browsing	Medium	Riparian shrubs and trees at lower elevations are most vulnerable.
Vulnerable to increased invasive	Medium to	Low elevations most vulnerable.

Vulnerability Factor	Rating	Comments
species and encroachments from natives	High	
Barriers to dispersal	High	For fens only.
Vulnerable to fire	-	Unknown.
Vulnerable to drought	Medium to High	Low elevations most vulnerable.
Vulnerable to timing of snowmelt	Low to High	Lower elevations most vulnerable. Fens not as vulnerable as others.
Vulnerable to phenologic change	-	Unknown.
Non-climate abiotic stressors	Low to High	Low elevation wetland and riparian areas are highly altered.

References

- Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, And J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications* 12:1418-1433.
- Allen, E.B., R.J. Steers, and S.J. Dickens. 2011. Impacts of fire and invasive species on desert soil ecology. *Rangeland Ecology and Management* 64:450-462.
- Amlin, N.M. and S.B. Rood. 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands* 22:338-346.
- Anderegg, L.D.L., W.R.L. Anderegg, J. Abatzoglou, A.M. Hausladen, and J.A. Berry. 2013. Drought characteristics' role in widespread aspen forest mortality across Colorado, USA. *Global Change Biology* 19:1526-1537.
- Anderson, M.D. and W.L. Baker. 2005. Reconstructing landscape-scale tree invasion using survey notes in the Medicine Bow Mountains, Wyoming, USA. *Landscape Ecology* 21:243-258.
- Asner, G.P. and K.B. Heidebrecht. 2005. Desertification alters regional ecosystem-climate interactions. *Global Change Biology* 11:182-194.
- Balch, J.K., B.A. Bradley, C.M. D'Antonio, and J. Gómez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980-2009). *Global Change Biology* 19:173-183.
- Barger, N.N., H.D. Adams, C. Woodhouse, J.C. Neff, and G.P. Asner. 2009. Influence of livestock grazing and climate on piñon pine (*Pinus edulis*) dynamics. *Rangeland Ecology and Management* 62:531-539.
- Bentz, B., D. Alston, and T. Evans. 2008. Great Basin insect outbreaks. In: Chambers, J.C., N. Devoe, and A. Evenden, eds. Collaborative management and research in the Great Basin - examining the issues and developing a framework for action. Gen. Tech. Rep. RMRS-GTR-204. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 45-48.
- Betancourt, J.L. 2004. Arid lands paleobiogeography: The fossil rodent midden record in the Americas. In Lomolino, M.V. and Heaney, L. R., Eds., *Frontiers in Biogeography: New Directions in the Geography of Nature*. Sinauer Associates Inc, p.27-46.
- Box, E.O. 1981. *Macroclimate and plant forms: an introduction to predictive modeling in phytogeography*. Junk, The Hague.
- Bradley, B.A. 2009. Climate change and plant invasions: restoration opportunities ahead? *Global Change Biology* 15:1511-1521.
- Bradley, B.A. 2010. Assessing ecosystem threats from global and regional change: hierarchical modeling of risk to sagebrush ecosystems from climate change, land use and invasive species in Nevada, USA. *Ecography* 33:198-208.

- Breshears, D.D., O.B. Myers, C.W. Meyer, F.J. Barnes, C.B. Zou, C.D. Allen, N.G. McDowell, and W.T. Pockman. 2008. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment* 7:185-189.
- Brown, D.E. 1994. Grasslands. In *Biotic communities: southwestern United States and northwestern Mexico*. D.E. Brown, ed. University of Utah Press, Salt Lake City, Utah.
- Brown, D.E. 1994. Great Basin Conifer Woodland. In *Biotic communities: southwestern United States and northwestern Mexico*. D.E. Brown, ed. University of Utah Press, Salt Lake City, Utah.
- Brown, D.E., F. Reichenbacher, and S.E. Franson. 1998. *A Classification of North American Biotic Communities*. University of Utah Press, Salt Lake City. 141 pp.
- Brown, H.E. 1958. Gambel oak in west-central Colorado. *Ecology* 39:317-327.
- Brown, P.M. and R. Wu. 2005. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. *Ecology* 86:3030-3038.
- Calinger, K.M., S. Queenborough, and P.S. Curtis. 2013. Herbarium specimens reveal the footprint of climate change on flowering trends across north-central North America. *Ecology Letters* 16:1037-1044.
- Cantor, L.F. and T.J. Whitham. 1989. Importance of belowground herbivory: pocket gophers may limit aspen to rock outcrop refugia. *Ecology* 70(4):962-970.
- Chambers, J.C., B.A. Roundy, R.R. Blank, S.E. Meyer, and A. Whittaker. 2007. What makes Great Basin sagebrush ecosystems invasible by *Bromus tectorum*? *Ecological Monographs* 77:117-145.
- Charron, I. and E.A. Johnson. 2006. The importance of fires and floods on tree ages along mountainous gravel-bed streams. *Ecological Applications* 16:1757-1770.
- Chimner, R.A., J.M. Lemly, and D.J. Cooper. 2010. Mountain fen distribution, types and restoration priorities, San Juan Mountains, Colorado, USA. *Wetlands* 30:763-771.
- Clifford, M.J., P.D. Royer, N.S. Cobb, D.D. Breshears, and P.L. Ford. 2013. Precipitation thresholds and drought-induced tree die-off: insights from patterns of *Pinus edulis* mortality along an environmental stress gradient. *New Phytologist* 200:413-421.
- Clow, D.W. 2010. Changes in the timing of snowmelt and streamflow in Colorado: a response to recent warming. *Journal of Climate* 23:2293-2306.
- Coop, J.D. and T.J. Givnish. 2007. Spatial and temporal patterns of recent forest encroachment in montane grasslands of the Valles Caldera, New Mexico, USA. *Journal of Biogeography* 34:914-927.
- Covington, W.W. and M.M. Moore. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. *Journal of Forestry* 92: 39-47.
- Cozzetto, K., I. Rangwala, and J. Neff. 2011. Downscaled air temperature and precipitation projections for the San Juan Mountain region. Narrative on regional climate model projections submitted to the San Juan Public Land Center, Durango, Colorado.

- Crookston, N.L., G.E. Rehfeldt, G.E. Dixon, and A.R. Weiskittel. 2010. Addressing climate change in the forest vegetation simulator to assess impacts on landscape forest dynamics. *Forest Ecology and Management*. 260:1198-1211. Models available at: <http://forest.moscowfsl.wsu.edu/climate/species/index.php>
- Cryer, D.H. and J.E. Murray. 1992. Aspen regeneration and soils. *Rangelands* 14(4): 223-226.
- D'Antonio, C.M. and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23:63-87.
- Daubenmire, R.F. 1943. Vegetational zonation in the Rocky Mountains. *Botanical Review* 9:325-393.
- Davies, K.E., T.J. Sevjar, and J.D. Bates. 2009. Interaction of historical and nonhistorical disturbances maintains native plant communities. *Ecological Applications* 19:1536-1545.
- Debinski, D.M., H. Wickham, K. Kindscher, J.C. Caruthers, and M. Germino. 2010. Montane meadow change during drought varies with background hydrologic regime and plant functional group. *Ecology* 91:1672-1681.
- DeRose, R.J. and J.N. Long. 2012. Drought-driven disturbance history characterizes a southern Rocky Mountain subalpine forest. *Can. J. For. Res.* 42:1649-1660.
- Dick-Peddie, W.A. 1993. *New Mexico vegetation, past, present, and future*. With contributions by W.H. Moir and Richard Spellenberg. University of New Mexico Press, Albuquerque, New Mexico.
- Eamus, D., and P.G. Jarvis. 1989. The direct effects of increase in the global atmospheric CO₂ concentration on natural and commercial temperate trees and forests. *Advances in Ecological Research* 19:1-55.
- Elliot, G.P. and W.L. Baker. 2004. Quaking aspen (*Populus tremuloides* Michx.) at treeline: a century of change in the San Juan Mountains, Colorado, USA. *Journal of Biogeography* 31:733-745.
- Ellison, L. 1946. The pocket gopher in relation to soil erosion on mountain range. *Ecology* 27:101-114.
- Erb, L.P., C. Ray, and R. Guralnick. 2014. Determinants of pika population density vs. occupancy in the Southern Rocky Mountains. *Ecological Applications* 24:429-435.
- Fall, P. 1997. Timberline fluctuations and late Quaternary paleoclimates in the Southern Rocky Mountains, Colorado. *GSA Bulletin*; October 1997; v. 109; no. 10; p. 1306-1320.
- Floyd, M.L., W.H. Romme, and D.D. Hanna. 2000. Fire history and vegetation pattern in Mesa Verde National Park, Colorado, USA. *Ecological Applications* 10:1666-1680.
- Glick, P., B.A. Stein, and N.A. Edelson, editors. 2011. *Scanning the Conservation Horizon: A Guide to Climate Change Vulnerability Assessment*. National Wildlife Federation, Washington, D.C.

- Grafius, D.R., G.P. Malanson, and D. Weiss. 2012. Secondary controls of alpine treeline elevations in the western USA. *Physical Geography* 33:146-164.
- Grissino-Mayer, H.D., W.H. Romme, M.L. Floyd, and D.D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* 85:1708-1722.
- Guetter, P.J. and J.E. Kutzbach. 1990. A modified Koppen classification applied to model simulations of glacial and interglacial climates. *Climatic Change* 16:193-215.
- Harper, K.T., F.J. Wagstaff, and L.M. Kunzler. 1985. Biology and management of the Gambel oak vegetative: a literature review. USDA Forest Service, General Technical Report INT-179. Intermountain Forest and Range Experiment Station, Ogden Utah.
- Hogg, E.H. 2001. Modeling aspen responses to climatic warming and insect defoliation in western Canada. In: Shepperd, W.D.; Binkley, D.; Bartos, D.L.; Stohlgren, T.J.; Eskew, L.G., comps. *Sustaining aspen in western landscapes: symposium proceedings*. Gen. Tech. Rep. RMRS-P-18. Fort Collins, CO: U.S. Department of Agriculture, USFS, Rocky Mountain Research Station. 460 p.
- Holdridge, L.R. 1947. Determination of world formations from simple climatic data. *Science* 105:367-368.
- Holtmeier, F-K. and G. Broll. 2005. Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local levels. *Global Ecology and Biogeography* 14:395-410.
- Howard, J.L. 1996. *Populus tremuloides*. In: *Fire Effects Information System*, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: <http://www.fs.fed.us/database/feis>
- Huntley, B. and T. Webb, III. 1988. *Vegetation history*. Kluwer, Dordrecht.
- Inouye, D.W. 2008. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. *Ecology* 89:353-362.
- Jamieson, D.W., W.H. Romme, and P. Somers. 1996. Biotic communities of the cool mountains. Chapter 12 in *The Western San Juan Mountains : Their Geology, Ecology, and Human History*, R. Blair, ed. University Press of Colorado, Niwot, CO.
- Jester, N., K. Rogers, and F.C. Dennis. 2012. Gambel oak management. *Natural Resources Series-Forestry Fact Sheet No. 6.311*. Colorado State University Extension, Fort Collins, Colorado.
- Johnston, B.C. 2001. Multiple Factors Affect Aspen Regeneration on the Uncompahgre Plateau, West-Central Colorado. Pages 395-414. In: Shepperd, W. D., D. Binkley, D. L. Bartos, T. J. Stohlgren, and L. G. Eskew, compilers. *Sustaining aspen in western landscapes: symposium proceedings*. USDA Forest Service Proceedings RMRS-P-18. Grand Junction, Colorado. 460 p.
- Kay, C.E. 1993. Aspen seedlings in recently burned areas of Grand Teton and Yellowstone National Parks. *Northwest Science*. 67(2): 94-104.

- Kaye M.W., C.A. Woodhouse and S.T. Jackson. 2010. Persistence and expansion of ponderosa pine woodlands in the west-central Great Plains during the past two centuries. *Journal of Biogeography* 37:1668-1683.
- Kaye, M.W. 2011. Mesoscale synchrony in quaking aspen establishment across the interior western US. *Forest Ecology and Management* 262:389-397.
- Kearns, H.S.J. and W.R. Jacobi. 2005. Impacts of black stain root disease in recently formed mortality centers in the piñon-juniper woodlands of southwestern Colorado. *Canadian Journal of Forest Research* 35:461-471.
- Keeley, J.E. 2000. Chaparral. Chapter 6 in *North American Terrestrial Vegetation*, second edition. M.G. Barbour and W.D. Billings, eds. Cambridge University Press.
- Knight, D.H. 1994. *Mountains and Plains: the Ecology of Wyoming Landscapes*. Yale University Press, New Haven and London. 338 pages.
- Koppen, W. 1936. Das Geographisches System der Klimate. In: *Handbuch der Klimatologie I(C)* (ed. by W. Koppen and R. Geiger). Gebrüder Borntraeger, Berlin.
- Körner, C. 2012. *Alpine treelines: functional ecology of the global high elevation tree limits*. Springer, Basel, Switzerland.
- Kufeld, R.C., O.C. Wallmo, and C. Feddema,. 1973. Foods of the Rocky Mountain mule deer. Res. Pap. RM-111. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.
- Kunkel, K.E, L.E. Stevens, S.E. Stevens, L. Sun, E. Janssen, D. Wuebbles, K.T. Redmond, and J.G. Dobson, 2013: *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 5. Climate of the Southwest U.S.*, NOAA Technical Report NESDIS 142-5, 79 pp.
- League, K. and T. Veblen. 2006. Climatic variability and episodic *Pinus ponderosa* establishment along the forest-grassland ecotones of Colorado. *Forest Ecology and Management* 228:98-107.
- Lin, G. S.L. Phillips, and J.R. Ehleringer. 1996. Monosoonal precipitation responses of shrubs in a cold desert community on the Colorado Plateau. *Oecologia* 106:8-17.
- Little, E.L., Jr. 1971. *Atlas of the United States trees. Volume 1. Conifers and important hardwoods*. Misc. Publ. 1146. Washington, DC U.S. Department of Agriculture, Forest Service. 320 p.
- Logan, J. 2008. *Gypsy Moth Risk Assessment in the Face of a Changing Environment: A Case History Application in Utah and the Greater Yellowstone Ecosystem. Restoring the West 2008: Frontiers in Aspen Restoration*, Utah State University, Logan, Utah.
- Madany, M.H. and N.E. West. 1983. Livestock grazing-fire regime interactions within montane forests of Zion National Park, Utah. *Ecology* 64:661-667.
- Manier, D.J. and N.T. Hobbs. 2007. Large herbivores in sagebrush steppe ecosystems: livestock and wild ungulates influence structure and function. *Oecologia* 152:739-750.

- Manomet Center for Conservation Science and Massachusetts Division of Fisheries and Wildlife. 2010. Climate Change and Massachusetts Fish and Wildlife: Volumes 1-3. <http://www.manomet.org/science-applications/climate-change-energy>
http://www.mass.gov/dfwele/dfw/habitat/cwcs/pdf/climate_change_habitat_vulnerability.pdf
- Mata-González R., T.L. Evans, D.W. Martin, T. McLendon, J.S. Noller, C. Wan, and R.E. Sosebee. 2014. Patterns of Water Use by Great Basin Plant Species Under Summer Watering. *Arid Land Research and Management* 28:428-446.
- Mearns, L.O., et al., 2007, updated 2012. The North American Regional Climate Change Assessment Program dataset, National Center for Atmospheric Research Earth System Grid data portal, Boulder, CO. Data downloaded 2014-09-25. [doi:10.5065/D6RN35ST]
- Moir, W.H., S.G. Rochelle, and A.W. Schoettle. 1999. Microscale patterns of tree establishment near upper treeline, Snowy Range, Wyoming. *Arctic, Antarctic, and Alpine Research* 31:379-388.
- Morelli, T.L. and S.C. Carr. 2011. A review of the potential effects of climate change on quaking aspen (*Populus tremuloides*) in the Western United States and a new tool for surveying sudden aspen decline. Gen. Tech. Rep. PSW-GTR-235. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 31 p.
- Mueggler, W.F. 1988. Aspen community types of the Intermountain Region. USDA Forest Service, Intermountain Research Station. General Technical Report INT-250. Available: http://www.fs.fed.us/rm/pubs_int/int_gtr250.pdf
- Munson, S.M., J. Belnap, C.D. Schelz, M. Moran, and T.W. Carolin. 2011. On the brink of change: plant responses to climate on the Colorado Plateau. *Ecosphere* 2:art68.
- Neilson, R. P. 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications* 5:362-385.
- Neilson, R. P., G. A. King, and G. Koerper. 1992. Toward a rule-based biome model. *Landscape Ecology* 7:27-43.
- Neilson, R.P. and L.H. Wullstein. 1983. Biogeography of two southwest American oaks in relation to atmospheric dynamics. *Journal of Biogeography* 10:275-297.
- Oliver, W. W., and R. A. Ryker. 1990. *Pinus ponderosa* Dougl. ex Laws. Ponderosa pine. p. 413-424. In: Burns, R. M. and B. H. Honkala (tech. coord.) *Silvics of North America Volume 1, Conifers*. USDA For. Serv. Agric. Handb. 654. Available at: http://www.na.fs.fed.us/pubs/silvics_manual/Volume_1/pinus/ponderosa.htm
- Paulsen, H.A., Jr. 1969. Forage values on a mountain grassland-aspen range in western Colorado. *Journal of Range Management* 22:102-107.
- Paulsen, H.A., Jr. 1975. Range management in the central and southern Rocky Mountains: a summary of the status of our knowledge by range ecosystems. USDA Forest Service Research Paper RM-154. Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins, Colorado.

- Peet, R.K. 1981. Forest vegetation of the Colorado Front Range: composition and dynamics. *Vegetatio* 45:3-75.
- Peet, R.K. 2000. Forests and meadows of the Rocky Mountains. Chapter 3 in *North American Terrestrial Vegetation*, second edition. M.G. Barbour and W.D. Billings, eds. Cambridge University Press.
- Perala, D.A. 1990. *Populus tremuloides* Michx. quaking aspen. Pp 555-569 In: Burns, Russell M.; Honkala, Barbara H., technical coordinators. *Silvics of North America: Volume 2, Hardwoods*. Agriculture Handbook 654. Washington, DC: U.S. Department of Agriculture, Forest Service. Available: http://www.srs.fs.usda.gov/pubs/misc/ag_654_vol2.pdf
- Perry, L.G., D.C. Andersen, L.V. Reynolds, S.M. Nelson, and P.B. Shafroth. Vulnerability of riparian ecosystems to elevated CO₂ and climate change in arid and semiarid western North America. *Global Change Biology* 18:821-842.
- Prentice, I.C. and A.M. Solomon. 1991. Vegetation models and global change. In: *Global changes of the past* (ed. by R.S. Bradley), pp. 365-384. UCAR/Office for Interdisciplinary Earth Studies, Boulder.
- Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R. A. Monserud, and A.M. Solomon. 1992. A global biome model based on plant physiology and dominance, soil properties and climate. *J. of Biogeography* 19: 117-134.
- Prentice, K.C. 1990. Bioclimatic distribution of vegetation for general circulation model studies. *J. Geophys. Res.* 95 (D8) 11 811-11 830.
- Rangwala I., J. Barsugli, K. Cozzetto, J. Neff and J. Prairie. 2012. Mid-21st Century Projections in Temperature Extremes in the Southern Colorado Rocky Mountains from Regional Climate Models. *Climate Dynamics*. DOI: 10.1007/s00382-011-1282-z.
- Rangwala, I. and J.R. Miller. 2010. Twentieth century temperature trends in Colorado's San Juan Mountains. *Arctic, Antarctic, and Alpine Research* 42:89-97.
- Redmond, M.D. and N.N. Barger. 2013. Tree regeneration following drought- and insect-induced mortality in piñon-juniper woodlands. *New Phytologist* 200:402-412.
- Rehfeldt, G.E., D.E. Ferguson, and N.L. Crookston. 2009. Aspen, climate, and sudden decline in western USA. *Forest Ecology and Management* 258: 2353-2364
- Rehfeldt, G.E., N.L. Crookston, C. Saenz-Romero, and E.M. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution of large classification problems. *Ecological Applications* 22:119-141.
- Richardson, A.D. and A.J. Friedland. 2009. A review of the theories to explain arctic and alpine treelines around the world. *Journal of Sustainable Forestry* 28:218-242.
- Rochefort, R.M., R.L. Little, A. Woodward, and D.L. Peterson. 1994. Changes in sub-alpine tree distribution in western North America: a review of climatic and other causal factors. *The Holocene* 4:89-100.

- Romme, W.H., M.G. Turner, R.H. Gardner, W.W. Hargrove, G.A. Tuskan, D.G. Despain, and R.A. Renkin. 1997. A Rare Episode of Sexual Reproduction in Aspen (*Populus tremuloides* Michx.) Following the 1988 Yellowstone Fires. *Natural Areas Journal*. 17:17-25.
- Rondeau, R., K. Decker, J. Handwerk, J. Siemers, L. Grunau, and C. Pague. 2011. The state of Colorado's biodiversity 2011. Prepared for The Nature Conservancy. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado.
- Rood, S.B., J.H. Braatne, and F.M.R. Hughes. 2003. Ecophysiology of riparian cottonwoods: stream flow dependency, water relations and restoration. *Tree Physiology* 23:1113-1124.
- San Juan Public Lands. 2008. Geodatabase of existing vegetation types and conditions. San Juan Public Lands Vegetation and GIS Teams. Dolores Public Lands Office, Dolores, Colorado.
- Schauer, A.J., B.K. Wade, and J.B. Sowell. 1998. Persistence of subalpine forest-meadow ecotones in the Gunnison Basin, Colorado. *Great Basin Naturalist* 58(3):273-281.
- Schlaepfer, D.R., W.K. Lauenroth, and J.B. Bradford. 2014. Natural regeneration processes in big sagebrush (*Artemisia tridentata*). *Rangeland Ecology & Management* 67:344-357.
- Shepperd, W.D. and M.A. Battaglia. 2002. Ecology, Silviculture, and Management of Black Hills Ponderosa Pine. General Technical Report RMRS-GTR-97. USDA Forest Service Rocky Mountain Research Station, Fort Collins, Colorado. 112 p.
- Shinneman, D.J. and W.L. Baker. 2009. Environmental and climatic variables as potential drivers of post-fire cover of cheatgrass (*Bromus tectorum*) in seeded and unseeded semiarid ecosystems. *International Journal of Wildland Fire* 18:191-202.
- Simonin, K.A. 2001. *Atriplex confertifolia*. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: <http://www.fs.fed.us/database/feis/>
- Sims, P.L., and P.G. Risser. 2000. Grasslands. Chapter 9 in: Barbour, M.G., and W.D. Billings, eds., *North American Terrestrial Vegetation*, Second Edition. Cambridge University Press.
- Smith, D.R. 1967. Effects of cattle grazing on a ponderosa pine-bunchgrass range in Colorado. USDA Forest Service Technical Bulletin No. 1371. Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins, Colorado.
- Smith, W.K. 1985. Western montane forests. Chapter 5 in Chabot, R.F. and H.A. Money, eds., *Physiological Ecology of North American Plant Communities*. Chapman and Hall, New York, 351 pp.
- Smith, W.K., M.J. Germino, T.E. Hancock, and D.M. Johnson. 2003. Another perspective on altitudinal limits of alpine timberlines. *Tree Physiology* 23:1101-1112.
- Stephenson, N.L. 1990. Climatic control of vegetation distribution: the role of the water balance. *American Naturalist* 135: 649-670.

- Stohlgren, T.J., L.D. Schell, and B. Vanden Huevel. 1999. How grazing and soil quality affect native and exotic plant diversity in rocky mountain grasslands. *Ecological Applications* 9:45-64.
- Stromberg, J.C. and T.J. Rycheneer. 2010. Effects of fire on riparian forests along a free-flowing dryland river. *Wetlands* 30:75-86.
- Tausch R. J. 1999. Historic pinyon and juniper woodland development. In: S. B. Monsen and R. Stevens [eds.]. *Proceedings of the Conference on Ecology and Management of Pinyon-Juniper Communities within the Interior West*. Ogden, Utah, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 12-19.
- Thompson, R. S., K. H. Anderson, and P. J. Bartlein. 2000. Atlas of relations between climatic parameters and distributions of important trees and shrubs in North America. U.S. Geological Survey Professional Paper 1650-A.
- Turner, G.T., and H.A. Paulsen, Jr. 1976. Management of Mountain Grasslands in the Central Rockies: The Status of Our Knowledge. USDA Forest Service Research Paper RM-161. Rocky Mountain Forest and Range Experiment Station, USDA Forest Service, Fort Collins, Colorado.
- USDA Forest Service, San Juan NF GIS Team. 2005. Cartographic Feature File: Boundaries, Land Status and Features - San Juan NF and San Juan Resource Area. San Juan Public Lands Center, Durango, Colorado.
- USDA Forest Service, Rocky Mountain Region, Forest Health Protection. 2010. Field guide to diseases & insects of the Rocky Mountain Region. Gen. Tech. Rep. RMRS-GTR-241 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 336 p.
- USGS National Gap Analysis Program. 2004. Provisional Digital Land Cover Map for the Southwestern United States. Version 1.0. RS/GIS Laboratory, College of Natural Resources, Utah State University.
- Van Auken, O.W. 2000. Shrub invasions of North American semiarid grasslands. *Annual Review of Ecology and Systematics* 31:197-215.
- Woodward, F.I. 1987. *Climate and plant distribution*. Cambridge University Press, Cambridge.
- Worrall J.J., L. Egeland, T. Eager, R. Mask, E. Johnson, et al. 2008. Rapid mortality of *Populus tremuloides* in southwestern Colorado, USA. *Forest Ecology and Management* 255(3-4): 686-696. <http://dx.doi.org/10.1016/j.foreco.2007.09.071>.
- Worrall J.J., S.B. Marchetti, L. Egeland, R. A. Mask, T. Eager, B. Howell. 2010. Effects and etiology of sudden aspen decline in southwestern Colorado, USA. *Forest Ecology and Management* 260(5): 638-648. <http://dx.doi.org/10.1016/j.foreco.2010.05.020>.
- Worrall, J.J., G.E. Rehfeldt, A. Hamann, E.H. Hogg, S.B. Marchetti, M. Michaelian, and L.K. Gray. 2013. Recent declines of *Populus tremuloides* in North America linked to climate. *Forest Ecology and Management* 229:35-51.

- Zeigenfuss, L.C., K.A. Schonecker, and L.K. Van Amburg. 2011. Ungulate herbivory on alpine willow in the Sangre de Cristo Mountains of Colorado. *Western North American Naturalist* 71:86-96.
- Zier, J.L. and W.L. Baker. 2006. A century of vegetation change in the San Juan Mountains, Colorado: An analysis using repeat photography. *Forest Ecology and Management* 228:251-262.