Chapter 1

Modeling and Predicting Vegetation Response of Western USA Grasslands, Shrublands, and Deserts to Climate Change

Megan M. Friggens[1], Marcus V. Warwell[2], Jeanne C. Chambers[3], and Stanley G. Kitchen[4]

[1] U.S. Forest Service, Rocky Mountain Research Station; Grassland, Shrubland, and Desert Ecosystems Program; Forestry Sciences Laboratory, Albuquerque, New Mexico

[2] U.S. Forest Service, Rocky Mountain Research Station; Forest and Woodland Ecosystems Program; Forestry Sciences Laboratory, Moscow, Idaho

[3] U.S. Forest Service, Rocky Mountain Research Station; Grassland, Shrubland, and Desert Ecosystems Program; Great Basin Ecology Laboratory, Reno, Nevada

[4] U.S. Forest Service, Rocky Mountain Research Station; Grassland, Shrubland, and Desert Ecosystems Program; Shrub Sciences Laboratory, Provo, Utah

Executive Summary

Experimental research and species distribution modeling predict large changes in the distributions of species and vegetation types in the Interior West due to climate change. Species' responses will depend not only on their physiological tolerances but also on their phenology, establishment properties, biotic interactions, and capacity to evolve and migrate. Because individual species respond to climate variation and change independently and differently, plant assemblages with no modern analogs can be expected in areas where novel climate conditions develop. The capacity to accurately predict how species distributions and plant assemblages will change under future warming is essential for developing effective strategies for maintaining and restoring sustainable ecosystems.

The rate of predicted change in climate is unprecedented relative to the three centuries prior to industrialization. A conservative forecast for western North America (using 21 global climate models for the A1B scenario) is a linear change in mean temperatures and precipitation ranging from +2.1 °C to +5.7 °C and -3% to +14%, respectively, over the rest of the century. A number of recent studies that have used bioclimatic and related models predict drastic changes in vegetation types and native and invasive flora at regional scales in response to the change in climate. By the end of the century, 55% of future landscapes in the West likely will have climates that are incompatible with the vegetation types that now occur on those landscapes. Specifically:

- Suitable habitat for Rocky Mountain subalpine conifer forests and Rocky Mountain and Great Basin alpine tundra declines substantially (>97%) or disappears.
- Projected habitat suitable for Great Basin pinyon and juniper woodlands moves northward and upslope.
- Semi-desert grassland habitat expands northward and occupies an area nearly four times that of the present.
- Habitat suitable for Great Basin shrub/grassland decreases by 40% and becomes fragmented.

- Great Basin montane scrub habitat experiences moderate decline (69% decrease) and displacement through time.
- Climate changes appear to be most favorable for Mohave Desert, Sonoran Desert, and Chihuahuan Desert scrub vegetation types, which are all projected to expand.

Species' specific analyses predict:

- Sagebrush (*Artemisia tridentata*), Joshua tree (*Yucca brevifolia*), saguaro (*Carnegiea gigantea*), and creosote bush (*Larrea tridentata*) shift northwards.
- Species with small distributions, such as smooth Arizona cypress (*Cupressus arizonica* ssp. *glabra*) and the endangered perennial MacFarlane's four-o'clock (*Mirabilis macfarlanei*), experience complete climate disequilibrium early in the century.
- Invasive species, such as buffelgrass (*Pennisetum ciliare*), Lehmann lovegrass (*Eragrostis lehmanniana*), spotted knapweed (*Centaurea biebersteinii*), and leafy spurge (*Euphorbia esula*), expand under future climate regimes.
- The invasive annual grass cheatgrass (*Bromus tectorum*) shifts northward with increased risk in Idaho, Montana, and Wyoming but reduced risk in southern Nevada and Utah and an overall loss of 13% of suitable habitat.

Currently, the three primary approaches for projecting the ecological effects of climate change are experimental and observational studies, mechanistic modeling, and bioclimatic modeling. A framework for integrating these approaches could improve our ability to forecast changes in vegetation types and species. Such a framework could include long-term experiments (for specific species, locations, and climate change scenarios) designed to support more comprehensive mechanistic models and to provide for testing bioclimatic models, and could be used to both identify and address the following critical research needs:

- Obtain the necessary species-specific data regarding important climate variables, biotic interactions, genetic variation, and adaptive capacity to improve predictive capacity.
- Determine the interacting effects of climate and other global change processes such as extreme events, increasing CO_2, nitrogen deposition, pests, and disease on species distributions and community composition to improve predictions and develop adaptation strategies.
- Evaluate the interacting effects of socioeconomic and biophysical factors on land use and land cover change and, consequently, on species distribution and community composition to improve predictions and develop adaptation strategies.
- Increase our knowledge of the effects of species diversity and functional groups on ecosystem processes as they relate to climate and other global change factors to improve predictions and develop adaptation strategies.
- Continue to advance modeling efforts that couple bioclimate analyses with models that are able to estimate feedback, competitive interactions, and disturbance effects.
- Continue to explore other modeling approaches, such as combining historic distribution data with contemporary distributions, to identify species-specific climate limitations that can then be used to parameterize models.

Introduction

Experimental research and species distribution modeling predict that large changes in the distributions of species and vegetation types will occur due to climate change.

Species responses will depend not only on their physiological tolerances but also on their phenology, establishment properties, biotic interactions (Brown and others 1997), and ability to evolve and migrate (Davis and Shaw 2001). The capacity of species and, thus, their distributions to respond to a warming environment also will be affected by changing disturbance regimes and other global change factors (Turner 2010). Because individual species respond to climate variation and change independently and differently, plant assemblages with no modern analogs can be expected (Williams and Jackson 2007). New plant assemblages might also arise in areas where novel climatic conditions develop (Williams and Jackson 2007). Support for predictions of novel climate regimes and corresponding plant assemblages is found in studies examining relationships among paleo-climate and plant community reconstructions. As Williams and Jackson (2007) pointed out: (1) many past ecological communities are compositionally unlike modern communities; (2) the formation and dissolution of past "no-analog" communities appear to be climatically driven and linked to climates without modern analogs; (3) many future climate regimes will probably lack modern analogs; and (4) novel communities and surprises should be expected in the future. Novel climate conditions coupled with vegetation communities that lack modern analogs pose significant challenges for resource managers. Accurate predictions of how species distributions will change under future warming are essential for developing effective strategies for maintaining and restoring sustainable ecosystems (Harris and others 2006).

Several factors make predicting how species distributions and vegetation communities will change difficult. Global Circulation Models (GCMs) exhibit significant variation in forecasts of future temperature and especially precipitation (Christensen and others 2007). This variation is often amplified for topographically variable areas such as the Interior West (Rehfeldt 2006; Saenz-Romero and others 2010). In addition, information on species' relationships to climate variables is often lacking and must be inferred from data on current species distributions. And other factors such as competitive interactions with other species and disturbance regimes often obfuscate interpretation of species climate profiles in projected future climate space.

In grassland, shrubland, and desert ecosystems, our understanding of likely changes in climate is limited. Also, we lack information on the climate profiles of the vast majority of species. Here, we provide (1) current forecasts for changes in climate over the remainder of the century and (2) available predictions for changes in regional vegetation types and individual species distributions. We then discuss the types of approaches that can be used to increase our predictive capacity and the research needs for these ecosystems.

How Is Climate Predicted to Change?

Global climate is predicted to continue to undergo substantial change through the current century. The rate of predicted change is unprecedented relative to the three centuries prior to industrialization (North and others 2006). The effect of greenhouse gas emissions on future temperatures is considered using a set of emission scenarios. These scenarios predict future CO_2 concentrations given human activities. The most optimistic scenario (B1) involves rapid reductions in emissions as societies turn toward a global vision of sustainable land use. More commonly used in modeling efforts, however, are scenarios that assume a continued increase in human population growth and consumption of fossil fuel. In particular, scenarios that predict a moderately high CO_2 output with continued focus on economic growth (A2) or a more optimistic scenario that includes an emphasis on multiple energy sources (A1B) are used in the models

discussed here. Western North American is projected (using 21 global models for the A1B scenario) to experience a linear change in mean temperatures and precipitation ranging from +2.1 °C to +5.7 °C and -3% to +14%, respectively, over the rest of the century (Christensen and others 2007). Recent models indicate that actual CO_2 concentrations are likely to be higher than those used in the A1B scenario resulting in temperatures at the warmer end of those ranges (Tom and Harte 2006; Füssel 2009).

Within the region, patterns of temperature and precipitation change are expected to vary in magnitude and direction and in seasonal timing across the landscape. Figures 1-1 through 1-3 illustrate this variation for projected change in summer temperatures (degree days >5 °C), winter temperatures (mean temperature in the coldest month), and aridity (dryness index) across the interior western United States using three GCMs under the assumptions of the A2 emissions scenario, (see Rehfeldt and others 2009). In general, summer temperatures and aridity are projected to increase the most in the southwestern United States and at lower elevations throughout the Interior West (figs. 1-1 and 1-3). Predicted patterns of occurrence vary broadly across the region by GCM. Winter temperatures are projected to increase by 2 °C to 9 °C (fig. 1-2). Changing balance of temperature and precipitation is projected to result in earlier spring snow run off (Stewart and others 2004), declines in snow pack in the northern and central Rocky Mountains (Plummer and others 2006) and in the Great Basin (Mote and others 2005), and increased frequency, duration, and spatial extent of drought events (Seager and others 2007; Sheffield and Wood 2008). Climate change effects are also likely to change disturbance processes, leading to increases in insect and disease outbreaks (see Chapter 7) and extended fire seasons with more frequent and intense fires (see Chapter 6).

Modeling Vegetation Response to Climate Change

Three main types of approach exist for projecting the ecological effects of climate change, and each of these differs in type of information provided and the zone of inference.

- **Experimental and observations** studies include climate manipulation experiments (e.g., Harte and Shaw 1995; Suttle and others 2007), observations across climate gradients (e.g., Peñualus and others 2007), and observations over time (e.g., Alward and others 1999). These studies generate detailed data and provide valuable information on the complex interactions between species- and system-level responses. Results are often specific to the study system and are primarily relevant at local to regional scales.
- **Mechanistic modeling** has been used to scale local processes to regional scales (Araújo and others 2005; Berger and others 2008; Jeltsch and others 2008). Mechanistic modeling is a bottom-up approach that uses measurements or expert opinion about species' life histories, physiology, and competitive interactions to predict distribution under changing climate conditions. The results of this approach differ depending on the emphasis of the model and are limited by whether the physiological constraints used to parameterize them hold at regional scales.
- **Bioclimatic envelope modeling** (BEM) uses the relationships among regional distributions of species and physical variables (e.g., climate) to constrain the potential distribution of species or groups of species (Pearson and Dawson 2003). BEM is a top-down approach that relies on biogeography to project distribution changes (Hijmans and Graham 2006), but that does not directly consider species attributes. BEMs have rarely been experimentally validated or tested (but see Chew and others 2004; Farber and Kadmon 2003). This general approach has been vastly improved

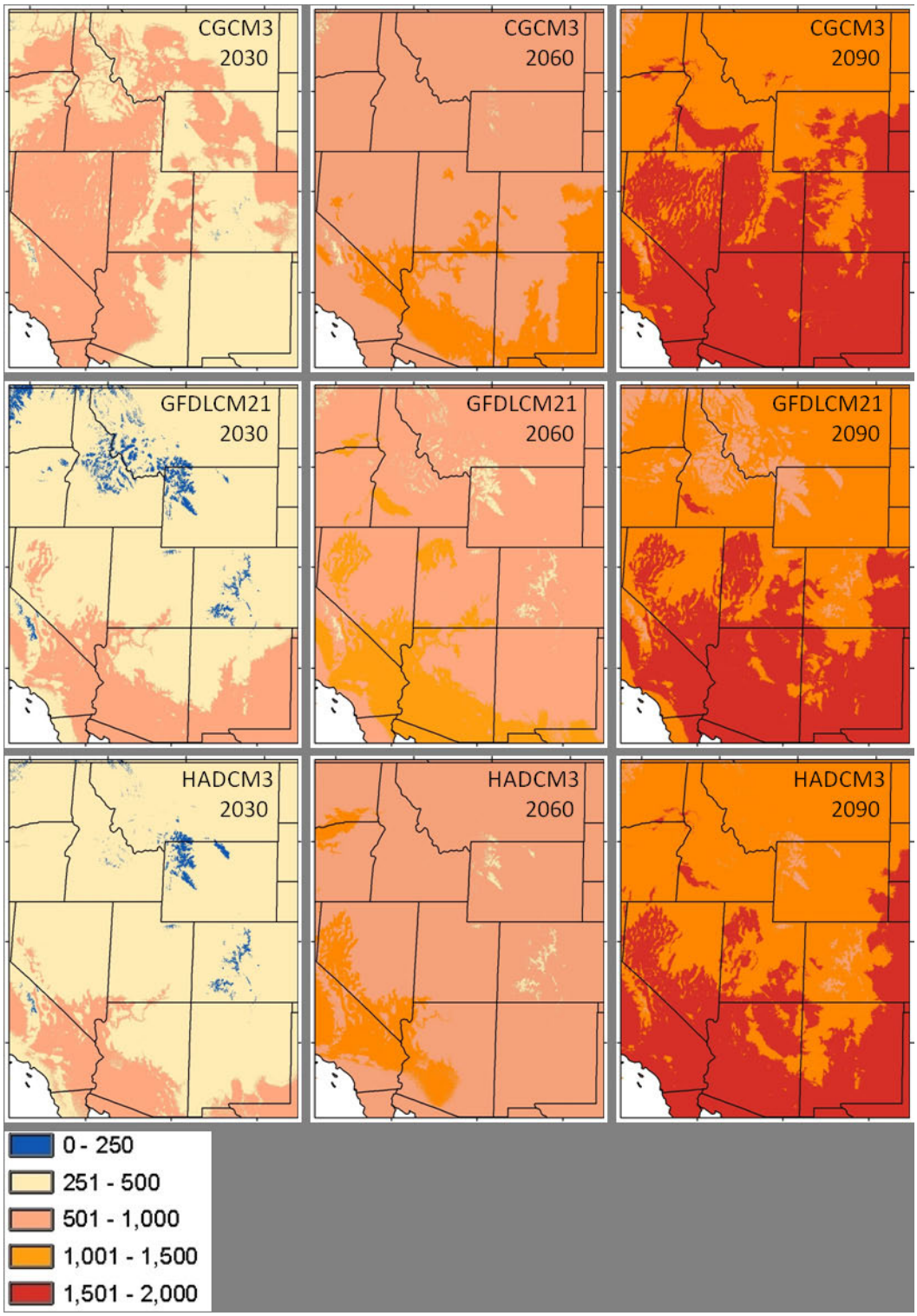

Figure 1-1. Mapped predictions of increase in the yearly accumulation of daily temperature sums over 5 °C for decades 2030, 2060, and 2090 relative to the contemporary climate (1961-1990) for the A2 scenario using Canadian Center for Climate Modeling (CGCM3), Geophysical Fluid Dynamics Laboratory (GFDLCM21) and Hadley Center/World Data Center (HADCM3) (see Rehfeldt and others 2009).

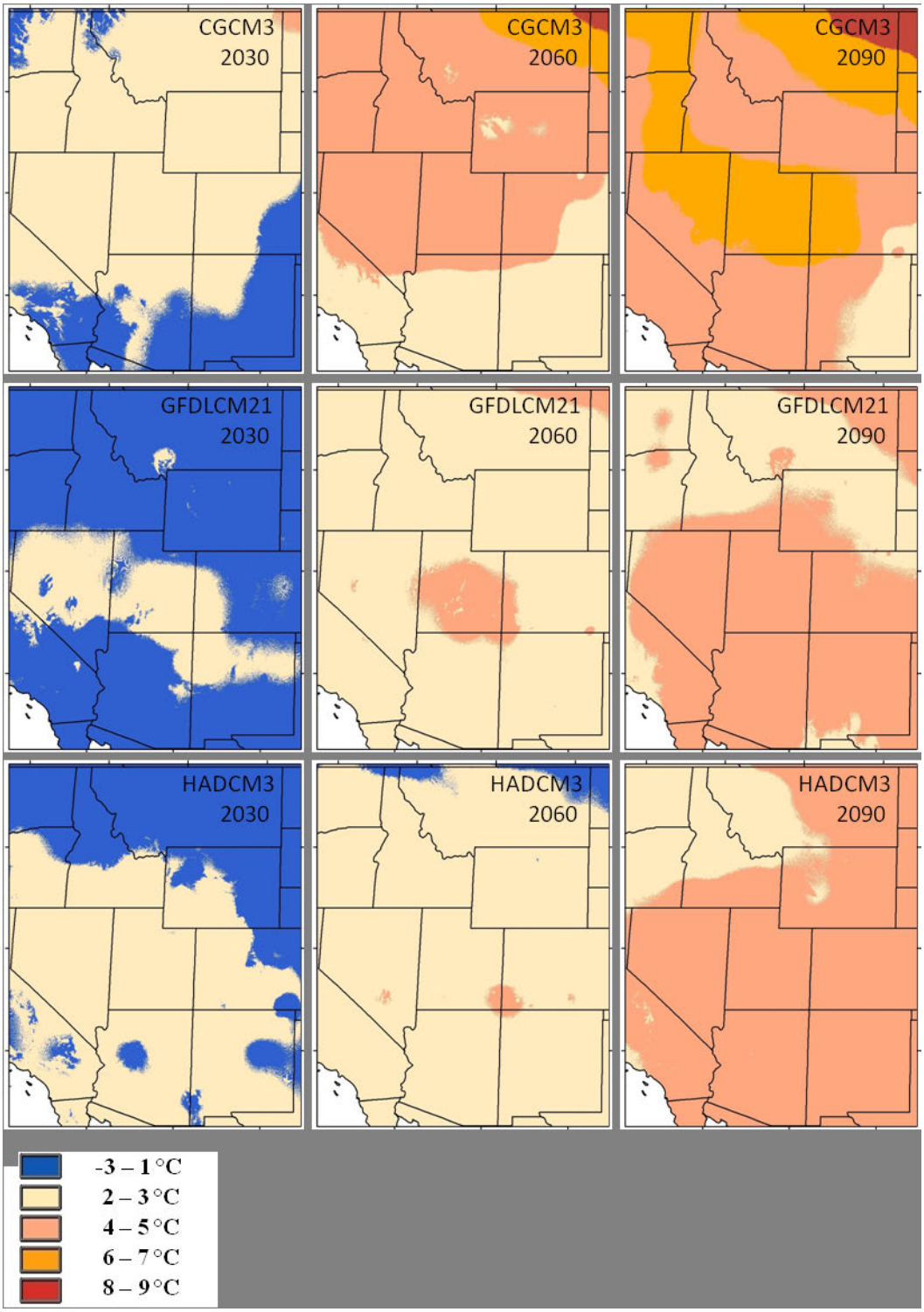

Figure 1-2. Mapped predictions of increase in mean temperature of the coldest month for decades 2030, 2060, and 2090 relative to the contemporary climate (1961-1990) for the A2 scenario using Canadian Center for Climate Modeling (CGCM3), Geophysical Fluid Dynamics Laboratory (GFDLCM21) and Hadley Center/World Data Center (HADCM3) GCMs (see Rehfeldt and others 2009).

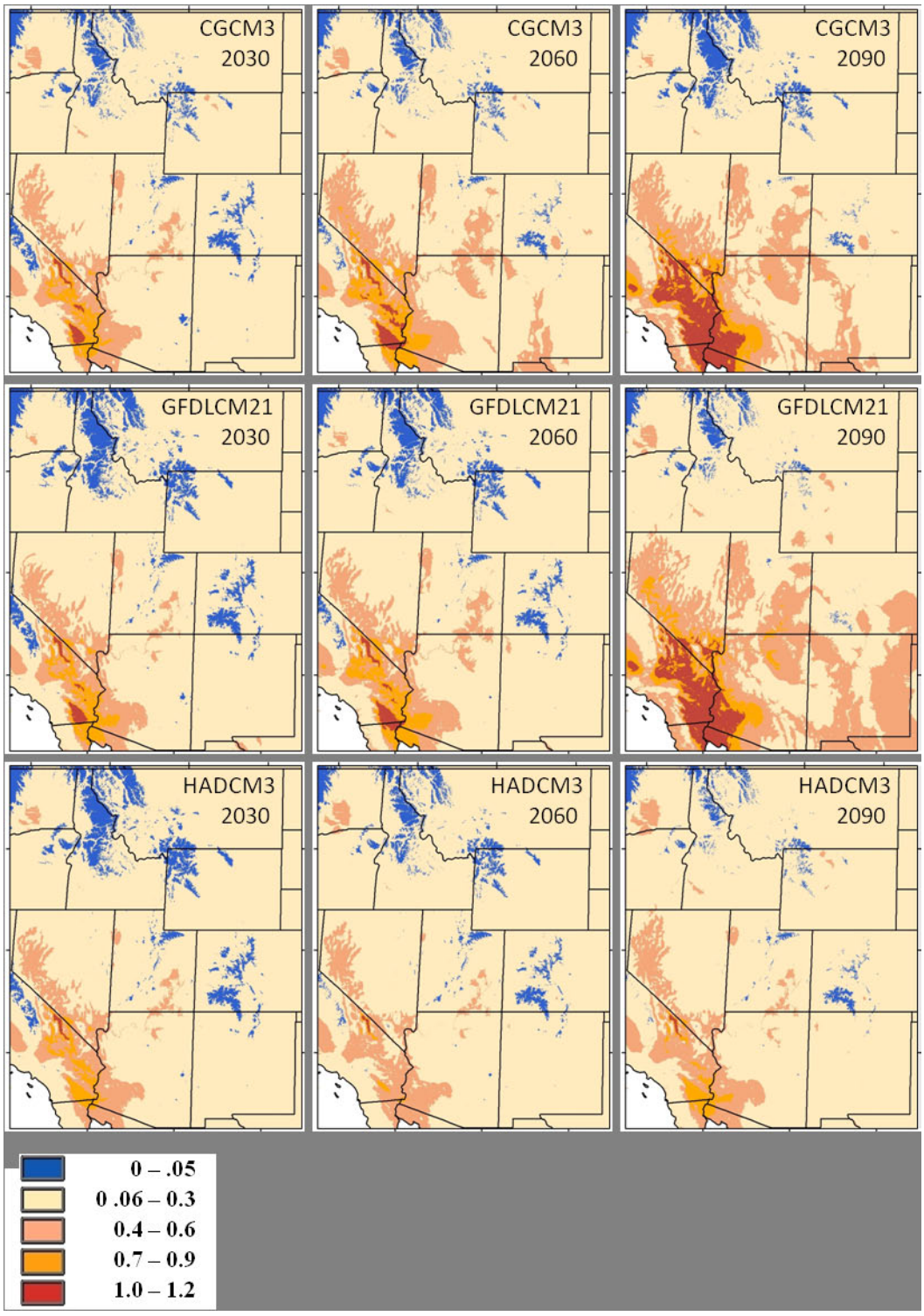

Figure 1-3. Mapped predictions of increase in annual dryness index for decades 2030, 2060, and 2090 relative to the contemporary climate (1961-1990) for the A2 scenario using Canadian Center for Climate Modeling (CGCM3), Geophysical Fluid Dynamics Laboratory (GFDLCM21) and Hadley Center/World Data Center (HADCM3) GCMs (see Rehfeldt and others 2009).

upon by newer bioclimate modeling techniques (see Rehfeldt and others 2006; Rehfeldt and Jaquish 2010; Saenz-Romero and others 2010). However, lack of detailed species distribution data limits the development of these more sophisticated bioclimate models for use in the Rocky Mountains.

How are Vegetation Types and Species Distributions Predicted to Change?

Understanding how species distributions and vegetation types will change due to increased temperature and altered precipitation regimes is essential for developing effective management and restoration approaches. In order to make efficient and effective decisions, managers must be able to identify the best management trajectory under future climate changes. Habitat protection, restoration, and facilitated adaptation are options that vary widely in their implementation, approach, and ultimate objectives. The feasibility of one approach over another will vary depending upon the degree and type of change experienced by an area. Consequently, many successful management decisions will be dependent on efforts to define future conditions.

Here, we present predicted changes in distribution of vegetation types and both native and invasive plant species in the interior western United States that are based on BEM and related analyses. Our capacity to predict the future distributions of species and vegetation types depends on our ability to accurately model future climate and relate species occurrence to environmental characteristics. BEMs describe the fundamental climate associated with the occurrence of a species and can incorporate detailed information on loss of suitable habitat and succession over time (Guisan and Thuiller 2005; Guisan and Zimmermann 2000; Franklin 1995). BEMs can be used to forecast a single species distribution based upon a set of environmental variables or can be more broadly applied to evaluate the distribution of a group of species (e.g., niche-theory models) (Botkin and others 2007). BEMs are commonly coupled with GCM output using various emission scenarios to predict the future distribution of species contemporary climate profiles or predicted realized climate niches based on their current distribution (Guisan and Thuiller 2005). In this application, resulting projections inherently retain substantial uncertainty associated with output from GCMs using emission scenarios.

Vegetation Types

The most comprehensive analysis of changes in vegetation types for the western United States was conducted by Rehfeldt and others (2006). In general, their predictions are consistent with those for more localized analyses of vegetation types (Kupfer and others 2004) and individual species (e.g., Neilson and others 2005). Rehfeldt and others (2006) modeled the contemporary distribution of Brown and others' (1998) biotic communities using climate variables and projected future distributions using the IS92a scenario (also known as the "business as usual" emission scenario) summarized for a combination of GCMs produced by the Hadley Center and Canadian Center for Climate Modeling and Analysis (table 1-1 and fig. 1-4). Rehfeldt and others (2006) estimated that by the end of the century, 55% of future landscapes in the West will have climates that are incompatible with the vegetation communities that now occur on those landscapes. In addition, 85% of the affected area is estimated to have a climate that does not match the climate profile of any contemporary western biotic communities. Figure 1-4 shows projections of the climate profile of Brown and others' (1998) biotic communities and responses under climate change during this century. The contemporary climate profile of the closest matching

Table 1-1. Mean and range of three climate variables for nine biomes (Brown and others 1998) of the Interior West.

		Degree-days >5 °C		Coldest month mean temperature (°C)		Annual moisture index[a]	
Biome	**Data points**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
Sonoran Desert	4,338	5849	2439–6379	11.2	2.2–12.8	0.47	0.18–1.00
Mojave Desert	5,963	4491	3041–6220	6.3	-6.5–9.4	0.43	0.20–0.68
Great Basin Desertscrub	29,047	2227	571–3088	-3.7	-10.8–11.9	0.19	0.11–0.29
Great Basin Shrub-Grassland	36,348	2030	1187–2933	-3.6	-81 – -0.4	0.14	0.07–0.25
Great Plains	16,153	2321	1498–3427	-2.8	-8.7–3.2	0.13	0.09–0.17
Pinyon-Juniper Woodlands	82,248	2189	322–3138	-2.1	-11.5–2.8	0.14	0.08–0.24
Rocky Mountain Montane Forest	52,735	1444	988–3425	-5.0	-8.1–3.2	0.07	0.04–0.09
Rocky Mountain Subalpine Forest	41,646	812	542–2149	-8.5	-11.4 – -3.4	0.02	0.01–0.03
Alpine Tundra	8,344	413	237–1711	-10.6	-13.2 – -3.4	0.02	0.01–0.03

[a] (degree-days >5 °C)$^{0.5}$ / mean annual precipitation.

biotic community is used. It is worthwhile to note several general trends (calculated as percent change between current and year 2060 projections):

- Suitable habitat for Rocky Mountain subalpine conifer forests that account for approximately 1% of current cover disappears almost completely (99.7%) by 2090. Suitable climate for Rocky Mountain and Great Basin alpine tundra disappears completely by 2060.
- Habitat with climate suitable for Rocky Mountain conifer forest shifts upslope, displacing habitat currently occupied by subalpine coniferous forests, and shows corresponding losses at low elevations. Localized extinctions are expected, especially in the south.
- Habitat suitable for Great Basin conifer woodlands is projected to move north and upslope with principal gains in Colorado and southwest Wyoming and losses in the Southwest. An equivalent spatial shift for this vegetation type would constitute a continuation of migratory trends documented from the late Pleistocene to the present (Betancourt 1987).
- The climate conducive for Plains grasslands is reduced slightly with losses occurring primarily in Colorado and New Mexico. Semi-desert grassland habitat expands northward from the Southwest into the Great Basin, Colorado Plateau, and southern Great Plains and occupies an area nearly four times that of the present. Habitat suitable for Great Basin shrub grassland decreases by 40% and becomes highly fragmented.
- In addition to semi-desert grasslands, projected climate changes through 2060 appear to be most favorable for Mohave Desert (85% increase), Sonoran Desert (79% increase), and Chihuahuan Desert (167% increase) scrub vegetation types. Between 2060 and 2090, Mojave and Sonoran Desert vegetation communities will continue to expand while Chihuahuan Desert vegetation will contract. In general, habitat suitable for the Sonoran Desert scrub type expands northward as the Mojave Desert scrub type migrates to the Great Basin and Snake and Columbia River Plains.
- Habitat favorable to Great Basin Desert scrub is projected to expand in the short term and then becomes fragmented as it contracts later in the century. Great Basin montane scrub habitat will experience moderate decline and displacement by Mojave Desert species through time (69% decrease) (fig. 1-4). Fragmentation of these and other habitats can exacerbate other negative effects of climate change and influence realized shifts and persistence of habitats and species.

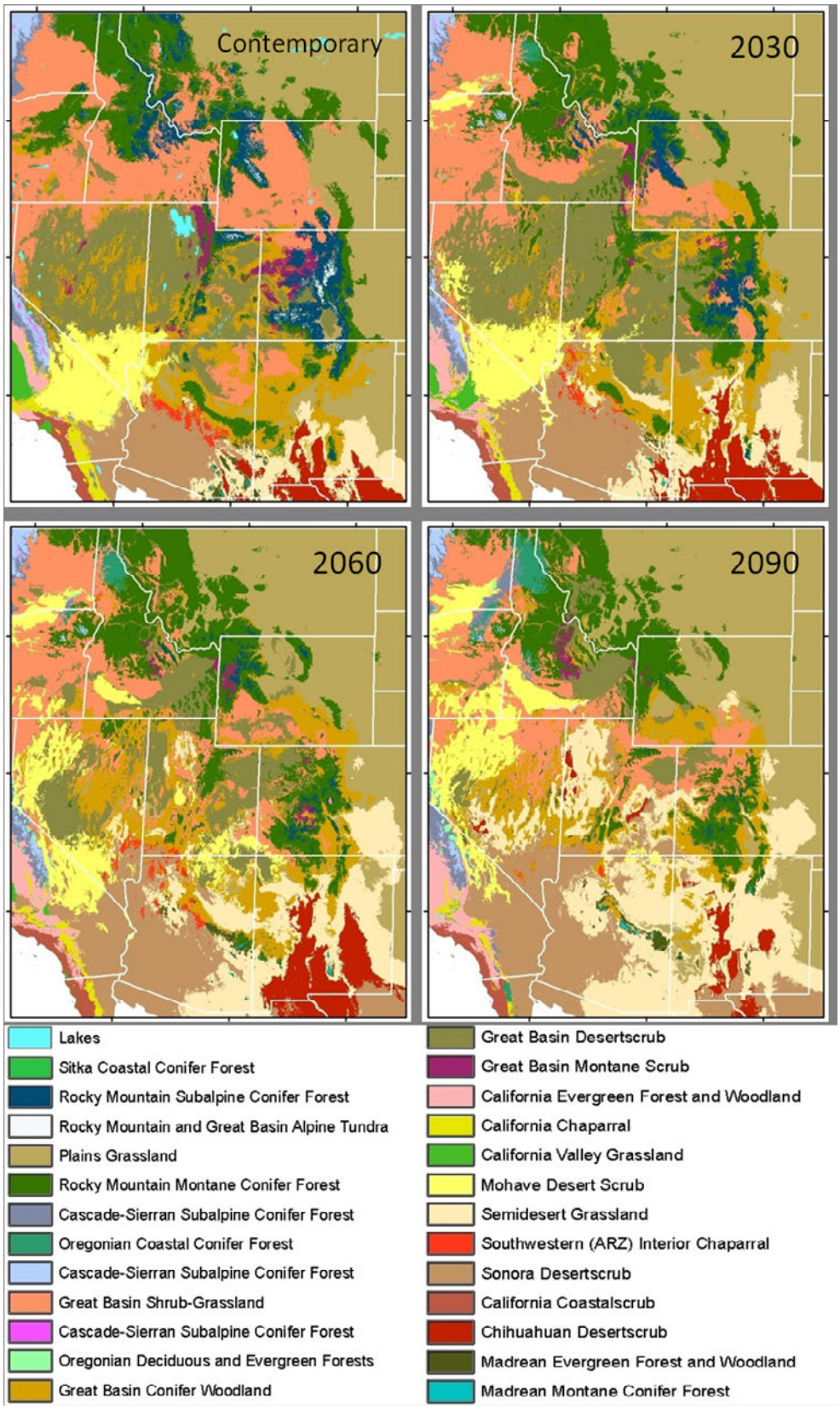

Figure 1-4. Modeled realized climatic niche (upper left) and their predicted future distributions for Brown and others (1998) biotic communities in the interior western United States (Rehfeldt and others 2006). Lake positions were omitted from future projections.

Native Species

Analyses specific to species in the Interior West are limited but provide insights into the effects of climate change on several of the region's keystone species. Following are some examples of these analyses:

- Crookston (see http://forest.moscowfsl.wsu.edu/climate/) used methodology described by Refeldt and others (2009) to create a species climate profile (contemporary realized climate niche) projected in six future climates (three GCMs and two scenarios) for several western species. Among these, one seed juniper (*Juniperus monosperma*) (fig. 1-5), Utah juniper (*Juniperus osteosperma*) (fig. 1-6), two needle pinyon pine (*Pinus edulis*) (fig. 1-7), and single leaf pinyon pine (*Pinus monophylla*) (fig. 1-8) are presented. These predictions generally agree with those of Rehfeldt and others (2006) for Great Basin conifer woodlands and indicate a continuation of migratory trends documented from the late Pleistocene to the present (Betancourt 1987).
- Neilson and others (2005) used a coupled bioclimate model to predict a decline in sagebrush habitat in the Great Basin due to the synergistic effects of temperature increases and fire and disease, and to displacement by species moving north from the Mojave Desert in response to the northward shift in frost lines.
- Bradley (2010) used risk analysis to assess the interactive impacts of land use conversion (woodland expansion), land use (roads, agriculture, etc.), and cheatgrass (*Bromus tectorum*) invasion on sagebrush (*Artemisia* spp.) habitat in Nevada. Changes to the climatic habitat of *Artemisia* spp. were estimated using an ensemble of 10 atmospheric-ocean GCMs and 2 BEMs. Sagebrush vegetation types in southern Nevada were at the greatest risk of losing suitable habitat due to climate change. Disturbance risk was greatest in the northern section of the state. Overall, Bradley (2010) supported the conclusion that climate change poses a substantial risk to sagebrush ecosystems in the Great Basin.
- Shafer and others (2001) used bioclimate modeling to predict that sagebrush (*Artemisia tridentata*) will shift northward and exhibit substantial range contraction due to increased summer moisture stress. They also predicted northward expansions of Joshua tree (*Yucca brevifolia*), saguaro (*Carnegiea gigantea*), and creosote bush (*Larrea tridentata*). Creosote bush is expected to expand northward into areas currently occupied by big sagebrush, matching Neilson and others' (2005) prediction**.**
- Warwell and others (2008) used bioclimate modeling to conclude that the contemporary populations of species with small distributions such as smooth Arizona cypress (*Cupressus arizonica* ssp. *glabra*) and the endangered perennial MacFarlane's four-o'clock (*Mirabilis macfarlanei*) are likely to be subjected to complete climate disequilibrium earlier in the century than more broadly distributed species.

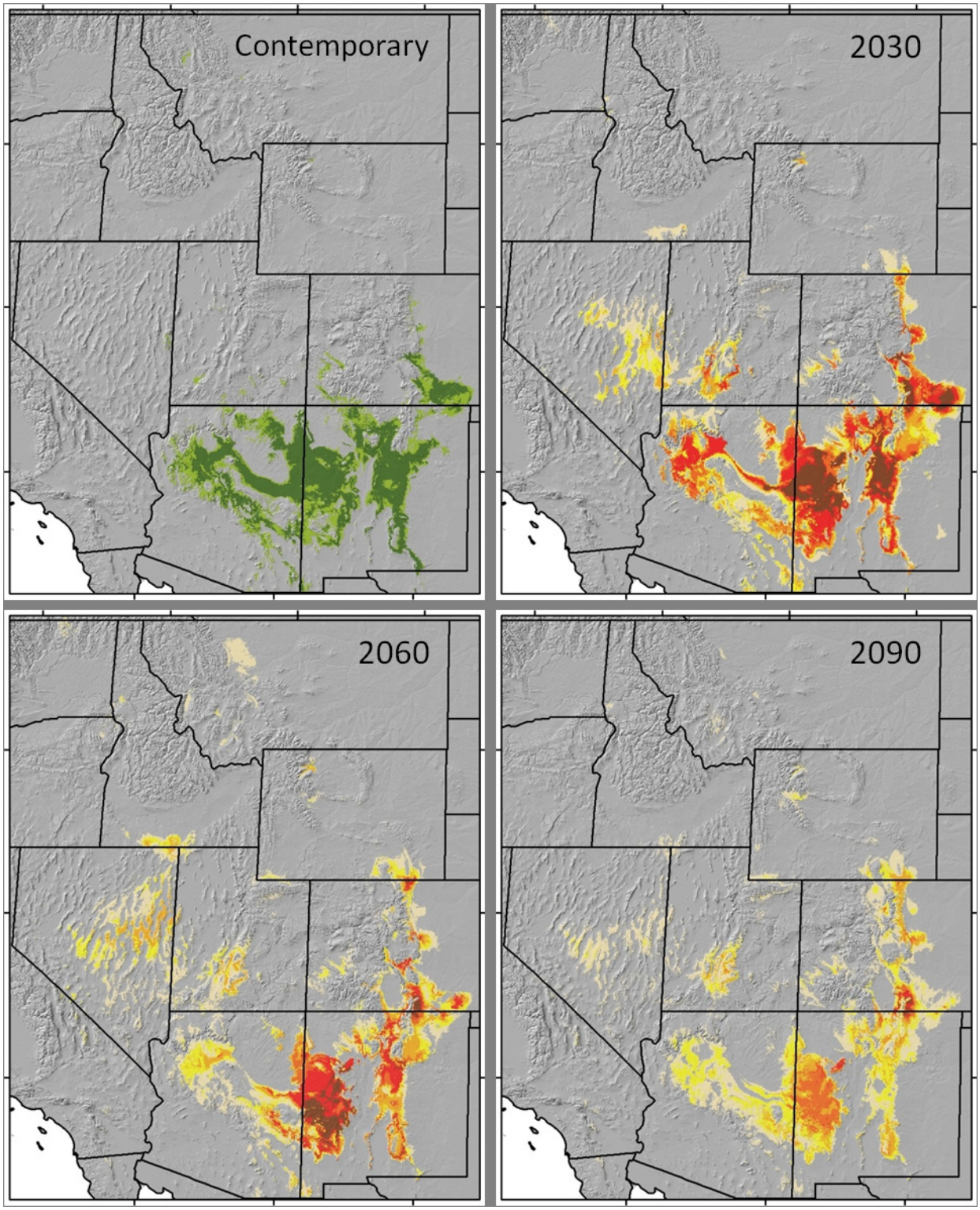

Figure 1-5. Mapped realized climate niche of one seed juniper (*Juniperus monosperma*; green) for contemporary climate (1961-1990) and future climates for decades 2030, 2060, and 2090. Colors coding in future projections indicate occurrence of agreement among 3 GCMs and 2 scenarios. Dark red = complete agreement for all 6 combinations; red = agreement for 5 combinations; dark orange = 4; orange = 3; yellow = 2; and tan = 1 (see Rehfeldt and others 2009).

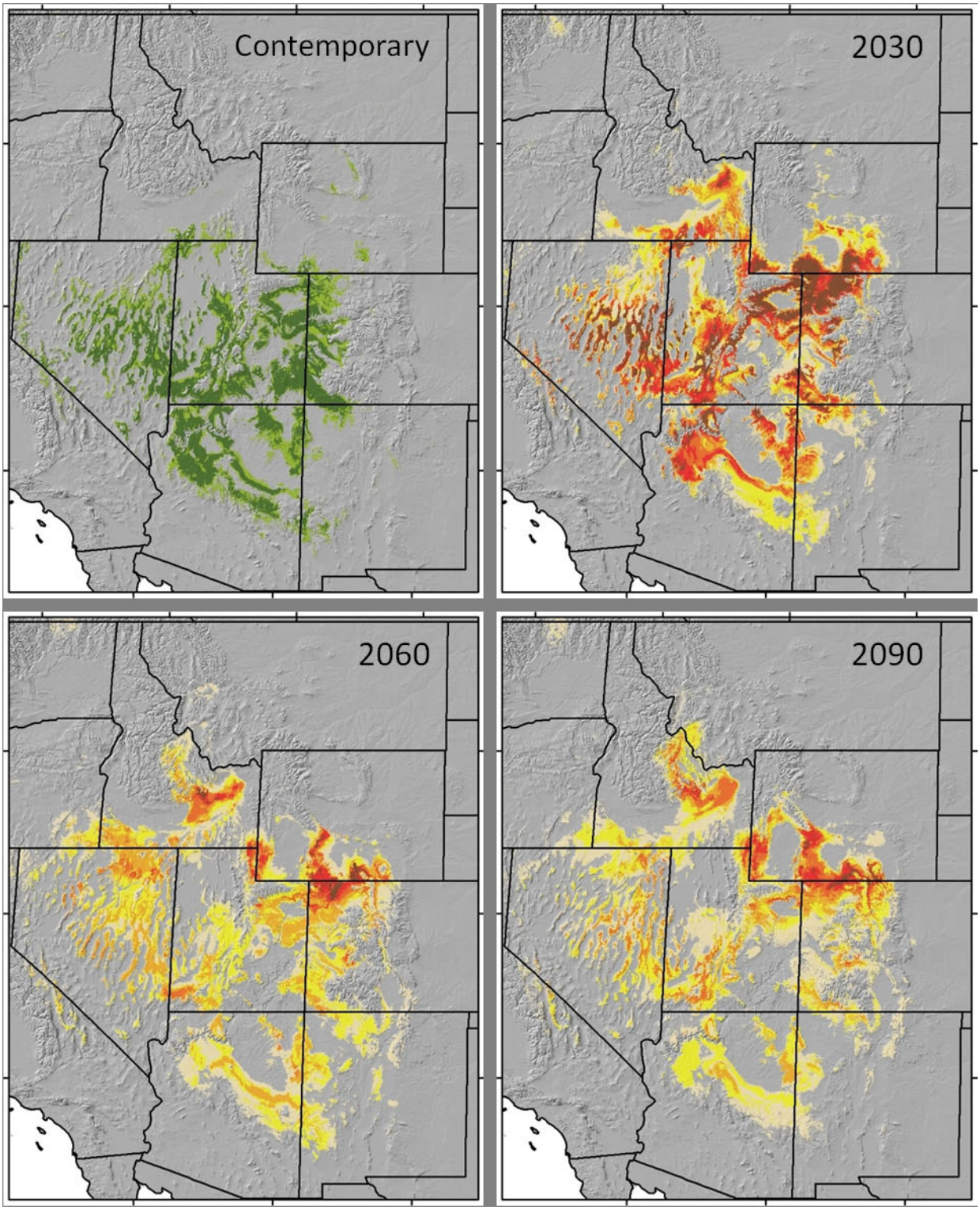

Figure 1-6. Mapped realized climate niche of Utah juniper (*Juniperus osteosperma*; green) for contemporary climate (1961-1990) and future climates for decades 2030, 2060, and 2090. Colors coding in future projections indicate occurrence of agreement among 3 GCMs and 2 scenarios. Dark red = complete agreement for all 6 combinations; red = agreement for 5 combinations; dark orange = 4; orange = 3; yellow = 2; and tan = 1 (see Rehfeldt and others 2009).

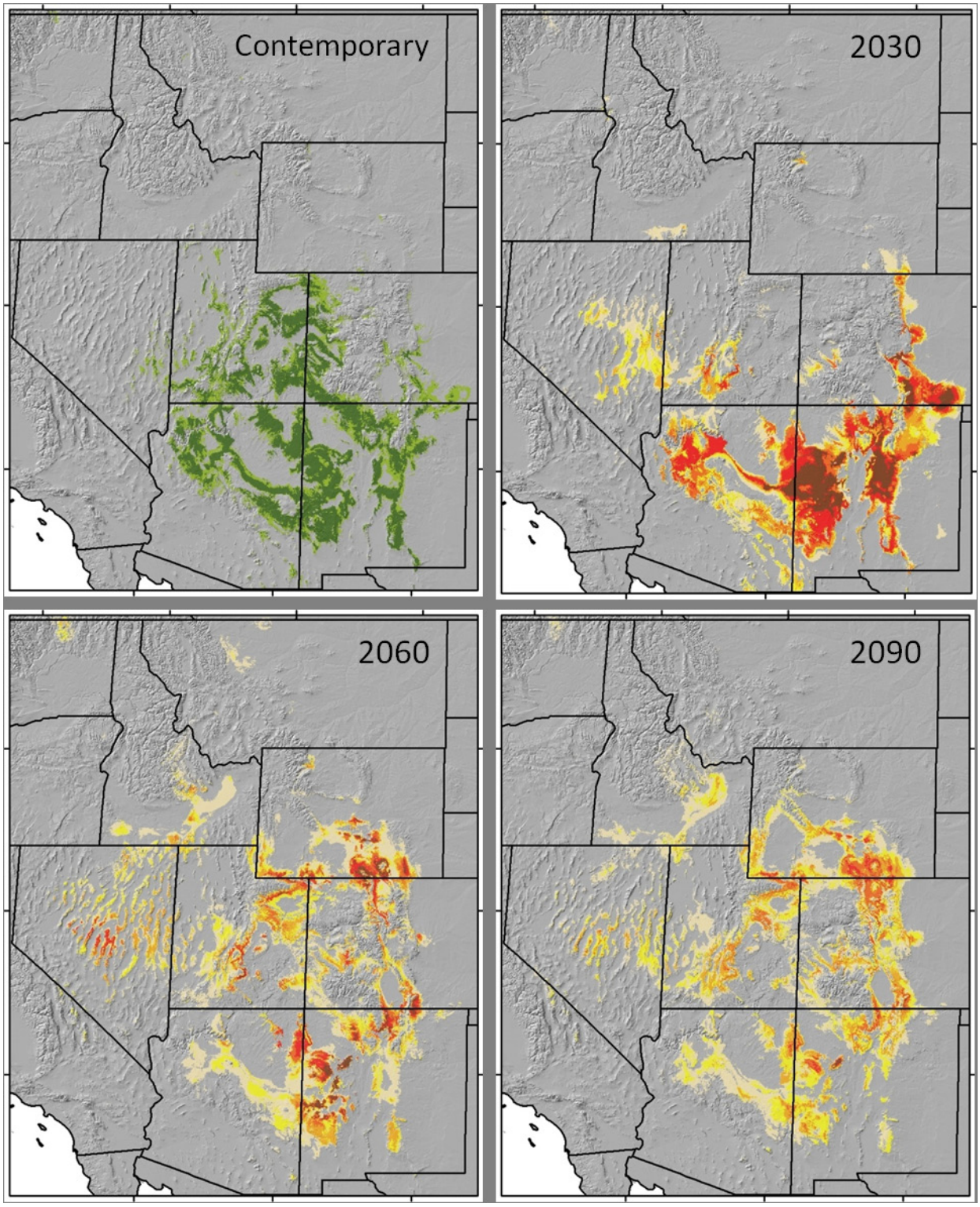

Figure 1-7. Mapped realized climate niche of two needle pinyon pine (*Pinus edulis*; green) for contemporary climate (1961-1990) and future climates for decades 2030, 2060, and 2090. Colors coding in future projections indicate occurrence of agreement among 3 GCMs and 2 scenarios. Dark red = complete agreement for all 6 combinations; red = agreement for 5 combinations; dark orange = 4; orange = 3; yellow = 2; and tan = 1 (see Rehfeldt and others 2009).

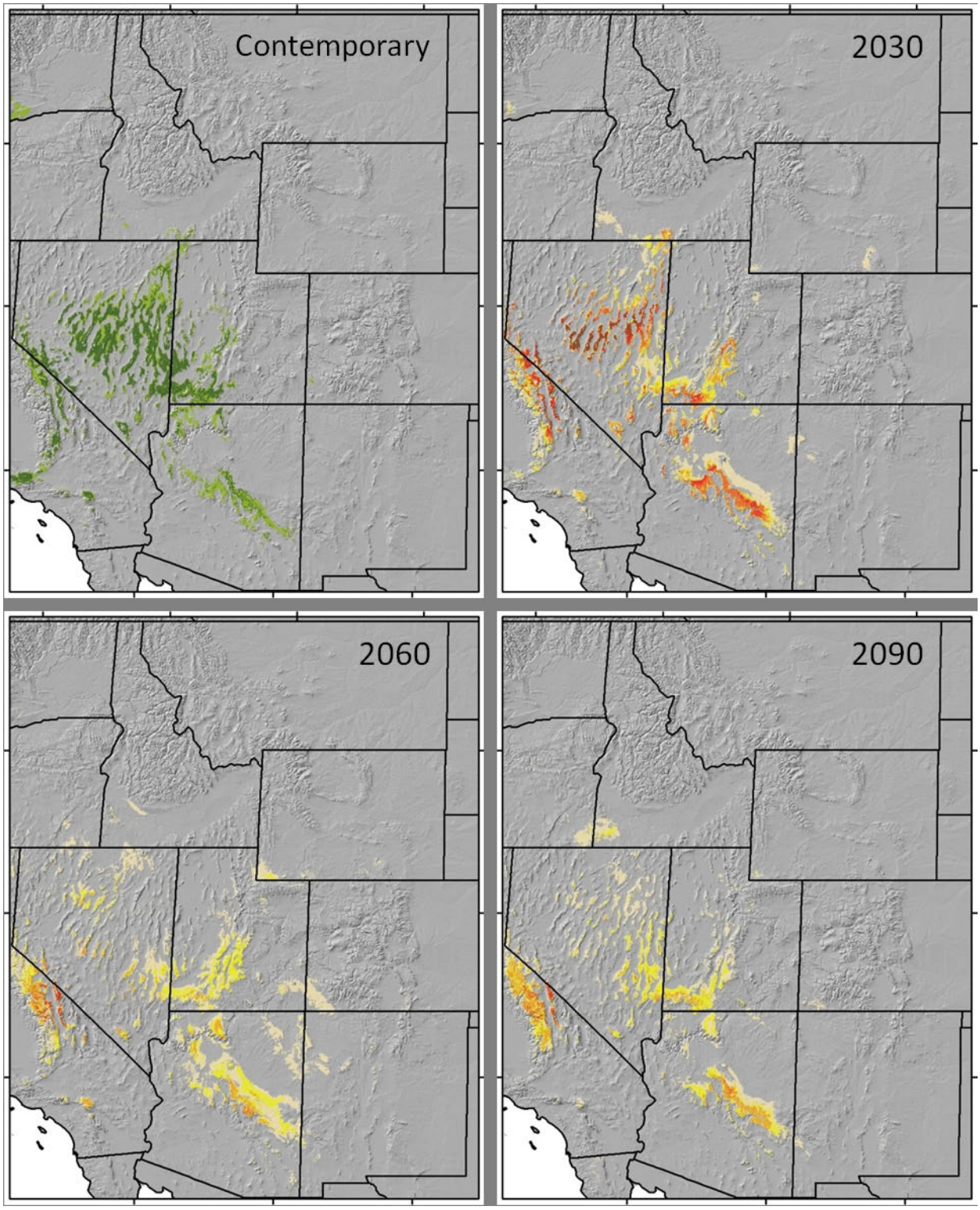

Figure 1-8. Mapped realized climate niche of one seed juniper (*Pinus monophylla*; green) for contemporary climate (1961-1990) and future climates for decades 2030, 2060, and 2090. Colors coding in future projections indicate occurrence of agreement among 3 GCMs and 2 scenarios. Dark red = complete agreement for all 6 combinations; red = agreement for 5 combinations; dark orange = 4; orange = 3; yellow = 2; and tan = 1 (see Rehfeldt and others 2009).

Invasive Species

There is increasing evidence that invasive species also are being affected by climate change (Dukes and Mooney 1999; Walther and others 2009; Bradley and others 2010). However, forecasting changes in invasive species distributions poses some unique challenges because these species may not be in equilibrium with their newly invaded habitat. Analyses specific to invasive species are limited for the Rocky Mountain region and focus on only a few species. Bradley and others (2009) used bioclimate models to identify the risk of spread of four invasive species in the western Unites States:

- Spotted knapweed (*Centaurea biebersteinii*) is expected to expand into new areas of California and Nevada. Its current distribution in the coastal states (California, Oregon, and Washington) showed little change (loss of suitability) under future scenarios, but climate change may result in a transition to higher elevations in interior states (e.g., Montana, Wyoming, Colorado, and Utah).
- Tamarisk (*Tamarix* spp.) distributions were not well constrained by environmental characteristics, and the authors found no evidence for temperature constraints. Not surprisingly, the risk of tamarisk spread, which occurs within riparian areas and elevated water tables across most of the western United States, was not shown to be influenced by the direct effects of climate change.
- In contrast, leafy spurge (*Euphorbia esula*) is expected to expand throughout the majority of northern states west of Mississippi and some of the rangelands west of the Rocky Mountains. However, leafy spurge is likely to retreat from Colorado, Nebraska, Oregon, and Idaho as result of warmer temperatures.
- Cheatgrass (*Bromus tectorum*) is constrained by multiple precipitation variables and winter maximum temperature. Climate change is expected to shift potentially susceptible habitats northward, creating an increased risk in Idaho, Montana, and Wyoming but reduced risk in southern Nevada and Utah. Currently infested areas of central Utah and southern and central Nevada did not appear to remain suitable to this species, which may indicate a future range contraction. As much as 13% of the current invaded lands may not be suitable for this species under global warming and replacement by other invasive species is probable (e.g., red brome [*Bromus rubens*]). This pattern may be repeated with other invasive species.

Research Needs

Developing a framework for integrating the different approaches could significantly improve our ability to forecast changes in vegetation types and species. Such a framework might include long-term experiments (e.g., for explicit species, locations, and climate change scenarios) designed to explore the local complexities of species and ecosystem responses to climate change that support more comprehensive mechanistic models and provide for testing BEMs. The integration of experimental work and modeling could further our understanding of the ecological consequences of climate change, improve our projections for the future, and provide information necessary to maintain ecosystem services through development of effective conservation and restoration strategies in the context of climate change. Frameworks for predicting vegetation response to climate change that include research experiments, mechanistic modeling, and species distribution modeling can be used to identify and address critical information gaps, including the following:

- Obtain the necessary species-specific data regarding important climate variables, biotic interactions, genetic variation, and adaptive capacity to improve model

predictions. To date, the primary emphasis has been placed on tree species. For deserts, grasslands, and shrublands, an increased emphasis needs to be placed on determining the relationships among climate variables and establishment and growth and reproduction of grasses, forbs, and shrubs. And in these arid to semi-arid systems, climate variables other than temperature and precipitation, such as snowpack duration and water-balance deficit, may better reflect the resources that are available for plant growth (Stephenson 1990, 1998).

- Determine the interacting effects of climate and other global change processes such as extreme events, increasing CO_2, nitrogen deposition, pests, and disease on species distributions and community composition to improve model predictions of the synergistic effects of these processes (Campbell and others 2000). Long-term research and regional monitoring may be necessary to distinguish the effects of climate from other change agents and identify the indirect effects of climate on species interactions (Pearson and Dawson 2003).
- Evaluate the interacting effects of socioeconomic and biophysical factors on land use and land cover change and, consequently, on species distribution and community composition (Hansen and others 2001).
- Increase our knowledge of the effects of species diversity and functional groups on ecosystem processes as they relate to climate and other global change factor.
- Continue to advance modeling efforts that couple bioclimate analyses with models that are able to estimate feedback, competitive interactions, and disturbance effects (e.g., Huntley and others 2010; Franklin 2010). Risk models can incorporate empirical, experimental, or observational information into a geospatial (GIS) framework to create spatially explicit predictions of threats and change (Bradley and others 2010).
- Continue to explore other modeling approaches, such as combining historic distribution data with contemporary distributions, to identify species specific climate limitations that may then be used to parameterize models (e.g., Arundel 2005).

Literature Cited

Alward, R. D., J. K. Detling and M. G. Milchunas. 1999. Grassland vegetation changes and nocturnal global warming. Science 283: 229.

Araújo, M. B., R. G. Pearson, W. Thuiller and M. Erhard. 2005. Validation of species-climate impact models under climate change. Global Change Biology 11: 1504-1513.

Arundel, S. T. 2005. Using spatial models to establish climatic limiters of plant species' distributions. Ecological Modelling 182: 159-181.

Berger, U., C. Piou, K. Schiffers and V. Grimm. 2008. Competition among plants: concepts, individual-based modeling approaches, and a proposal for a future research strategy. Perspectives in Plant Ecology Evolution and Systematics 9: 121-135.

Betancourt, J. L. 1987. Paleoecology of pinyon-juniper woodlands: summary. In: Everett, R. L., compiler. Proceedings: Pinyon-Juniper Conference. Gen. Tech. Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 164-185.

Botkin, D. B., H. Saxe, M. B. Araujo, R. Betts and others. 2007. Forecasting the effects of global warming on biodiversity. Bioscience 57: 227-236.

Bradley, B. A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Global Change Biology 15: 196-208.

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.

Bradley, B. A., D. M. Blumenthal, D. S. Wilcove and L. H. Ziska. 2010. Predicting plant invasions in an era of global change. Trends in Ecology and Evolution 25: 310-318.

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 p.

Brown, J. H., T. J. Valone and C. G. Curtin. 1997. Reorganization of an arid ecosystem in response to recent climate change. Proceedings of the National Academy of Science 94: 9729-9733.

Campbell, B. D. 2000. A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications. Agriculture, Ecosystems and Environment 82: 39-55.

Chew, J. D., C. Stalling and K. Moeller. 2004. Integrating knowledge for simulating vegetation change at landscape scales. Western Journal of Applied Forestry 19: 102-108.

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen and others. 2007. Regional climate projections. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

Davis, M. B. and R. G. Shaw. 2001. Range shifts and adaptive responses to quaternary climate change. Science 292: 673-679.

Dukes, J. S. 2002. Comparison of the effect of elevated CO2 on an invasive species (*Centaurea solstitialis*) in monoculture and community settings. Plant Ecology 160: 225-234.

Dukes, J. S. and H. A. Mooney. 1999. Does global change increase the success of biological invaders? Trends in Ecology and Evolution 14: 135-139.

Farber, O. and R. Kadmon. 2003. Assessment of alternative approaches for bioclimatic modeling with special emphasis on the Mahalanobis distance. Ecological Modeling 160: 115-130.

Franklin, J. 1995. Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. Progress in Physical Geography 19: 474-499.

Franklin, J. 2010. Moving beyond static species distribution models in support of conservation biogeography. Diversity and Distributions 16: 321-330.

Guisan, A. and W. Thuiller. 2005. Predicting species distribution: offering more than simple habitat models. Ecology Letters 8: 993-1009.

Guisan, A. and N. E. Zimmermann. 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135: 147-186.

Hansen, A. J., R. P. Neilson, V. H. Dale, C. H. Flather and others. 2001. Global change in forest: responses of species, communities and biomes. BioScience 51: 765-779.

Harris, J. A., R. J. Hobbs, E. Higgs and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14:170-176.

Harte, J. and R. Shaw. 1995. Shifting dominance within a montane vegetation community—results of a climate-warming experiment. Science 267: 876-880.

Hijmans, R. J. and C. H. Graham. 2006. The ability of climate envelope models to predict the effect of climate change on species distributions. Global Change Biology 12: 2272-2281.

Huntley, B., P. Barnard, R. Altwegg, L. Chambers and others. 2010. Beyond bioclimatic envelopes: dynamic species' range and abundance modeling in the context of climatic change. Ecography 33: 621-626.

Intergovernmental Panel on Climate Change [IPCC]. 2007. Climate Change 2007: Impacts, adaptation and vulnerability. In: Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, eds. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press. 976 p.

Jeltsch, F., K. A. Moloney, F. M. Schurr, M. Kochy and M. Schwager. 2008. The state of plant population modeling in light of environmental change. Perspectives in Plant Ecology Evolution and Systematics 9: 171-189.

Kupfer, J. A., J. Balmat and J. L. Smith. 2004. Shift in the potential distribution of shy island plant communities in response to climate change. In: Gottfried, G. J., B. S. Gebow, L. G. Eskew, C. B. Edminster, eds. Proceedings: Connecting mountain islands and desert seas: biodiversity and management of the Madrean Archipelago II. RMRS-P-36. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 485-590.

Nielson, R. P., J. M. Lenihan, D. Bachelet and R. J. Drapek. 2005. Climate change implications for sagebrush ecosystems. Transactions of the 70th North American Wildlife and Natural Resources Conference, March 16-19, 2005. Arlington, VA: Wildlife Management Institution Publications Department: 145-159.

North, G. R., F. Biondi, P. Bloomfield, J. R. Christy and others. 2006. Surface temperature reconstructions for the last 2,000 years. The National Academies Press. Washington, DC. 160 p.

Pearson, R. G. and T. P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12: 361-371.

Peñuelas, J., P. Prieto, C. Beier, C. Cesaraccio and others. 2007. Response of plant species richness and primary productivity in shrublands along a north–south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. Global Change Biology 13: 25632581.

Plummer, D. A., D. Caya, A. Frigon, H. Côté and others. 2006. Climate and climate change over North America as simulated by the Canadian Regional Climate Model. Journal of Climate 19: 3112-3132.

Randall, D. A., R. A. Wood, S. Bony, R. Colman and others. 2007. Climate models and their evaluation. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

Rehfeldt, G. E. 2006. A spline model of climate for the western United States. Gen. Tech. Rep. RMRS-GTR-165. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 21 p.

Rehfeldt, G. E., N. L. Crookston, M. Warwell and J. S. Evans. 2006. Empirical analyses of plant-climate relationships for the western United States. Journal of Plant Science 167: 1123-1150.

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. and B. C. Jaquish. 2010. Ecological impacts and management strategies for western larch in the face of climate-change. Mitigation and Adaptation Strategies for Global Change 15(3): 283-306.

Sáenz-Romero, C., G. E. Rehfeldt, N. L. Crookston, P. Duval and others. 2010. Spline models of contemporary, 2030, 2060, and 2090 climates for Mexico and their use in understanding climate-change impacts on the vegetation. Climatic Change 102: 595-623.

Seager, R., M. F. Ting, I. Held, Y. Kushnir and others. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316: 1181-1184.

Shafer, S. L., P. J. Bartlein and R. S. Thompson. 2001. Potential changes in the distribution of western North America tree and shrub taxa under future climate scenarios. Ecosystems 4: 200-215.

Sheffield, J. and E. F. Wood. 2008. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Climate Dynamics 31: 79-105.

Stewart, I. T., D. R. Cayan and M. D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual' climate change scenario. Climatic Change 62: 217-232.

Suttle, K. B., M. A. Thomsen and M. E. Power. 2007. Species interactions reverse grassland responses to changing climate. Science 315: 640-642.

Torn, M. S. and J. Harte. 2006. Missing feedbacks, asymmetric uncertainties, and the underestimation of future warming. Geophysical Research Letters 33, L10703.

Turner, M. G. 2010. Disturbance and landscape dynamics in a changing world. Ecology 91(10): 2833-2849.

Walther, G. R., A. Roques, P. E. Hulme, M. T. Sykes and others. 2009. Alien species in a warmer world: risks and opportunities. Trends in Ecology and Evolution 24: 686-693.

Warwell, M. V., G. E. Rehfeldt and N. L. Crookston. 2010. Modeling species realized climatic niche space and predicting their response to global warming for several western forest species with small geographic distributions. In: Pye, J. M., H. M. Rauscher, Y. Sands, D. C. Lee and J. S. Beatty, eds. Advances in threat assessment and their application to forest and rangeland management-Volume 1. Gen. Tech. Rep. PNW-GTR-802. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest and Southern Research Stations: 36-59.

Williams, J. J. and S. T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. Paleoecology 5(9): 475-482.