

## Invited Synthesis

# Climate Change and North American Rangelands: Trends, Projections, and Implications

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### Abstract

The amplified “greenhouse effect” associated with increasing concentrations of greenhouse gases has increased atmospheric temperature by 1°C since industrialization (around 1750), and it is anticipated to cause an additional 2°C increase by mid-century. Increased biospheric warming is also projected to modify the amount and distribution of annual precipitation and increase the occurrence of both drought and heat waves. The ecological consequences of climate change will vary substantially among ecoregions because of regional differences in antecedent environmental conditions; the rate and magnitude of change in the primary climate change drivers, including elevated carbon dioxide (CO<sub>2</sub>), warming and precipitation modification; and nonadditive effects among climate drivers. Elevated atmospheric CO<sub>2</sub> will directly stimulate plant growth and reduce negative effects of drying in a warmer climate by increasing plant water use efficiency; however, the CO<sub>2</sub> effect is mediated by environmental conditions, especially soil water availability. Warming and drying are anticipated to reduce soil water availability, net primary productivity, and other ecosystem processes in the southern Great Plains, the Southwest, and northern Mexico, but warmer and generally wetter conditions will likely enhance these processes in the northern Plains and southern Canada. The Northwest will warm considerably, but annual precipitation is projected to change little despite a large decrease in summer precipitation. Reduced winter snowpack and earlier snowmelt will affect hydrology and riparian systems in the Northwest. Specific consequences of climate change will be numerous and varied and include modifications to forage quantity and quality and livestock production systems, soil C content, fire regimes, livestock metabolism, and plant community composition and species distributions, including range contraction and expansion of invasive species. Recent trends and model projections indicate continued directional change and increasing variability in climate that will substantially affect the provision of ecosystem services on North American rangelands.

**Key Words:** atmospheric CO<sub>2</sub>, atmospheric warming, climate variability, greenhouse gases, livestock production, precipitation patterns

## INTRODUCTION

Climate change science predicts warming and greater climatic variability for the foreseeable future, including more frequent and severe droughts and storms, as a consequence of increasing atmospheric concentrations of greenhouse gases (GHGs). A climate change footprint has become evident in the form of atmospheric warming, rapid glacial retreat, accelerated plant phenology, modified precipitation patterns, and increasing wildfires (Parmesan and Yohe 2003; IPCC 2007). These changes to the Earth system are consistent with those of a warmer and more variable climate and have important

consequences for the provisioning of ecosystem services to an increasing and more affluent human population (Walther 2003, 2010). Greater warming and climatic variability, expressed against the backdrop of large-scale and accelerating shifts in land use, pose a major challenge to society and more directly to natural resource managers, producers, and policymakers (Parmesan and Yohe 2003; Rockstrom et al. 2009).

The science of climate change inevitably contains uncertainties partly because climatic and ecological systems are complex and the consequences of this unprecedented phenomenon will be expressed over long time frames. Despite these uncertainties, it would be irresponsible to ignore the cumulative evidence for climate change—both the current footprint and model projections—on the basis that the rates and magnitude of change are not fully known. Unfounded optimism regarding climatic consistency currently constrains our ability to anticipate and develop effective contingency plans for nominal weather variation, and this perspective will pose a challenge to the development of strategies for confronting climate change (Joyce et al. 2013 [this issue]).

This synthesis was developed to provide an objective, concise assessment of climate trends and projections and potential

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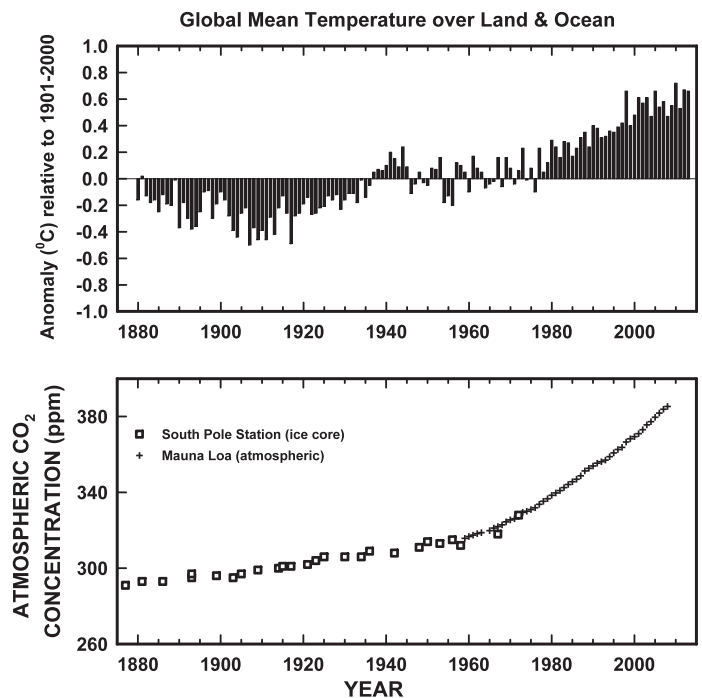
ecological implications of climate change that are of direct relevance to North American rangelands. This synthesis is organized to summarize individual and integrated impacts of the three major climate change drivers—elevated atmospheric carbon dioxide (CO<sub>2</sub>), biospheric warming, and modified precipitation regimes—on ecological processes relevant to the provision of rangeland ecosystem services. Specific objectives are to 1) present climatic trends documented during the 20th century 2) identify predictions for climate change in the 21st century, and 3) present evidence for ecological implications of current and future climate change, including synoptic scenarios of four ecoregions. We draw on data and case studies specific to North American rangelands, but we anticipate that this synthesis will have broader implications by informing management and policy recommendations and guiding future research programs. Adaptation and mitigation strategies designed to contend with climate change are presented in a companion paper (Joyce et al. 2013 [this issue]).

## CLIMATE TRENDS AND PROJECTIONS

### Recent Climatic Trends

Climate change refers to a significant and lasting change in the statistical distribution of meteorological conditions and variations. The Earth's climate has changed throughout geological history in response to natural events, including orbital variation of the planet's axis and volcanic eruptions that altered the amount of solar energy reaching Earth. However, the Earth has now entered an era in which human impacts on the fluxes of radiative energy through the Earth system have demonstrable effects on climate (Intergovernmental Panel on Climate Change [IPCC] 2007; Fig. 1). The rapid increase in atmospheric concentration of trace gases known collectively as GHGs represents the dominant mechanism contributing to climate change. These gases, which include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and tropospheric ozone (O<sub>3</sub>), reduce cooling of the Earth by partially blocking the emission of long wave infrared radiation into space. The "greenhouse effect" is vital to life on Earth, as it buffers day-night temperature fluctuations to maintain a relatively constant mean planetary temperature of 15°C by balancing incoming solar radiation with the emission of infrared radiation into space. A doubling of atmospheric CO<sub>2</sub> would disrupt this energy balance by about 2% (Lindzen 1999) to produce what is called "climate forcing" or "radiative forcing." GHG concentrations will continue to rise for the foreseeable future even if emissions rates decline because GHGs may remain in the atmosphere for hundreds of years (Karl et al. 2009). Increased GHG concentrations will amplify the current greenhouse effect to further warm the Earth and thereby modify numerous interrelated processes within the Earth system.

Global mean temperature has risen during recent decades, particularly in northern latitudes and over land (IPCC 2007). Six of the 10 years from 1998, the hottest year on record, to 2007 were among the hottest 10% recorded in the United States, and 2012 was the hottest year ever recorded for the contiguous United States (NOAA National Climatic Data Center 2013). The mean frost-free period for the United States

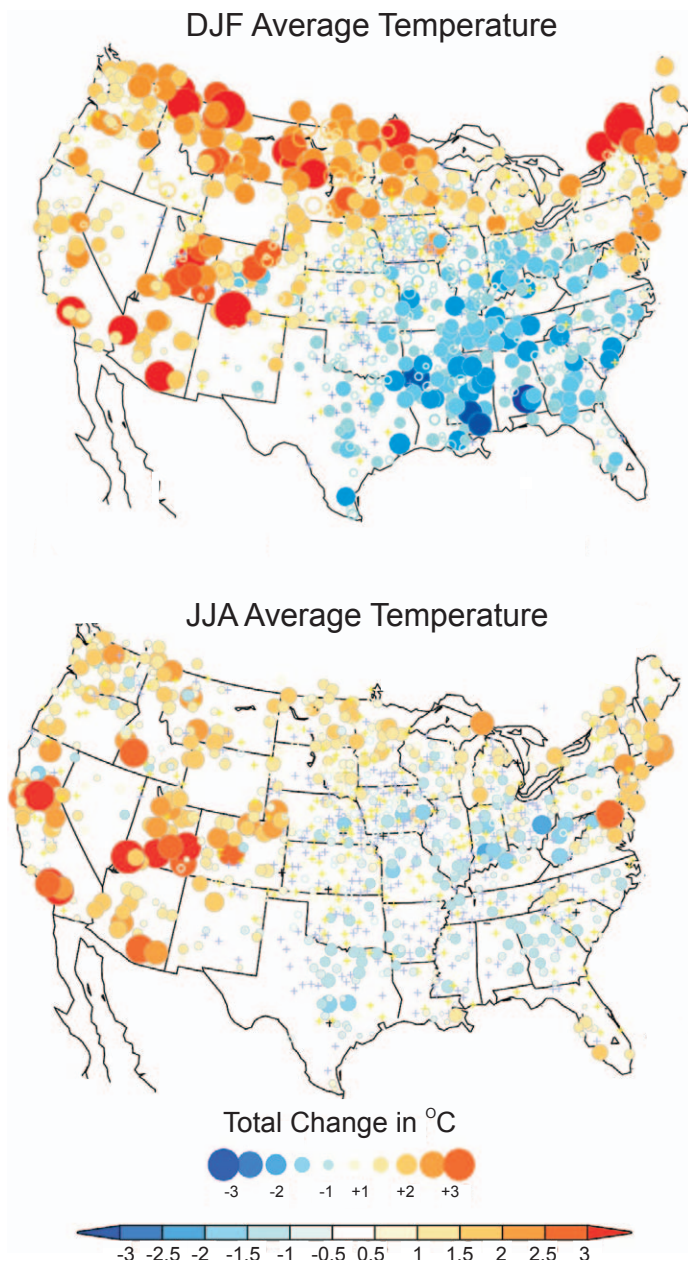


**Figure 1.** Departure of the global mean temperature from the average global temperature for the period 1901–2000 (temperature anomaly; upper panel) and atmospheric CO<sub>2</sub> concentration (lower panel). A positive temperature anomaly during a given year indicates that the observed temperature was warmer than the long-term average. The CO<sub>2</sub> concentration is from air extracted from dated layers of ice cores from the South Pole, Antarctica, and direct measurements of atmospheric CO<sub>2</sub> at Mauna Loa, Hawaii (lower panel). The temperature figure is from <http://www.ncdc.noaa.gov/cmb-faq/anomalies.php>. The CO<sub>2</sub> figure was redrawn from Friedli et al. (1986) and updated with data from Keeling et al. (2009).

has increased by 2 weeks since 1900 in response to this warming trend. Warming over the last century has been even greater than projected by climate models in the western United States (Fig. 2; e.g., Menne and Williams 2009; Menne et al. 2009) possibly because of poorly understood feedback mechanisms or "natural" climate variability associated with the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) and the North Atlantic Oscillation (NAO; Hurrell et al. 2003). On the other hand, temperature has changed little in other portions of the United States and has even decreased in the Southeast over the last century.

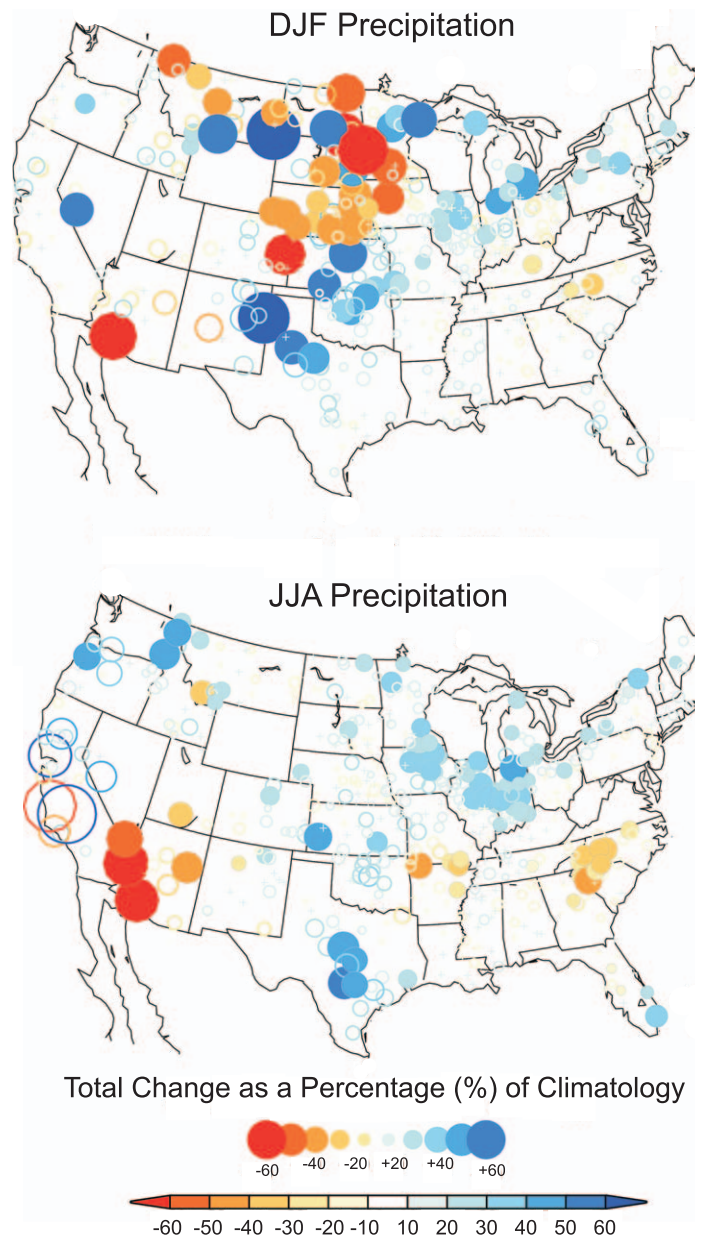
Precipitation increased by 7% in the United States during the last century, but precipitation trends varied among regions (US Climate Change Science Program [CCSP] 2008; Fig. 3). Precipitation increased over much of the central Great Plains, especially during summer months, but changed little during the last century in the western United States with the exception of a large decrease in southwestern Arizona (e.g., Menne and Williams 2009; Menne et al. 2009). Over shorter time periods (years to decades), precipitation patterns are influenced by decadal changes in PDO–El Niño Southern Oscillation or NAO and may appear to be inconsistent with longer-term climate trends.

A climate change signature also is evident in the form of an increasing frequency of "extreme weather events," including greater precipitation variability. Heat waves are increasing in



**Figure 2.** US temperature trends ( $^{\circ}\text{C}$ ) over the last century (1911–2010) as derived using data from the Global Historical Climate Network, data version 2.9. Upper panel: December/January/February (DJF); lower panel: June/July/August (JJA). Filled symbols indicate statistically significant trends.

frequency (e.g., Meehl et al. 2009), and daily precipitation events are increasing in size over most of the United States but currently are significant only east of the Mississippi River (Kunkel et al. 2003; Groisman et al. 2004). The amount of annual precipitation that has fallen as the most intense 1% events has increased by 20% over the last century, even though total precipitation has increased by only 7% (Groisman et al. 2004; CCSP 2008). The mean proportion of the United States affected by drought was 14% in the 20th century, but it has been 35–40% in recent years compared to 65% in 1934 (CCSP 2008). By contrast, flooding events are fewer in the southwestern United States and show no significant trend with long-term



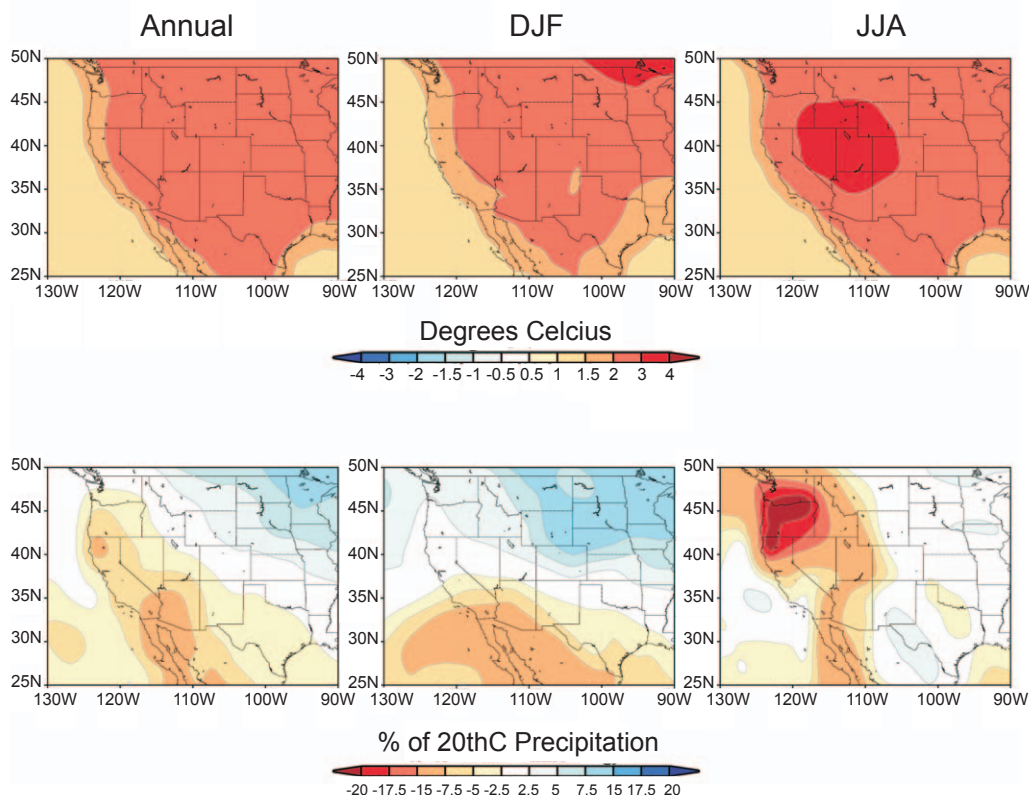
**Figure 3.** US precipitation trends over the last century (1911–2010), expressed as change over this period divided by its long-term average for each station. Upper panel: December/January/February (DJF); lower panel: June/July/August (JJA). Filled symbols indicate statistically significant trends.

changes in GHG concentrations in other regions of the country (Hirsch and Ryberg 2012).

### Climate Change Projections

An ensemble of coupled climate models was used to simulate temperature and precipitation projections for the year 2050 (Meehl et al. 2007) based on a scenario of “moderate” rates of GHG emissions during coming decades (IPCC 2007). Climate change models project that average annual temperature will increase by about 2–4 $^{\circ}\text{C}$  in the western United States (Fig. 4), with minimum temperatures increasing more rapidly than maximum temperatures (i.e., warming will be greatest at

## CMIP Projected Change at 2050



**Figure 4.** Climate model (Coupled Model Intercomparison Project) projections of temperature (top) and precipitation (bottom) for 2050 relative to the 20th century. Values are presented for the entire year (left), winter (center), and summer (right).

night). Warming is expected to be greatest in the North and during the winter throughout North America, except in the West, where it will be greatest in the summer (IPCC 2007). Greater uncertainty is associated with projected changes in precipitation than CO<sub>2</sub> concentration or warming, but the current consensus is for drier summers in much of western United States and wetter winters in northern United States and southern Canada (Seager and Vecchi 2010). The increase in winter precipitation could exceed the decline in summer precipitation in the North, but annual precipitation is expected to decline by > 2.5% in the Southwest. It is not known whether climate change will favor El Niño over La Niña events in the future (IPCC 2007). La Niña typically heralds drier-than-average conditions in the Southwest.

Warming is anticipated to increase weather extremes and both intra- and interannual precipitation variability by altering atmospheric hydrological processes and circulation patterns (Easterling et al. 2000; Hoerling and Kumar 2003; McCabe and Clark 2006). Warming is anticipated to reduce the frequency of rainfall events but increase the size or intensity of events when they do occur (Groisman et al. 2005; Wentz et al. 2007; Karl et al. 2009). Heat waves are anticipated to continue to increase in both frequency and magnitude in proportion to increasing mean global temperature, while extreme freezing events are expected to moderate more rapidly (Kharin et al. 2007). For example, hot days that would have occurred once every 20 yr last century are anticipated to occur every 3 yr by 2050 (CCSP 2008). The resulting increase in frost-free periods is anticipated to be a

major driver of community composition and range distributions (Weiss and Overpeck 2005). Precipitation extremes are expected to vary more greatly than annual or seasonal means (CCSP 2008). These extreme events by definition fall outside the normal range of variation, so they are likely to have adverse effects on ecosystems and may induce cascading effects over long periods by modifying the amount and seasonality of soil water (Kharin et al. 2007; CCSP 2008; Reyer et al. 2013). The timing of extreme events may be as important as their intensity and frequency because major ecological consequences may be restricted to narrow temporal windows (Craine et al. 2012).

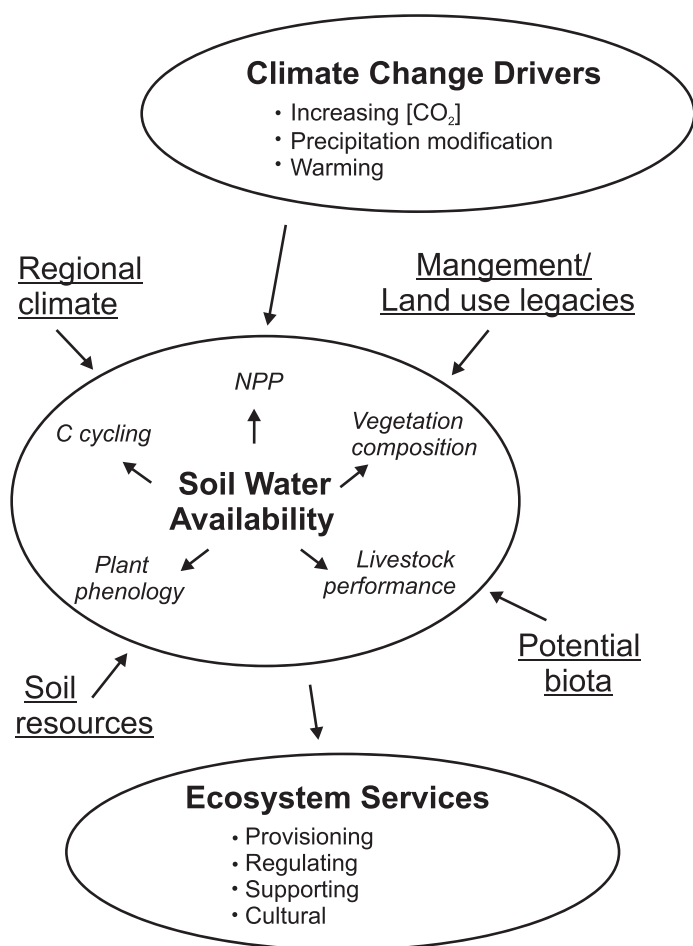
Snowpack reductions likely will continue and be greatest in the milder climates of the Oregon Cascades and at mid-elevations and smallest at high elevations in the Rockies and southern Sierras (Mote et al. 2005; Christensen and Lettenmaier 2006; Ray et al. 2008). Reduced snowpack will have pronounced ecological effects on stream flow and the structure and function of riparian systems (Marshall et al. 2008). Earlier and more rapid snowmelt, in conjunction with higher temperatures and an increased fraction of precipitation as rainfall, may result in both an earlier initiation and cessation of ecological processes that may amplify the intensity of summer drought.

Uncertainties necessarily attend issues as complex as the calculation of global GHG accumulation and its consequences to current and future climate patterns. Several uncertainties recently have been resolved (see Supplemental Material; available online at <http://dx.doi.org/10.2111/REM-D-12->

00068.s1), but uncertainty remains as to the sensitivity of future climate to higher GHG concentrations. Alone, a doubling of CO<sub>2</sub> will increase temperature by a mean of about 1°C, similar to that experienced during the last 150 yr (Lindzen 1999). Current climate models project a much greater increase in temperature partly because they incorporate feedbacks from water vapor and clouds and from temperature on infrared emissions that act to amplify temperature sensitivity to CO<sub>2</sub> and other GHGs. Warming will accompany GHG accumulation even in the absence of positive feedbacks from water vapor albeit at a lower rate than currently projected.

## ECOLOGICAL IMPLICATIONS OF CLIMATE CHANGE

The drivers of climate change, coupled with greater frequency and intensity of extreme weather events, will collectively affect



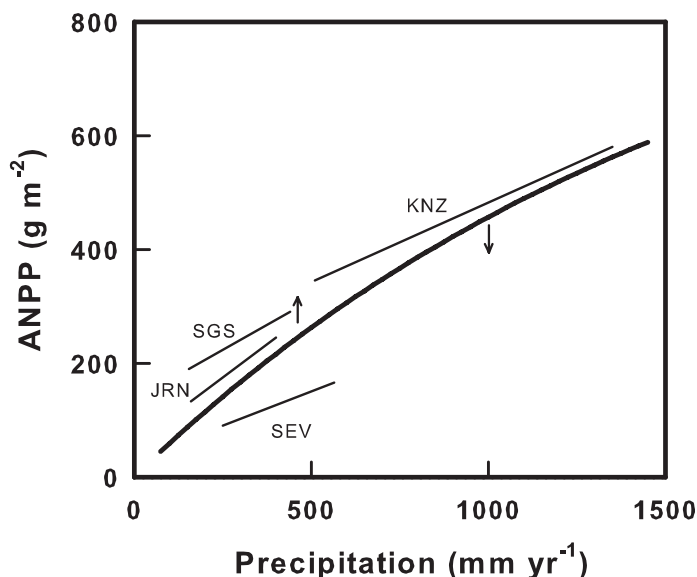
**Figure 5.** A conceptual model illustrating the response of rangeland systems to climate change. Climate change drivers will affect ecological processes/properties (italicized) largely by modifying spatial and temporal dynamics of soil water availability and secondarily by altering plant photosynthesis and water use efficiency. Climate change effects on ecological processes will differ among regions and even locations within regions in response to differences in mediating variables (underlined). Both positive and negative consequences of climate change are anticipated and will affect the services that humans derive from rangeland ecosystems.

soil water availability to influence many aspects of ecosystem structure and function, even though these drivers have unique and potentially counteracting effects (Luo 2007; Knapp et al. 2008; Morgan et al. 2011). Climate change impacts will vary regionally because the magnitude, decadal timing, or seasonal patterns of warming and precipitation modification will be expressed differently among regions and interactive effects among climate drivers are nonadditive. Ecosystem responses to these climate change drivers will vary among locations within a given region because of local differences in soil characteristics, including water-holding capacity, the extant plant species pool, management practices (e.g., grazing intensity, fire regimes), and historical land use patterns (Fig. 5). The potential consequences of these climate change drivers, individually and in combination, on primary productivity, vegetation composition, plant phenology, ecosystem C dynamics, and livestock production are discussed in the following sections.

### Primary Productivity

Rangeland plant (primary) productivity (NPP) and carbon cycling depend primarily on the amount and seasonal distribution of precipitation and only secondarily on other climatic variables. This is demonstrated by the strongly linear relationship between aboveground net primary productivity (ANPP) and mean annual precipitation for most rangelands (Sala et al. 1988).

**Precipitation Variability.** Rangeland ANPP varies among years in response to interannual precipitation variability, but



**Figure 6.** The relationship between rangeland ANPP and precipitation. ANPP increases, on average, as mean precipitation increases (bold line) but varies more in response to interannual precipitation variability in mesic and semiarid than arid rangelands, as indicated by lines illustrating ANPP-precipitation responses for mesic (Konza Prairie, Kansas [KNZ]), semiarid (Shortgrass Steppe, Colorado [SGS]), and desert (arid) grasslands (Jornada, New Mexico [JRN] and Sevilleleta, New Mexico [SEV]). Delivering a given amount of annual precipitation as fewer but larger events reduces ANPP in mesic systems but increases ANPP in arid and semiarid systems, as illustrated with arrows. The figure is modified from Huxman et al. (2004b). ANPP indicates aboveground net primary productivity.

**Table 1.** Responses of plant attributes to CO<sub>2</sub> enrichment in six ecosystems. Key citations are listed for each experiment. CO<sub>2</sub> treatments are presented in the second row. Responses to CO<sub>2</sub> were positive (+), negative (–), or not significant (0). The predominant response is listed first. Water relations refers to measurements of plant or soil water status, with “+” and “–” indicating more and less available water, respectively.

Rangeland CO <sub>2</sub> experiments	Shortgrass steppe, Colorado <sup>1–3</sup>	Mixed-grass prairie, Wyoming <sup>4,5</sup>	Temperate grassland, Tasmania <sup>6–9</sup>	Annual grassland, California <sup>10–12</sup>	Tallgrass prairie, Texas <sup>13,14</sup>	Tallgrass prairie, Kansas <sup>15,16</sup>
Carbon dioxide (ppmv)	Ambient to 720	Ambient to 600	Ambient to 550	Ambient to 680	250–500	Ambient to 720
Plant biomass	+	+,0	+,0	0	+,0	0,+
	41% increase in ANPP; 100% increase during a dry year	25% increase in ANPP; no response during a wet year	60% increase in ANPP		0–117% increase in ANPP among soils and years	No response of ANPP in wet years
Phenology		0	0	Forbs, slightly advanced; Grasses delayed		
Water relations	+	+	0,+,-	+	+	+
Functional group responses for biomass	+ C <sub>3</sub> grasses + C <sub>3</sub> shrub 0 C <sub>4</sub>	+ C <sub>3</sub> grasses +,0 C <sub>4</sub> grasses	+ C <sub>4</sub> grass 0 C <sub>3</sub> grasses	– forbs 0 grasses	+ C <sub>4</sub> tall grass – C <sub>4</sub> mid-grass	0 C <sub>4</sub> grasses – C <sub>3</sub> grasses + forbs

<sup>1</sup>Morgan et al. (2004a). <sup>2</sup>Milchunas et al. (2005). <sup>3</sup>Morgan et al. (2007). <sup>4</sup>Reyes-Fox (2008). <sup>5</sup>Morgan et al. (2011). <sup>6</sup>Williams et al. (2007). <sup>7</sup>Hovenden et al. (2008a). <sup>8</sup>Hovenden et al. (2008b). <sup>9</sup>Pendall et al. (2011). <sup>10</sup>Zavaleta et al. (2003a). <sup>11</sup>Dukes et al. (2005). <sup>12</sup>Cleland et al. (2006). <sup>13</sup>Fay et al. (2012). <sup>14</sup>Polley et al. (2012b). <sup>15</sup>Owensby et al. (1993). <sup>16</sup>Owensby et al. (1999).

variability in ANPP does not increase proportionately with precipitation variability (Fig. 6). ANPP is more responsive to interannual variability in precipitation in mesic and semiarid than desert rangelands because most ANPP (> 70%) in mesic systems is associated with rainfall pluses that coincide with periods of high light and soil N availability (Knapp and Smith 2001). ANPP does not respond as dramatically to precipitation pulses in arid (particularly desert) systems because plant growth is limited by inherently low leaf area and plant density. Greater sensitivity of ANPP to interannual precipitation variability in mesic than arid rangelands implies that the response of ANPP to multiyear drought will be greatest in the most productive rangelands.

Impacts of fewer but larger precipitation events on NPP will be contingent on mean annual precipitation currently received (Knapp et al. 2008). Larger but less frequent precipitation events in mesic systems are likely to increase the frequency and duration of dry periods as well as water losses to runoff and percolation to groundwater. As a result, soil water content will fall below plant stress thresholds more often than under the current precipitation regime. In contrast, precipitation that arrives in fewer, larger events is anticipated to reduce seasonal water stress and promote plant growth in arid ecosystems by increasing the proportion of water that percolates into deeper soil layers, where it is less susceptible to evaporative loss and potentially available for absorption by plants. These contrasting responses are illustrated in field experiments where the same total annual precipitation delivered as fewer but larger events increased ANPP by 30% in semiarid shortgrass steppe but decreased ANPP by 10–18% in tallgrass prairie (Knapp et al. 2002; Heisler-White et al. 2009). A 10% reduction in tallgrass ANPP following precipitation delivery as fewer, larger events (Knapp et al. 2002) was comparable to a decrease in ANPP caused by a 30% reduction in total rainfall with ambient frequency and intensity of events (Knapp et al. 2002; Fay et al. 2003; Swemmer et al. 2007). The response of soil water content to modified precipitation delivery will also depend on how soil texture influences runoff,

infiltration, deep drainage, and evaporation rates (Noy-Meir 1973; Huxman et al. 2004a; Knapp et al. 2008).

**CO<sub>2</sub>.** Net effects of CO<sub>2</sub> enrichment on NPP (Table 1) also depend largely on the amount and seasonal distribution of precipitation. Individual plants respond to elevated CO<sub>2</sub> with an increase in photosynthesis rates (Percy and Ehleringer 1984) and decrease in stomatal conductance that reduces transpiration and increases water use efficiency (WUE; photosynthesis/transpiration; Wand et al. 1999). Elevated CO<sub>2</sub> stimulates plant growth to the greatest extent in systems in which NPP is or will become moderately water limited (Morgan et al. 2004b, 2011; Nowak et al. 2004; Webb et al. 2012) and soil nitrogen (N) is readily available (Luo et al. 2004; Reich et al. 2004).

**Warming.** Temperature regulates the rates of chemical reactions in both soils and plants and drives water and energy fluxes between land surfaces and the atmosphere. These two direct influences of warming often have contrasting effects on NPP. Warming may enhance productivity by alleviating low temperature limits on plant growth (Luo 2007; Lin et al. 2010), extending the growing season, and increasing N mineralization rates provided that sufficient water is available (Rustad et al. 2001; Parton et al. 2007; Dijkstra et al. 2008). Alternatively, warming may reduce ANPP (Pepper et al. 2005; Hovenden et al. 2008a) by increasing the vapor pressure deficit of air, leading to greater evapotranspiration and reduced soil water availability (Harte et al. 1995; Wan et al. 2002; Hovenden et al. 2008a; Sherry et al. 2008) and a decrease in plant water or transpiration use efficiency (McKeon et al. 2009). These opposing influences of warming may explain why many grassland experiments have shown little to no effect of warming on plant growth or NPP (Table 2; Dukes et al. 2005; Klein et al. 2007; Pendall et al. 2011; but see Lin 2010). However, warming in the presence of elevated CO<sub>2</sub> may increase NPP in semiarid systems because of the water-conserving effect of CO<sub>2</sub> enrichment (Morgan et al. 2011).

## Vegetation Composition

Climate change may modify plant community composition, shift the geographical distribution of communities, and contribute to expansion and contraction of the distributional ranges of exotic, invasive plant species. Range expansions are anticipated when the functional traits of species are better suited to the altered climatic conditions. Climate change will affect plant species composition largely by shifting the amount, seasonal pattern, and vertical placement of soil water to influence the outcome of plant competition (Dukes and Mooney 1999; Knapp et al. 2008; Volder et al. 2013). Land cover change resulting from overgrazing, woody encroachment, and exotic plant invasion currently impact rangeland hydrology and will influence water and vegetation responses to climate change (Wilcox et al. 2011).

**CO<sub>2</sub>.** Plant species and functional groups differ considerably in their responses to elevated CO<sub>2</sub> (Table 1), contributing to variable responses of species relative abundance and community composition. CO<sub>2</sub> enrichment preferentially stimulates photosynthesis in species with the C<sub>3</sub> compared to C<sub>4</sub> metabolic pathway (often considered “cool-season” and “warm-season” species, respectively) and thus may favor forbs, small shrubs, and even trees over warm-season grasses (Ehleringer and Monson 1993; Owensby et al. 1999; Polley et al. 2003; Morgan et al. 2007; Buitenwerf et al. 2012). Elevated CO<sub>2</sub> may also contribute to shifts in species composition by reducing transpiration to prolong soil water availability within a growing season (Morgan et al. 2004b; Polley et al. 2012a), provided that low light or N availability does not limit the growth or establishment of potentially responsive species (Owensby et al. 1999). Results from a simulation model imply that CO<sub>2</sub> enrichment will lead to a strong directional increase in woody vegetation in African deserts, grasslands, and savannas (Higgins and Scheiter 2012). Woody abundance is anticipated to increase both because CO<sub>2</sub> enrichment enhances photosynthesis and growth among trees and shrubs and because increased woody growth initiates a positive feedback involving light competition that favors trees over grasses. The transition from grasses to trees depends critically on grazing history, fire regime, and soil type; consequently, a clear climate change signal on woody encroachment has remained elusive (Archer et al. 1995).

**Warming.** Plant responses to warming are species specific because individual species possess unique temperature optima and encounter different limitations to growth (Table 2; Loik and Harte 1997; Luo 2007). Woody plants generally show a more consistent response to warming than do herbaceous species (Lin et al. 2010). Models based on the current correlation between climate and C<sub>3</sub> and C<sub>4</sub> abundances predict that warming will favor warm-season over cool-season grass species in rangelands of North and South America (Epstein et al. 2002). However, CO<sub>2</sub> enrichment is anticipated to reduce adverse effects of warming on photosynthetic efficiency of C<sub>3</sub> plants and limit changes in the geographic ranges of C<sub>3</sub> and C<sub>4</sub> species (Sage and Kubien 2003).

**Intra-Annual Variability in Precipitation.** Plant species have evolved unique traits and life history strategies in response to environments with varied amounts, depths, and seasonal

patterns of soil water availability (Noy-Meir 1973). Consequently, sustained alteration of precipitation delivery may alter species abundances or community composition (Ignace et al. 2007; Resco et al. 2008). Experimental variation of precipitation seasonality modified species richness and density of a sotol grassland community in the Chihuahuan Desert (Robertson et al. 2010). Grasses were more responsive to summer rainfall, whereas forbs were most sensitive to winter rainfall. Herbaceous plants and shallowly rooted woody plants are often more responsive to small rainfall events than are deeper rooting woody species (BassiriRad et al. 1999; Huxman et al. 2004a).

A shift to larger, less frequent precipitation events may also influence vegetation change by creating pulses of high soil N availability. N pulses occur during periods of water stress when mineralization exceeds plant N absorption (Austin et al. 2004; Augustine and McNaughton 2006; Yahdjian and Sala 2006). These N pulses will be preferentially accessed by species that quickly resume growth following a period of drought (Gebauer and Ehleringer 2000), and this species-specific variation may alter both competitive interactions among established plants and plant recruitment and invasion (Lloret et al. 2004; Peñuelas et al. 2004; Volder et al. 2010).

**Interannual Variability in Precipitation.** It is well established in both the historical (Weaver and Albertson 1943; Breshears et al. 2005, 2009) and the paleoecological records that severe multiyear drought can substantially modify species composition (Woodhouse et al. 2010). For example, the 1930s drought induced major shifts in community composition in the Great Plains (Weaver and Albertson 1943). Cover of blue grama (*Bouteloua gracilis*) declined precipitously in eastern Colorado, where it had been the dominant perennial grass, whereas western wheatgrass (*Pascopyrum smithii*), a subordinate cool-season grass, became a dominant species throughout much of the central Great Plains, apparently by taking advantage of limited water available early in the growing season. Most forbs succumbed to the drought, especially in the shortgrass steppe and mixed grass prairie, with the complete loss of shallowly rooting forbs early in the drought, later followed by deeper-rooted forbs. Collectively, evidence from the 1930s drought illustrates that plant species with deep roots, high water use efficiency, or growth patterns that match the seasonality of precipitation likely will fare best during protracted droughts.

Severe drought may also shift the balance between trees and grasses by reducing competition from grass to favor woody recruitment and reducing mortality of woody plants relative to grasses (Scholes and Archer 1997; Van Auken 2000; Bond 2008; Volder et al. 2010). On the other hand, severe drought has caused extensive mortality of trees worldwide recently (Breshears et al. 2005; van Mantgem and Stephenson 2007; Allen et al. 2010) and could at least temporarily slow woody encroachment or consolidation.

**Fire Regimes.** Climate change can indirectly affect rangeland vegetation by altering fire regimes. Increasing fire frequency leads to a replacement of fire-sensitive with fire-tolerant plant species (Nelson and Hu 2008). Patterns of prairie expansion during the Holocene appear to have been driven by both climate and fire, for example (Nelson and Hu 2008). Globally, fires over the past two millennia have been strongly influenced by climatic conditions (Marlon et al. 2008). Most wildfires in

**Table 2.** Responses of plant attributes to an experimentally imposed increase in air or soil temperature in eight ecosystems. Key citations are listed for each experiment. Temperature treatments are presented in the second row. See Table 1 for an explanation of the symbols used to indicate responses.

	Semi-arid grassland, New Mexico <sup>1</sup>	Mixed-grass Prairie, Wyoming <sup>2,3</sup>	Temperate grassland, Tasmania <sup>4-6</sup>	High-elevation meadow, Tibet <sup>7</sup>	High-elevation shrubland, Tibet <sup>7</sup>	Annual grassland, California <sup>8-11</sup>	High-elevation meadow, Colorado <sup>12-14</sup>	Tallgrass prairie, Oklahoma <sup>15,16</sup>
Temperature treatments	Nighttime (average 2.5°C air warming)	1.5/3°C day/night canopy warming	2°C canopy warming	1-2°C air warming	1-2°C air warming	1°C canopy/air warming	1.7°C soil warming	1.1°C air warming; 2.0- 2.6°C soil warming
Plant biomass	25% increase in plant cover (1 yr only)	0	0	13% decrease in ANPP	0	0	0,+	9-21% increase in ANPP
Phenology		Flowering advanced (3 of 5 species)	Flowering advanced			Greening, flowering advanced		Flowering advanced in early species; delayed in late species
Water relations	-	-	-,+	0	0	+	-	-,0
Functional group responses	+ southern C <sub>4</sub> grass	+ C <sub>4</sub> grass 0 C <sub>3</sub> grass	Variable	- grass	- grass + shrub	- forbs 0 grasses	+ shrub 0 grasses	+ C <sub>4</sub> grass 0 C <sub>3</sub> grass
for biomass	0 northern C <sub>4</sub> grass					0 grasses	0,+ forbs	

<sup>1</sup>Collins et al. (2010). <sup>2</sup>Reyes-Fox (2008). <sup>3</sup>Morgan et al. (2011). <sup>4</sup>Hovenden et al. (2008a). <sup>5</sup>Hovenden et al. (2008b). <sup>6</sup>Pendall et al. (2011). <sup>7</sup>Klein et al. (2007). <sup>8</sup>Zavaleta et al. (2003a). <sup>9</sup>Zavaleta et al. (2003b). <sup>10</sup>Dukes et al. (2005). <sup>11</sup>Cleland et al. (2006). <sup>12</sup>Harte and Shaw (1995). <sup>13</sup>Loik and Harte (1997). <sup>14</sup>de Valpine and Harte (2001). <sup>15</sup>Wan et al. (2002). <sup>16</sup>Sherry et al. (2007).



the western United States occur during the hottest, driest portion of the year (Westerling et al. 2003), and the size of the area burned during any single year is correlated with the current drought condition (i.e., Palmer drought severity index) and with wetter-than-normal conditions in May and August of the previous year. Fires are largest in grass- and shrub-dominated ecosystems when unusually wet summers during which fine fuels accumulate are followed by dry conditions that enhance fuel flammability and ignition (Littell et al. 2009). Conversely, fires are largest in western forested ecosystems when precipitation is low and temperature is high in both the fire year and the preceding year. Fire activity is projected to increase considerably in the western United States as the climate becomes both warmer and drier (Pechony and Shindell 2010).

**Exotic Plant Invaders.** Climate change need not favor exotic or invasive over native plant species, but successful exotics often share traits that could contribute to a capacity to increase relative abundances and rapidly shift or extend ranges and exploit habitat openings (Dukes and Mooney 1999). These traits include short generation times, high fecundity and strong dispersal ability to expand into new habitats, broad environmental tolerances for attributes critical in the establishment of new individuals, rapid growth and high fecundity for colonization including the efficient use of resources like CO<sub>2</sub> and N, and independence from mutualistic organisms (Bradley et al. 2010). Despite these common traits, the particular mechanisms by which rising CO<sub>2</sub> or climate change will influence invasive species depends on plant community composition and competition for critical soil resources (Dukes and Mooney 1999), both of which can vary considerably among ecosystems. Consequently, invasive species will be addressed more fully in a section on regional scenarios.

Resource pulses and more frequent droughts are anticipated to favor exotic species, especially when dominant natives are suppressed by disturbances (Dukes and Mooney 1999; Smith et al. 2000; Buckland et al. 2001; Dukes et al. 2011), and to increase opportunities for invasive plant establishment by reducing competition from native species (White et al. 2001). For example, drought is thought to have contributed to the invasion of California grasslands by exotic annual grasses by reducing the density of native species (Jackson 1985; Everard et al. 2010).

Climate change will lead to combinations of seasonal temperature and precipitation that differ from current climatic conditions. This shift in climatic conditions, together with species differences in dispersal and the introduction or spread of exotic species, may produce plant communities that are compositionally unlike any found today (no-analog communities; Williams and Jackson 2007). No-analog communities (also termed “novel” or “emerging” communities or ecosystems) represent species combinations and relative abundances that have not occurred previously in a given biome (Hobbs et al. 2006). Novel communities of species having different biogeographical origins exist in grasslands in the central Plains as the result of human transformation (Wilsey et al. 2011). Climate change is anticipated to contribute to novel communities first in areas that warm the faster, possibly including the western United States (Williams and Jackson 2007).

## Plant Phenology

Observational data indicate that warming is leading to earlier spring bud burst and flowering and a longer growing season in mid- and high-latitude regions (Badeck et al. 2004; Menzel et al. 2006). Meta-analyses of global data document an advancement of spring events by 2.3 d per decade and shifts in species ranges (Parmesan and Yohe 2003). Results from manipulative experiments generally confirm this trend, as experimental warming tends to advance the onset of growth and reproduction of plants (Zavaleta et al. 2003b; Cleland et al. 2006; Sherry et al. 2007; Hovenden et al. 2008b; Reyes-Fox 2008), although responses vary considerably among species and years (Table 2). Indeed, warming can retard phenological development of some species (Sherry et al. 2007) but promote earlier growth in other species and expose plants to more frequent damage from late frosts (Inouye 2008). Warming thus may lengthen the growing season for plant communities (Stelzer and Post 2009), and is projected to continue to do so especially on high-latitude and high-altitude rangelands unless plant responses are constrained by water limitation (Cleland et al. 2006).

## Soil Organic Carbon and Sequestration

Carbon fluxes between soil and atmospheric pools are the net effect of well-understood ecological processes (Follett et al. 2001; Piñeiro et al. 2010) that are controlled by precipitation patterns and land use management. However, background variation associated with soils, geomorphology, vegetation, and disturbance regime add considerable complexity to these dynamics. Plant compounds are decomposed by soil microbes to form a relatively dynamic soil fraction known as particulate organic matter (POM). Most of the C in POM is rapidly released into the atmosphere as CO<sub>2</sub> via microbial respiration, but a small portion may be stabilized within aggregates associated with clay or silt particles and turn over on decadal time scales. These aggregates, assemblages of mineral and organic materials, are the repository for active soil C, the soil C pool that responds most readily to management, but may be lost locally to soil erosion (Post and Kwon 2000). Recalcitrant organic C (charcoal) and inorganic C (calcium carbonate) may also form significant pools of soil C, but they generally are not responsive in management time frames.

**Precipitation.** The amount and seasonality of precipitation directly control C input into soil through their strong effect on NPP. Most rangeland ecosystems are characterized by short periods of high C uptake (2–3 mo) and long periods of C balance or small respiratory C loss (Svejcar et al. 2008). Ungrazed sagebrush steppe and Great Plains grasslands were C sinks during most years of investigation, whereas desert sites in the southwestern United States were consistent C sources (Svejcar et al. 2008). NPP increases to a greater extent than respiration during wet years, resulting in a net increase in (positive) ecosystem exchange (NEE; C assimilation-emission), but NEE declines and often becomes negative during drought years to represent a C source (Zhang et al. 2010). Intra-annual variation in NEE also is highly correlated with precipitation patterns and other water-related environmental variables (Polley et al. 2010).

CO<sub>2</sub>. CO<sub>2</sub> enrichment may either increase soil organic C by stimulating NPP (Hungate et al. 1997; Williams et al. 2000) or

exert little effect if the rate of soil organic matter (SOM) decomposition increases to match that of NPP (Table 3; Gill et al. 2002; Pendall et al. 2004, 2011; Polley et al. 2006; Carrillo et al. 2011) Increased C inputs to soil often are accompanied by enhanced losses of pre-existing and mineral-associated SOM at elevated CO<sub>2</sub>, apparently because microbes preferentially decompose older SOM to acquire sufficient N (Gill et al. 2002; Pendall et al. 2003, 2011). For example, SOM pools in mesic grassland did not change over 4 yr in response to experimentally elevated CO<sub>2</sub> (Gill et al. 2002), whereas modest amounts of SOC accumulated in annual grassland at elevated CO<sub>2</sub> when productivity increased slightly (Hungate et al. 1997).

**Warming.** Soil microbial and plant respiration, like photosynthesis, are sensitive to temperature, implying that warming may reduce NEE and soil C by preferentially increasing respiration and C flux to the atmosphere. However, a meta-analysis of warming (0.3–6.0°C) effects on tundra, grassland, and forest systems indicated that C inputs (NPP) increased by about the same percentage as soil respiration (19–20%; Rustad et al. 2001). Warming (1–2°C) increased soil respiration in tallgrass prairie in eastern Oklahoma during the spring and fall but reduced soil respiration during the summer (Wan et al. 2005; Zhou et al. 2006). The proportional response of soil respiration to warming was similar to that of NPP, implying that warming had little effect on NEE.

### Livestock Production

Climatic change may affect livestock production both directly via physiological impacts on animal performance and indirectly via modifications to forage quality and quantity (the latter discussed previously) and the abundance of ectoparasites (Table 3). Warming likely will adversely affect livestock production in warm regions, such as the southwestern United States, but increase it in cooler regions by moderating winter temperatures (Baker et al. 1993; Eckert et al. 1995; Rotter and Van De Geijn 1999). Ames and Ray (1983) described a thermo-neutral zone in which food intake and energy requirements of livestock are not affected by temperature. However, at temperatures below the thermo-neutral zone, termed “lower critical temperature,” animals increase energy production and food intake to maintain homeostasis. At temperatures above the thermo-neutral zone, termed “upper critical temperature,” animals become heat stressed and must dissipate heat by reducing walking and spending more time in shade. Extreme heat and

**Table 3.** Summary of anticipated responses of key rangeland variables to climate change. See Table 1 for an explanation of the symbols used to indicate responses.

Response variable	↑[CO <sub>2</sub> ]	Warming	↑ Precipitation variability	Drought
C sequestration	0,+	0,–	0	–
C <sub>3</sub> /C <sub>4</sub> species ratio	0,+	–		+
Livestock production	–,+	– southern and warm areas + cool areas	– mesic + arid	–

cold may alter voluntary animal intake by –50% and +30%, respectively (CCSP 2008).

**Thermal Livestock Stress.** Heat stress decreases forage intake and milk production (Wyman et al. 1962) and the efficiency of feed conversion (McDowell 1968). One of the most critical outcomes of heat stress is reduced reproductive rates. Male and female gamete production, embryonic development, and fetal growth can be adversely affected by heat stress (Hansen 2009). Heat stress can be fatal to livestock, especially those fed large quantities of high-quality feeds (Haun 1997). This accounts for the occurrence of mass animal mortality in feedlots during heat waves. Temperature humidity index (THI; the weighted product of air temperature and relative humidity) values greater than 85 are considered an emergency for feedlot cattle (Haun 1997). Increases in temperatures of 1–5°C could cause high mortality among feedlot cattle unless sprinklers, additional shade, or similar measures to cool animals are employed (Howden et al. 2008). When nighttime temperatures remain above 23°C, feedlot cattle also may not be able to recover from high daytime temperatures, and the probability of animal mortality increases. Howden and Turnpenny (1997) reported that the number of “heat stress” days for cattle (THI > 80) increased by 60% during the last 40 yr in some areas of Australia.

Warmer temperatures may further suppress livestock performance by increasing winter survival and abundance of ectoparasites and their adverse impacts on animals (Karl et al. 2009). Of the 50 or more species of ectoparasites that affect cattle, horn flies (*Huematobia irritans* [L.]) are the biggest concern in the United States (Byford et al. 1992). Horn flies can reduce cattle weight gain by 4–14%, and both increase water intake and reduce nitrogen retention (Byford et al. 1992). Horn flies also affect livestock behavior by increasing time spent walking and engaging in other avoidance behaviors, such as tail switching (Harvey and Launchbaugh 1982). These additional activities and energy expenditures directly contribute to reduced livestock performance. Of all ectoparasites, ticks (*Amblyomma americanum* Koch) have the most adverse impact on cattle performance and can reduce weight gains of British breeds, such as Hereford, by > 30% (Byford et al. 1992). By contrast, ticks have little if any effect on Brahman cattle. In a modeling exercise, White et al. (2003) reported that livestock gains in Australia could decrease by > 18% because of increased tick infestations associated with climate change unless European and British cattle breeds are replaced by Brahmans or other tick resistant breeds.

**Forage Quality.** The effects of rising CO<sub>2</sub> and temperature on plants are complex and are likely to have mixed and site-dependent effects on forage quality. Rising CO<sub>2</sub> can increase shoot total nonstructural carbohydrates, thereby increasing forage quality (Read et al. 1997; Lilley et al. 2001), but also reduce forage quality, especially in dry, N-limited rangelands, by increasing the C:N ratio, lowering crude protein content, and increasing fiber content (Cotrufo et al. 1998; Morgan et al. 2001), all of which decrease digestibility (Morgan et al. 2004a; Milchunas et al. 2005; Owensby et al. 1996; but see Allard et al. 2003). Forage quality is suppressed to a greater extent in C<sub>3</sub> than C<sub>4</sub> grasses by elevated CO<sub>2</sub>, but crude protein content and digestibility are inherently higher in C<sub>3</sub> grasses (Wand et al.

1999; Barbehenn et al. 2004). For example, CO<sub>2</sub> enrichment to 600 ppmv reduced the crude protein content of C<sub>3</sub> grasses in all years, whereas the sole C<sub>4</sub> species blue grama (*B. gracilis*) showed greatest reductions only in dry years (Milchunas et al. 2005). Increases in temperature can increase lignin and cell wall contents in plants (Ford et al. 1979; Cherney and Hall 2007; Sanz-Sáez et al. 2012; Thorvaldsson 2007), which lowers digestibility.

Ecosystem-level responses to warming may amplify or dampen warming effects on forage quality of individual plants or species. For example, warming may accelerate organic matter mineralization to enhance soil N availability (Rustad et al. 2001; Pendall et al. 2004; Dieleman et al. 2012) and shoot N concentration in grasslands (Dijkstra et al. 2010). However, warming also may reduce (Link et al. 2003; An et al. 2005) or have no effect on shoot N concentration, depending on prevailing temperatures, plant species, soils, the degree of warming, water availability, and time (Turunen et al. 2009). The few experiments in which effects of both higher CO<sub>2</sub> and warmer temperatures were investigated show declining forage quality as a result of reduced crude protein and higher fiber contents (Dieleman et al. 2012; Sanz-Sáez et al. 2012), but little of this work has been done on rangelands.

Variation in precipitation adds even more complexity to forage quality. Moderately dry conditions can increase forage quality by concentrating N in plant tissues (Murphy et al. 2002) and delaying maturity (Craine et al. 2009), but severe drought that results in plant senescence has a decidedly negative effect. Forage N concentration, cell soluble contents, and digestibility decrease rapidly during senescence, and values for recent dead forage can be less than one-half of those of live forage (Kamstra 1973).

An extensive analysis of cattle fecal material collected throughout the continental United States (21 000 samples collected over 14 yr) provided evidence that livestock become more nutrient limited in warmer and drier climates as both the dietary crude protein and the digestible organic matter content of forages decrease (Craine et al. 2010). Warmer temperature had a stronger negative effect on forage quality than did decreasing precipitation. At the spatial scale of this analysis, trends in forage quality reflected both direct and indirect effects of climate, the latter including effects on management strategies and ecosystem properties, such as plant species composition. Consequently, these trends may not reflect those observed in a specific ecosystem in response to climate change. For example, forage protein content increases across the continental United States as precipitation increases (Craine et al. 2010), whereas plant N concentration often is lower and plant C:N ratios are higher in grasses in mesic than arid ecosystems (Wedin 1995; Murphy et al. 2002).

The differential effects of climate change drivers on plant species (Izaurre et al. 2011; Polley et al. 2012b) will contribute to species shifts on rangelands that may either increase (Polley et al. 2011) or decrease (Morgan et al. 2007) forage quality, depending on which species are favored. For example, elevated CO<sub>2</sub> reduced forage digestibility on short-grass steppe partly by increasing production of the grass with the lowest digestibility, *Stipa comata* (Morgan et al. 2004a). Unfortunately, our ability to predict plant community species shifts and the consequences for forage quality are generally

poor. Regions like the Southwest that are expected to experience more extreme drought (Seager and Vecchi 2010) will be vulnerable to declines in forage quality that result because drought hastens plant senescence. However, forage quality may change little or even be enhanced in ecoregions in which combined changes in climate change drivers have little effect on species composition and have a less adverse effect on or even promote plant growth. The length of growing season will provide the primary constraint on forage quality and quantity by establishing the duration and periodicity when live forage is present. Reduced forage quality is associated with greater methane production per unit of gross energy consumed (Benchaar et al. 2001). Therefore, livestock may become a greater source of methane in the future if the reduction in forage quality is not offset by a decrease in forage intake.

## REGIONAL SCENARIOS

The ecological consequences of climate change will vary substantially among geographic regions in response to antecedent environmental conditions and nonadditive interactions among major climate change drivers (Fig. 5). Climate change models project unique climatic scenarios for the southwestern United States and northern Mexico, the southern Plains, the northern Plains and south-central Canada, and the northwestern United States and southwestern Canada (IPCC 2007). Therefore, the ecological consequences of these unique projections are assessed independently for greater geographic specificity and to emphasize this regional variation. Two important qualifiers are associated with the interpretation of regional scenarios: climate change models simulate average regional values, meaning that results cannot be reliably downscaled to local areas or short time periods (years to decades; Kerr 2011), and greater uncertainty is associated with projected changes in precipitation than CO<sub>2</sub> concentration and warming.

### Southwestern United States and Northern Mexico

**Climate Projections.** Climate change is well under way in this region with clear trends of both warming and drying (US Global Change Research Program 2009; Seager and Vecchi 2010). This is partially a consequence of a northward shift in the track of winter and spring storms. Temperatures are expected to increase by 2.0–3.0°C by 2050 (Fig. 4) and 2.2–5.5°C by 2100, and spring precipitation is anticipated to decrease by 20–40% by the end of the century, but the contribution of summer monsoon remains uncertain (US Global Change Research Program 2009). Monsoons have been delayed by approximately 10 d in northern Mexico over the last half century. Multiyear droughts are projected to increase by mid-century, with some persisting for a decade or more (Cayan et al. 2010). In spite of this drying trend, flooding events are anticipated to increase in response to greater storm intensities falling on a larger proportion of bare soil.

**NPP and Forage Quality.** Warming and drying will synergistically reduce soil water availability to decrease NPP. Greater

plant WUE resulting from elevated CO<sub>2</sub> and an increase in the proportion of available soil water resulting from fewer but larger precipitation events will likely be insufficient to offset regional warming and drying. Forage quality is very likely to decrease in response to synergistic interactions among warming, elevated CO<sub>2</sub>, and drought stress.

**Livestock Production.** Livestock production will be reduced by lower forage quantity and quality and a decrease in voluntary animal intake associated with lower-quality forage, higher temperatures, and more frequent heat stress (CCSP 2008). Heat stress can be fatal for cattle in feedlots in this region if temperature increases by 1–5°C, especially for those fed large quantities of high-quality feeds (Haun 1997; Howden et al. 2008).

Extremely high temperatures combined with water deprivation can result in livestock losses on rangelands (Kay 1997). Surface water availability will decrease as springs and dugouts dry during drought, requiring that livestock travel greater distances for water. Walking increases the heat load on animals such that livestock must increase sweating and respiration rates to maintain homeostasis (Moran 1973). Consequently, livestock modify their behavior on rangelands by spending more time near water and shade and in riparian areas (Kay 1997; Parsons et al. 2003), reducing the total area grazed with negative effects on plant communities and forage production. Management responses likely will include a switch in cattle breeds. *Bos indicus* (“Indian” or oriental breeds, such as Brahman) are better adapted to high temperature and water limitations than are *Bos taurus* (“European” breeds, such as Angus) cattle. The skin of Brahman has greater capacity for nonevaporative heat transfer (Finch 1986; Carvalho et al. 1995), hair color and structure is more resistant to solar radiation (Peters et al. 1982), and water turnover rates are one-half those of European cattle breeds (MacFarlane et al. 1971).

**Vegetation Composition.** More frequent and severe droughts may contribute to species specific replacement and to episodic die-offs to modify vegetation composition. For example, the severe drought of 2002–2003 caused greater than 90% mortality of pinyon pine (*Pinus edulis*) in the Southwest, whereas associated trees of *Juniperus monosperma* survived (Breshears et al. 2005, 2009). Rainfall amount was similar during the recent and 1950s droughts, but die-off was greater during the 2000s drought because current temperatures are warmer than previously, leading to greater drying and plant water stress. The Sonoran Desert may exhibit major species and community range shifts, including those of such iconic species as Saguaro cactus (*Carnegiea gigantea*) and Joshua trees (*Yucca brevifolia*), in response to an increasing frequency of severe drought and wildfires (Weiss and Overpreck 2005; CCSP 2008). Increasing fire frequency in the Mojave Desert and Great Basin in the past 20 yr has converted communities of desert shrublands and shrub steppe to annual grasslands (CCSP 2008; Balch et al. 2013).

Climate change is anticipated to both positively and negatively affect exotic or invasive species by facilitating local extinctions, migration, and new invasions. Yellow starthistle (*Centaurea solstitialis*) is projected to maintain its current area and expand into more of California and Nevada (Bradley et al.

2009). Rising CO<sub>2</sub> may contribute to the invasive nature of cheatgrass and its close relative red brome (*Bromus madritensis* subsp. *rubens*; Smith et al. 2000; Ziska et al. 2005), although climate change is also expected to reduce the risk for cheatgrass invasion from current portions of its southern range in southern Nevada and Utah (Bradley and Wilcove 2009; Bradley et al. 2009). Red brome may replace cheatgrass in some of its southern range (Salo 2005). Shifts from snow to rain may favor cheatgrass invasion at higher elevations because rainfall frequency is more critical to its success than rainfall amount (Concilio et al. 2013). Increased aridity will have a less negative impact on recruitment of exotics like *Tamarix* compared to more drought-sensitive natives such as willows (*Salix* spp.) and cottonwoods (*Populus* spp.) in riparian corridors (Perry et al. 2013), which could enhance invasion by these exotics. However, expansion of *Tamarix* and likely other such riparian species beyond these corridors may be limited (Bradley et al. 2009).

Community boundaries were documented to synchronously migrate upslope along a 2 000-m elevation gradient in the Santa Rosa Mountains of California during the past 30 yr (Kelly and Goulden 2008). These elevational increases in community boundaries closely correspond to mean temperature increases observed over this time period and imply a direct effect of warming on the migration of entire plant communities rather than only specific species.

## Southern Plains

**Climate Projections.** Warming and drying are projected for this region as for the Southwest. Warming will be greatest in the North and drying greatest in the South (Fig. 4). Temperature is projected to increase by as much as 3.3°C in 2050 and 5.5°C in 2100, and precipitation may decrease by 5–10% by mid-century (US Global Change Research Program 2009).

**NPP and Forage Quality.** Warming and drying are anticipated to reduce both NPP and forage quality as described for the Southwest. Warming (2°C) alone increased plant production by as much as 21% in tallgrass prairie in Oklahoma, but the growth responses were negative during the dry summer (An et al. 2005; Wan et al. 2005). A decrease in forage quality may necessitate that producers provide additional supplementation to meet the nutritional requirements of livestock, which of course would increase operating costs. Supplements and other feeds currently account for more than one-half of the direct operating expenses of cow–calf operations (Short 2001).

**Livestock Production.** Responses are likely to be similar to those in the Southwest but may be less severe.

**Vegetation Composition.** More frequent and severe droughts are anticipated to lead to species-specific replacement and episodic die-offs that will modify vegetation composition. For example, eastern red cedar (*Juniperus virginiana*) was the only southern savanna dominant in which neither survival nor aboveground mass was adversely affected by experimentally imposed warming and intensified summer drought (Volder et al. 2010, 2013). Growth of both eastern red cedar and post oak (*Quercus stellata*) were reduced by intensified summer drought, but growth of eastern red cedar increased in response to

warming, while that of post oak did not. Similarly, establishment and growth of *Quercus emoryi* were especially sensitive to intensified summer drought in the Southwest (Weltzin and McPherson 2000). These results suggest that juniper encroachment is very likely to accelerate in response to climate change based on greater drought tolerance and positive response to warming (Volder et al. 2010, 2013).

### Northern Plains and South Central Canada

**Climate Projections.** A temperature increase of 4.3°C (2.8–7.1°C) and a precipitation increase of 15% (8–31%), especially in the winter, are projected for the region (Fig. 4; IPCC 2007). The amount of precipitation falling as snow is anticipated to continue to decline.

**NPP and Forage Quality.** Warming and increased precipitation, coupled with elevated atmospheric CO<sub>2</sub> concentrations, are anticipated to increase NPP by alleviating environmental growth limitations to both initiate growth earlier and extend the growing season (CCSP 2008). Warming has been shown to increase NPP in semiarid grasslands if combined with elevated CO<sub>2</sub> because of the water-conserving effect of CO<sub>2</sub> enrichment (Morgan et al. 2011). Forage quality is likely to remain constant or even increase, unless the benefits of increased precipitation for forage quality are offset by negative effects of CO<sub>2</sub> enrichment and, possibly, warming.

**Livestock Production.** Increased NPP and length of growing season, along with reduced feeding costs during the winter, will likely increase total production and the efficiency of production (CCSP 2008). However, subtle shifts in the periodicity of annual rainfall can significantly modify livestock production. For example, mid- and late-summer precipitation had offsetting effects on bison weight gain in tallgrass prairie (Craine et al. 2009). Late-season precipitation increased animal gain, but midsummer precipitation decreased gain by stimulating culm development in these grasses that reduced forage quality and animal performance.

**Vegetation Composition.** Warmer, wetter winters likely will favor plants that grow early in the season or access soil water accumulated early in the growing season. For example, ponderosa pine (*Pinus ponderosa*) established in grassland-forest ecotones in northern Colorado during years when spring and autumn precipitation were high in association with El Niño events (League and Veblen 2006). By increasing soil water content, higher CO<sub>2</sub> and precipitation also may favor recruitment and subsequent growth of taprooted invasive forbs like leafy spurge (*Euphorbia esula*), diffuse knapweed (*Centaurea diffusa*), and baby's breath (*Gypsophila paniculata*) as well as some shrubs (Owensby et al. 1999; Morgan et al. 2007; Blumenthal et al. 2008). On the other hand, climatic suitability for spotted knapweed (*Centaurea biebersteinii*) is expected to shift to higher elevations, leading to both contractions and expansion in Montana, Wyoming, Utah, and Colorado. Leafy spurge (*E. esula*) is likely to retreat from Nebraska, and parts of Oregon and Idaho, reducing invasion risk in the northern Plains but increasing invasion risk in southern Canada (Bradley et al. 2009).

### Northwest

**Climate Projections.** Temperature is projected to increase by 3.4°C (2.0–5.7°C), and precipitation is expected to show a modest increase (5%) in winter but a decrease in summer by the end of this century (IPCC 2007; US Global Change Research Program 2009; Diffenbaugh et al. 2005). Snow cover and depth have declined in the western United States since the mid-20th century with reductions approximating 25% and 10% in the Oregon Cascades and high elevations of the Rockies and southern Sierras, respectively (Mote et al. 2005; Christensen and Lettenmaier 2006; Ray et al. 2008). Snowpack reductions likely will continue by as much as 40% by mid-century in the Cascades. Spring snowmelt and stream flow is occurring 20–40 d earlier than in 1900 (Mote et al. 2005). An increased amount and intensity of winter rain is anticipated to produce greater flooding and increase wildfire frequency in conjunction with drier summers.

**NPP and Forage Quality.** Warming is likely to decrease soil water availability, especially in the latter portion of the growing season, and reduce NPP. Earlier snowmelt (10–15 d in 50 yr) and reduced stream flow is anticipated to reduce production in riparian systems (CCSP 2008). Elevated CO<sub>2</sub>, coupled with warming and drying, has the potential to suppress forage quality, but net effects of climate change are uncertain.

**Livestock Production.** Benefits of milder, wet winters may offset negative effects of longer and drier summers on livestock production, with negligible net effect of climate change. Animals may require supplemental feed during the extended dry summers.

**Vegetation Composition.** The current range of yellow starthistle (*C. solstitialis*) in northern California, Oregon, and Washington is expected to remain relatively constant, although greater proliferation within the region is expected (Bradley et al. 2009). Shrublands and grasslands in the intermountain West are currently invaded or under threat of invasion by cheatgrass (*Bromus tectorum*), medusahead (*Taenatherum capetmedusa*), and red brome. Increasing atmospheric CO<sub>2</sub> and greater frequencies of fire and other disturbances are expected to exacerbate these threats, especially at higher elevations and in northern parts of these species' current ranges (Smith et al. 2000; Ziska et al. 2005; Chambers and Pellant 2008; Bradley et al. 2009).

## SYNOPSIS OF ECOLOGICAL IMPLICATIONS

- The three major drivers of climate change—rising atmospheric CO<sub>2</sub> concentration, atmospheric warming, and modified amounts and temporal patterns of precipitation—collectively affect soil water availability to influence many aspects of rangeland systems.
- The ecological consequences of climate change will vary substantially among biogeographic regions in response to antecedent environmental conditions and the differing expression of warming and precipitation modification among regions. Ecosystem processes such as NPP will decrease in the South in response to warming and a decrease in precipitation, increase in the North as a result of warming

and greater precipitation, and decrease in the Northwest as a result of drier summers.

- Climate change may modify the composition of rangeland vegetation and induce a shift in geographic distributions of plant species, including exotic (invasive) species. In some instances, vegetation reorganization may produce communities that are compositionally unlike any found today (i.e., no-analog communities).
- An increasing occurrence of climatic extremes, specifically successive wet vs. dry seasons or years, will likely increase the frequency and extent of wildfires in grasslands and necessitate greater attention to fuel management and safeguards to human life and property.
- Climate change will have modest and regionally variable effects on soil organic C content that will minimize the magnitude of shifts in C content, making them difficult to detect with current technology. This has important implications for the development and monitoring of successful mitigation strategies emphasizing C sequestration (Joyce et al. 2013 [this issue]).
- Livestock production systems will be increasingly constrained by the combined effects of reduced forage quality and quantity, greater thermal stresses on animals, and increasingly adverse effects of ectoparasites. Varied and often multiple adaptation strategies will be required to sustain economically viable livestock enterprises (Joyce et al. 2013 [this issue]).
- Directional change in climatic means and increasing climatic variability and extreme events indicate that a “business as usual” approach to rangeland management is no longer viable. Previous climatic and weather patterns may no longer serve as a reliable guide to future conditions.

## KNOWLEDGE GAPS

- Precise projections of mean climatic trends, especially at regional levels, and of the intensity, frequency, and ecological consequences of extreme climatic events (Diffenbaugh et al. 2005; Reyer et al. 2013).
- Sufficient insight into interactive effects among climate change drivers on soil water and NPP in major rangeland ecoregions (Fay et al. 2008; Knapp et al. 2008; Heisler-White et al. 2009).
- Extent of species and community shifts that may occur in response to climate change, including range shifts in invasive species and the expansion of native woody plants, and plant and animal pathogens (Weiss and Overpeck 2005; Bradley et al. 2009).
- Response of riparian systems to warming, decreasing snowpack, earlier and smaller stream flows, and prolonged summer dry periods (Mote et al. 2005; Christensen and Lettenmaier 2006).
- The capacity of existing concepts, models and tools within the profession to accommodate the dynamics and uncertainty associated with climate change.
- A national database for archiving and managing information to document the various impacts of climate change on rangeland systems, including the outcomes of climate change

drivers on major management strategies (IPCC 2007; US Global Change Research Program 2009).

## MANAGEMENT IMPLICATIONS

A compelling footprint of climate change has been emerging since the mid-20th century that lends tremendous credibility to model projections of increased deviation from mean climatic trends and greater climatic variability. Uncertainties regarding climate projections and the specific consequences of these changes are to be expected given the unprecedented rate and scale of this phenomenon. However, it would be irresponsible to ignore the cumulative evidence for climate change and its current and future implications. The long-recognized significance of climate variability in rangeland ecosystem function and enterprise viability clearly justifies the need for an objective and comprehensive assessment of the implications of climate change for management recommendations, policy decisions, and research agendas. Increased preparedness for climate change does not require a precise projection of future conditions, only a recognition that sufficient directional change and greater extremes may exist to modify the services provisioned by current ecosystems to adversely affect human well-being.

Consensus projections of numerous climate change models indicate that the Southwest and southern Plains will become both warmer and drier, the Northwest will become warmer and drier during summer with reduced snowpack in winter, and the northern United States and southern Canada will become warmer and wetter, especially during the winter. Substantial variation among ecoregions demonstrates that climate change will not be expressed as a uniform series of events at a continental scale but rather will be characterized by substantial spatial and temporal variability. Increasing variability and uncertainty may be of greater consequence to rangeland systems than the long-term deviation in climatic trends.

We contend that an unrealistic perception of climatic consistency has hindered the development and implementation of sufficient contingency planning to manage for current weather variability and that it poses a major impediment to recognition of the emerging consequences of climate change as well as development of effective strategies to contend with these consequences. It is essential for the rangeland profession to recognize that 1) shifts in mean climatic trends have already been documented, 2) accelerated rates of climate change will have dramatic effects on the provisioning of rangeland services and human well-being, and 3) many of the adverse consequences of climate change may be effectively confronted with the proactive development and implementation of appropriate adaptation and transformation strategies (Joyce et al. 2013 [this issue]).

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