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# Vulnerability of Cattle Production to Climate Change on U.S. Rangelands

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## Abstract

We examined multiple climate change effects on cattle production for U.S. rangelands to estimate relative change and identify sources of vulnerability among seven regions. Climate change effects to 2100 were projected from published models for four elements: forage quantity, vegetation type trajectory, heat stress, and forage variability. Departure of projections from a baseline (2001–2010) was used to estimate vulnerability. Projections show: (1) an increase in forage quantity in northerly regions, (2) a move toward grassier vegetation types overall but with considerable spatial heterogeneity, (3) a rapid increase in the number of heat-stress days across all regions, and (4) higher forage variability for most regions. Results are robust across multiple elements for declining production in southerly and western regions. In northern and interior regions, the benefits of increased net primary productivity or more grassy vegetation are mostly tempered by increases in heat stress and forage variability. Because projected directions of change differed, use of projections for only one element will limit our ability to anticipate impacts and manage for sustained cattle production.

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**Keywords**—climate change, livestock operations, impact analysis, vulnerability assessment, grasslands

On the cover (clockwise from top left): alpine grassland in northern New Mexico (photo by K. Bagne), cattle grazing on restored Colorado grassland (photo by USDA Agricultural Research Service), annual spring wildflowers on Carrizo Plain in California (photo by A. Vernon, Wikimedia Commons), Konza Prairie in Kansas (photo by U.S. Environmental Protection Agency).

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## Executive Summary

We examined the vulnerability of cattle production on U.S. rangelands to climate change effects by estimating changes in forage quantity, vegetation type trajectory, heat stress, and forage variability. Our measure of vulnerability assumed livestock operations were sustainable under climate conditions of recent experience, thus providing a locally derived estimate of change. Projections to 2100 for each element were generated at approximately 8 km<sup>2</sup> and compiled into seven major rangeland regions: Southwest, Desert Southwest, Interior Mountain West, Great Basin, Northern Great Plains, Southern Great Plains, and Eastern Prairies. The projections were translated into vulnerability as departure from the current baseline (2001–2010), converted to an index score, and summed to estimate overall vulnerability of sustained cattle operations. Forage quantity was taken from a biogeochemical cycling model of net primary productivity (NPP) and is projected to increase in northerly regions, potentially benefiting cattle production. The trajectory of vegetation type toward or away from preferred cattle forage was estimated by using the dynamic vegetation model MC2. Vegetation types are projected to move toward more grass types overall, but there is considerable heterogeneity across the rangeland extent and within regions. Heat stress was estimated as the number of days per year where the thermal neutral zone for beef cattle would be exceeded. The number of heat-stressed days increases rapidly across all regions, with the largest departure in the Interior Mountain West and the Pacific Southwest. Forage variability, as measured by interannual NPP variability, increases for most regions.

Anticipation of changing conditions and the identification of sources of vulnerability are critical to selecting effective adaptation measures. Rangeland changes are not expected to be uniform over time or across the landscape; thus, adaptation actions cannot be universally applied. Trends in expected change to 2100 are mostly nonlinear and differ by element and region. The spatial pattern of change across multiple elements was used to further examine the weight of evidence for future cattle production scenarios. Projected impacts are consistently negative across multiple elements in southerly and western rangeland regions, providing strong evidence for declining production over time. In northern and interior regions, benefits of increased NPP or movement toward grassier vegetation types are mostly tempered by negative impacts from increasing heat stress and forage variability. Disagreement among elements as to the direction of change indicates that reliance on projections for a single element will limit our ability to anticipate impacts and manage for long-term sustainability of livestock production.

# Contents

<b>Executive Summary</b> .....	
<b>Introduction</b> .....	<b>1</b>
Rangelands Defined .....	1
Extent and Importance of Rangelands in the United States .....	1
Changing Rangelands .....	2
Climate Change Effects on Rangelands .....	4
Vulnerability to Climate Change .....	6
<b>Vulnerability of Cattle Production</b> .....	<b>6</b>
Introduction .....	6
Cattle Vulnerability Elements .....	8
Modeled Elements .....	9
Elements Not Modeled .....	10
Combining Vulnerability Elements .....	11
Vulnerability Model Methods .....	12
Vulnerability Model Results .....	16
<b>Discussion and Applications</b> .....	<b>26</b>
Key Findings of Cattle Production Vulnerability .....	26
Multiple vs. Single Element Vulnerability .....	26
Uncertainty .....	27
Implications .....	28
Next Steps .....	30
<b>References</b> .....	<b>30</b>

## **List of Figures**

- Figure 1—Extent of rangelands ecoregions
- Figure 2—Cattle grazing on grasslands
- Figure 3—Eroded wind-blown soils during the 1930s Dust Bowl
- Figure 4—Density of beef cattle by county
- Figure 5—Dakota Prairie National Grassland in North Dakota
- Figure 6—Vulnerability index
- Figure 7—Average percentage change over time from the baseline for all elements in each ecoregion
- Figure 8—Vulnerability index for change in vegetation type trajectory
- Figure 9—Vulnerability index for change in heat stress index.
- Figure 10—Vulnerability index for change in forage variability
- Figure 11—Average vulnerability index based on percentage change over time from baseline (2001–2010)
- Figure 12—Overall vulnerability index (sum) and standard deviation
- Figure 13—Average overall vulnerability index over time for each ecoregion.
- Figure 14—Predicted direction of change from overall vulnerability index and agreement among elements
- Figure 15—Juniper in a New Mexico grassland

## **List of Tables**

- Table 1—Source of data for elements and variables used to calculate climate change vulnerability of U.S. cattle production on rangelands
- Table 2—Combinations of general circulation models (GCMs) and emissions scenarios used to estimate future climates
- Table 3—Classification of vulnerability scores
- Table 4—Hypothetical example of how the vulnerability index score is calculated for each pixel, each year, in each scenario.
- Table 5—Adaptation options for affected U.S. regions as suggested by average predicted climate change effects to 2100

## Introduction

This report contains a spatial analysis of future cattle production vulnerability on U.S. rangelands using four key ecological elements sensitive to climate change. This section provides an introduction to U.S. rangelands and potential climate change effects along with an overview of vulnerability assessment. The next section presents the analysis of and results for cattle production vulnerability in the coterminous United States. Vulnerability is described spatially as departure from current conditions for forage quantity, vegetation type trajectory, heat stress, and forage variability. In the last section, we interpret the results and discuss implications of the analysis. Relationships between multiple vulnerability elements are considered.

## Rangelands Defined

Rangelands are widespread and diverse ecosystems that provide many key goods and services. The definition of a rangeland has been widely debated, but is generally considered to be land dominated by grass, forb, or shrub species, but not specifically modified for grazing purposes (Frank et al. 1998; Lund 2007; Reeves and Mitchell 2012). Rangelands include grassland, shrubland, and desert ecosystems and represent nearly half of the global terrestrial land area (Food and Agriculture Organization of the United Nations 1990).

To conduct the spatial analysis for this study, we needed an explicit definition of rangeland. We followed the methods outlined by Reeves and Mitchell (2011) to identify rangelands across the United States corresponding to the National Resources Inventory (NRI) definition. Rangelands were identified and classified by querying for the following attributes from LANDFIRE:

1. Historical vegetation dominated by grass, forb, or shrub species
2. Tree canopy cover currently less than 25 percent
3. Height of shrubs currently less than 4 m
4. Patch size greater than 2 ha.

Classifications for current rangeland are circa 2001 (Reeves and Mitchell 2011; Rollins 2009). Rangelands include woodlands with tree cover less than 25 percent and sites that are currently tree-dominated (afforested or encroached) but have climax-potential natural vegetation dominated by shrub or herbaceous species (Natural Resources Conservation Service 2007) (see box 1). Transitional rangelands or those lands with a tree-dominated climax-potential natural vegetation that are currently classified as herb- or shrub-dominated do not meet the NRI definition and were not included (Reeves and Mitchell 2011).

## Extent and Importance of Rangelands in the United States

Rangelands occupy approximately 268 million ha or 35 percent of the coterminous United States (Reeves and Mitchell 2011) (fig. 1). Throughout the study, this estimated rangeland extent was held constant and not allowed to transition to agricultural, urban, or natural vegetation classes. Rangelands currently used for livestock grazing are either privately or government owned, with about 64 percent in non-Federal ownership (Joyce 1989). Major rangeland expanses include the Great Plains, the Desert Southwest, and the sagebrush steppe of the Great Basin. These regions are ecologically diverse and support a variety of goods and services important to human societies (fig. 2).

## Box 1. Delineating Rangelands

We identified rangeland following the National Resources Inventory (NRI) definition (NRCS 2007): “A land cover/use category that includes land on which the climax or potential plant cover is composed principally of native grasses, grass-like plants, forbs or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland.” The geospatial layers from the LANDFIRE project (Rollins 2009) identifying Existing Vegetation Type (EVT), Existing Vegetation Height (EVH), Existing Vegetation Cover (EVC), and Biophysical Settings (BPS) were used to determine if a pixel should be classified as rangeland or not. Thirty  $m^2$  pixels were combined into  $\geq 2$  ha sites based on the majority classification to meet minimum patch size from the NRI definition, as smaller patches are too isolated and disjunctive to be managed as rangelands. A pixel was classified as rangeland if historic vegetation was dominated by grass, forb, or shrub species (from BPS) and current canopy cover of trees or of shrubs taller than 5 m was less than 25 percent (from EVC and EVH). Rangelands also included afforested areas where woody plants have encroached on historically herb- or grass-dominated regions. Historically forested lands based on potential vegetation (from BPS) that were in early successional phases were excluded as they were considered only temporarily vegetated with grasses, forbs, or shrubs (Reeves and Mitchell 2011). The resultant rangeland domain used for this study matched the spatial resolution of vulnerability elements at  $8\text{ km}^2$  resolution. Since the source data from Reeves and Mitchell (2012) was  $30\text{ m}^2$  resolution, resampling was necessary. To create the rangeland extent seen in figure 1, the proportion of  $30\text{ m}^2$  “rangeland” pixels that underlie each  $8\text{ km}^2$  pixel was calculated. Only those  $8\text{ km}^2$  pixels with  $\geq 50\%$  rangeland pixels were retained for the vulnerability analysis.

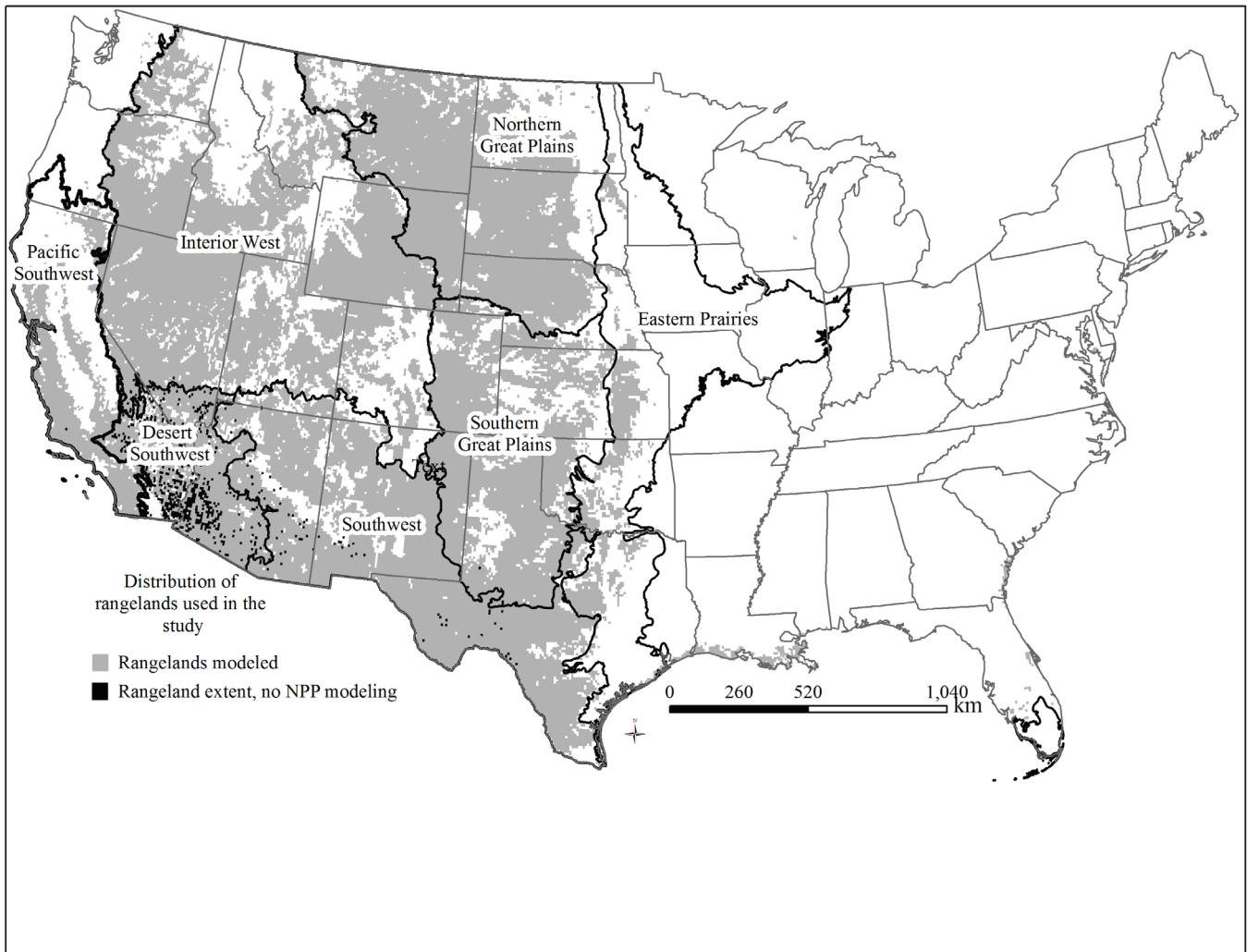
Sustainability of ecosystem goods and services has become a platform for evaluating rangeland health and setting management guidelines. Tangible resource output from rangelands is inextricably linked to net primary production (NPP), because NPP ultimately controls the amount of forage available for use by domestic livestock and native herbivores. Cattle production on U.S. rangelands has historically had the greatest market value of rangeland goods and services. Rangelands are also important for the variety of other goods, services, and resources they provide, such as energy, recreational opportunities, soil stability, and aquifer recharge (Mitchell 2010).

## Changing Rangelands

Rangelands have been subject to a long history of resource extraction, degradation, and land conversion (fig. 3). U.S. rangelands have been extensively modified for cropland and residential development. At least 34 percent has been lost from historical coverage and an average of 142,000 ha per year has been converted since 1982 (Reeves and Mitchell 2012). Grassland bird populations in the United States are declining more than any other bird group and the few intact grassland tracts remaining may be insufficient to maintain viable populations (With et al. 2008). In recent decades, the spread of invasive weeds and the expansion of oil and gas development have further modified or degraded rangelands (Copeland et al. 2009; Reeves and Mitchell 2012). At the same time, livestock productivity on U.S. rangelands has remained fairly constant (Reeves and Mitchell 2012).

Rangeland extent in the United States is expected to slowly decline, not uniformly but rather in association with land conversion near centers of population growth (Mitchell 2000). Additionally, impacts from oil and gas exploration are expected to accelerate. Development extends outward beyond the physical footprint of a new land use with indirect effects on nearby goods and services (Leu et al. 2008; McDaniel and Borton 2002). Invasion by exotic species, another growing threat to rangeland with ties to development, can rapidly alter rangeland condition and ecological function over large areas. Exotic plant invasions affect livestock forage, native biodiversity, wildlife habitat, wildfire, soils, and water resources (DiTomaso 2000).





**Figure 1**—Extent of rangelands resampled from 30 m<sup>2</sup> to 8 km<sup>2</sup> based on Reeves and Mitchell (2011). Study area is divided into seven ecoregions.



**Figure 2**—Cattle grazing on grasslands. Grassland ecosystems support a range of goods and services such as cattle grazing, an important component of U.S. agricultural production. (Photo by USDA, Agricultural Research Service.)



**Figure 3**—Eroded wind-blown soils covering farms and ranches near Cimmaron, OK, during the 1930s Dust Bowl, the culmination of climate and management practices (photo by A. Rothstein, USDA, Farm Security Administration).

The economic loss resulting from invasion of exotic plants on U.S. rangelands was estimated at \$2 billion annually (DiTomaso 2000) and is likely to be much higher today. Native species can also alter rangelands and cause economic loss. For example, woody species, particularly juniper (*Juniperus* spp.) and mesquite (*Prosopis* spp.), may encroach upon open landscapes, altering soil and water cycles and reducing grass and forb cover (Wheeler et al. 2007).

### Climate Change Effects on Rangelands

Climate change is expected to have a wide range of effects that will potentially alter rangeland ecosystems (Polley et al. 2013). Climate change can exacerbate current threats to rangeland health in many ways, such as by expanding ranges of invasive species, increasing duration and severity of droughts or floods, and decreasing aquifer levels. Multiple drivers and factors regulate the response of rangelands to climate change; consequently, alteration of goods and services from U.S. rangelands will not occur uniformly either through time or across the landscape. Careful consideration of local response is needed before adaptation measures are applied.

Multiple drivers and factors regulate the response of rangelands to climate change; consequently, alteration of goods and services from U.S. rangelands will not occur uniformly either through time or across the landscape.

The future of rangelands will be shaped by complex interactions and responses, but numerous studies and analyses point toward some robust predictions for rangeland vegetation. Elevated carbon dioxide (CO<sub>2</sub>), global warming, and altered precipitation regimes are major drivers of change to contemporary rangeland ecosystems (Polley et al. 2013). Of particular

importance to ecosystem function are the subsequent changes to soil water availability (Knapp et al. 2008; Luo 2007). Precipitation, and especially its variability, is a major factor affecting plant response to CO<sub>2</sub> levels, and increasing rainfall variability alone has been shown to reduce NPP (Fay et al. 2002, 2003; Izaurrealde et al. 2001; Larsen et al. 2011; Milchunas et al. 2005).

Changes in NPP, however, are not expected to be uniform across the landscape. Patterns of rainfall timing, intensity, and interannual variability as well as differences in plant species composition and soils will further affect plant productivity, resulting in complex patterns of response and regional differences (Fay et al. 2002). For example, periods of intense rainfall in arid regions reduce water stress by increasing the relative availability of deep soil water where it is less prone to evaporation; in more mesic regions, plant water stress increases as the period between rainfall events lengthens (Heisler-White et al. 2009; Knapp et al. 2002). Benefits of increased CO<sub>2</sub> levels may be greatest in semiarid regions, because the largest increases in NPP are generally observed during dry years, when the effect of increased water use efficiency is most pronounced (Izaurrealde et al. 2011). Others suggest that NPP will be highest under elevated CO<sub>2</sub> in wet years, because of effects on soil respiration and nutrient availability (Parton et al. 2007). An experiment in a California grassland found little effect of elevated CO<sub>2</sub> or warmer temperatures on NPP over 5 years, emphasizing the difficulty of generalizing about plant response to climate change (Dukes et al. 2005).

Although modeled projections for individual plant and animal species are limited, our understanding is that differences in species response to climate change drivers will alter community composition and potentially ecosystem function (Izaurrealde et al. 2011). Expanding ranges of invasive plants threaten rangelands and can diminish forage resources, but some regions will become less suitable for these invasive species and present opportunity for restoration. For example, yellow starthistle (*Centaurea solstitialis*) will probably expand its range broadly, but cheatgrass (*Bromus tectorum*) is expected to expand northward while contracting to the south (Bradley 2009). Encroachment of woody species is increasing in many regions due to a complex set of environmental and management factors, but continued expansion will depend on several interacting factors, including precipitation patterns, grazing, and fire frequency (Peters et al. 2006). In arid regions, however, water stress associated with drought increases mortality in woody species although stress tolerance differs by species (Breshears et al. 2009; Plaut et al. 2012).

Even small changes in precipitation can have large effects on forage production for grazing species (McKeon et al. 2009). Greater forage production and decreased costs associated with supplemental feed are expected to increase cattle production in the northern Great Plains, but gains may eventually be limited by soil nutrient cycling and poorer forage associated with reduced nitrogen content (Baker et al. 1993; Hanson et al. 1993). Reductions in forage quality may be greatest where soils are already nitrogen limited and under dry conditions, but forage quality also depends on species composition and rainfall variability, making long-term regional projections difficult (Milchunas et al. 2005; Morgan et al. 2004; Murphy et al. 2002).

Altered climate regimes will further affect herbivores through incidences of extreme weather (particularly heat waves), changing water availability, and altered disease susceptibility (Howden and Turnpenny 1998; Howden et al. 2008; Polley et al. 2013). Heat stress, for example, is expected to increase, particularly in warmer regions, and can lead to diminished weight gain, greater divergence from uniform range utilization, and reduced meat safety (Baker et al. 1993; Gregory 2010; Hart et al. 1993; Howden and Turnpenny 1998).

## Vulnerability to Climate Change

Evaluating change in goods and services in response to predicted climate change can ensure that management planning and decisions are appropriate to probable future conditions or proactive in addressing undesirable outcomes (Glick et al. 2010; Luers et al. 2003). We can examine the potential range of futures of a specific ecosystem element, good, or service by translating climate change impacts into vulnerability to help us interpret change (Friggens et al. 2013). Vulnerability is considered to be the degree to which a system is exposed to negative impacts (Mitchell et al. 1989). A vulnerability assessment examines a system's attributes of concern, such as cattle production, as exposed to stressors—here, change in climate—within a particular time period (Füssel and Klein 2006). The vulnerability of the system can be seen as the combination of exposure, sensitivity, and adaptive capacity, but these factors are often intertwined in practice (Turner et al. 2003). For example, cattle response to high temperature in the form of heat stress, which is a combination of sensitivity to heat (the temperature at which energy needs to be expended to maintain body function) and the capacity to dissipate excess heat (for example, sweating, coat reflectivity), will further depend on the availability of shade or water (West 2003). Thus, vulnerability can encompass a wide range of complex intrinsic and extrinsic processes.

We can think of vulnerability in a general sense as the potential for change from a desired state. For example, increasing dominance of plant species exhibiting the C4 (warm-season) photosynthetic pathway over those with a C3 (cool-season) pathway during the next 50 years cannot generally be considered a more or less vulnerable state for rangeland unless tied to a more specific element or value such as habitat availability for greater sage-grouse (*Centrocercus urophasianus*), retention of a historical species composition, or quality of summer grazing forage. Thus, if sage-grouse habitat were composed of primarily C3 species, then conditions that favor C4 species would be a more vulnerable state for sage-grouse, but not necessarily for other rangeland goods or services.

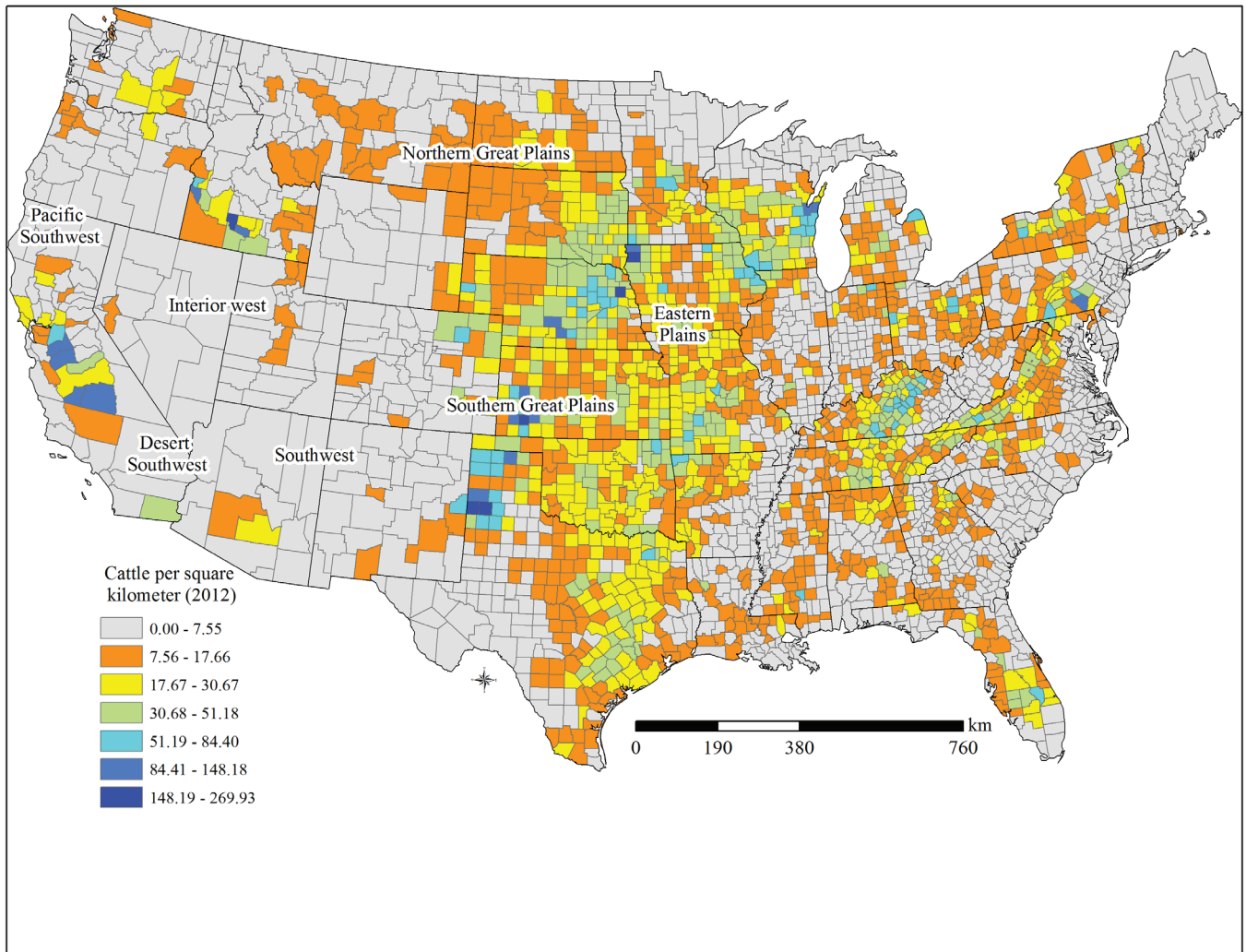
Potential changes in future cattle production on rangelands—rather than on pastures or in feedlots—as a result of climate change were the target for this vulnerability analysis. We measured vulnerability as the modeled future departure, or the difference, from a baseline of recent values in a specific location for ecological elements related to cattle and climate. Thus, vulnerability or the interpretation of the direction of impact is relative to local current conditions and may indicate declining (more vulnerable) or increasing (less vulnerable or more resilient) potential for cattle production. This approach is particularly useful for a variable such as cattle production because current management of livestock operations can be considered to be adapted to and reasonably sustainable under the range of conditions recently experienced.

## Vulnerability of Cattle Production

### Introduction

The United States is the world's largest producer of beef with fairly constant production over the past decade at about 97 million cattle (fig. 4). Production on rangeland, as opposed to pasture, is concentrated throughout the Great Plains States, the Interior Mountain West, and California (Reeves and Mitchell 2012; fig. 5). Beef cattle account for a large portion of goods and services derived from rangeland and consume most of the grazed forage (Joyce 1989). In the coming decades, livestock and livestock operations are expected to be exposed not only to varying environmental factors such as warming temperatures, altered precipitation patterns,

and changing fire regimes, but also to changing socioeconomic factors such as land use, global market demand, and government subsidy programs (Howden et al. 2008; Izarraulde 2011; Polley et al. 2013; Thornton 2010). Climate and key biotic interactions such as predators, parasites, and invasive species will further influence the future of livestock operations in the United States.



**Figure 4**—Density of beef cattle per km<sup>2</sup> in 2012 based on U.S. county data (National Agricultural Statistics Survey 2014) .



**Figure 5**—Dakota Prairie National Grassland in North Dakota. Annual net primary productivity is expected to increase on grasslands of the northern Great Plains (photo by A. Bagne).

Similar to the analysis presented in this report, Baker et al. (1993) examined U.S. cattle production by using simulations of forage and cattle production. Forage production was simulated by a software program Simulation of Production and Utilization of Rangelands (SPUR), for which climate data from three general circulation models (GCMs) and nominal climate history were applied at CO<sub>2</sub> concentrations of 550 ppm, or twice their preindustrial average. Forage utilization was then linked to a model of weight gain in individual cattle to simulate the life cycle of herds. Important aspects of production of both forage (peak standing crop, nitrogen content, soil organic matter) and individual cows (forage intake, forage digestibility, supplementation needs, weaning weight) were used to determine vulnerability of 46 regions dependent on cattle production. Projected responses of the three plant response elements and four animal intake elements were assigned to categories of increase, decrease, or no change in production, and then summed, for a CO<sub>2</sub> level forecast for the year 2050 (Long et al. 2006). Overall, California and the southern Great Plains were expected to have lower production. The northern Great Plains, Intermountain region, and Northwest were expected to have production gains. The seven response elements did not show a consistent direction of change within any one region, indicating that future production depends on the balance of multiple elements.

We took a similar approach to integrating multiple vulnerability elements and examined effects of climate change on cattle production across U.S. rangelands to 2100 by using contemporary datasets and models. We focused on ecological effects, including vegetation and physiological thresholds, and created a regionally explicit portrait of the future potential of beef cattle production in the coterminous United States.

## Cattle Vulnerability Elements

We viewed future cattle production as production potential from an ecological perspective and ignored the complex of social, economic, and other factors involved in setting actual stocking rates. Rather than model weight gain for individual cattle as in Baker et al. (1993), we examined key climate-sensitive variables, which approximated sensitivity and adaptive capacity. For each variable, we projected the magnitude and direction of change under three GCMs and four emissions scenarios to the year 2100 (tables 1 and 2). Our metric of vulnerability was

**Table 1**—Source of data for elements and variables used to calculate climate change vulnerability of U.S. cattle production on rangelands.

Element	Variable used	Units <sup>a</sup>	Data source	Citation <sup>b</sup>
Forage quantity	Total annual net primary productivity (NPP)	kg C ha <sup>-1</sup> · yr <sup>-1</sup>	Biome-BGC	Reeves and others (2014)
Vegetation type trajectory	Pixels projected as grass or forb types each yr	Percent per decade	MC2	Bachelet and others (2001)
Heat stress	Temperature humidity index (THI)	Days · yr <sup>-1</sup> THI >stress threshold	IPCC 3rd Assessment	Coulsen and others (2010a,b)
Forage dependability	NPP interannual variability	Decadal SD of annual NPP (kg C ha <sup>-1</sup> · yr <sup>-1</sup> )	Biome-BGC	Reeves and others (2014)

<sup>a</sup> Output units are for each rangeland pixel (2.5 arc minute or ~8 km<sup>2</sup>).

<sup>b</sup> Full citations appear in the References.

**Table 2**—Combinations of general circulation models (GCMs) and emissions scenarios used to estimate future climates developed by Coulson and others (2010a,b) and Bachelet and others (2001).

	IPCC scenario (storyline)			
	B1	B2	A2	A1B
General description	Globalization, convergence	Slow change, localized	Regionalism, less trade	Rapid growth, technology
Growth in gross domestic product	Medium	Low	Low	High
Population growth	Low	Medium	High	Low
GCMs <sup>a</sup>	HadCM2SUL, CGCM1	GCGM2, HadCM3	GCGM2, CSIRO MK2, MIROC3.2	GCGM2, CSIRO MK2, MIROC3.2

<sup>a</sup> See text for sources of models. Emissions are from the Third Assessment of the Intergovernmental Panel on Climate Change (IPCC; Nakicenovic and others 2000).

departure from current conditions (2001–2010) because of its relevance to sustainable livestock operations, local knowledge, and ease of interpretation. Importantly, a contemporary baseline

Importantly, a contemporary baseline period includes a range of variability and extreme events that we assumed are anticipated and incorporated into local livestock operations.

period includes a range of variability and extreme events that we assumed are anticipated and incorporated into local livestock operations. For example, a managed livestock operation in a desert region would already be more flexible in responding to variable rainfall and dry years than one in a more mesic region where operations experience more

stable precipitation levels. Selection of model datasets was limited to available georeferenced projections based on Intergovernmental Panel on Climate Change (IPCC) scenarios to at least 2100. The time and spatial scale of analysis were broad and drivers of intra-annual change or other short-term impacts, such as fire effects on forage quantity, were not considered.

## Modeled Elements

### *Forage Availability*

Forage availability is essential to setting stocking rates and is the combination of primary production and the proportion of that production that is usable by cattle (Holechek 1988). Although elevated CO<sub>2</sub> can stimulate plant growth, NPP fluctuates with climate variables, particularly soil water availability, and ultimately drives the number of cattle that can be raised. Accordingly, change in NPP is expected to vary spatially and temporally (Reeves et al. 2014). Drought years in particular limit available forage and strain livestock operations (Eakin and Conley 2002). Woody plant species can spread rapidly and greatly reduce cover of herbaceous forage plants preferred by cattle (Briggs et al. 2002; Engle et al. 1987). Expansion of woody species is projected in some regions, such as for red cedar (*Juniperus virginiana*) in the Great Plains; conversely, contraction may occur in arid regions as woody species succumb to drought stress (Breshears et al. 2005; Iverson et al. 2008). We examined forage availability as two variables: total annual NPP as a measure of forage quantity regardless of vegetation type, and the trajectory of potential vegetation type toward or away from types dominated by woody species.

## *Heat Stress*

The impact of heat on livestock production is of growing concern as global temperatures rise (Baker et al. 1993; Howden et al. 2008). High temperatures and humidity can induce heat stress in livestock, which increases water demand and reduces weight gain as rumination ceases and energy is expended to reduce body temperature (Bonsma et al. 1940; Finch 1986; Howden et al. 2008). In one study, weight gain in an individual was reduced by 0.4 kg/day for each 1 °C of body temperature above the thermal neutral zone (Crescio et al. 2010; Finch 1986). Other heat stress effects include male sterility, lowered immune response, and, at extreme levels, mortality (Bonsma et al. 1940; Hahn 1997). Heat is also a factor associated with meat safety and outbreaks of food-borne illness (Gregory 2010).

Heat stress in cattle is related to the temperature-humidity index (THI), a simple index correlated to physiological heat response that has been shown to closely track more extensive models of heat transfer (Howden and Turnpenny 1998). Humidity is particularly important in predicting stress response in cattle and corresponds to the relatively high rate of heat-related mortality in the southeastern United States (Finch 1986; West 2003). Mortality rises rapidly with each increment of THI (Crescio et al. 2010). The number of consecutive days above a threshold value of THI and nighttime temperatures needed for recovery also factor into effects of heat stress, as do cattle breed and coat color (Finch et al. 1984; Gaughan et al. 2008). A climate change projection for Australia found safe values of THI were exceeded on 38 percent of days as compared to 16 percent of days under current conditions (Howden and Turnpenny 1998). We examined heat stress relative to current local conditions by using the number of days when a threshold value of THI was exceeded.

## *Forage Quantity Variability*

The predictability of forage, or forage dependability, is one of the most critical of the livestock production factors that determine the viability of livestock operations in a region (Ash et al. 2012; Eakin and Conley 2002). Variation in NPP can alter availability of forage as well as the long-term sustainability of livestock operations. Increasing rainfall variability affects plant response to elevated CO<sub>2</sub> and availability of nitrogen, resulting in lower NPP regardless of rainfall amount (Fay et al. 2002, 2003; Izaurralde et al. 2001; Larsen et al. 2011; Milchunas et al. 2005). Interannual variation in NPP is a contributing factor to vulnerability regardless of total production, because variation creates unpredictable conditions and requires increasing flexibility in cattle operations, such as stocking rates, herd size, herd movement, or use of supplemental feed (Ash et al. 2012; McKeon et al. 2009). For example, in extreme drought situations, animal numbers must be decreased due to lack of forage, and competition increases for forage alternatives (Brunson and Tanaka 2011).

## **Elements Not Modeled**

We lacked relevant datasets for other factors that will affect future cattle production, such as forage quality, changes in surface water availability, pests, disease, and biodiversity (Thornton 2010). Elevated CO<sub>2</sub> can increase nonstructural carbohydrates and reduce crude protein and nitrogen content, but results differ by species and environmental conditions (Ehlringer et al. 2002; Frehner et al. 1997; Izaurralde et al. 2011; Taub et al. 2008). Changes in species composition further alter availability of cattle forage (Bradley et al. 2009; Epstein et al. 2002). Available drinking water has a strong influence on rangeland utilization and animal productivity (Ganskopp 2001; Hart et al. 1993; Holechek 1988). Projecting water supply for free-ranging



cattle is complicated by small-scale and large-scale variability in the number and size of artificial catchments, wells, and natural water sources (Smith et al. 2002). Water is an important variable in range utilization and longer distances to water reduce grazing uniformity and thus efficient stocking rates (DelCurto et al. 1999; Fusco et al. 1995; Harris et al. 2002; Hart et al. 1993; Pinchak et al. 1991).

Altered temperature and rainfall patterns will affect prevalence of pests and diseases significant to the cattle industry (Lindgren et al. 2000; Lysyk and Danyk 2007; White et al. 2003). The horn fly (*Haemotobia irritans irritans*), an important ectoparasite affecting weight gain, is expected to expand northward as temperatures warm although high temperatures may reduce populations in parts of Texas (Schmidtmann 1989). A number of vector-borne diseases, including bluetongue and anaplasmosis, are expected to increase in range and season of prevalence in northern regions as temperatures warm and winters become milder (Stem et al. 1989; Walton et al. 1984). As with crop species, the number of varieties of livestock species has been steadily declining, thereby threatening the long-term sustainability of production under changing conditions (Notter 1999). Continuing loss of genetic resources and endemic breeds means less adaptability and variation available for future breeding programs to promote resilient genotypes and sustain production under changing conditions (Thornton 2010).

## Combining Vulnerability Elements

The ultimate goal of this study was to examine the regional vulnerability of cattle production to climate change relative to the present day in the coterminous United States. Taking into account the many pathways by which climate change can alter cattle production, we chose to use a vulnerability index to simultaneously examine multiple ecological elements considered important in determining production. A composite score or “vulnerability index” is helpful in the absence of a deterministic mathematical model, because it integrates multiple vulnerability elements into one quantitative metric that can be used to make regional comparisons temporally and spatially.

To create a composite index, all elements that affect the target variable can be set to a consistent unit, such as percentage change or a categorical index score, to allow multiple elements to be summed or averaged (Hurd et al. 1999; Joyce et al. 2008). In the simplest form, elements can be combined based on predicted direction of change, regardless of magnitude, and can balance a set of increasing and decreasing impacts (Bagne et al. 2011; Baker et al. 1993; Batima 2006; O’Brien et al. 2004). For example, a region might be considered highly vulnerable if exposed to both sea level rise and more intense hurricanes, or moderately vulnerable if exposed to only sea level rise. We used this simple index approach to integrate elements. Alternatively, vulnerability elements may be complementary rather than additive, such as habitat suitability and dispersal potential, which together determine the future distribution of a species (Prasad et al. 2013).

Several issues arise when trying to integrate multiple effects on a target variable, particularly in the absence of an explicit mathematical model. Difficulty arises when combining elements, because a large projected change in value for any one element does not necessarily translate to a large change for the variable of interest. For example, would an 80-percent decline in NPP have an equally negative impact on the potential number of cattle produced as an 80-percent increase in the number of days under heat stress? Explicit functions describing relationships of an element to the target variable, even if they are available, may differ with time and location, complicating the integration of multiple elements. Group consensus methods, such as Delphi, are also used to set vulnerability thresholds, which could facilitate combining elements, but are

sensitive to participants' perceptions and values (Rowe and Wright 1999). Combining elements is further complicated when measures of vulnerability have both linear and nonlinear relationships (Turner et al. 2003). For example, NPP is likely to have a linear relationship to livestock capacity, but heat stress begins to have negative impacts at a threshold value.

Below we briefly describe the climate models used, and then expand on the key ecological elements of livestock production subject to alteration by climate change.

## Vulnerability Model Methods

### *Climate Models and Emissions Scenarios*

A consistent set of U.S. futures scenarios, which include projections for population, economic activity, climate, and bioenergy, were used to evaluate possible futures for rangeland. Here climate change is defined as the future potential climates developed by IPCC's Working Group III (Nakicenovic and Swart 2000). The scenarios have different storylines depending on the underlying assumptions about socioeconomic drivers, such as population growth, gross domestic product, and technological innovation, and greenhouse gas emissions.

For estimates of future climate data we used GCMs from the Climate Centre for Modelling and Analysis (CGCM; GCM1 for the MC2 data from Bachelet et al. [2001] and CGCM2), Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO MK2), the United Kingdom's Hadley Centre for Climate Prediction and Research (HadCM3), and the Model for Interdisciplinary Research on Climate (MIROC 3.2) (table 2). Future potential climates corresponded to IPCC's A1B, A2, and B1 or B2 scenarios (Nakicenovic and Swart 2000), and the corresponding downscaled climate data came from Coulson et al. (2010a,b) or Bachelet et al. (2001). Vegetation type using the MC2 model was the only element modeled with the B1 rather than the B2 scenario. Output of monthly averaged maximum and minimum temperature, precipitation, and potential evapotranspiration at the 1° spatial resolution were spatially downscaled to 5 arc minutes (about 8 km<sup>2</sup>) for the coterminous United States by Coulson et al. (2010a,b), which generally followed the methods of Price et al. (2004). The procedures for spatially downscaling the GCM data are provided in Joyce et al. (2011, 2014).

The fifth IPCC assessment revised the scenario process to be more comprehensive and flexible (Stocker et al. 2013). The new scenario process uses Representative Concentration Pathways (RCPs) as levels of radiative forcing brought about by greenhouse gas emissions under different socioeconomic conditions and decisions on mitigation or adaptation. Projected temperature increases based on the original emissions scenarios and the RCPs differ in trajectory, but, within a given time period, have similar outcomes (Rogelj et al. 2012). In a comparison of projected CO<sub>2</sub> emission levels to 2100, A1B is roughly equivalent to RCP6, B2 approximates RCP4.5 until 2050 and then projects closer to RCP6 by 2100, and A2 approximates RCP8.5 by 2100 (IPCC 2013).

The spatial extent of this vulnerability assessment was all rangeland in the coterminous United States identified from Reeves and Mitchell (2011) (fig. 1). Non-forest areas (those where tree cover is <25 percent) dominated by agriculture, including crops and pasture, were not considered rangeland. In addition, arid rangeland areas dominated by succulents were excluded due to limitations in the biogeochemical model of NPP. For illustration purposes, results were also aggregated to seven ecoregions: the Northern Great Plains, Southern Great Plains, Eastern Prairies, Southwest, Desert Southwest, Interior Mountain West, and Pacific Southwest (fig. 1).

## *Forage Quantity*

Forage quantity was estimated by evaluating changes in NPP values generated by the biogeochemical model Biome-BGC (Running and Hunt 1993). Total annual NPP in each year for each 8-km<sup>2</sup> pixel was used to calculate percentage change from the 10-year average baseline NPP (2001–2010). We interpreted larger reductions from the baseline to imply greater vulnerability and, similarly, greater increases from the baseline to imply greater resilience or potential benefit. Net primary productivity estimates for U.S. rangelands were taken from Reeves et al. (2014) and briefly described below. This dataset provides estimates of daily NPP (kg C ha<sup>-1</sup> yr<sup>-1</sup>) from 2001 to 2100.

Biome-BGC requires daily estimates of input variables as well as soil and existing vegetation by plant functional group. The delta method (Mote and Salathé 2009) was used to temporally downscale the monthly GCM data. Daily estimates of vapor pressure deficit (VPD), solar radiation, and day length were created by using the MT-CLIM algorithms (Kimball et al. 1997).

Daily estimates of CO<sub>2</sub> concentration and nitrogen deposition were also needed and extrapolated from decadal estimates of CO<sub>2</sub> and nitrogen oxides (NO<sub>x</sub>) given by the IPCC emissions scenarios. The soils data were derived from the State Soil Geographic database (STATSGO; U.S. Department of Agriculture 1994). Plant functional groups (C3, C4, and shrub) were held constant for the projection period based on existing vegetation types circa 2001 from the LANDFIRE project (Comer and Schultz 2007; Rollins 2009). Note that Biome-BGC does not model the Crassulacean acid metabolism (CAM) functional group, so CAM-dominated regions were not modeled (Reeves et al. 2014).

## *Vegetation Type Trajectory*

Forage quantity based on NPP does not fully describe forage availability as not all plant materials are considered suitable cattle forage. We used a simple metric related to available forage to indicate if vegetation was projected to become grassier or woodier compared to present day. Cattle preferentially utilize forbs and grasses over shrubs or other woody plants. Thus, trajectories toward greater herbaceous dominance would be beneficial to cattle, and those toward more woody vegetation would indicate greater vulnerability for cattle production. Future potential vegetation was simulated by using output from the dynamic global vegetation model MC2, the latest version of MC1 (Bachelet et al. 2001; Peterman et al. 2014). This model combines a modified version of CENTURY (Parton et al. 1993) to simulate carbon, nitrogen, and hydrologic cycles, with biogeography rules derived from Neilson (1995). This is a physiological model that simulates potential vegetation as life forms (e.g., evergreen or deciduous tree, C3 or C4 grass) based on biogeography and leaf area index. These life forms can be further interpreted as forest, woodland, savanna, or grassland. Vegetation should be seen as a potential, because many other factors such as site history and species composition affect observed vegetation types. Fire disturbance and mortality are integrated into the model (Bachelet et al. 2001).

Each 8-km<sup>2</sup> pixel was assigned to a potential life form each year, and we calculated the proportion of years for each preceding decade in preferred vegetation types. Preferred types for cattle grazing were assumed to be C3 or C4 grasses, but not shrub or tree plant forms. The proportion in preferred vegetation types for the preceding 10 years was subtracted from the proportion of preferred types during the baseline decade (2001–2010), which was also modeled, to approximate the trajectory of potential vegetation toward or away from a preferred forage type. A prediction of new vegetation type for a pixel, particularly within a single decade, does not mean we expect new types to actually be established on a site, but rather indicates a shift from

ideal environmental conditions associated with those types. We did not attempt to correct baseline vegetation potential created by MC2 with known distributions of vegetation types, because we were focused on the general trajectory of driving forces associated with particular vegetation types rather than quantifying changes in the distribution of vegetation types. Taken together, forage quantity and vegetation type trajectory approximate forage availability.

### *Heat Stress*

Projected daily values for average daily temperature ( $T_{\text{air}}$  in degrees Celsius) and relative humidity (RH) were used to calculate THI as:

$$\text{THI} = 0.8 \times T_{\text{air}} + \text{RH} \times (T_{\text{air}} - 14.4) + 46.4$$

following Hahn et al. (1995) and Brown-Brandl et al. (2006). Note that the daily climatological data included only VPD and minimum and maximum temperature ( $T_{\text{min}}$ ,  $T_{\text{max}}$ ). Average daily air temperature was computed as:

$$T_{\text{air}} = (T_{\text{min}} + T_{\text{max}}) / 2$$

Relative humidity was computed from VPD by using:

$$\text{RH} = \frac{e_a(T_{\text{air}}) - \text{VPD}}{e_s(T_{\text{air}})}$$

where  $e_a$  is ambient vapor pressure and  $e_s$  is saturation vapor pressure given by Tetens's formula:

$$e_s(T) = a \exp\left(\frac{bT}{T + c}\right)$$

where  $T$  is temperature (degrees Celsius) and  $a$ ,  $b$ , and  $c$  are constants that were assigned values consistent with environmental biophysics applications ( $a = 0.611$  kPa,  $b = 17.502$ ,  $c = 240.97$  °C) (Campbell and Norman 1998).

Our index of heat stress vulnerability for cattle production (HSI) was calculated from the total number of days per year where THI exceeds a stress threshold of 74. When THI is greater than 74, a heat stress alert for beef cattle is triggered under the Livestock Weather Safety Index (Livestock Conservation Incorporated 1970 as cited in Hahn et al. 2009). The number of consecutive heat-stress days is associated with lower weight gain and greater mortality risk for cattle, but it is not a practical measure for generating an annual value because multiple heat stress periods of varying lengths may occur within a year. Thus, for HSI we used the total number of days in a given year exceeding the THI threshold to estimate annual heat stress then formulated vulnerability as the percentage change from the average of the baseline decade. For example, if the number of days in the year 2035 that THI exceeds 74 at a pixel is estimated at 40 and the baseline period average at the pixel was 20 days, then the difference is a 100-percent increase in THI. Because we wanted to relate values to locally experienced conditions by using percentage change, our HSI can attain high values in regions that currently have few days above the THI threshold.

### *Forage Variability*

Dependability of forage supply was attributed to variability in forage quantity and measured as the decadal interannual variation in NPP as previously described under "Forage Quantity." Interannual variability was measured by change in the decadal moving average of standard deviation (SD) of annual NPP from the 10-year baseline average SD. For example, the first moving average value represents the years 2000 through 2010, and the second represents 2001

through 2011. The trend of the moving average was determined by using a simple linear trend as there were significant nonlinear features observed in the NPP variation response. We examined vulnerability relative to current conditions rather than categorizing high and low levels of variability. By measuring vulnerability as departure from the baseline, we assumed that some level of flexibility in operations already exists based on recent local experience. A greater departure from current levels of variability suggests more difficulty in sustaining cattle operations over periods longer than 10 years (Ash et al. 2012; McKeon et al. 2009).

### Overall Vulnerability

We categorized vulnerability for each of the four elements by the proportion of departure from the baseline (table 3). These four measures of vulnerability were then summed to create an index of overall vulnerability for each pixel in each projected year (table 3). Thus, all elements were considered to be independent and equally important to vulnerability of cattle production. By setting all thresholds equal, a 20-percent change in forage quality has the same relative impact to vulnerability as a 20-percent change in forage variability even if they may not translate to the same change in numbers of cattle that can be produced. In the absence of a more comprehensive quantitative model, this approach makes the results easy to interpret, flexible to adjustment, and transparent. Each of the four elements can have a vulnerability score of  $-2$  to  $+2$ , so the range of potential values in the overall vulnerability index is  $-8$  to  $+8$ . An example calculation is shown in table 4.

**Table 3**—Classification of vulnerability scores.

Relative change in vulnerability element <sup>a</sup> (%)	Vulnerability score (unitless)
value < $-20$	$-2$
$-20 \leq$ value < $-10$	$-1$
$-10 \leq$ value $\leq 10$	0
$10 <$ value $\leq 20$	1
value > $20$	2

<sup>a</sup> Change is relative to baseline conditions (2001–2010).

**Table 4**—Hypothetical example of how the vulnerability index score is calculated for each pixel, each year, in each scenario.

Vulnerability elements	Example 1 <sup>a</sup>		Example 2 <sup>b</sup>	
	Hypothetical % change by 2060	Vulnerability Score <sup>c</sup>	Hypothetical % change by 2060	Vulnerability Score <sup>c</sup>
Forage quantity	$-19$	$-1$	$+6$	0
Veg. type trajectory	$+15$	1	$-20$	$-1$
Heat stress	$+72$	$-2$	$+12$	0
Forage variability	$-11$	1	$+30$	$-2$
<b>Overall</b>		<b><math>-1</math></b>		<b><math>-3</math></b>

<sup>a</sup> Example 1 shows opposing element effects.

<sup>b</sup> Example 2 has more consistent change among elements.

<sup>c</sup> Negative vulnerability scores indicate worsening conditions. Positive scores indicate improvement in reference to cattle production under baseline conditions (2001–2010).

## *Standard Deviation*

We calculated the standard deviation of the scores that make up overall vulnerability for each pixel. This value measured the range of scores and indicated the relative amount of agreement among the four estimates of vulnerability. Less deviation would indicate general agreement among the elements as to the relative vulnerability of a pixel or region. Larger deviations indicate disagreement. We also calculated the average deviation for each ecoregion.

## **Vulnerability Model Results**

### *Forage Quantity*

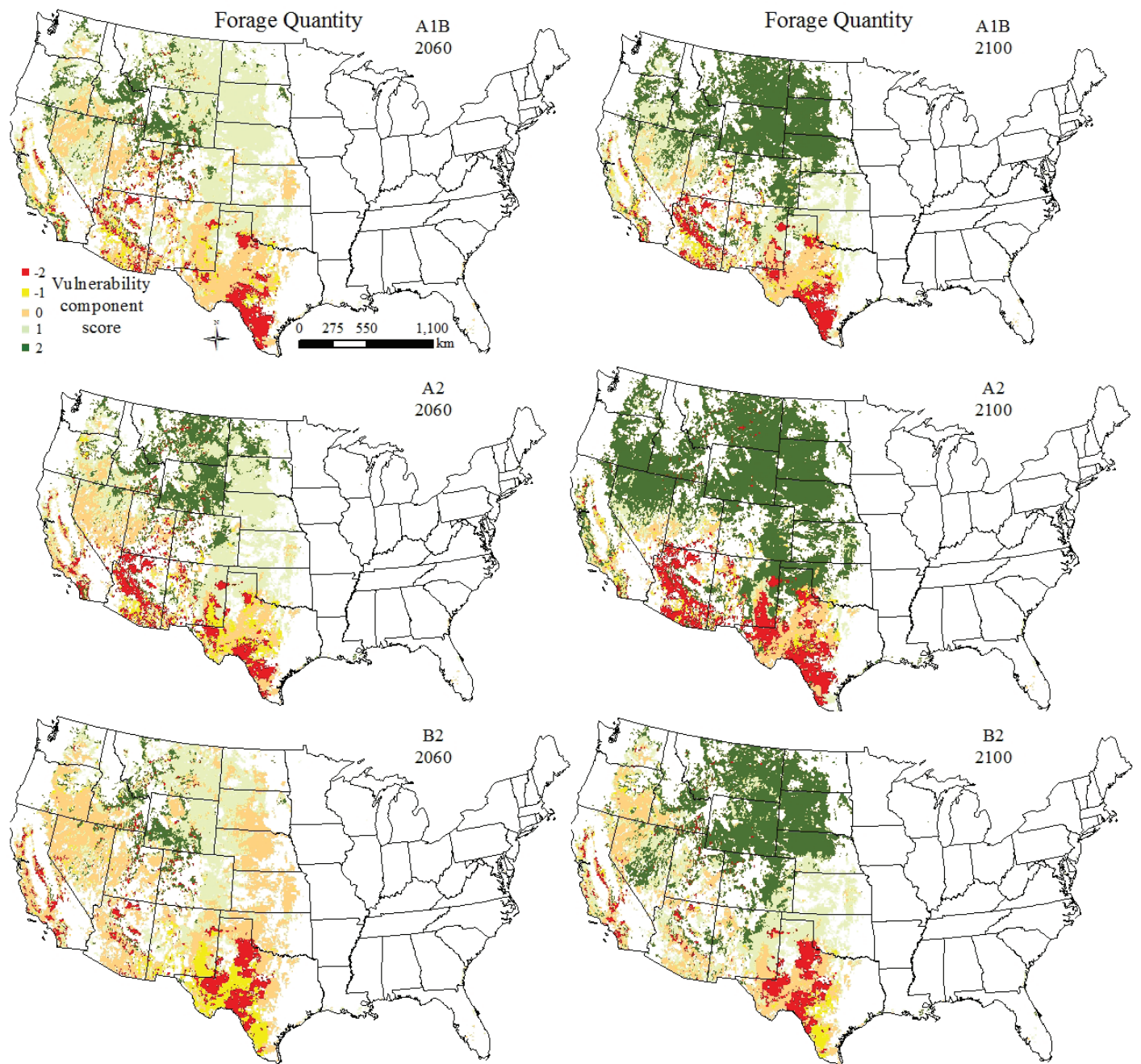
Across models, there emerges a general pattern of greater total annual NPP in the north and decreased NPP in the south. Differences in projected NPP among models are mainly in timing of change; the geographic pattern is similar (fig. 6). The greatest increase in NPP over time is projected for the Interior Mountain West and Northern Great Plains, and more moderate increasing trends are predicted for the Eastern Prairies and Southern Great Plains (fig. 7). Declines are limited mostly to the southwestern States, including Desert Southwest and Southwest ecoregions (figs. 6 and 7). Declines in NPP also extend northward into the Sierra Nevada foothills of California and into parts of Utah (fig. 6). Production in the Great Basin either increases or remains unchanged, depending on scenario (fig. 6).

### *Vegetation Type Trajectory*

All three emissions scenarios (A1B, A2, B1) represented in the MC2 output are similar in the projected pattern of grassier and woodier regions (fig. 8). Change appears in bands along the eastern edge of the Great Plains and, at a smaller spatial extent, along mountain ranges (fig. 8). A smaller parallel band toward the interior of the Great Plains shows woodier vegetation types (fig. 8). These bands represent potentially large-scale change for regions currently dominated by mixed-grass prairie. Woody trajectories are common throughout the interior, interspersed with opposing grassier trajectories. Together the results predict considerable spatial heterogeneity at these scales. Arid regions tend to be more stable with respect to projected vegetation type (fig. 8). Rapid changes in vegetation potential are most likely driven by fires, which were not suppressed in our model runs (fig. 7). In another outcome consistent with fire effects, trajectories tend to equilibrate to a steady state with respect to current conditions by the latter half of the century (fig. 7). Although regions include considerable spatial heterogeneity, most are expected to be grassier on average (fig. 7).

### *Heat Stress*

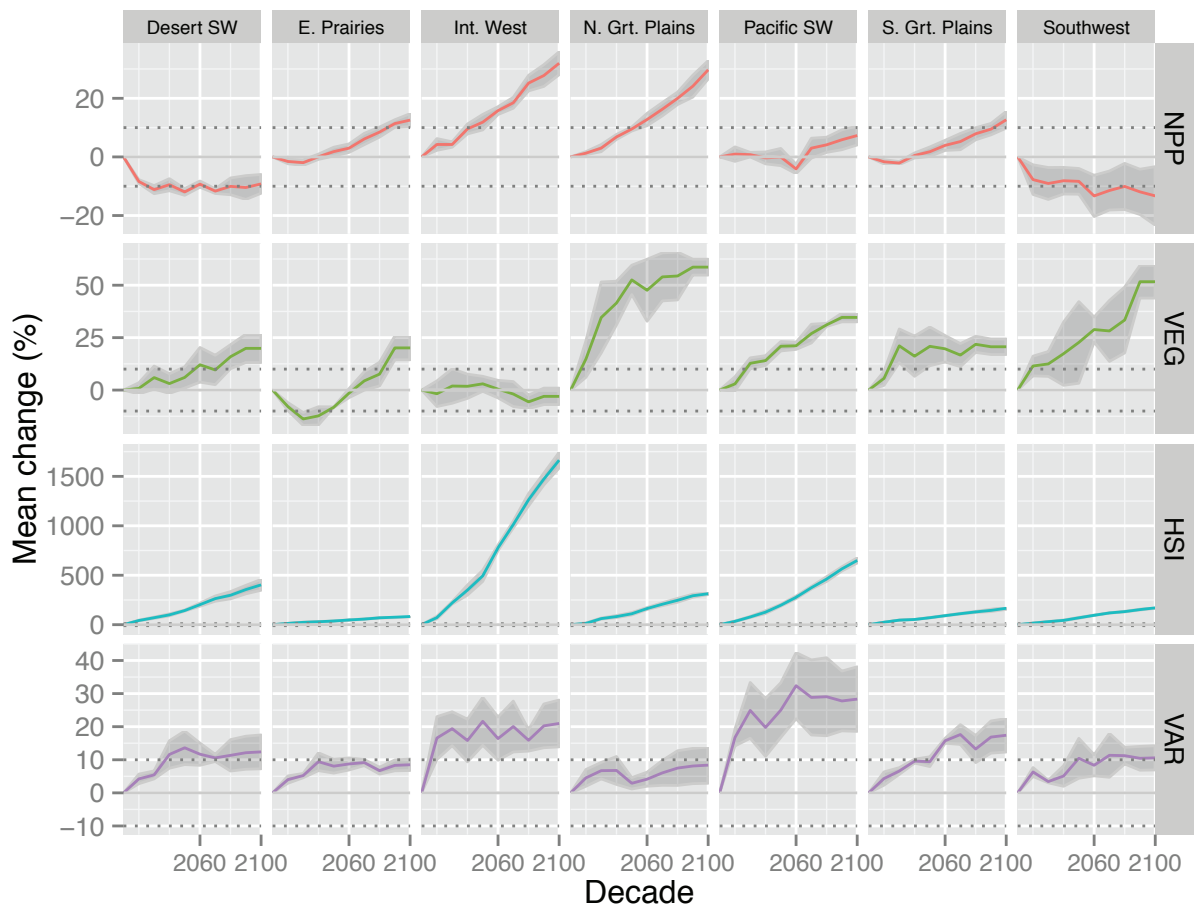
Heat stress increases very sharply in the coming decades across all U.S. rangelands (fig. 7). The increase in days where cattle would be under heat stress progresses northward and westward through time (fig. 9). The Interior Mountain West and the Pacific Southwest experiences the largest proportional increases in heat stress over time relative to current conditions (fig. 7). Warm regions also show longer periods of heat stress, but a smaller increase relative to current climate than those regions that have not typically been subject to excessive heat (fig. 7).



**Figure 6**—Vulnerability index based on percentage change from the baseline (2001–2010) in forage quantity or annual net primary productivity (NPP) for 2060 and 2100 under A1B, A2, and B2 emissions scenarios for U.S. rangelands. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.

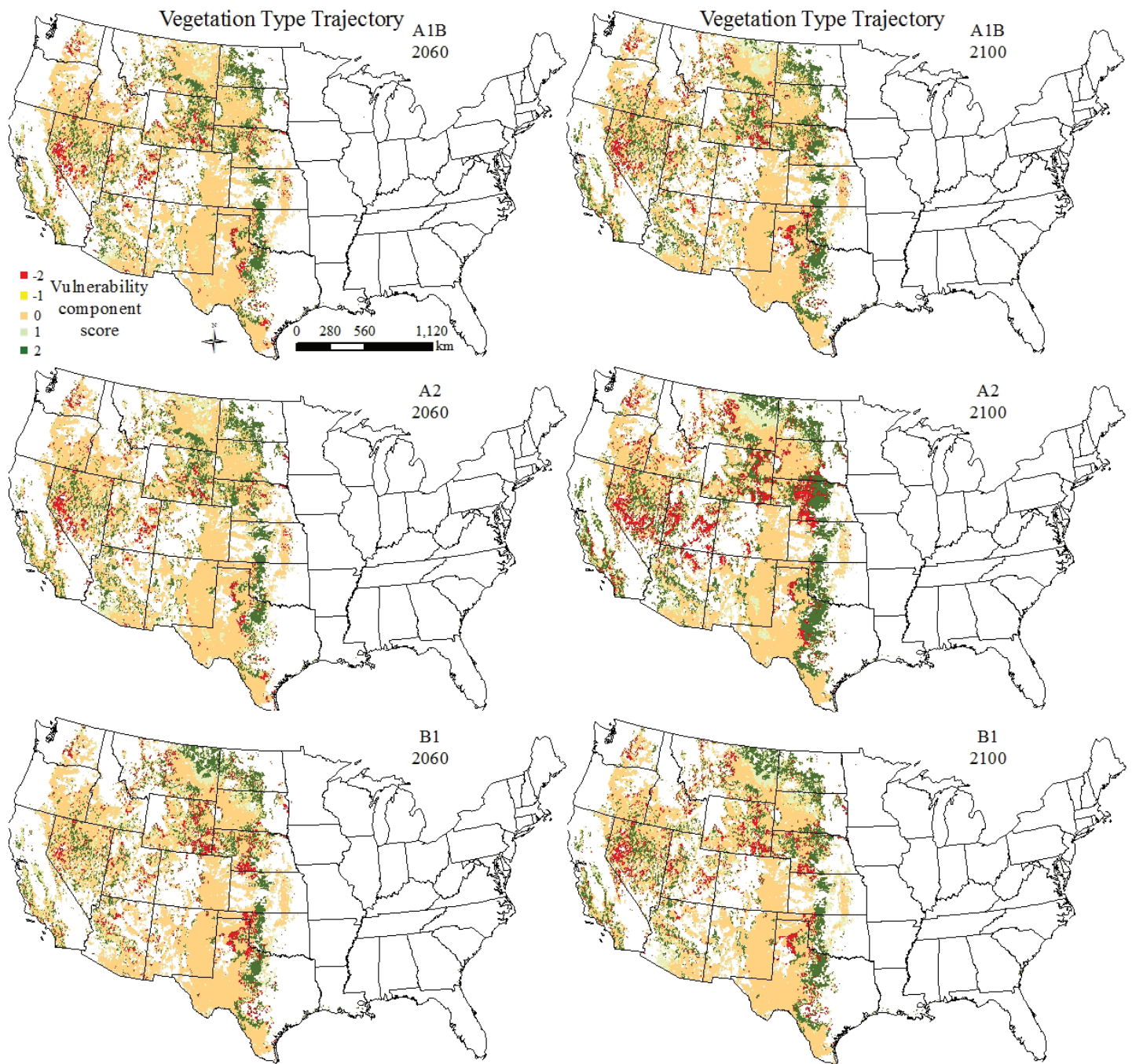
## Forage Variability

Scenarios differ in projections of forage variability (fig. 10). Models A2 and A1B are similar in geographic pattern of change with mostly increasing variability, whereas model B2 projects relatively less change in forage variability along with reductions in the north (fig. 10). Averaged over ecoregions and scenarios, interannual variability in NPP mostly increases over time relative to current variability, indicating a general trend in declining forage dependability throughout U.S. rangelands (fig. 7). Variability increases and thus dependability decreases consistently for the Pacific Southwest and Interior Mountain West, but for the remaining regions change is often <10 percent, the cut-off for the vulnerability index (fig. 7). No region is consistently projected to be more dependable by all three GCMs (fig. 7).

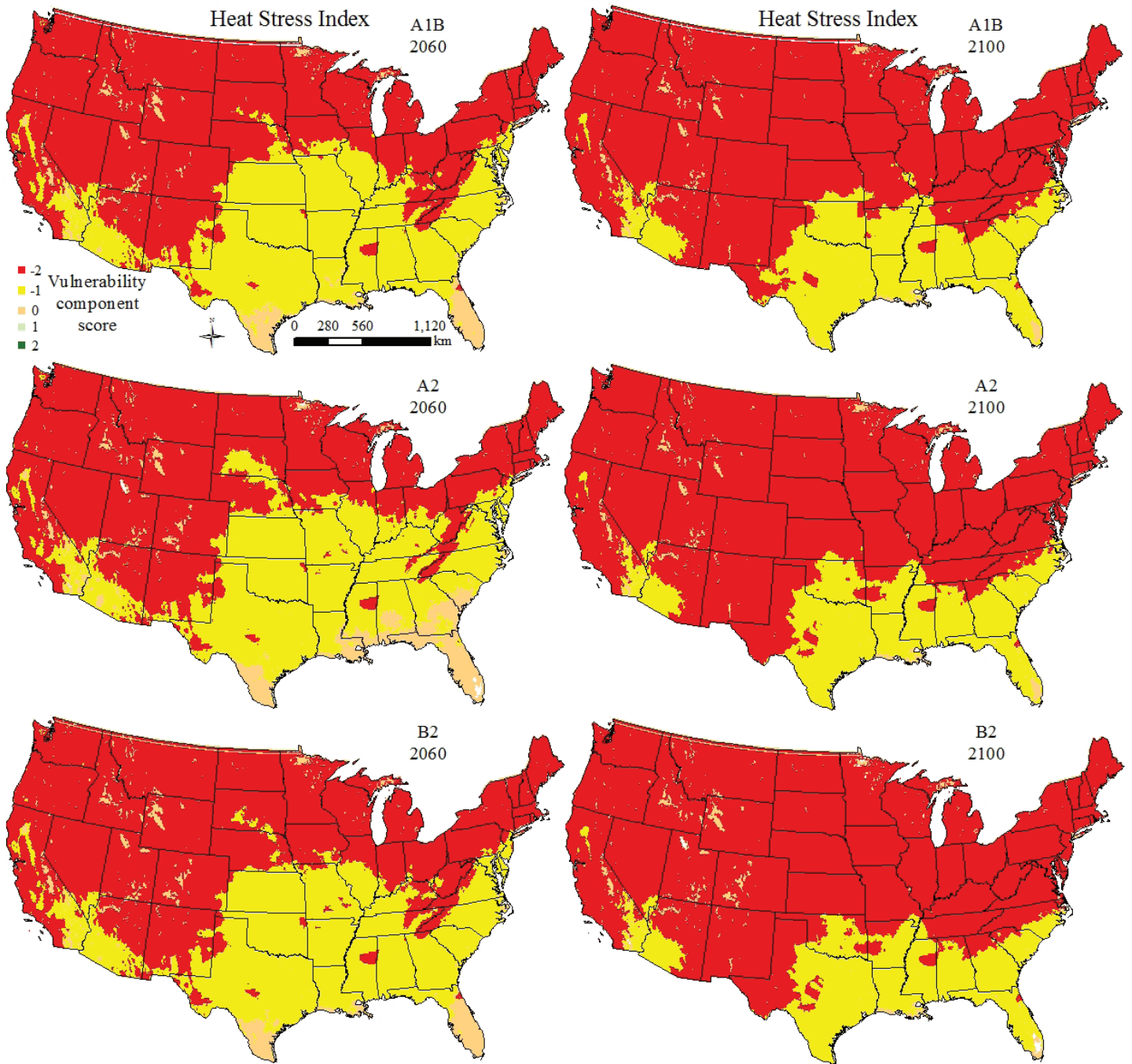


**Figure 7**—Average percentage change over time from the baseline (2001–2010) in U.S. rangeland ecoregions for forage quantity (NPP), vegetation type trajectory (VEG), heat stress (HSI), and forage dependability (interannual variation of VAR). Change is averaged among emissions scenario results, and their standard error is shown in shaded region.

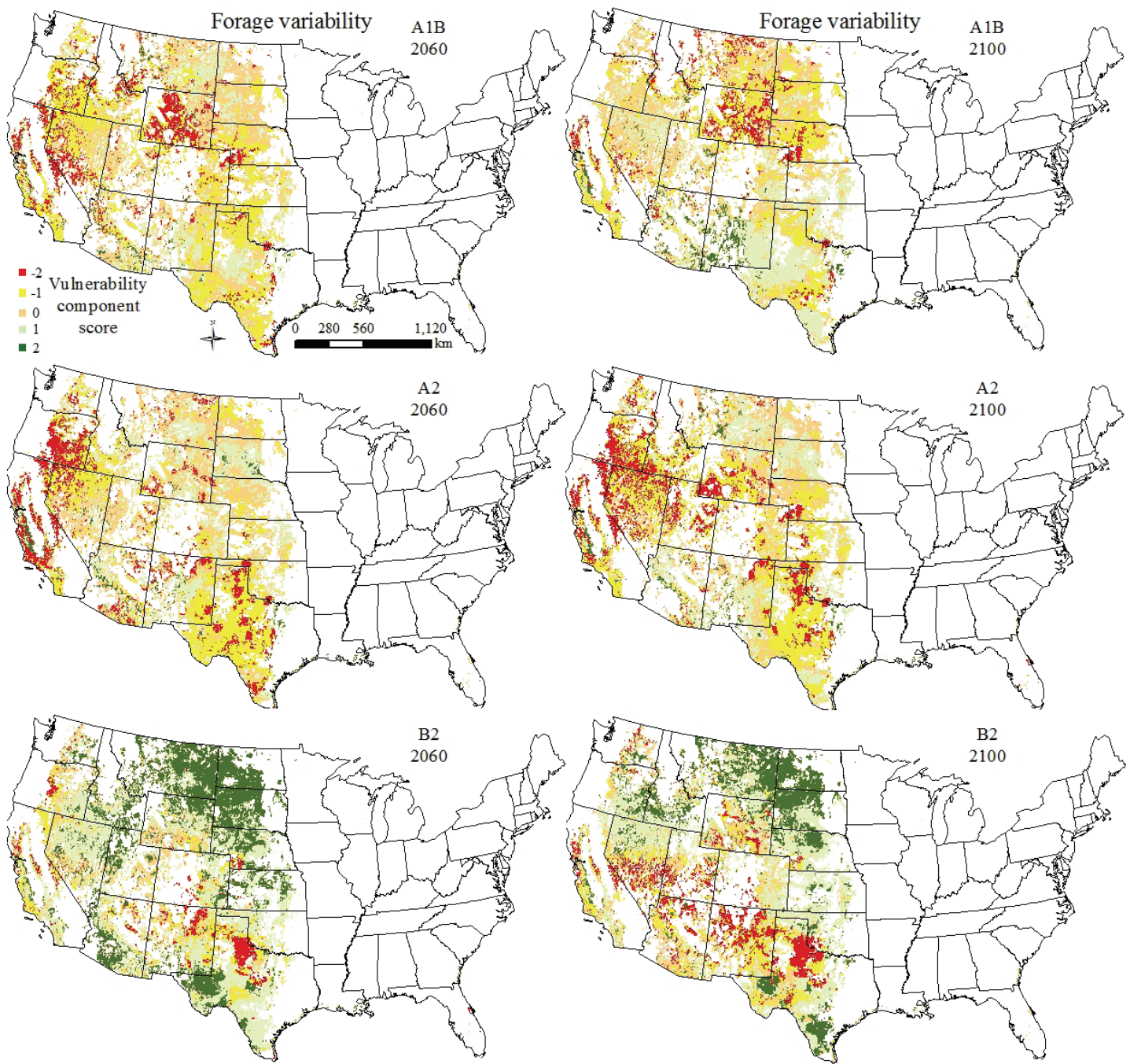




**Figure 8**—Vulnerability index based on percentage change from the baseline (2001–2010) in heat stress index (HSI) for 2060 and 2100 under A1B, A2, and B2 emissions scenarios for U.S. rangelands. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.



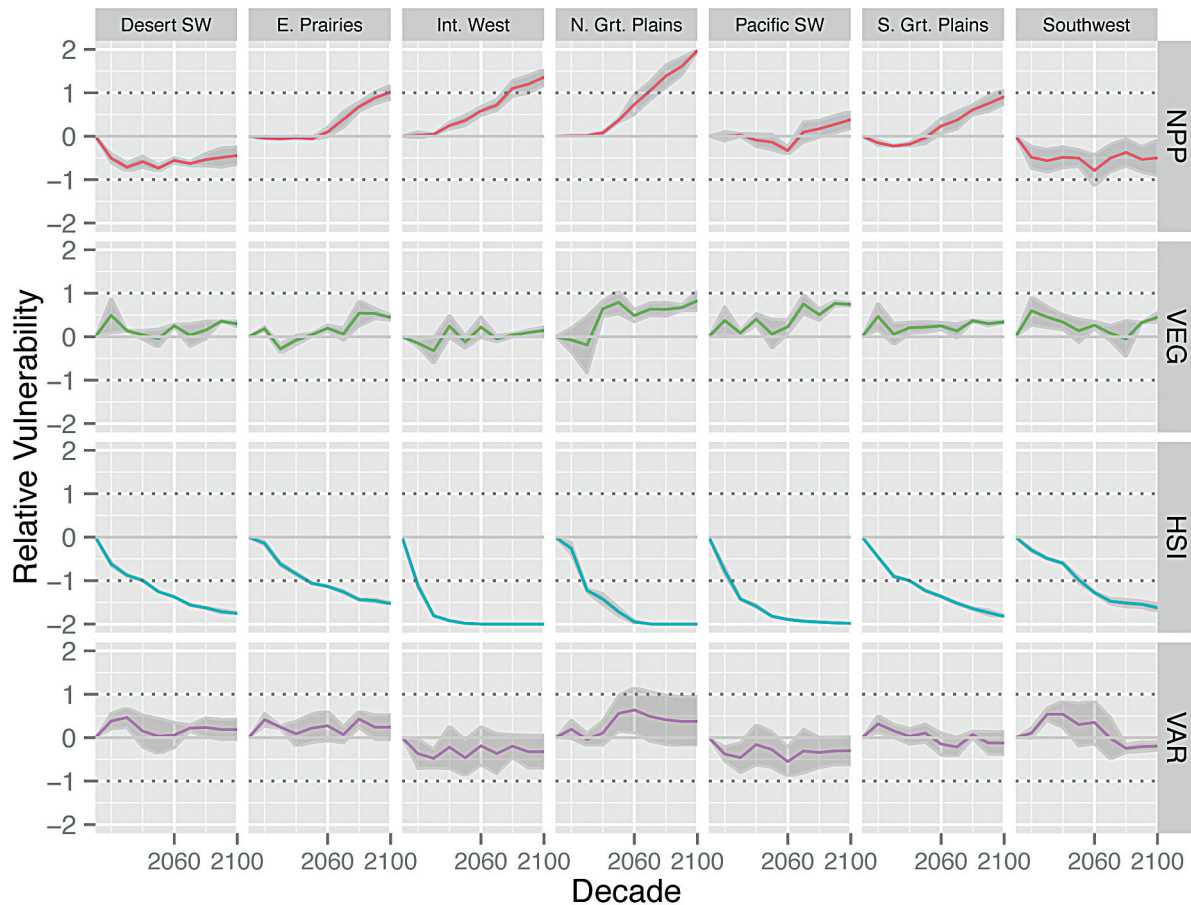
**Figure 9**—Vulnerability index based on percentage change from baseline (2001–2010) in vegetation type trajectory for 2060 and 2100 under A1B, A2, and B1 emissions scenarios for U.S. rangelands. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.



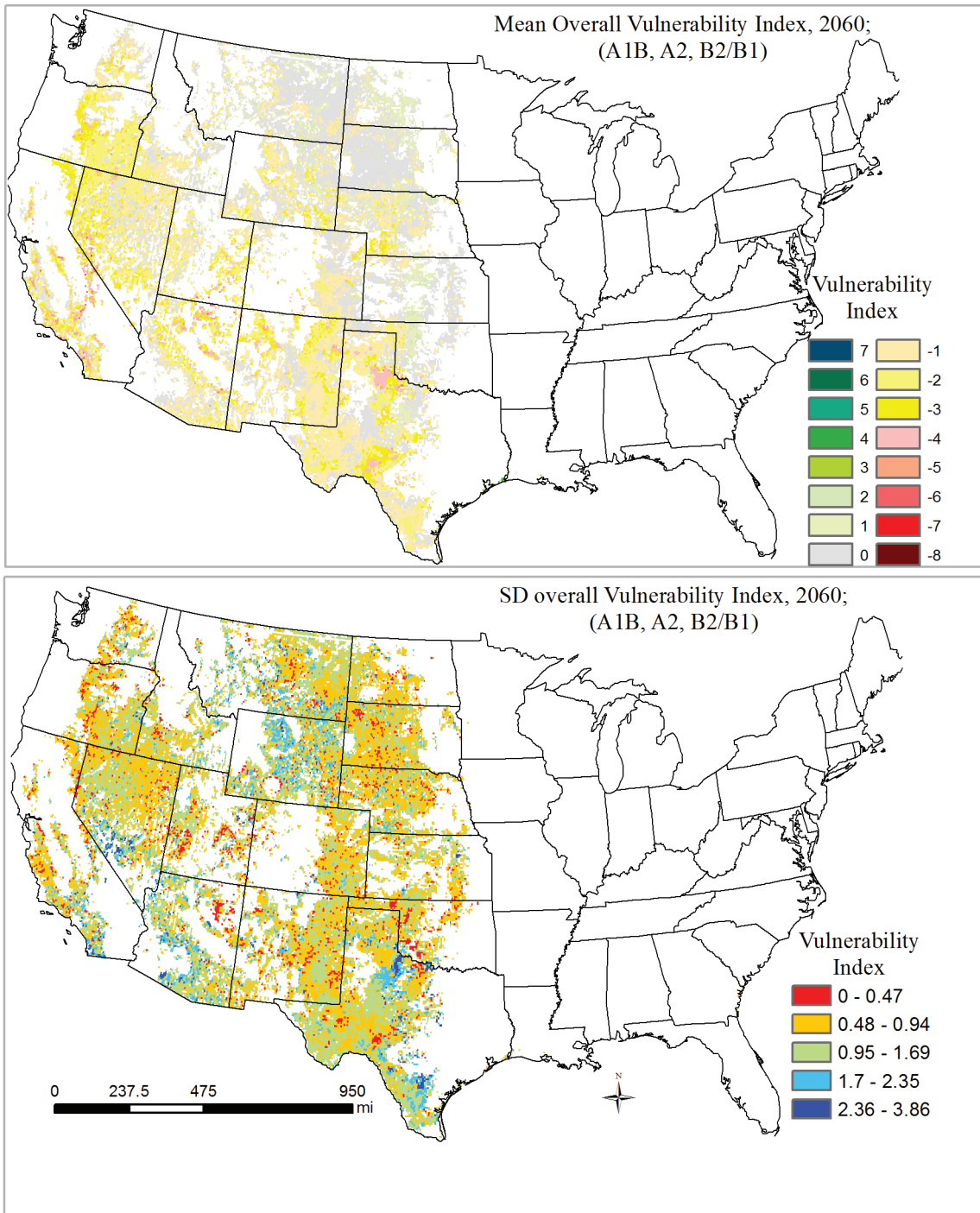
**Figure 10**—Vulnerability index based on percentage change from baseline (2001–2010) in forage quantity or annual net primary productivity (NPP) for 2060 and 2100 under A1B, A2, and B2 emissions scenarios for U.S. rangelands. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.

## Overall Vulnerability

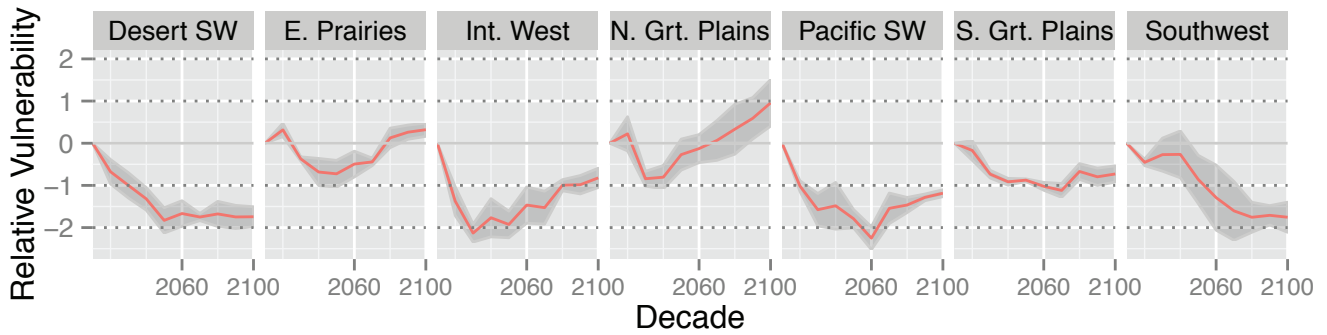
Relative percentage change from the baseline was translated into vulnerability in terms of improving or declining cattle production (table 3, fig. 11). These simple vulnerability index scores for the four elements were then summed for an overall index of vulnerability (figs. 12 and 13). Levels of the index were not directly related to cattle production values, but showed the expected overall direction of change as driven by four key elements related to cattle production. Results indicate greater vulnerability of cattle production for much of the rangeland extent in the United States (figs. 12 and 13). More arid regions have the strongest trends toward greater vulnerability, and most elements agree on the direction of change (fig. 13). Eastern Prairies and the Great Plains were expected to change the least and showed some areas of potential resilience or improving conditions for production by the latter half of the century (figs. 12 and 13). Importantly, this relatively low vulnerability for the prairies and plains was due to opposing trends across elements rather than a consistent set of predictions for minimal climate change effects (fig. 11).



**Figure 11**—Average vulnerability index based on percentage change over time from baseline (2001–2010) in U.S. rangeland ecoregions for forage quantity (NPP), vegetation type trajectory (VEG), heat stress (HSI), and forage dependability (VAR). Change is averaged among emissions scenario results, and their standard error is shown in the shaded region. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.



**Figure 12**—Overall vulnerability index (sum) and standard deviation from vulnerability indices of forage quantity, vegetation type trajectory, heat stress, and forage dependability for 2060 and 2100 under averaged emissions scenarios for U.S. rangelands. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.



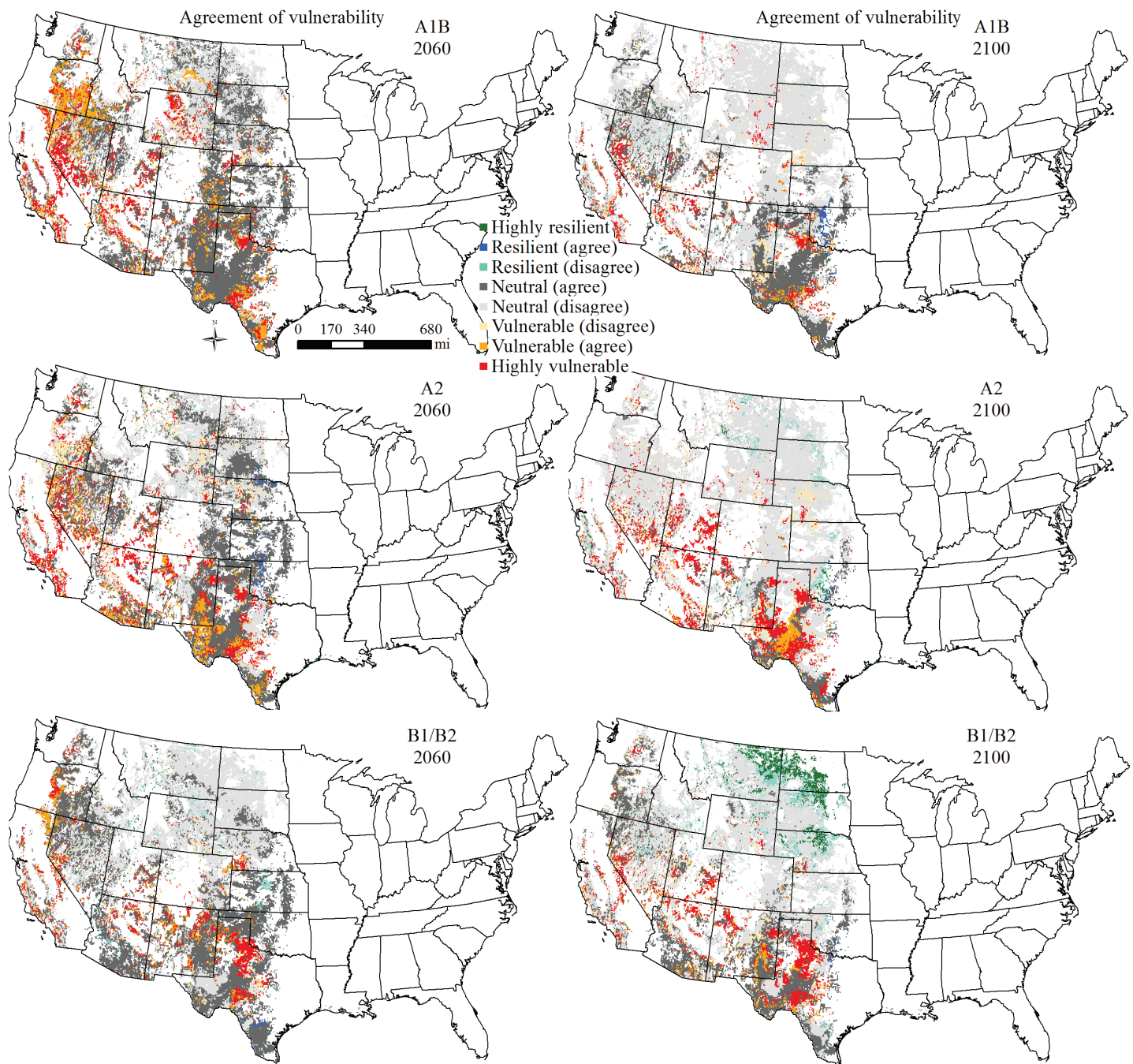
**Figure 13**—Average overall vulnerability index over time for U.S. rangeland ecoregions. Change is averaged among emissions scenario results, and their standard error is shown in the shaded region. Negative numbers indicate lower potential production, and positive numbers indicate higher potential production compared to the baseline.

### *Standard Deviation*

The standard deviation of index scores increased over time for all regions as scores became more opposing rather than converging. Scores among elements differed the most in the north and some parts of the Southwest, particularly Texas (fig. 12). The western extent of rangeland tended to have lower score deviation (fig. 12). The largest possible deviation or set of most-opposing scores results in an SD of 2.3 and the set of the most minor opposing scores has an SD of 0.8.

The standard deviation of scores gives an indication of agreement among elements, which is important in interpreting overall vulnerability. For example, we need score deviation to distinguish low vulnerability scores that result from a large departure from the baseline in opposing directions and those that result from multiple pathways predicting little departure. We classified deviation and overall vulnerability to create a spatially explicit representation of this concept. Overall scores were classified as highly resilient ( $\geq 4$ ), resilient ( $> 2$ ), neutral ( $\leq 2$  and  $\geq -2$ ), vulnerable ( $< -2$ ), or highly vulnerable ( $\leq -4$ ). Scores were considered as agreeing if  $SD < 1.15$  and as disagreeing if  $SD \geq 1.15$ . The value 1.15 is the SD of the score set 2, 2, 0, 0, which we considered to be a threshold between agreement and disagreement, because the set includes equal evidence for high vulnerability and neutrality.

With deviation overlaid on vulnerability, we can identify robust change as well as regions with opposing predictions where the interplay of elements will be critical to predicting future production (fig. 14). There were strong indications across multiple elements and scenarios that vulnerability will increase in the Southwest and Desert Southwest, particularly in California, the Texas panhandle, and northern Arizona (fig. 14). Resilience was indicated in the Northern Great Plains, Kansas, and small areas of coastal California, but there was more variation among emissions scenarios than for the Southwest and Desert Southwest. The Northern and Southern Great Plains showed little change in vulnerability through 2059. But divergence increased among elements, as indicated by loss of agreement from 2060 to 2100, particularly for the A1B and A2 scenarios (fig. 14). This divergence is notable because future cattle production in these regions will depend on the interplay and intensity of different effects of a changing climate.



**Figure 14**—Summary of the direction of predicted change based on overall vulnerability index and agreement among modeled elements for 2060 and 2100 under A1B, A2, and B1/B2 emissions scenarios for U.S. rangelands.

## Discussion and Applications

### Key Findings of Cattle Production Vulnerability

We examined how climate change could affect cattle production vulnerability and generated a relative prediction of how change from multiple factors could influence livestock operations regionally in the United States. We were able to project spatial patterns of cattle vulnerability to 2100 based on four critical ecological elements affecting production: forage availability based on NPP and the trajectory of suitable vegetation types, number of heat-stress days, and forage variability as measured by the interannual variability of NPP. Results should be interpreted as a broad prediction of the expected relative change in potential cattle production due to these four elements. Relative to the current baseline (2001–2010), we found:

- NPP increases in a number of regions, thus potentially benefiting cattle production;
- Vegetation types move toward more grass overall, but vary considerably across the rangeland extent and within regions;
- The number of days when cattle may be heat stressed increases sharply across all regions with the largest departure from the baseline in the Interior Mountain West and Pacific Southwest;
- Regional trends do not indicate a steady progression of impact over time, except for heat stress, but instead show nonlinear fluctuations and the presence of thresholds;
- Expected impacts are consistently negative across multiple elements in southerly and western rangeland regions; and
- Benefits of increases in NPP or grassy vegetation types in more northerly latitudes are mostly tempered by increasing heat stress and variability in forage production.

### Multiple vs. Single Element Vulnerability

Results reveal a different picture of the future for cattle production depending on the element of vulnerability examined and the region of interest.

Results reveal a different picture of the future for cattle production depending on the element of vulnerability examined and the region of interest. The standard deviation among scores tends to be high, particularly in northern regions, indicating that the predicted direction of change is frequently opposing among elements (fig. 14). This uncertainty arises not from inadequacies of the models, but because changes in climate can affect a resource of interest

in a variety of ways, which can be detrimental or beneficial or both. Predictions for arid southern and western regions agree the most (were the least opposing), but portray a relatively bleak outlook for sustaining current levels of cattle production (fig. 14). Parts of these regions, particularly Texas and California, also produce large numbers of cattle (fig. 4). Regions of relatively little change overall, but with high deviation (in other words, neutral, but disagreeing), such as the Northern Great Plains, will need closer examination as future production will depend on the relative importance of separate climate change effects (fig. 14).

Among individual elements, forage quantity and heat stress show the largest and most consistent change over time. Forage variability and the trajectory of vegetation type tend to shift less dramatically from the baseline and attain a new steady state earlier; thus, these elements are important for determining vulnerability in the near future (fig. 13). In the latter half of the century, heat stress drives a ubiquitous negative response to climate change and is opposed by a



trend of steadily increasing NPP in northern rangeland regions, where precipitation is generally not limiting. Despite considerable spatial heterogeneity, increased forage dependability tends to offset lower NPP in arid regions. Increased dependability accompanies a trajectory toward grassier vegetation for the Northern Great Plains and Eastern Prairies, resulting in short-term improvements.

Influence of other elements and interactions are expected, but could not be explored because of a lack of spatially explicit data. Decreases in forage quality, such as reduced protein and digestibility, may override benefits to livestock production from increased forage quantity, particularly late in the season when forage quality is already reduced or during summer when temperatures are high (Hanson et al. 1993; Milchunas et al. 2005). Although elevated CO<sub>2</sub> has a greater impact on growth of plants with C3 metabolism, C4 plants, which are often less nutritious, have lower water needs and greater tolerance for high temperatures (Epstein et al. 2002). Thus, in very arid regions there may be further reductions in protein content of forage related to conditions that favor C4 plants. Finally, forage availability will be affected by range expansion or contraction of plant species that may be unpalatable or toxic to cattle (Bradley et al. 2009).

Dry years with poor forage may force cattle to graze farther from water, but greater travel expenditures will reduce weight gain, especially under high temperatures (Finch and King 1982; Hodder and Low 1978). Increase in livestock congregation as water sources decline not only affects range utilization and environmental degradation, but can also increase disease transmission, either within livestock herds or with wild species (Khasnis and Nettleman 2005). Disease vectors and hosts will also differ in their responses to climate change effects on vegetation, standing water, and high temperatures, further complicating evaluation of disease risk (Stem et al. 1989). In addition, water content of forage is important in water balance and affects the need for livestock to drink (DelCurto et al. 2005; Harris et al. 2002).

## Uncertainty

Modeling the future will always be uncertain. Uncertainty stems from multiple processes during vulnerability assessment: from modeling and downscaling climate to integrating multiple and interacting sources of impacts (Izaurre et al. 2011; Kerr 2011). In most cases, the direction of change for an element is well supported by all GCMs, but the timeline of change is uncertain as it depends on numerous factors affecting atmospheric greenhouse gas levels. Although differences among GCM projections are not great, they tend to be larger in arid regions and for estimates of forage variability.

Methods and thus uncertainty differed among the models used to estimate each element. Biome-BGC does not factor in disturbance or changes to species assemblages when projecting NPP (Reeves et al. 2014). Model determination of vegetation types was based on biophysical drivers and only represented potential vegetation. The dynamic global vegetation model MC2 is sensitive to soil depth and is thereby limited by the quality of soil data (Peterman et al. 2014). We chose to run MC2 without fire suppression, which affected vegetation trajectories in some locations, although the effect on overall vulnerability was probably small. Under a modeled state of fire suppression, vegetation trajectories would be more toward woody species overall. Considerable heterogeneity at the regional level, particularly for vegetation type, led to a loss of information during aggregation to ecoregions. Examination at smaller scales may be more informative. For heat stress, the use of a single THI threshold approximates heat load and duration, but does not include the accelerating level of impact, culminating in cattle mortality, as THI increases.

Raw values of percentage change were truncated during conversion to the vulnerability index (figs. 7 and 12). Cut-offs for vulnerability or resilience were conservative, requiring a change of 10 percent from the baseline, but it is likely that smaller changes in at least some of the elements may be significant to production. The overall vulnerability index was a simple sum and did not attempt to equalize elements with respect to cattle production because mathematical relationships were not well known for all four elements despite their key role in future outcome. Elements could further interact synergistically or antagonistically although such feedbacks were not explored here. This interplay of climate change effects will be important, particularly in those areas where multiple effects were opposing (light colors in fig. 14).

## Implications

This assessment of the future of U.S. cattle production on rangelands sets the stage for initiating more-detailed studies and designing adaptation solutions for sustainable goods and services applicable at regional scales. Rangelands, in particular, are conducive to adaptation measures because of the close connection with goods and services, history of cooperation between rangeland scientists and managers, and the diversity of available solutions (Joyce et al. 2013). We chose cattle production because of its economic importance, but recognize that rangelands provide a great variety of goods and services that will not necessarily respond to climate change similarly.

Adaptation, in the context of vulnerability, is an action taken by individuals, groups, or governments as a reactive or proactive response (Adger et al. 2005). Effectiveness of adaptation will depend on goals as applied to chosen spatial and temporal scales, but because outcomes of actions and response to future climate are uncertain, actions should have robust benefits and be flexible to changing conditions (Adger et al. 2005). Many adaptation options are available. The spectrum of predicted change can be viewed as akin to a range of adaptive management choices from resistance or maintenance of the resource in its current condition to supporting the transition of rangeland to a new condition accompanied by a new set of goods and services (table 5) (Millar et al. 2007; Peterson et al. 2011).

Even resilience or potential benefits, such as increasing forage quantity, need to be anticipated and tracked to realize the full potential of any gain. The ability to match stocking rates to forage varies regionally, because the early onset of the growing season in northern areas allows forage quantity to be anticipated earlier than in rangelands in the arid south, where forage quantity is determined late in the summer during monsoonal rains (Torell et al. 2010). Flexibility, although profitable, is limited by added cost and risk associated with restocking after years of low productivity (Torell et al. 2010). Better forecasting would improve rangeland utilization and promote sustainable ranching practices, although livestock producers have traditionally based decisions on only short-term weather forecasts (Coles and Scott 2009; Johec et al. 2001). Managers of rangelands are already experienced with managing resources under harsh and variable conditions, but they may not be prepared for the accelerating and exacerbating impacts of future climate change (Ash et al. 2012). Government programs that offer emergency relief from losses associated with drought or fires will have to adapt to climate change and anticipate greater demand. Programs such as Environmental Quality Incentives Program (EQIP) can provide funding for adaptation measures, and others such as the Conservation Reserve Program (CRP) can provide flexibility in supplemental forage (Wallander et al. 2013).

**Table 5**—Adaptation options for affected U.S. regions as suggested by average predicted climate change effects to 2100.

<b>Element</b>	<b>Regions most likely affected</b>	<b>Adaptation options</b>
Forage quantity (decreasing)	Southwest, Desert Southwest	Supplemental feed, conservative stocking, fire and weed management
Forage quantity (increasing)	Intermountain West, Northern Great Plains	Flexible stocking and rotation, forage harvest
Veg. type = grassier	Eastern Prairies, California	Flexible stocking and rotation
Veg type = woodier	Texas panhandle, eastern Wyoming, western Nevada	Woody plant removal, change livestock species
Heat stress (increasing)	All	Change livestock breeds or species, select for lighter coats, add shade and water, alter rotation schedule
Forage dependability (decreasing)	Intermountain West, Pacific Southwest	Increase flexibility or reduce stocking rates, carryover of yearlings, use forecasting
Forage dependability (increasing)	Northern Great Plains	Increase stocking rates, increase utilization rates

Heat stress is likely to be an increasingly important factor in production across all rangeland regions. Howden and Turnpenny (1998) estimated a doubling of the number of days above a threshold of cattle heat stress for Queensland, Australia. Shade can offer the opportunity to reduce solar radiation and can be provided in many open-range situations (Gaughan et al. 2008). Altering stocking schedules could help to avoid the hottest parts of the year. Resistance to heat stress can also be managed by selection of livestock breeds and species. For example, *Bos indicus* is more resistant to heat stress than *Bos taurus*, and cattle with lighter coats can keep body temperatures lower (Bonsma et al. 1940; Finch et al. 1984). Furthermore, water availability should be considered as part of any adaptation actions related to heat (Howden and Turnpenny 1998; Thornton et al. 2009). In addition to animal performance, the distribution of both water and shade during hot and humid conditions has implications for range utilization and degradation (DelCurto et al. 2005; Finch and King 1982; Hodder and Low 1978).

Prediction of future species composition of rangelands is uncertain, but fire management will play an important role in forage availability. Fire management and success of suppression efforts could potentially influence encroachment of woody vegetation (fig. 15). Weed management and woody species removal are additional adaptation options to counter increasing encroachment by woody or unpalatable species (Ash et al. 2012). Use of livestock species or breeds with broader foraging preference, such as goats, could also be an option to adapt to changing vegetation types.



**Figure 15**—Juniper in a New Mexico grassland. Encroachment of grasslands by woody species such as juniper may increase in some regions and retract in others. Fire and its management provide key interactions that will affect outcome (photo by K. Bagne).

## Next Steps

Climate affects goods and services in complex ways along many pathways. Our examination of four key elements affecting cattle production demonstrates that focus on a single element of change, such as NPP, may not adequately represent the future. The variability in future vulnerability portrayed by the four elements argues for a multiple-element or integrative approach. We need a better understanding of the interaction and combined effects of multiple elements affecting cattle production as well as most other ecosystem goods and services. Information is also needed for additional elements such as disease or pests, which may prove critical in some regions. Despite limitations, our modeled results clearly indicate the need for proactive measures to combat the multiple sources of impact projected for arid rangeland regions of the United States.

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