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Potential Climate Change Impacts on Four Biophysical Indicators of Cattle Production from Western US Rangelands☆

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ABSTRACT

We examined multiple environmental factors related to climate change that affect cattle production on rangelands to identify sources of vulnerability among seven regions of the western United States. Climate change effects were projected to 2100 using published spatially explicit model output for four indicators of vulnerability: forage quantity, vegetation type trajectory, heat stress, and interannual forage variability. Departure of projections from the baseline (2001–2010) was used to estimate vulnerability of present-day cattle operations. The analysis indicated 1) an increase in forage quantity in northern regions; 2) a move from woody dominance toward grassier vegetation types overall but with considerable spatial heterogeneity; 3) a substantial increase in the number of heat-stress days across all regions beginning as early as 2020–2030; and 4) higher interannual variability of forage quantity for most regions. All four factors evaluated in tandem suggest declining production in southern and western regions. In northern and interior regions, the benefits of increased net primary productivity or increasing abundance of herbaceous vegetation are mostly tempered by increases in heat stress and forage variability. Multiple indicators point toward increasing vulnerability of cattle production in southwestern regions providing strong support for the need for adaptation measures and suggest significant change to the industry. Opposing indicators in northern regions point toward the need for cattle operations to increase flexibility to take advantage of periods of favorable production while preparing for uncertainty, variability, and increasing stress from individual factors.

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Introduction

The United States is the world's largest producer of beef, contributing approximately 19% of global production in 2014 (Cook, 2014). In 2013, gross income from the national inventory of approximately 89 million cattle was nearly 102 billion USD. Of the many ecosystem services derived from rangelands, grazing by domestic livestock is one of the most widespread globally (Allred et al., 2014). Most beef cattle production on western US rangelands occurs in the Great Plains states, the Interior-West, and California (Reeves and Mitchell, 2012) with production concentrated in the central region from Texas to North Dakota (Fig. S1, available online at 10.1016/j.rama.2017.02.005). Many cattle are produced in southern and eastern states, but these states generally do not support significant areas of rangelands.

Present trends and conditions indicate that the United States is already undergoing climatic change. Average temperature has increased by 1.3°F — 1.9°F since 1895, and most of this increase has occurred since 1970 (Melillo et al., 2014). Further evidence that climates are changing is demonstrated by atmospheric warming, glacial retreat, variable and hastened plant phenology, altered precipitation patterns, and increasing wildfire activity (Parmesan and Yohe, 2003; Polley et al., 2013). Impacts to ecosystem services such as forage production for wild and domestic ungulates are predicted to vary regionally in concert with differences in projected precipitation and temperature, as well as in vegetation type, soils, fire regimes, and the adaptive capacity of livestock operations (Walthall et al., 2012; Polley et al., 2013). Impacts on livestock operations vary with lower risk observed on larger ranches with shorter grazing periods, multiple income sources, and livestock diversification (Kachergis et al., 2014). Ranchers typically increase preparedness following negative events such as drought but may not adequately address high-severity events or the lasting strain on finances (Coppock, 2011; McClaran et al., 2015).

These recent climatic trends interact with biotic factors including predators, parasites, and invasive species, which will compound to negatively impact the future of cattle operations (Polley et al., 2013), especially in the southwestern United States. Each of these stressors alone

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will affect the sustainability of cattle production within a context of socioeconomic factors that affect production decisions and the ability to adapt. Together they create a set of stressors to future cattle production, especially when expressed against the backdrop of projected climatic change over the next century. In the coming decades, cattle and cattle operations are expected to be exposed to varying environmental factors such as warming temperatures, altered precipitation patterns, more extreme weather, and changing fire regimes, as well as to changing socioeconomic factors such as land use, global market demand, and government subsidy programs (Howden et al., 2008; Thornton, 2010; Izaurralde et al., 2011; Polley et al., 2013).

Despite the economic and cultural importance of cattle production, few studies have examined the possible impacts of changes in climate and associated rangeland ecosystem responses on future US cattle production. This type of research is critical to selecting effective adaptation strategies to sustain production such as flexible herd and grazing management (Joyce et al., 2013; Roche et al., 2015), selection of breeds or species of livestock, pest management, supplemental forage, and geographic relocation of cattle (Joyce et al., 2013; Roche et al., 2015).

To improve our understanding of this complex issue, we examined four biophysical indicators of sustainable beef cattle operations on rangelands. The actual future of cattle production depends on many social, economic, and management factors but is ultimately controlled by the environment. Many other factors, such as lifestyle and international markets, affect cattle production decisions (Torell et al., 2001), but biophysical indicators suggest upper constraints, or the best-case scenario. The factors examined were forage quantity, vegetation type, forage dependability, and heat stress. These factors were chosen because of known links to cattle production, as outlined later, and the availability of spatially explicit future projections over the coterminous United States based on multiple climate models and global change scenarios (Table 1).

Vegetation quantity combined with vegetation type controls overall forage supply and, ultimately, the capacity to produce livestock. Vegetation type is essential to setting stocking rates because it controls the proportion of primary production that is usable by cattle (Holechek, 1988). For example, changing plant species composition affects forage availability because cattle exhibit grazing preferences such as selection of herbaceous over woody species (Petersen et al., 2014). Woody plant species can spread rapidly and greatly reduce cover of herbaceous forage plants preferred by cattle (Engle et al., 1987; Briggs et al., 2002). Expansion of woody species under climate change 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 or where fire frequency is increased (Breshears et al., 2005; Peters et al., 2006; Iverson et al., 2008).

As with changes in vegetation type, changes in net primary production (NPP) are not expected to be uniform across the landscape (Reeves et al., 2014). For example, benefits of increased CO_2 levels may be greatest in semiarid regions where the effect of increased water use efficiency is most pronounced (Izaurralde et al., 2011). Others suggest that NPP will be highest under elevated CO_2 in wet years because of effects on soil respiration and nutrient availability (Parton et al., 2007). Although elevated CO_2 can stimulate plant growth, patterns of rainfall timing, intensity, and interannual variability will also affect plant productivity, resulting in regional differences (Fay et al., 2002; Polley et al., 2015).

In a similar manner, the predictability of forage quantity, or forage dependability, is one of the most critical of the livestock production factors that determine the viability of livestock operations in a region (Eakin and Conley, 2002; Ash et al., 2012). Variation in productivity creates unpredictable conditions and requires increasing flexibility in cattle operations, such as stocking rates, herd size, herd movement, or use of supplemental feed (McKeon et al., 2009; Ash et al., 2012). For example, animal numbers should be reduced during drought because local forage production is insufficient and competition increases among livestock operations for forage alternatives (Eakin and Conley, 2002; Brunson and Tanaka, 2011). Furthermore, increased rainfall variability results in lower than expected NPP because variability affects plant response to elevated CO_2 and availability of nitrogen (Fay et al., 2002, 2003; Milchunas et al., 2005; Izaurralde et al., 2011; Larsen et al., 2011).

The impact of excessive 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. Concurrently, natural surface water sources will be increasingly scarce and operations may need to supplement water supplies. The added heat stress reduces weight gain as rumination decreases 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 cow was reduced by 0.4 kg day^{-1} for each 1°C of body temperature above the thermal neutral zone (Finch, 1986; Crescio et al., 2010). Other heat stress effects include sterility, lowered immune response, and, at extreme levels, mortality (Bonsma et al., 1940; Hahn, 1999). Heat stress in cattle is related to the temperature-humidity index (THI), a simple index correlated to physiological heat response that closely tracks more extensive models of heat transfer (Howden and Turnpenny, 1998). Humidity is 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). A climate change projection for Australian rangelands found safe values of THI for beef cattle were exceeded on 38% of days under doubled CO_2 as compared with 16% of days under current conditions (Howden and Turnpenny, 1998).

The present study seeks to quantify the influence of climate change on biophysical properties and identify implications for cattle production from US rangelands. For the first time, we evaluate the concurrent performance of the four biophysical indicators subjected to three climate change scenarios and create an index to aid quantification of the impacts to cattle operations. To do this, the vulnerability of cattle and cattle operations to climate change was estimated spatially and temporally for the four biophysical indicators as a departure from the baseline of 2001–2010 up to the yr 2100. Importantly, a contemporary baseline period includes a range of variability and occurrence of extreme events that we assumed to be incorporated into local livestock operation design and maintenance. Use of the 2001–2010 period creates a conservative assessment of vulnerability because it includes significant climatic change when compared with the 20th century. The projected departure of each indicator (forage quantity, vegetation type, forage dependability, and heat stress) was first quantified separately for the coterminous US rangeland extent by seven regions. These four factors were then

Table 1
Global Circulation Model (GCM) combinations and emissions scenarios used to estimate future climates developed by Coulson et al. (2010a, 2010b) and Bachelet et al. (2001). Emissions scenarios are from the IPCC Third Assessment (Nakicenovic et al., 2000)

	IPCC scenario (storyline)			
	B1	B2	A2	A1B
General description	Globalization, convergence	Slow change, localized	Regionalism, less trade	Rapid growth, technology
GDP growth	Medium	Low	Low	High
Population growth	Low	Medium	High	Low
GCMs	HadCM2SUL, CGCM1	GCGM2, HadCM3	GCGM2, CSIRO MK2, MIROC3.2	GCGM2, CSIRO MK2, MIROC3.2

combined into a vulnerability index to examine their agreement with regard to departure from baseline conditions. This allowed identification of rangeland regions where outcome is more uncertain and where negative impacts from multiple factors threaten sustainable cattle operations.

Methods

The potential effects of climate change on potential cattle production were evaluated across four emission scenarios from the Intergovernmental Panel on Climate Change (IPCC; Nakicenovic et al., 2000) and the average and variability of four General Circulation Models (GCMs) (Table 1). These scenarios and GCMs were chosen on the basis of data availability, which was constrained by the NPP data produced by Reeves et al. (2014). Data corresponding to these scenarios came from Coulson et al. (2010a, 2010b) and Bachelet et al. (2001). For each of the four vulnerability indicators (Table 2), the magnitude and direction of change were quantified under the emissions scenarios to the yr 2100 (see Table 1). In addition, all the GCMs for a given scenario were averaged such that the data represent primarily differences among scenarios instead of among GCMs. Results are reported at the scenario level to represent the potential range of vulnerability of cattle operations to climate change.

All indicators were available at a spatial resolution of 8 km and covered the extent of rangelands in the coterminous United States. The rangeland extent was estimated from Reeves and Mitchell (2011), who developed a 30 m spatially explicit depiction of coterminous US rangelands. To match the spatial resolution of the vulnerability indicators, the rangeland extent was resampled to 8 km (Fig. 1). This was accomplished by identifying all of the 8 km pixels containing >50% coverage by 30 m pixels considered as rangeland in Reeves and Mitchell (2011). Figure 1 illustrates the regions for analysis including Northern Great Plains, Southern Great Plains, Desert Southwest, Southwest, Eastern Prairies, Pacific Southwest, and Interior West. Results for these regions are summarized.

Forage Quantity

Forage quantity was derived from annual net primary production (NPP) estimates from Reeves et al. (2014) (see Table 2). These annual NPP estimates were generated through use of the biogeochemical model Biome-BGC (Running and Hunt, 1993), enabling estimates of annual NPP (kg C ha^{-1} yr^{-1}) from 2001 to 2100. Total annual NPP in each year for each 8 km pixel within the study area was used to calculate percentage change from the 10-yr average baseline NPP (2001–2010). Larger reductions from the baseline were assumed to produce greater vulnerability and, similarly, greater increases from the baseline to imply greater resilience or potential benefit. Not all NPP is available as forage because it describes both aboveground and belowground production and woody production where it occurs. For this study, the projected NPP is compared with the baseline as an indicator of change rather than an absolute value of forage availability. In addition, the amount of NPP potentially available for use by cattle is tempered by projected changes in vegetation type since a trend toward increasing woody dominance is assumed to be less favorable in this assessment.

Vegetation Type Trajectory

Future vegetation types were estimated 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 MAPSS (Neilson, 1995). This is a physiological model that simulates potential vegetation (e.g., evergreen or deciduous tree, C3 or C4 grass). Fire disturbance and mortality are integrated into the model, and we selected the output with no fire suppression (Bachelet et al., 2001).

To convert the MC2 potential vegetation data into suitable information for inclusion in the vulnerability analysis, each 8-km^2 pixel was coded as either preferable (value = 1) or nonpreferable (value = 0) for each year. Preferred types for cattle grazing were herbaceous-dominated classes of either C3 or C4 grasses, but not shrub or tree plant forms. The number of years for each decade in preferred vegetation types was then summed. The proportion of years in each decade occupied by preferred vegetation types was compared with the baseline decade enabling a quantitative approximation of the trajectory of potential vegetation toward or away from a preferred forage type. The available model output from MC2 did not include the B2 scenario, as was used for the other indicators, and the B1 scenario from the MC2 output was used in its place.

Heat Stress

Heat stress in cattle is related to 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). Projected daily values for average temperature (T_{air} in degrees Celsius) and relative humidity (RH) were used to calculate THI as:

$$THI = 0.8 \times T_{air} + RH \times (T_{air} - 14.4) + 46.4 \quad [1]$$

following Hahn (1995)and Brown-Brandl et al. (2006). The climatological data needed for quantifying THI came from Coulson et al. (2010a,

Table 2
Source of data for elements and variables used to calculate climate change vulnerability of US cattle production on rangelands. Output units are for each rangeland pixel (2.5 arc minute or ~8 km)

Element	Variable used	Units	Data source	Citations
Forage quantity	Total annual NPP	kg C ha^{-1} yr^{-1}	Biome-BGC	Reeves et al. (2014)
Vegetation type trajectory	Pixels projected as grass or forb types each year	Percent per decade	MC2	Bachelet et al. (2001)
Heat stress	THI	Days yr^{-1} THI > stress threshold	IPCC 3rd Assessment	Coulson et al. (2010a, 2010b)
Forage dependability	NPP interannual variability	Decadal SD of annual NPP (kg C ha^{-1} yr^{-1})	Biome-BGC	Reeves et al. (2014)

NPP, net primary production; THI, temperature humidity index; SD, standard deviation.
Sources:

Reeves, M., A. Moreno, K. Bagne, and S. Running. 2014. Estimating the effects of climate change on net primary production of US rangelands. *Climatic Change* 126:429–442.
Bachelet, D., J. Lenihan, C. Daly, R. Neilson, D. Ojima, and W. Parton. 2001. MC1: a dynamic vegetation model for estimating the distribution of vegetation and associated ecosystem fluxes of carbon, nutrients, and water. Corvallis, OR, USA: USDA Forest Service Pacific Northwest Research Station, General Technical Report PNW-GTR-508.
Coulson, D., L. Joyce, D. Price, and D. McKenney. 2010a. Climate scenarios for the conterminous United States at the county spatial scale using SRES scenarios B2 and PRISM climatology. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at: https://www.fs.usda.gov/rds/archive/Catalog?freesearch=coulson. Accessed 31 March 2017.
Coulson, D., L. Joyce, D. Price, D. McKenney, R. Siltanen, P. Papadopol and K. Lawrence. 2010b. Climate scenarios for the conterminous United States at the 5 arc minute grid spatial scale using SRES scenarios A1B and A2 and PRISM climatology. Fort Collins, CO, USA: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. Available at: https://www.fs.usda.gov/rds/archive/Catalog?freesearch=coulson. Accessed 31 March 2017.

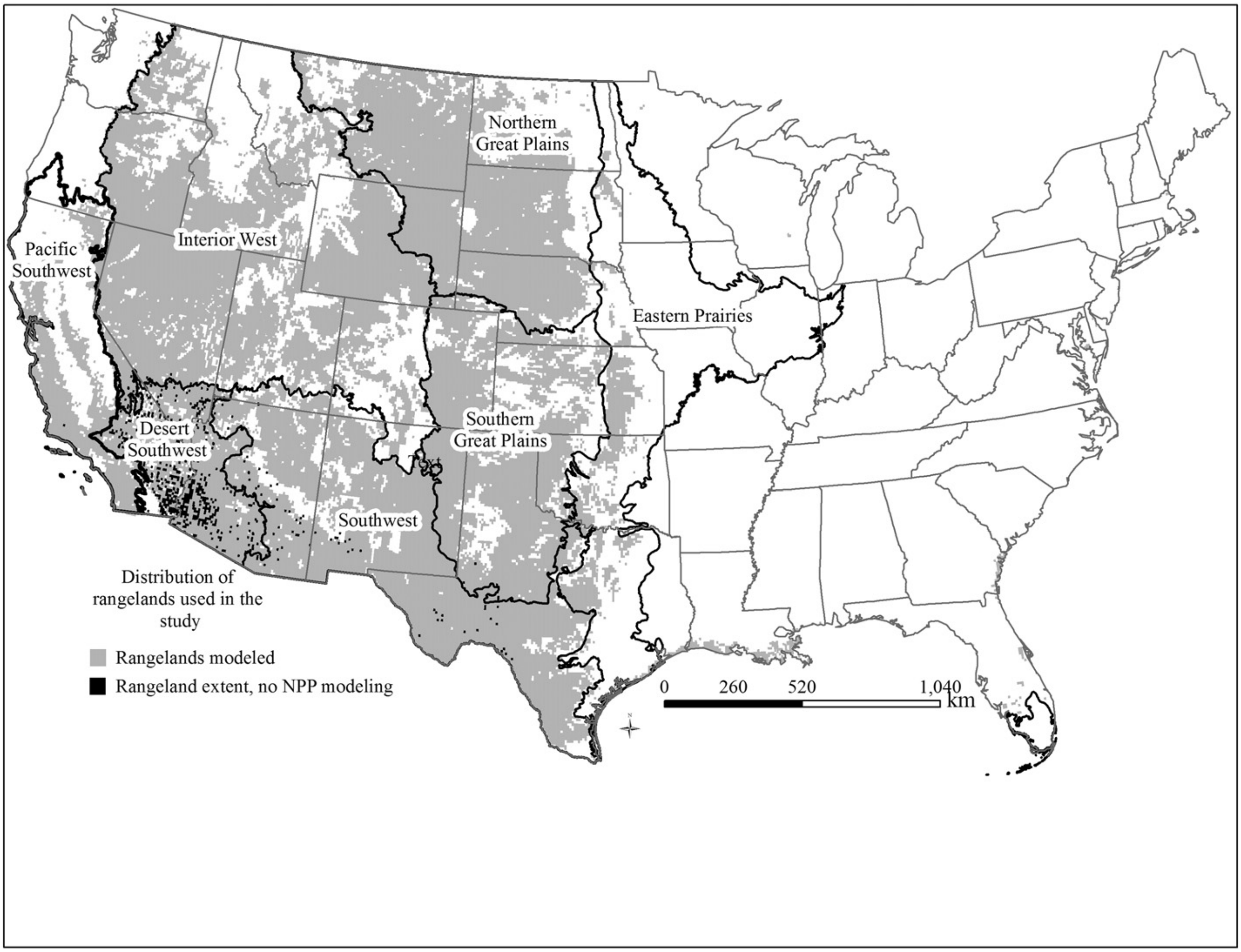

Figure 1. Extent of rangelands resampled from 30 m to 8 km based on Reeves and Mitchell (2011). Study area is divided into seven regions.

2010b) as monthly averages. Because the computation of THI required daily values for temperature and RH, temporal downscaling was needed. Temporal downscaling of monthly averaged maximum and minimum temperatures and precipitation to daily estimates was achieved using the delta method for each GCM and Special Report on Emissions Scenarios (SRES) case (Mote and Salathé, 2010). The delta method compares current climate to projected climate at each grid cell, and a ratio between these two data points is used as a "change factor" that is multiplied by current climate data. This assumes a linear relationship between the two data points and is a widely used method for spatially downscaling in climate change studies. Note that the daily climate data for each GCM and scenario combination only included downscaled daily minimum and maximum temperature (Tmin, Tmax) (Coulson et al., 2010a, 2010b) and vapor pressure deficit (VPD) (Reeves et al., 2014). However, the THI formula requires RH and average temperature. Thus, average daily air temperature was computed as:

$$T_{air} = {}^{(T_{min} + T_{max})}/_{2} \quad [2]$$

Relative humidity was computed from VPD by using:

$$RH = \frac{e_a(T_{air})\text{-VPD}}{e_s(T_{air})} \quad [3]$$

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

$$e_s(T) - a\ exp\left(\frac{bT}{T+c}\right) \quad [4]$$

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). The index of heat stress vulnerability for cattle production (HSI) was calculated from the total number of days per year where THI exceeded a stress threshold of 74. When THI is > 74, a heat stress alert for beef cattle is triggered under the Livestock Weather Safety Index (Hahn et al., 2009). Vulnerability due to heat stress was subsequently formulated as the percentage change from the average of the baseline decade.

Forage Dependability

Dependability of forage supply was attributed to interannual variability in forage quantity and measured as the mean decadal interannual variation in NPP. The NPP available for this computation was derived from Reeves et al. (2014) as stated earlier. Interannual variability was measured by change in the decadal average of standard deviation (SD) of annual NPP from the 10-yr baseline average SD. As with the other three indicators, vulnerability was quantified relative to current conditions. Increasing variability was assumed to be a negative factor and acted to increase the estimated vulnerability for a given area.

Vulnerability Index

An index was used to simultaneously examine vulnerability based on the biophysical indicators. A composite score or "vulnerability index" is helpful in the absence of a deterministic model because it integrates multiple vulnerability indicators into one quantitative metric that can be used to make regional comparisons temporally and spatially. To create a composite index, all indicators that affect the target variable can be set to a consistent unit, such as percentage change or a categorical index score indicating direction of change, to allow multiple indicators to be summed or averaged (Baker et al., 1993; Hurd et al., 1999; O'Brien et al., 2004; Bagne et al., 2011).

The change for each of the four indicators was standardized by the amount of departure from the baseline. Change was scored as 1 if > 10% and 2 if > 20%. Sign of the score designated the direction of change with negative values indicating worse conditions for cattle production. Changes ≤ 10% were given a score of 0. These breakpoints are arbitrary but remain consistent among indicators across space and through time, enabling relative changes in the overall environment for cattle operations to be identified. All indicators were considered to be independent and equally important to vulnerability of cattle production. The vulnerability scores of the indicators were then summed to create an index of overall vulnerability in each projected year. Each of the four indicators can have a vulnerability score of -2 to $+2$, so the range of potential values in the overall vulnerability index is -8 to $+8$. Overall scores were classified as highly resilient (≥ 4), resilient (> 2), neutral (≤ 2 and ≥ -2), vulnerable (< -2), or highly vulnerable (≤ -4).

Scenario Variation and Agreement Among Vulnerability Indicators

Model outcome varied with scenario and by GCM. Outputs from GCMs are shown as an average and SD for each emissions scenario. Where scenarios were averaged, the SD was provided as a combined measure of disagreement between scenarios. To aid interpretation of vulnerability index results, the agreement among the four indicators was quantified as the SD of the four vulnerability index values rather than of the GCMs or scenarios. This metric of agreement forms a powerful context to interpret the vulnerability results because it differentiates between projections that are opposing and those that are consistent in the direction of change predicted for cattle production. For example, an overall vulnerability score of 0 could be a result of all individual factors having an index value of 0, or little change from present day (= small index SD), or a 0 score could result from combining strongly opposing factors, such -2 and 2 (= large index SD). Scores were considered as agreeing if SD < 1.15 and disagreeing if SD ≥ 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.

Results And Discussion

Overall Vulnerability and Agreement Among Indicators

As expected, projected change for cattle production differed over space and time depending on the indicator that was examined, but given the importance of all four factors to production, we can glean some robust patterns for the future. To interpret the combined factors, both index scores (vulnerability based on direction and magnitude of change) and SD of index scores (agreement among factors) were considered. Overall, increased vulnerability of cattle production was observed for much of the United States, but the greatest vulnerability occurred in the Southwest and Desert Southwest, particularly in the Texas panhandle, Nevada, and Arizona (Figs. 2 and 3). This vulnerability in southern and western arid regions is supported by the agreement among indicators (Fig. 4). Northern regions of the Great Plains and Eastern Prairies show some potential for positive effects on production, mostly in the latter part of the century. Much of the central Great Plains and northern Great Basin were categorized as neutral, but it is critical to note that here neutrality is due to opposing trends from individual indicators rather than lack of impact, particularly as warming progresses, as shown by the shift from dark to light gray (see Fig. 4). In these regions where disagreement is higher, the interplay and relative influence of the individual factors will ultimately determine effects on production.

Focus on the warmest scenario (A2) may be warranted as recent global CO_2 trends suggest that this scenario, which shows high vulnerability in the southern regions and opposing factors for much of the north, is more probable than more moderate findings under either the A1B or B2 scenarios (Fuss et al., 2015). Because differences from the baseline needed to surpass 10% to indicate vulnerability, results are likely conservative and designate broad-scale patterns for the cattle industry. Our findings are similar to the simulations by Baker et al. (1993) in which relatively positive effects on cattle production were projected in northern regions (see Fig. 3) while production declined in southwestern regions, putting economic survivability at risk.

Forage Quantity

Forage quantity generally increased above 39° north latitude but tended to decrease below this latitude within the study area. Differences in projected NPP among scenarios were mainly in timing of change, but the geographic pattern and direction of change were similar (Fig. S2, see available online at 10.1016/j.rama.2017.02.005). The greatest increase in NPP over time was projected for the Interior West and Northern Great Plains. These increases ranged from 1.5% to 4% per decade with more moderate increases predicted for the Eastern Prairies and Southern Great Plains (approximately 1–2% per decade) (Fig. 5). In contrast, NPP

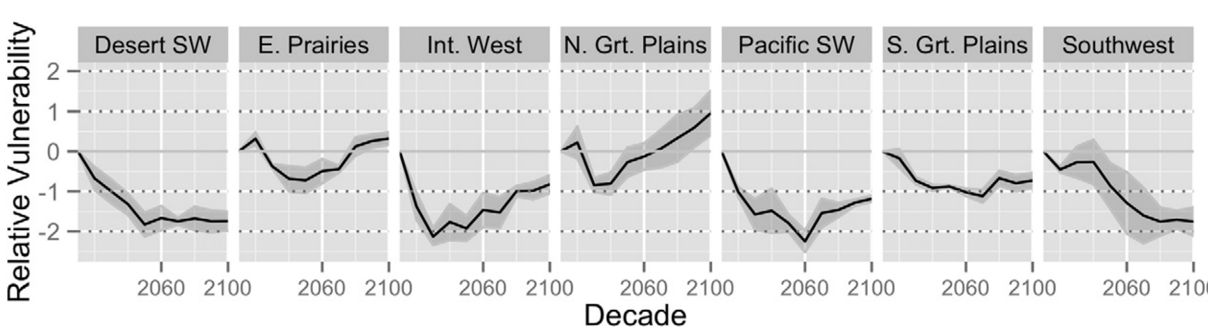

Figure 2. Average overall vulnerability index over time for US rangeland regions. Change is averaged among emission scenarios and their standard error shown in the shaded region. Negative numbers indicate greater vulnerability (potentially lower cattle production), and positive numbers indicate decreased vulnerability (potentially higher cattle production).

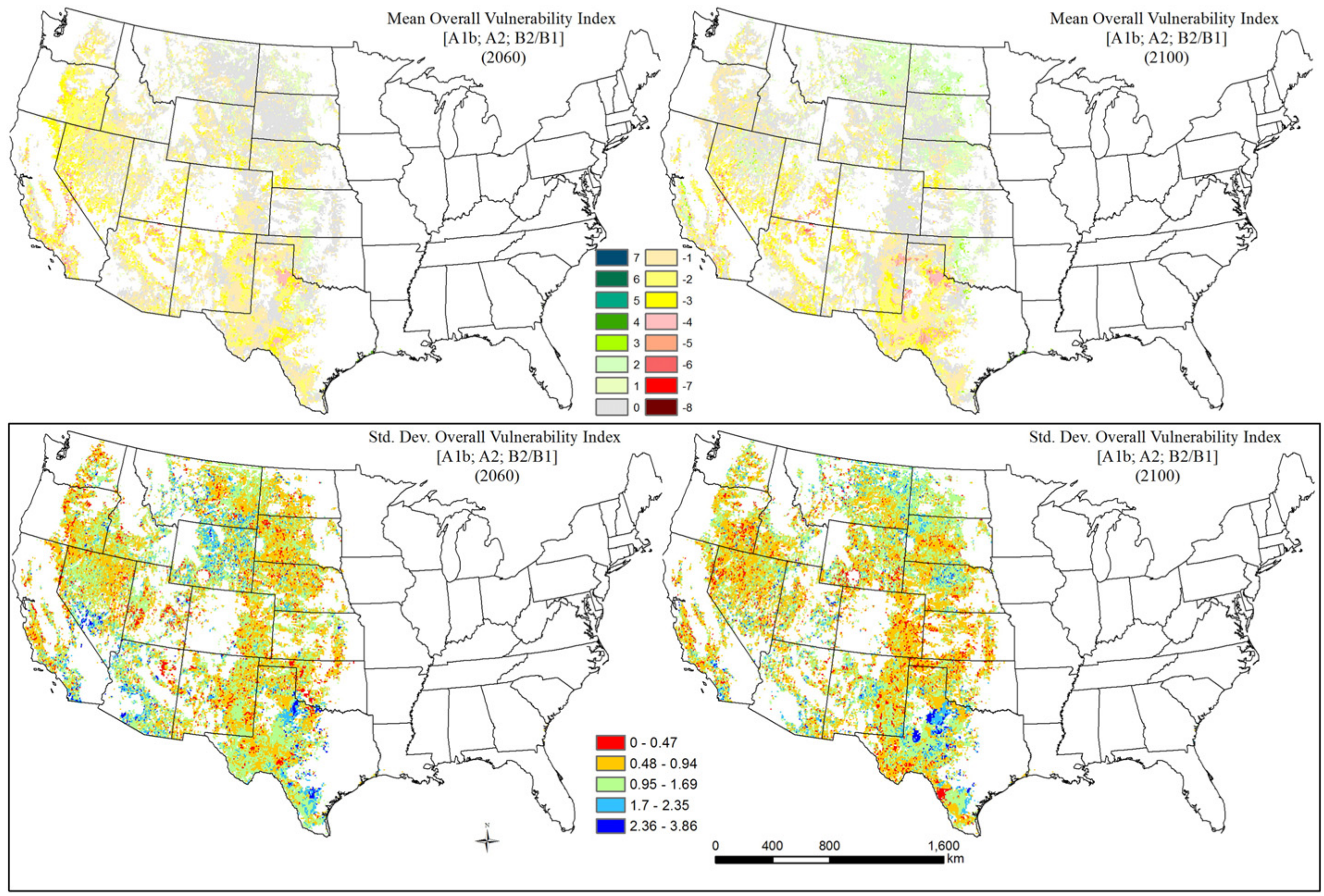

Figure 3. Overall vulnerability index (sum) and standard deviation for 2060 and 2100 under averaged emissions scenarios for US rangelands. Here the index is a sum, but it is the average sum derived from all scenarios. The standard deviation represents disagreement among scenarios. Negative numbers indicate greater vulnerability (potentially lower cattle production), and positive numbers indicate decreased vulnerability (potentially higher cattle production).

declined in the Desert Southwest and Southwest regions (see Fig. S2, Fig. 5) by an average of about 0.5% per decade but also exhibited considerable variability among the emission scenarios. These findings are similar to those identified in Polley et al. (2013) where warmer and wetter conditions on the northern plains were conjectured to enhance NPP while warming and drying were anticipated to reduce NPP in southern regions. Likewise, Morgan et al. (2011) reported an increase of aboveground productivity by an average of 33% over 3 yr on Northern Great Plains in response to similar increases in CO_2 concentrations used in this study. The lengthened growing season that accompanies increased minimum temperatures rather than precipitation has been shown to be the main driver of increased NPP in Northern Great Plains regions (Reeves et al., 2014). Lengthening of the grazing season could benefit livestock operations through reduced need for stored forage and could lead to different grazing rotations.

Vegetation Type Trajectory

Available forage depends on not just quantity but also vegetation type. Change toward decreased woodiness appeared in longitudinal bands along the eastern edge of the Great Plains and, at a smaller spatial extent, along mountain ranges throughout the study area (Fig. S3, see available online at 10.1016/j.rama.2017.02.005). Arid regions tended to be more stable through time (see Fig. S3). Projected changes in vegetation type are likely influenced by increased wildfire activity, which was not suppressed in this version of the MC2 model output (Sheehan et al., 2015) (see Fig. 5). The modeled lack of fire suppression is against the current paradigm of fire management but reflects the reality of larger future fires that tend to defy suppression efforts (Fernandes et al., 2016). Although there was considerable change over time, an overall condition of increased abundance of herbaceous-dominated vegetation was predicted throughout US rangelands, which is positive from the perspective of rangeland forage for cattle, unless the increased herbaceous content manifests as invasive or noxious species, which reduces forage quality and rangeland health. Extent of invasive annual grasses such as cheatgrass *(Bromus tectorum)* is expected to increase across US rangelands in the future but will vary locally (Prevey and Seastedt, 2014; Blumenthal et al., 2016; Boyte et al., 2016; Bradley et al., 2016).

Heat Stress

Heat stress increased sharply during the projection period across all US rangelands (see Fig. 5). The Intermountain West, for example, exhibits the potential for twofold to threefold increases in heat stress. This is similar to results for Queensland, Australia where Howden and Turnpenny (1998) found a doubling of days under heat stress with climate change. The increase in days where cattle would be subjected to heat stress progressed northward and westward through time (Fig. S4, see available online at 10.1016/j.rama.2017.02.005). The Interior West exhibited the greatest proportional increase (~300% by 2100) in the number of heat stress days relative to baseline conditions (see Fig. 5). The large-percentage increases in heat stress days in the Interior West are partly due to the very few days per year in the baseline climate crossing HSI thresholds. Warmer regions also exhibited longer periods of heat stress in the future, but the increase is small relative to baseline conditions (< 20% increase) (see Fig. 5, Fig. S4). Aspects of cattle

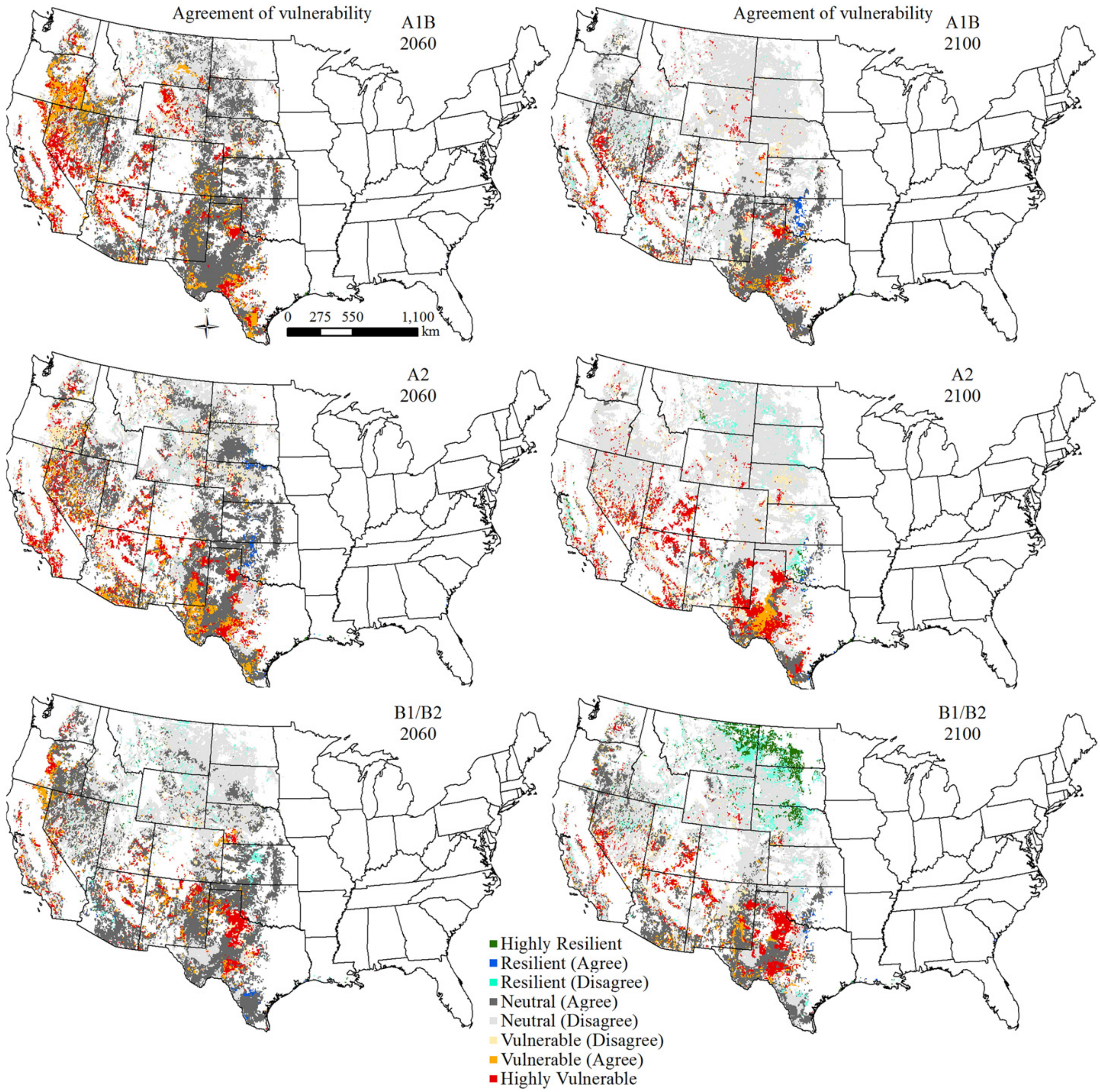

Figure 4. Summary of the direction of predicted change based on overall vulnerability index and agreement among modeled elements for 2060 and 2100 under A1B, A2, and B1/B2 emissions scenarios for US rangelands. Highly resilient (green) indicates that the overall index score was relatively high and agreement among all of the four biophysical indicators is also high. Likewise, highly vulnerable areas received a low index score and the agreement among all four indicators is high (red).

operations that relate to heat sensitivity, such as watering locations, cattle breeds, and grazing season, may be reasonably well adapted to the biophysical and climatic conditions presently experienced. Less predictable is how much more capacity is available to reduce heat stress where current impacts are relatively high or how well new strategies to ameliorate impacts can be incorporated into operations where heat stress has been rare (e.g., the Interior West).

Forage Dependability

Scenarios differed in projections of forage dependability (Fig. S5, see available online at 10.1016/j.rama.2017.02.005), as measured by interannual variability in NPP, primarily due to changes in timing and intensity of precipitation. Models A2 and A1B were similar in geographic pattern of change projecting an overall increase in forage variability on US rangelands. The B2 scenario indicates less variability in forage quantity through time (see Fig. S5) but may not be a reasonable depiction of the future given the trajectory of recent emissions (Fuss et al., 2015). We found a pronounced decrease in forage variability on the Northern Great Plains (see Fig. 5), but greater storm intensity may temper this finding. Although the Biome BGC model accounts for effects of intense rainfall events, the ability of GCM's to depict when and where these storms occur in the future is limited (Jiang et al., 2013). Not only can intense storms increase forage variability, but extreme precipitation

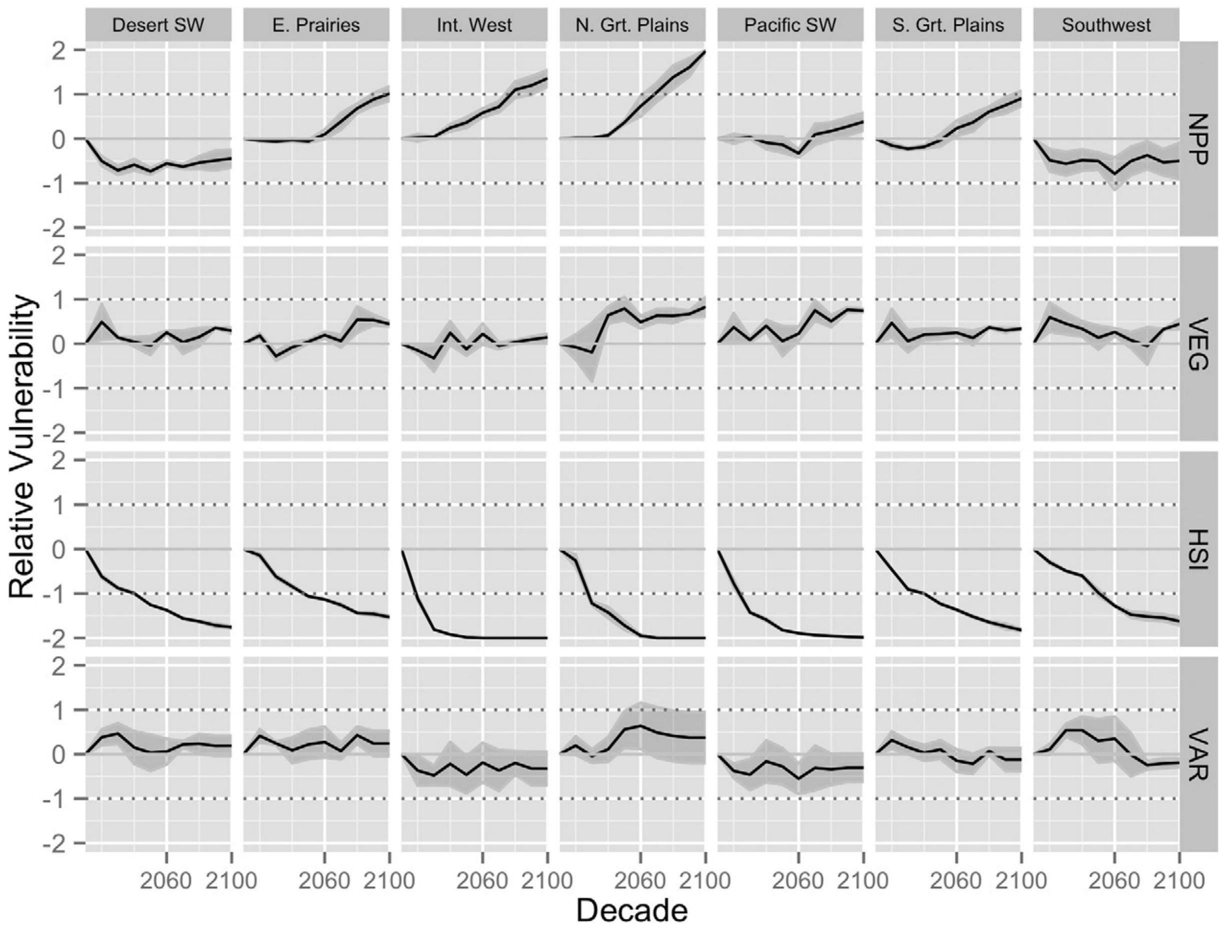

Figure 5. Average classified change (index scores) over time from baseline (2001–2010) in US rangeland regions for forage quantity (NPP), vegetation type trajectory (VEG), heat stress (HSI), and interannual variation of forage quantity "forage dependability" (VAR). Change is averaged among emission scenarios. Standard error is shown in shaded region. Positive numbers indicate improving conditions (lower vulnerability) relative to baseline conditions.

events can offset prolonged drought by increasing soil water storage benefiting some semiarid grasslands (Heisler-White et al., 2009).

Changes in forage dependability have potentially large ramifications for cattle production as interannual variation in forage amount creates unpredictable conditions regardless of total NPP and requires increasing flexibility in cattle operations (McKeon et al., 2009; Torell et al., 2010; Brunson and Tanaka, 2011; Ash et al., 2012). The increased flexibility in stocking rate is equally important for operations as it is for the ecosystems, especially in the western United States, given the potential for permanent soil degradation and transition to new ecological states (Laycock, 1991; Milchunas and Lauenroth, 1993; Jones, 2000).

Other Factors

Other factors will affect cattle production through climate change but could not be quantified because of a lack of available spatial data. For example, land use change will influence the future of cattle production in the United States. Likewise, decreases in forage quality, such as reduced protein and digestibility, may offset benefits to livestock production from increased forage quantity, particularly during summer when temperatures are high (Hanson et al., 1993; Milchunas et al., 2005). Overall, forage quality is expected to decrease (Polley et al., 2011) but not necessarily in the northern United States (Craine et al., 2010) if winters become wetter as anticipated. Forage quality, as well as rangeland health, could further be reduced by expansion of invasive species that have lower nutritional value, are noxious to livestock, or facilitate transition to new ecological states (DiTomaso, 2000; Polley et al., 2013; Boyte et al., 2016; Bradley et al., 2016).

Water availability affects rangeland utilization and weight gain, especially during dry years with poor forage or high temperatures (Hodder and Low, 1978). Disease vectors and hosts will vary in response to climate change depending on effects on vegetation, standing water, and temperature, further complicating evaluation of potential vulnerability (Stem et al., 1989). For example, warmer temperatures could facilitate increased winter survival of ectoparasites (Karl et al., 2009), such as ticks and horn flies, which are problematic across the study area. These ectoparasites typically affect British breeds, such as Hereford (Byford et al., 1992), more than Brahman cattle (Utech et al., 1978; George et al., 1985), suggesting breed selection may be an important adaptation or coping strategy.

Analysis of multiple factors simultaneously, although insightful, can induce problems associated with model stacking, or the overlay of results derived from multiple models. Model stacking can potentially compound model errors, reducing confidence in results. We reduced the potential for biased model output by giving all models equal weight and setting conservative thresholds to indicate vulnerability and resilience. Even if there was low confidence in an indicator for a particular region, it is not likely that all four factors would be biased in the same direction simultaneously, lending confidence to our regional findings. In the absence of a more comprehensive mechanistic, quantitative model, our simplified approach makes the results easy to interpret and transparent to the reader.

Implications

In addition to climate change, cattle production and operations are currently at risk due to land use change, invasive species, altered fire regimes, and fluctuating global markets. Our projections for the arid southern and western regions portray a relatively bleak outlook, and animal agriculture may become unsuitable in some regions. Parts of these regions, particularly Texas and California, also produce large numbers of cattle. Thus, these regions could potentially undergo large changes relative to the present day, suggesting a variety of adaptation strategies will be needed, including adjustments to stocking rates and grazing schedules, or cattle production will need to shift to other regions. In contrast, northern areas may offer slightly increased or maintenance of existing production and could be the recipient of cattle that are moved from operations originating in southerly regions. Flexibility in cattle numbers, grazing periods, and operation type could also address changes in production while anticipating increasing variability. Where indicators are in disagreement about the course of future production, we need to improve our understanding of how factors may interact and the sensitivity of production to different ecological factors.

Although producers make decisions based more on near-term climate expectations (Ritten et al., 2010; Torell et al., 2010), the projection period used here is relevant to policy makers and presents an opportunity for producers to include longer-term projections in management plans and implement monitoring to detect initiation of critical impacts. In addition, this work presents an opportunity for producers to consider longer-term projections when adapting to various biophysical conditions.

The biophysical indicators presented here are important to decision making but are also influenced by economic and social perspectives (Fox et al., 2009). Producers are going to respond to changes in the environment based on their own goals. Torell et al. (2001) and Gentner and Tanaka (2002) found that producers do not place profit high in terms of reasons to own a ranch; rather, lifestyle and family considerations ranked highest. What this indicates from a sustainability perspective is that regardless of what happens with climate change impacts, many producers will decide what to do based on lifestyle and family choices rather than strictly on maximizing profit. Sustainability from the ecological, economic, and social perspectives will ultimately set stocking rates (Fox et al., 2009). Because of this, the biophysical indicators only tell part, but an important part, of the story in terms of grazing animal numbers and inform more comprehensive assessments that include cost analysis of impacts and adaptation measures, availability of technology, and influence of global markets (Walthall et al., 2012).

Rangelands, in particular, are amenable to adaptation measures because of the close connection with goods and services, history of cooperation between rangeland scientists and managers, and diversity of available solutions (Joyce et al., 2013). Although managers of rangelands are already experienced with managing resources under harsh and variable conditions, they may not be prepared for the accelerating and exacerbating impacts under future climate change (Ash et al., 2012). Altering stocking schedules could help avoid exposure to the greatest temperatures, and shade can be provided in many situations (Gaughan et al., 2008). Resistance to heat stress can be managed by selection of livestock breeds and species (Bonsma et al., 1940; Finch et al., 1984). Water availability should be considered in designing adaptation actions related to heat (Howden and Turnpenny, 1998; Thornton et al., 2009). Furthermore, decisions related to cattle production need to consider other goods and services from rangelands that society will desire into the future and the sustainability of overall ecosystem health. The analysis presented here provides impetus for livestock operations to consider proactive adaptation strategies that can enable continued livestock production along with healthy rangeland ecosystems into the future.

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