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A climate change indicator framework for rangelands and pastures of the USA

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Abstract
Rangelands and pastures include grasslands, savannas, shrublands, and woodlands and are often maintained to support grazing animals. Rangelands and pastures cover more than one-third of the land area in the USA and a similar extent globally. The ecosystem goods and services associated with rangeland and pastureland include critical wildlife habitat, forage for livestock, amenities related to water conservation, sustainable soil functions, and soil stabilization and support a diversity of biota and livelihoods. This paper provides a framework for development of a socio-ecological system (SES)–oriented set of indicators for rangeland and pasture systems to support evaluation of impacts of climate and land use changes. These indicators will also serve to inform adaptive management practices. We present a rationale for using an SES approach to evaluate trends and vulnerabilities of rangeland and pasture systems and provide an example of a set of system indicators arising from the SES approach. The indicators include evaporative demand, land cover extent, aboveground plant biomass, human demographics (population age distribution), cattle numbers, and economic value of cattle products relative to total agricultural value. These indicators are not meant to be comprehensive but are offered to illustrate how they might be used in a SES approach to plan for, assess, and mitigate climate change impacts. The conceptual framework provides a systems perspective on the impact of climate change on the socio-ecological dynamics of rangeland and pasture systems including measures of the resilience and vulnerability of ecosystem services with respect to the six indicators. The article focusses on livestock production in rangeland ecosystems, recognizing that additional work is needed to address pastures and other ecosystem services. Examples of the types of regional information associated with the indicators are provided. Guidance for future efforts in indicator development is offered. This framework will serve to guide future development of indicators for rangeland and pasture components of a larger national effort of indicators.

Keywords Rangelands · Pastures · Climate change · Socio-ecological system indicators

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1 Introduction

Rangelands and pastures include grasslands, savannas, shrublands, and woodlands and are often maintained to support grazing animals. These systems support various livelihood operations associated with ranching, conservation, cultural activities, and recreation enterprises that reflect an active socio-ecological system (SES) relationship between ecosystem services and livelihoods (Hruska et al. 2017). Most rangelands and some pastures typically occur in semi-arid to arid climate zones and are characterized by low and highly variable productivity. Despite the moisture constraints, these systems serve as critical water and land resources and habitat for wildlife and livestock, dryland crops, energy production, and other critical ecosystem services supporting rural livelihoods (Briske et al. 2015; Ojima et al. 2015; McNeeley et al. 2017). Collectively, rangelands and pastures represent the largest global land cover/land use category surpassing agricultural and forested landscapes (White et al. 2000; Gibson 2009). In the USA, rangelands and pastures make up over one-third of land cover (Reeves and Mitchell 2012), of which approximately half is owned and managed by the federal government (USDA 2015).

While climate and vegetative structure and cover metrics have been widely used to characterize rangelands and pastures, there has been extensive discussion on how these lands are distinguished and defined (Lund 2007; Reeves and Mitchell 2011). We adopt an inclusive definition of rangelands and pastures that integrates language from the US Forest Service Forest Inventory Analysis (USFS FIA; USFS 2016) and the Natural Resources Conservation Service (NRCS) National Resources Inventory (NRI; USDA NRCS 2015) programs. We define rangelands and pastures as areas dominated by herbaceous and shrub vegetation typically maintained by natural processes or human interventions, including fire, herbivory (grazing or browsing by livestock and wildlife), drought, and climate (White et al. 2000). Additionally, savannas and some wetlands are included in our definition.

Rangelands dominate the landscapes of the western and central US covering > 60% of the land surface or more than 500 million ha (Reeves and Mitchell 2011). Rangelands include the shrublands of the Great Basin and hot deserts (Chihuahuan, Sonoran, Mojave), blue and post oak savannas of California, pinyon-juniper woodlands, the Cross Timbers, and the Great Plains grasslands (tall-, mixed-, and short-grass prairies) (Gibson 2009). In contrast, pastures are concentrated in humid and marginally semi-arid environments, generally in the eastern half of the USA. Rangelands are extensively managed, whereas pastures are more intensively managed and may involve seeding, fertilization, irrigation, and weed control. Pastures may be embedded within a matrix of rangeland watersheds.

Changes in climatic drivers, such as rainfall and growing season temperatures, influence biodiversity and ecosystem processes that include evapotranspiration, soil moisture retention, biogeochemical cycling (i.e., carbon, nitrogen, and phosphorus), and productivity (Polley et al. 2013; Ojima et al. 2015). Climate regimes within most rangelands typically have low or high variable annual precipitation along with high evaporative demand (Asner et al. 2004; Zomer et al. 2006; Havstad et al. 2007; Reeves et al. 2014). Shorter-term climate variability and longer-term climate change in rangelands and pastures are environmental factors that affect temperature ranges and extremes and the frequency, intensity, form, and duration of precipitation events (Holmgren et al. 2006; Polley et al. 2013). Warming across these systems in recent decades has been documented with drought as a major and on-going concern (Joyce et al. 2013; Reeves et al. 2014; Hanberry et al. 2019; McIntosh et al. 2019) along with some areas experiencing changing phenological patterns, untimely freezing events, and seasonally extreme, heavy precipitation events (Holmgren et al. 2006; USGCRP 2017).

Rangelands and some pastures are also characterized as having relatively low nutrient availability (though there are noted exceptions such as the fertile prairie soils in the central regions of the USA which have been converted from range/pasture to row-crop agriculture) with nitrogen content of arid soils often being less than 0.1% (Asner et al. 2004). The vegetation is also sensitive to over-grazing that result in loss of vegetation cover and increased erosion. In addition, woody encroachment, invasive species, and desertification can alter delivery of ecosystem services (DiTomaso 2000; Archer et al. 2017; Breshears et al. 2016; Bestelmeyer et al. 2018) supporting the ecological integrity and socio-economic livelihoods (Ojima et al. 2015; Hruska et al. 2017; McNeeley et al. 2017).

Rangeland and pastures operate as tightly interactive SES (Havstad et al. 2007; Hruska et al. 2017; McCollum et al. 2017) and provide critical habitat for wildlife and domestic grazing animals, agricultural production, and a variety of other ecosystem services that support livelihoods related to ranching, wildlife management, conservation, and recreation (White et al. 2000; Lund 2007; Fernández-Giménez et al. 2019). Globally, rangeland and pastures provide a multitude of ecosystem goods and services that have an estimated value increasing from $1.2 trillion in 1997 (Costanza et al. 1997) to greater than $18 trillion in 2011 (relative a total global ecosystem service valuation of $124.8 trillion) (Costanza et al. 2014).

Natural resource managers facing changing climate regimes that affect natural resources and flows of ecosystem services, will require adaptive management tools (Sauchyn and Kulshreshtha 2008; Bestelmeyer and Briske 2012; McCollum et al. 2017; Fernández-Giménez et al. 2019; Hanberry et al. 2019). Provision of useful information related to the dynamics of the SES associated with the natural and social capital of rangelands and pastures will enable more informed and objective assessments of climate change impacts and provide information useful in crafting adaptive management strategies (Ojima et al. 2013; Briske et al. 2015; McNeeley et al. 2017; McCollum et al. 2017; Joyce and Marshall 2017). An integrative SES evaluation scheme with appropriate indicators to guide decision makers and natural resource managers of these systems are needed to inform managers developing or implementing adaptive management strategies.

Recent global environmental changes affecting rangelands and pastures include sudden on-set of droughts, extreme storm events, land fragmentation, and introduction of non-native species (Polley et al. 2013; Archer et al. 2017; Bestelmeyer et al. 2018). Rangeland and pasture SESs are also sensitive to socio-economic changes affecting operation costs, commodity prices, consumer preferences, energy development, and environmental policy (Hruska et al. 2017). This growing list of internal and external forces and consequences propel the need for useful indicators and metrics to support adaptive management practices (Bestelmeyer and Briske 2012; Derner et al. 2012; Derner and Augustine 2016; McCollum et al. 2017). Qualitative and quantitative efforts to monitor rangeland and pastureland at scales relevant to management and decision-making exist (e.g., Pyke et al. 2006; Mitchell 2010; McCollum et al. 2017), but integration of these efforts into a more holistic SES framework would enhance adaptive management efforts.

Here, we describe a SES framework using indicators that assess the direction and magnitude of climate change and management effects on rangelands and pastures. This framework emerges from a series of workshops supported by the National Climate Indicator System (NCIS) program (Kenney et al. 2014, 2016). The goal of NCIS is the development of a "system of physical, natural, and societal indicators that communicate and inform decisions about key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness" (Kenney et al. 2016, Kenney et al. 2018). The primary purpose of the NCIS is to support the on-going US National Climate Assessment (Melillo et al. 2014) by providing long-term, regularly updated information about key impacts that are of broad concern to the US public, including rangeland and pasture, as required by the 1990 Global Change Research Act (Kenney et al. 2016).

Our national-scale framework incorporates indicators that are based on currently available information and that represent rangeland and pastures as complex and dynamic SES's. This framework provides the structure and information necessary to guide adaptive management strategies to contend with climate and land use changes affecting rangeland and pasture systems and to promote their sustainable management and economic viability.

2 Conceptual framework

Rangelands and pastures operate as an SES integrating natural and social capital (Fig. 1) (McCollum et al. 2017; Hruska et al. 2017; Fernández-Giménez et al. 2019). These systems support livelihoods associated with ranching, conservation, recreation, and cultural amenities and are reliant on key ecosystem processes underlying habitat integrity, biological productivity, water resource quality and quantity, biodiversity, and soil health. Natural capital is the collection of environmental resources associated with the land, air, water, and biota that

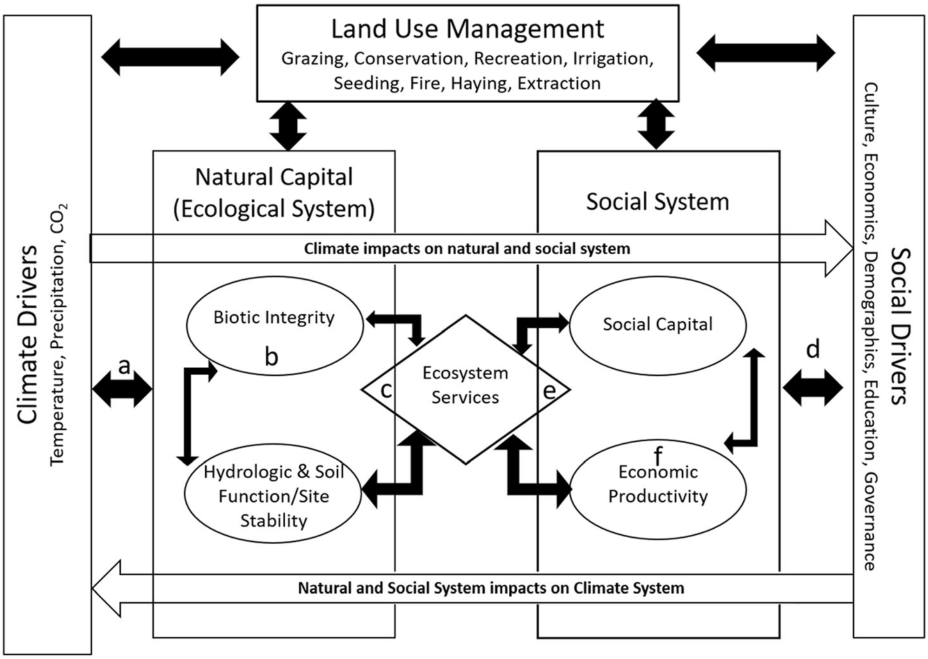

Fig. 1 Conceptual Social Ecological System framing in support of integrated climate change indicator scheme for rangeland and pastures. Rangeland and pastures are influenced by both climate and socio-economic drivers, which interact with each other to affect the delivery of ecosystem goods and services. The dynamic linkages between the natural capital and the social capital are important properties of how these lands function and respond to management interventions aimed at coping with climate change. Management interventions range from extensive approaches associated with open-rangeland and conservation areas such as prescribed fire and manipulation of livestock stocking rates to more intensive management that includes altering species selection, irrigation, fertilization, and mechanical removal of forage. Possible example indicators exemplifying key components affecting the SES of the rangeland and pasture in this paper include the following: (a) evaporative demand, (b) land cover extent, (c) aboveground plant biomass, (d) median age of the human population, (e) beef cattle numbers and distribution, and (f) economic value of cattle products relative to total agricultural value

influence the maintenance and delivery of valuable ecosystem services, such as forage, habitat, and meat products. Social capital includes a set of shared assets including knowledge, available technology, cultural values, institutional structures, physical infrastructure, and access to commodities, markets, and services supporting various livelihood strategies. Social capital provides a metric of the capacity of knowledge and tools that enables land managers to utilize natural capital to meet livelihood and management goals.

Climate and land use changes are affecting the socio-ecological dynamics of rangeland and pasture systems. Ecosystem services, such as water supply, habitat for wildlife, soil fertility and organic matter cycling, and land productivity associated with biotic integrity are being impacted by warming atmospheric conditions, changes in rainfall patterns, and extreme weather events (e.g., flash droughts, flooding, heat waves, and out-of-cycle freezes) (Ojima et al. 2015). Changes in land use and fragmentation of landscapes resulting from grazing, mining, energy production, and conservation management efforts are affecting ecosystem services supporting broader socio-economic livelihoods. Management of rangelands and pastures needs to meet multiple, often competing, goals and accommodate ranching—conservation—economic development tradeoff across sectors.

Rangeland and pastures operate as a complex adaptive system and require an adaptive management approach that recognizes the existence of multiple states and the importance of change (Bestelmeyer and Briske 2012; McCollum et al. 2017; McNeeley et al. 2017; Fernández-Giménez et al. 2019). Our conceptual framework brings together elements of ecosystem and social system components that are interconnected through the production, maintenance, and use of ecosystem services. The framework also reflects the multiple drivers affecting the SES dynamics related to climate, economic considerations, and policy changes that directly and indirectly influence rangeland and pastures.

Interactions among climate, management, and ecosystem processes of rangeland and pastures are complex. These interactions affect the biotic integrity, soil processes, soil stability, and hydrologic attributes critical to sustaining livelihoods and the functional integrity of rangeland and pasture ecosystems (Pyke et al. 2006; McCollum et al. 2017). Our suite of indicators aims to synthesize and encapsulate these interactions. For example, aboveground green biomass, a surrogate for available forage, represents a component of biotic integrity and soil health that is sensitive to water availability and is affected by factors such as evaporative demand, grazing intensity, and land cover and is an essential ecosystem service to livestock and wildlife needs (Mitchell 2010).

3 Indicators to evaluate SES of rangelands and pastures

Our conceptual framework serves as a guide to identify indicators that reflect the sensitivity of rangeland and pastures to changes in climate and shifts in land use that encompass various livelihood strategies and goals of sustainable stewardship of these systems. The framework recognizes both direct and indirect factors that affect rangeland and pasture, along with indicators of change in either the natural or social capital. To illustrate the connectivity and feedbacks between the natural and social components, we focus on a small suite of indicators: (a) evaporative demand (Hobbins et al. 2016; Dewes et al. 2017), (b) land cover extent (Jin et al. 2019), (c) aboveground plant biomass, (d) human demographics (age distribution) (US Department of Commerce 2016), (e) cattle numbers (NASS 2016), and (f) relative value of cattle products (USDA NASS 2019) (Fig. 1). These variables are illustrative of the interdependencies between ecological and social processes and how those interactions influence responses to climate and other environmental changes (Hruska et al. 2017; McCollum et al. 2017). Collectively, these indicators provide a set of system variables associated with SES dynamics and key ecosystem services that support diverse livelihoods and management decisions related to ranching, conservation, and recreation enterprises. A focus on cattle ranching serves to illustrate the interdependencies of climate, biotic integrity, and social dynamics of rangeland and pasture systems. Aspects related to changes in human population, cattle numbers, and cattle commodity prices provide a link to economic and social capital assets. These indicators are not meant to be comprehensive but are offered to illustrate how they might be used in a SES approach to assess and mitigate climate change impacts.

3.1 Evaporative demand

Climate change over the past decades has increased atmospheric warming, resulting in events now referred to as "flash-droughts" (Hobbins et al. 2016). Adapting to flash-droughts is a challenge due to the rapid on-set of drought conditions, even following periods of average winter recharge. Atmospheric conditions forecasting flash-drought have been developed to help managers anticipate and prepare for these events. The Evaporative Demand Drought Index (EDDI) is a real-time drought monitoring tool that updates daily using the latest atmospheric conditions (Hobbins et al. 2016; McEvoy et al. 2016; Dewes et al. 2017). The tool serves as an indicator of both flash-droughts that occurs on the scale of a few weeks and of longer-term drought. The short-term indicators can be used, for example, to anticipate irrigation requirements on a day-to-day basis. Longer-term (e.g., 6-month) projections can be used to assess fire season risk or need to destock grazing animals. EDDI is available on the WWA Climate Dashboard page. Additional efforts provide localized climate change information to national parks and federal and state agencies to assist with mitigation of potential climate shifts on critical natural resources.

3.2 Land cover extent

Land cover extent (areal extent, ha) reflects climate, land use, and vegetation composition and is an important attribute of biotic integrity. Changes in land cover across rangeland and pastures represent structural changes in landscape characteristics related to herbaceous and woody cover, erosion effects, and land fragmentation accompanying changes in climate and land use. Assessments of the areal extent, rates, and patterns of land cover change are foundational, as they provide the spatial and temporal context within which other socio-ecological factors operate.

We defined the spatially explicit extent of rangeland and pastures in the conterminous USA and Alaska using 10 classes from the 2016 National Land Cover Database (NLCD, Jin et al. 2019) (Fig. 2). The National Oceanic Atmospheric Administration (NOAA) Coastal Change Analysis Program's (C-CAP) 2010 land cover map was used for Hawaii. The 2016 NLCD was simultaneously produced together with the 2001, 2004, 2006, 2008, 2011, and 2013 thematic maps of the USA that were derived from 30-m pixel resolution Landsat satellite imagery (Jin et al. 2019). Such maps represent a baseline from which to gauge future changes in the pattern, extent, and composition of fundamental vegetation cover classes.

3.3 Aboveground biomass

Satellite remote sensing has been used to estimate gross and net primary productivity (GPP and NPP, respectively) with varying levels of success at local to global scales

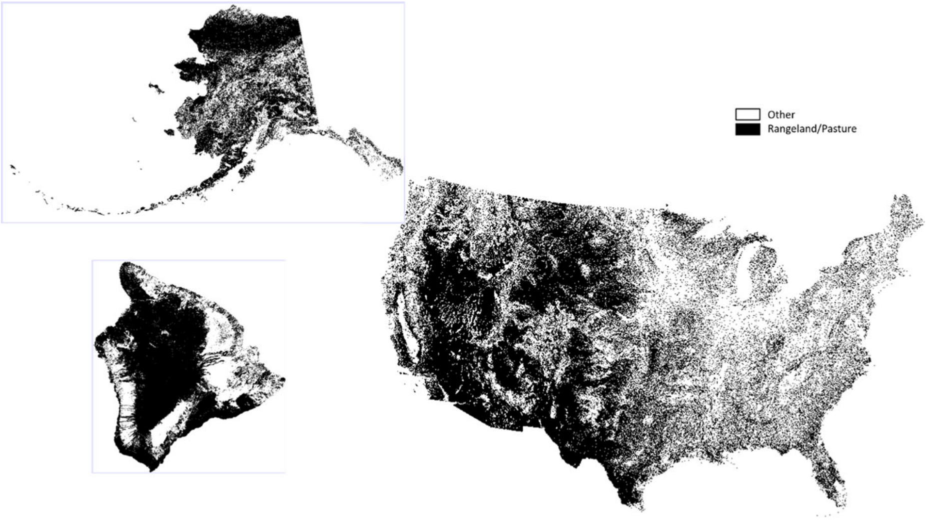

Fig. 2 Land cover extent of rangeland and pasture extent within the conterminous USA and Alaska can be used to examine the trend of indicators, e.g., aboveground biomass, within the individual land cover types. This map is adapted from the 2016 National Land Cover Dataset (NLCD, https://www.mrlc.gov/data; Jin et al. 2019) and the NOAA Coastal Change Analysis Program (C-CAP, https://coast.noaa.gov/htdata/raster1/landcover/bulkdownload/hires/hi/) for the Hawaii 2010 land cover product

(Running et al. 2004; Robinson et al. 2018). Here, we use 1-km^2 pixel resolution Moderate Resolution Imaging Spectroradiometer (MODIS) NPP data to estimate the temporal and spatial distribution of aboveground biomass (AGB, kg/m^2) as a surrogate for the amount of forage potentially available for wild and domestic herbivores from 2000 to 2012 (USFS 2012; Washington-Allen 2015) (Fig. 3). Though this methodology under represents the amount of browse available in the landscape, our focus on forage availability to cattle. This remotely sensed AGB provides an estimate of annual and monthly changes in herbaceous vegetation which is the most important feed for cattle and sheep on rangelands. If remotely sensed AGB predictions are adjusted for plant cover type the relationship between changes in this metric should be a good indicator of cattle forage and other ruminant forage. Shrubs and trees can affect NDVI values and reduce the accuracy of the prediction of livestock forage availability using AGP or NPP. However, there are techniques to adjust AGB for plant cover type and improve accuracy (e.g., Robinson et al. 2019).

Robinson et al. (2018) produced 30-m and 250-m NPP datasets from Landsat satellite imagery from 1984 to 2018 and MODIS satellite imagery from 2000 to 2018. This effort on the Landsat data set was further refined to incorporate subpixel analysis of plant functional types to create a time series from 1984 to 2019 of plant productivity (Robinson et al. 2019). The Landsat NPP dataset is of the conterminous USA; the MODIS dataset is global. Both datasets can be converted to AGB. Reeves et al. (2020) have produced the Rangeland Production Monitoring Service (RPMS 2018) from Landsat 5, 7, and 8 imagery. This is a spatially explicit and publicly available dataset that produces annually updated aboveground NPP, currently from 1984 to 2018, that can be converted to AGB. Reeves et al. (2014) has forecasted the impacts of climate change on US rangeland NPP. Other approaches for forecasting the AGB potentially available for animal consumption have been recently

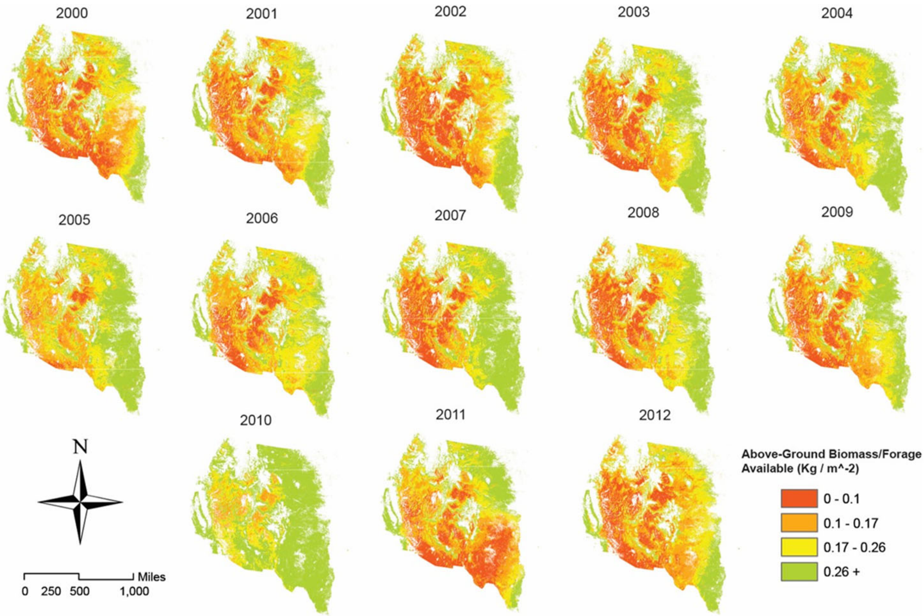

Fig. 3 Estimated aboveground biomass, or forage available (FA, kg m^{-2}), to livestock from 2000 to 2012 for US lands west of the Mississippi River. FA is derived from 1-km resolution Moderate Resolution Imaging Spectroradiometer (MODIS) net primary productivity (NPP) Collection 5 MOD17 data. Unpublished data prepared by Washington-Allen and McNelis

developed in the Great Plains (Chen et al. 2019; Klemm et al. 2020). *Grass-Cast*, in particular, is a tool that uses field observations, the above remote sensing data, and growing season climate forecasts as inputs (Chen et al. 2019). *Grass-Cast* provides projections of growing season grass production on rangelands across the Great Plains and is currently being tested at the USDA Northern Plains Climate Hub (Peck et al. 2019). The forecasts begin in late April and weekly updates are provided based on regular weather updates.

3.4 Human demographics (population age distribution)

The population of rural areas across the USA has been aging faster than urban or suburban areas, and this change is especially apparent across the Great Plains (Ojima et al. 2015). The local knowledge and stewardship activities associated with multi-generational, family-operated ranches on rangelands, and pasture are an important cultural and economic resource. However, as these populations are aging in many counties classified as rangeland or pasture, the median age is observed to be typically > 40 years (Fig. 4). This in addition to low replacement rates due to net outmigration are undermining the social, cultural, and knowledge continuity needed to effectively manage these ecosystems. Knowledge of demographic changes (e.g., age structure, number per area, etc.) are thus a key component of social capital providing insights on how human resources are changing. Demographic information collected by the US Census can be used to track the social structure of populations operating rangeland and pasture systems. Trends in such data over time can indicate how populations and human resources are changing and provide insights into how and why livelihood values and resource demands are changing.

3.5 Beef cattle numbers

Livestock production is a critical operation associated with US rangelands and pastures, and livestock on these lands is primarily cattle and sheep. Our focus on cattle production includes livestock raised on both public and private lands and consists of production associated with steer-rearing and cow-calf operations. The number of cattle on these lands will vary owing to economic and environmental conditions (Briske et al. 2015; Ojima et al. 2015) and can fluctuate regionally as well as locally.

Historical data on beef cattle numbers are available at the county and state level for livestock types (Fig. 5) and beef cattle, sheep, and goat numbers can be standardized to serve as an index of change in livestock numbers (Forde et al. 1998), forage demand (Mitchell 2010; USFS 2012; Reeves and Mitchell 2012), productivity/weight, meat/skins/fiber produced (Wilcox et al. 2012), and livestock herd value. Beef cattle numbers (Fig. 5a), as a subset of livestock numbers, integrate across a combination of interacting natural and social capital factors and inform socio-economic aspects of rangeland and pasture management and policy (Mitchell 2010). Factors affecting beef cattle numbers include forage amount, availability, and quality (e.g., nitrogen content), all of which are affected by land use and climate (i.e., precipitation amount and seasonality, air and soil temperature, evapotranspiration). Reductions in livestock numbers will be amplified in areas where the frequency, intensity, and duration of drought increase, and relaxed in areas where rainfall approximates or increases relative to the long-term mean (Dean and Macdonald 1994; Havstad et al. 2016). Socio-economic trends and market forces further affect livestock numbers (including beef cattle) as demands and cultural values change (Mitchell et al. 2010). Reliable, meaningful interpretation of changes and trends in the number of livestock will require knowledge of these interactions.

The USDA National Agricultural Statistics Service (NASS) tracks livestock numbers including cattle (1873 to present; Mitchell 2010; Reeves and Mitchell 2012) and their spatial distribution by county and state. National-level trends of herd size and grazing livestock have been evaluated (USFS 2012; Reeves and Mitchell 2012). Additional

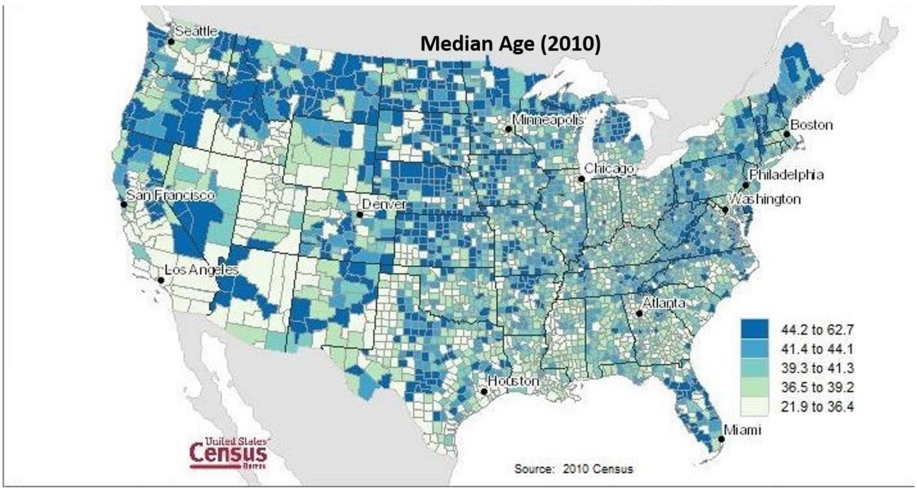

Fig. 4 Median age of population from the 2010 U.S. Census (U.S. Department of Commerce 2016)

analyses have been conducted to estimate forage demand at county and state levels (Wilcox et al. 2012; USFS 2012; Reeves and Mitchell 2012). Spatial maps of changes of livestock distribution from 2012 to 2017 (Fig. 5b) provide an indication of the changes in cattle operations over time ostensibly associated with some combination of climate- and economic-related factors.

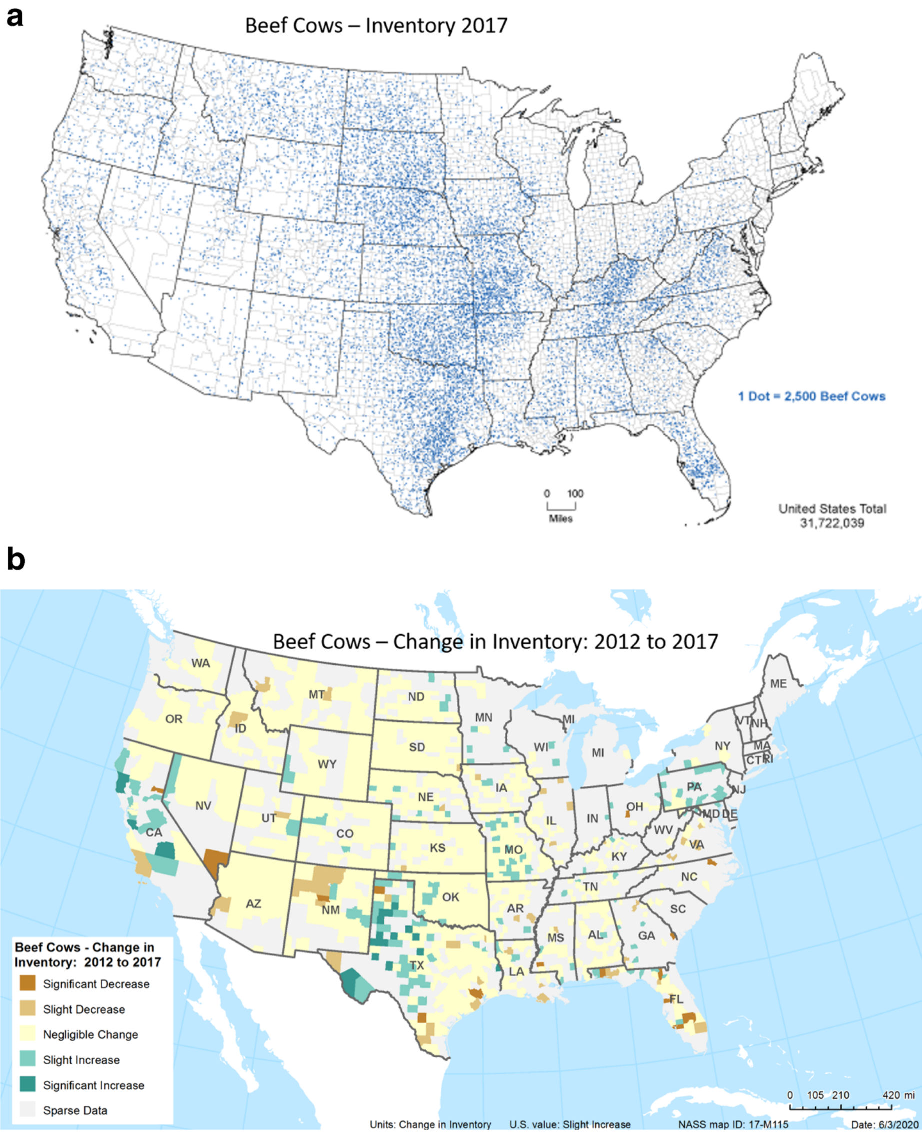

Fig. 5 Beef cattle inventory by county in 2017 (https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Atlas_Maps/17-M208.php) (**a**) and the changes in beef cattle by county from 2012 to 2017 (https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Census_Web_Maps/index.php) (**b**)

3.6 Relative economic value of cattle product

A key indicator of economic productivity in rangelands and pastures is the economic value of livestock products (US$), which support rural communities and livelihoods. The percent of total market value of agricultural commodities of cattle and calves sold can be tracked by county and represents the relative importance of this commodity to the agricultural sector (Fig. 6). Systematic economic valuation of commodities derived from rangeland and pasture through time reveal a combination of regional/national trends in animal production and prices in response to market forces and climate effects on forage production and animal numbers and performance.

4 Discussion

The biophysical and socio-economic indicators described in the previous sections provides an example set of indicators to illustrate a SES approach to assessing climate change impacts and supporting information for adaptive management actions. These independent, but inter-related components respond differentially in space and time to changes in climate, management, and socio-economic drivers to mediate impacts and feedbacks at local-to-regional scales. Adaptive management seeking to enhance resilience or to modify actions to capitalize on emerging environmental and social changes will be highly nuanced by the local socio-ecological setting (Bestelmeyer and Briske 2012; Fernández-Giménez et al. 2019). Socio-economic indicators yield insights into the changing human and cultural fabric and form the underlying basis for management decisions on rangeland and pastures. By placing demographic patterns of communities associated with rangeland and pastures within the context of other indicators, the emerging suite of information will provide both

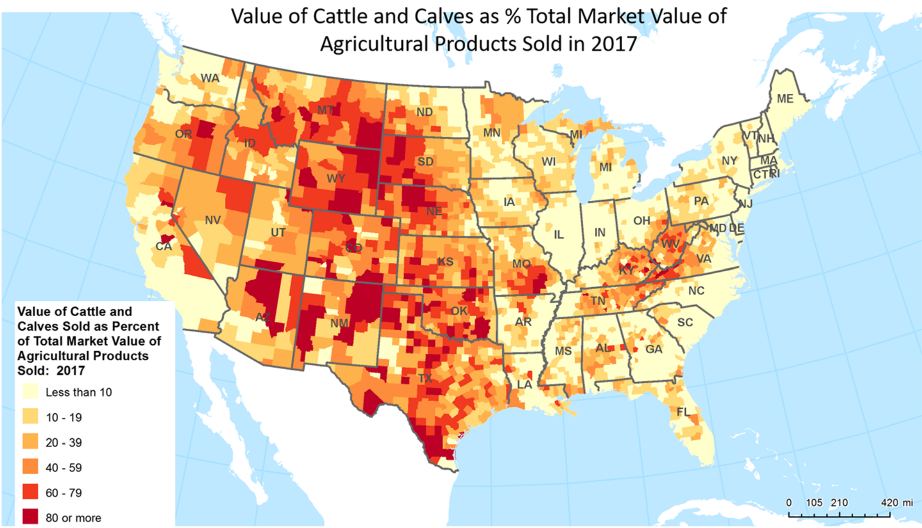

Fig. 6 Percent of total market value of agricultural products represented by cattle and calves sales by county (USDA National Agricultural Statistics Service 2016; https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Ag_Census_Web_Maps/index.php)

knowledge *and* understanding of how and why climate change may influence decision-making and livelihood. The proposed indicators illustrate how climate change and management of these SESs impact agricultural and food production, while demonstrating their uniquely complex and coupled nature.

Our indicators provide a starting point and framework wherein refinements and additional indicators and interrelationships can be assessed. For instance, reductions in AGB associated with the 2012 drought contributed to a northward shift in cattle numbers to regions where forage was more abundant (Joyce et al. 2013; Reeves and Bagne 2016; Reeves et al. 2017). Cattle prices and sales also changed in response to these climate impacts on grass productivity. Climate changes leading to changes in plant composition (e.g., from palatable, mesophytic grasses to unpalatable, xerophytic woody plants) may, in turn, cause a shift in livestock classes (e.g., away from cattle and toward sheep and goats) (Lemaire et al. 2011). Importantly, the proposed indicators build on existing indicator efforts, data gathering initiatives, and monitoring projects (e.g., Mitchell 2010). We purposefully intend a bottom-up approach to indicator development and perspectives to build in measurements and metrics that are decision-relevant and scalable.

Recognition of SES structure and process feedbacks affecting system responses and potential management options to deal with changes in climate and environmental conditions point to more place-based engagement and assessment of local adaptive capacity (Joyce et al. 2013; Briske et al. 2015; Hruska et al. 2017; Fernández-Giménez et al. 2019). The adaptive capacity of communities supporting a diversity of livelihood enterprises dependent rangeland and pasture ecosystem services is highly variable. Application of socio-ecological vulnerability assessments of these communities and enterprises provides useful insights into the adaptive capacity of individual operators and levels of vulnerability (Joyce and Marshall 2017; McNeeley et al. 2017). Indicators that provide a way to analyze system response to change while also enabling a projection of outcomes from various management scenarios will be increasingly needed to track and reliably project climate and socio-environmental change.

Provision of information in support of adaptive management across a diversity of enterprises and livelihoods will require greater engagement between local practitioners, decision-makers, and climate-adaptation researchers (Homsy and Warner 2013; McNeeley et al. 2017; Joyce and Marshall 2017; Fernández-Giménez et al. 2019; Hanberry et al. 2019). Cross-scale county, state, and regional efforts will be required for concurrent coordinated and complimentary bottom-up and top-down linkages in support of climate adaptation measures and selection of meaningful socio-ecological indicators that are relevant to individual livelihood goals. Federal-level efforts are evolving with collaborations among state agencies, universities, commodity groups, non-governmental organization, and local operators (Averyt et al. 2018; Steiner et al. 2015; Fernández-Giménez et al. 2019). These efforts embrace collaborative engagements that closely align with local needs and promote the identification of indicators and assessment activities to address vulnerabilities and to assess progress with adaptive management actions.

Socio-economic data such as livestock census numbers and human demographics provide a contextual basis for interpreting agricultural and market responses to climate change, and vice versa. For example, adaptive management strategies have been implemented in the southwestern USA despite aging demographics and less predictable precipitation (Havstad et al. 2016). On-going vulnerability assessments and research related to managing, adapting to, and mitigating impacts of climate change on agricultural and natural resources (e.g., Havstad et al. 2016; Joyce and Marshall 2017; McNeeley et al. 2017; Hanberry et al. 2019) provide a platform for continued indicator development involving livestock numbers and demographic information.

5 Summary and recommendations for future work

Rangeland and pastures collectively embody a significant fraction of US land cover and provide goods and services supporting the livelihoods of the diverse communities with which they are associated. The sheer areal extent of rangeland and pastures across multiple climate regimes, and their multiple land uses and management practices for agro-ecological needs, highlight the challenges for sustaining diverse livelihood strategies that rely on ecosystem services. These tightly coupled SES dynamics are also susceptible to both short-term weather extremes and long-term changes in climate. We propose a suite of inter-related indicators that allows us to track how climate variability and climate change might influence the socio-ecological conditions within rangeland and pastures, and vice versa. Our example is focused on livestock production in rangeland ecosystems, but offers an illustration of how other enterprises operating in rangeland and pastures might be developed within the context of a coupled SES relationship needed in an indicator effort.

While the intensity of land use and management activities on rangeland and pastures vary, and these ecosystems are tightly coupled to and shaped by dynamic environmental conditions. These climate drivers coupled with land use management are strong determinants of key ecosystem services and the interactions of the SES components of the local situation. Changes in both climate and management have historically interacted to influence livelihoods and modify the landscapes themselves. The proposed indicators are not meant to be comprehensive but represent a representative set of indicators that are linked to key outcomes of associated with livelihoods and ecosystem processes operating in rangelands and pastures. This framework is offered to illustrate how construction of future indicators might be used in a SES approach to plan for, assess, and mitigate climate change impacts.

Future efforts should seek to develop additional indicators within the context of an SES framework. Indicator development and refinement will require sustained engagement among research scientists (natural and social), managers, and stakeholders to ensure that they are relevant, practical, locally relevant, and readily obtainable over time. With support from government and non-governmental partnerships, the proposed and future indicators will position decision-makers to better anticipate and address issues on our extensive rangeland and pastures. This, in turn, will inform strategies for sustainable management and economic viability under future climatic conditions for the benefit of all.

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