RESEARCH ARTICLE

Climate change effects on rangelands and rangeland management: affirming the need for monitoring

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Abstract. Uncertainty as to the extent and magnitude of changes in conditions that might occur due to climate change poses a problem for land and resource managers as they seek to adapt to changes and mitigate effects of climate variability. We illustrate using scenarios of projected future conditions on rangelands in the Northern Great Plains and Desert Southwest of the United States. These two regions are different in the ways climate change is projected to affect the regions. Projection of a longer and warmer growing season in the Northern Great Plains could lead to increased forage production and land productivity. Highly uncertain effects on summer monsoons that primarily control rangeland productivity in the Desert Southwest, combined with the possibility of more intense and/or frequent drought events, could present land managers with challenges stemming from decreased forage production and land productivity. Climate projections, though uncertain, provide land managers with basic insight into future conditions they might encounter. They need more. A focus on vulnerability and resilience, with explicit recognition of interactions between ecological and socio-economic factors, coupled with systematic monitoring and assessment of observable conditions on the land to supplement information based on climate projections, will more effectively provide critical and specific information managers need to adaptively manage rangelands under uncertain climate futures.

Key words: *adaptive management; climate change; indicators; monitoring; rangelands; resilience; uncertainty; vulnerability.*

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Introduction

Rangelands encompass over 40% of the earth's land area. They are traditionally characterized by native plant communities, often associated with wildlife and/or domestic grazing, and managed by ecological rather than agronomic methods (Society for Range Management 2014). Rangeland ecosystems can be found on all continents, except Antarctica, and they significantly contribute to associated socio-economic systems. There is general agreement that climatic conditions are changing rangeland ecosystem processes and properties (Polley et al. 2013). However, uncertainty remains regarding spatial variation in rates of temperature and precipitation changes (Christensen et al. 2007).

For slow-changing arid and semi-arid rangelands of the United States, uncertainty can profoundly affect how managers adapt to climatic fluctuations. In general, rising atmospheric CO_2 concentration has two important direct effects on plant physiology: increasing photosynthesis and reducing transpiration. These direct responses to CO_2 may actually enhance plant productivity and water-use efficiency, although some non-native plants may be preferentially benefited (Smith et al. 2000, 2014, Ziska et al. 2005, Morgan et al. 2007). Implications of these direct CO_2 responses and their interactions with warming temperatures, changes in precipitation patterns, and storm frequencies and intensities, among others, are poorly understood. Further, the degree to which climate change will impact rangelands will vary by region (Briske et al. 2015).

One way for managers at all scales to deal with uncertainty like that presented under climate change scenarios is to build capacity to adapt (Marshall and Smajgl

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2013). Active adaptive management is the process of implementing decisions as scientifically based management experiments that test predictions and assumptions in management plans, and use the resulting information to improve the plans (Walters and Holling 1990). It is management based on uncertainty. The idea is that potentially adverse effects can be detected and corrected before serious or irreversible damage occurs, allowing managers to respond proactively. Further, adaptive management is intended to give local communities the opportunity to participate in developing and applying creative solutions to natural resource issues (Moir and Block 2001). Unfortunately, the practice of adaptive management has been less successful than one might expect from its intuitive appeal. Obstacles include the following: the long timeframes of ecological processes in which short-term management responses may be transient and may not reveal critical thresholds or longer lag periods; monitoring data can be inadequate or inconsistent; and the ability to collect and use long-term data in policy making is often infeasible (Lee 1999, Moir and Block 2001, Ruhl 2005, Walters 2007).

The crux of adaptive management is monitoring. Although long-term monitoring is no easy task, it is necessary to provide relevant and consistent information to inform and evaluate management decisions (Lawler et al. 2010).

Adaptive management across multiple spatial scales requires "big data." Such data are becoming available from landscape-level programs and applications to assess ecosystem vulnerability. The U.S. Geological Survey is using conceptual models of ecosystem structure and function to guide monitoring and management in the Great Basin region of the interior western United States (Miller et al. 2010). The U.S. Department of the Interior (USDI), Bureau of Land Management (BLM), is conducting Rapid Ecoregional Assessments throughout the western United States and Alaska intended to provide a landscape-scale perspective of ecological conditions and trends of an ecoregion (BLM 2015). Large geospatial data sources such as LANDFIRE can be used to simulate how ecosystems will respond to climate change and other disturbances under different management actions (LANDFIRE 2015).

In the United States, several federal agencies maintain broad-scale monitoring systems that incorporate indicators of rangeland conditions. Two sources of data are the U.S. Department of Agriculture (USDA) Forest Service's Forest Inventory and Analysis (FIA) Program (Smith 2002) and the USDA Natural Resource Conservation Service's National Resources Inventory (NRI) Program (Nusser and Goebel 1997). Both are comprised of data collected on individual local land plots that can be aggregated to larger scales. Although both monitoring systems have a sampling grid that incorporates all lands, FIA data have only been collected from plots on forested ecosystems, and NRI data are only collected on non-federal lands. A recent study has shown that (at least some) consistent information can be collected and analyzed for an area using both protocols (Patterson et al. 2014), suggesting the possibility of consistent analyses across different land types and ownerships. The BLM has established an Assessment, Inventory, and Monitoring Strategy designed to assess rangeland health at various scales from local to regional (Toevs et al. 2011, Taylor et al. 2012). The USDI National Park Service has developed an ecological monitoring program for its parks, although individual indicators can vary from park to park (Fancy et al. 2009).

Aggregating multiple data sets must overcome obstacles of consistency, spatial and temporal extent, grain, and even definitions of variables. Further, access to these databases is hindered by their size and complexity. Data must be available to the broad spectrum of land managers in order to achieve their full potential benefit. Regardless, progress is being made; for example, Herrick et al. (2010) employed a subsample of the NRI sampling grid to collect data on qualitative and quantitative indicators of rangeland health for numerous ecological sites.

The monitoring systems described above all revolve around ecological states and processes. Monitoring and assessment of more than just ecological states and processes is necessary to achieve sustainable adaptive rangeland management. Indicators of economic and social conditions and resilience, interacting with biophysical measures, provide a higher level of knowledge that can be used to enhance resource management. Fox et al. (2009) described a framework through which indicators of sustainability can illustrate biophysical and socio-economic system feedbacks and interactions. The framework is not a structural model of an ecosystem. Rather, it focuses on ecosystem goods and services as the bridge between biophysical and socio-economic systems. This conceptual framework will be used to consider climate change scenarios predicted for the Northern Great Plains and Desert Southwest of the United States (Fig. 1), thereby illustrating the need to include social and economic states and processes, and their interactions with ecological states and processes. These regions were selected because of the large extent of their rangeland systems, and differences in their expected responses to predicted climate changes. The framework can be adapted for rangeland systems across the globe as well as to other types of ecosystems.

The paper proceeds to briefly overview the two regions and some effects and issues that might occur under projected changes in climate. The focus is on general directions, not detailed impacts, to lay out the general context in which managers might find themselves. Following the overviews, it is argued that a focus on vulnerability and resilience, along with explicit recognition of interactions with social and economic factors, can better facilitate adaptive management. Finally, an illustration is presented of interactions between ecological conditions and social/economic conditions on rangelands, and how those might affect management in the two regions. The

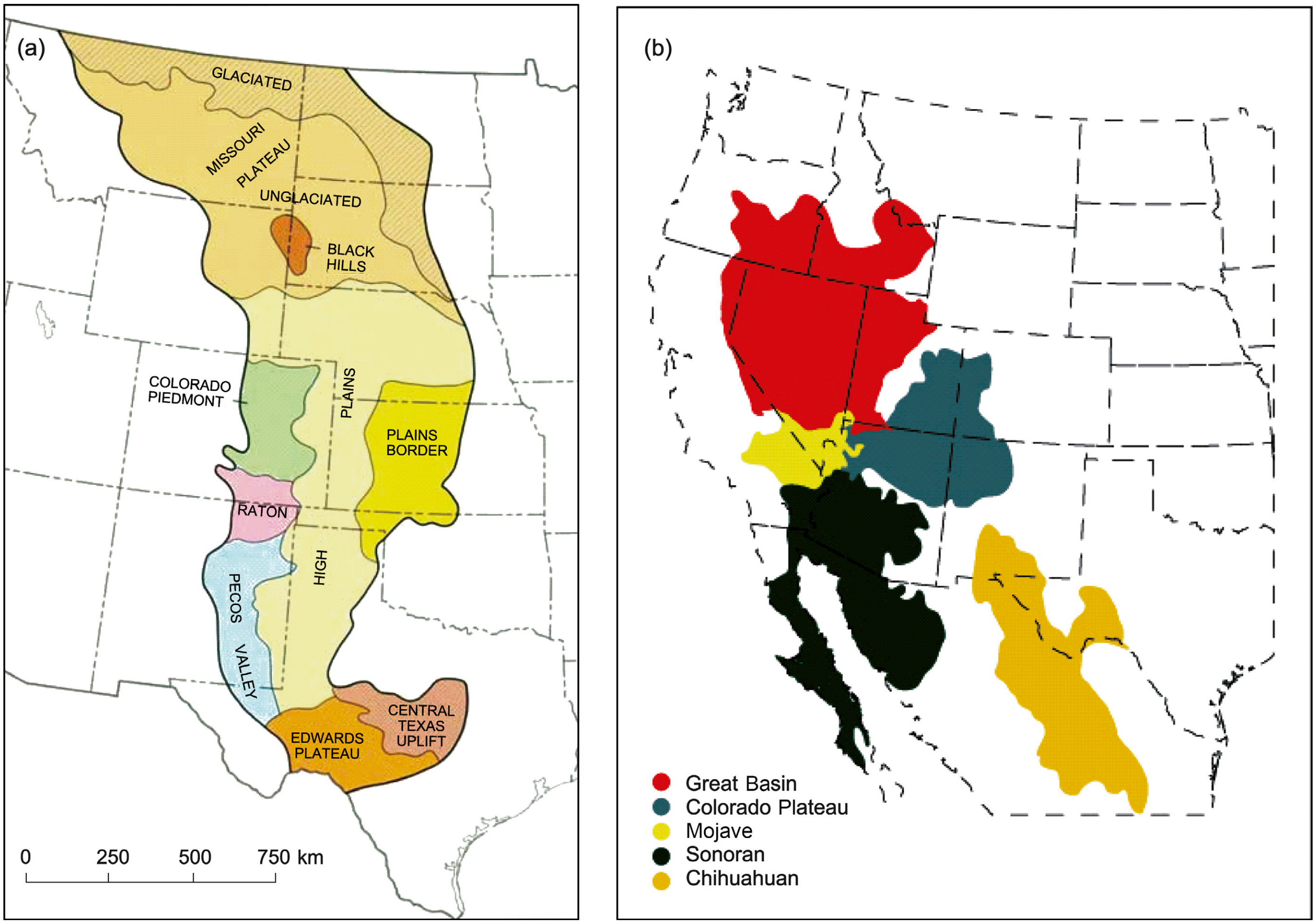

Fig. 1. (a) The Great Plains and (b) Desert Southwest regions.(Source: (a) Trimble 1980:8; (b) Tanaka et al. 2009:3). (Reprinted from Rangeland Ecology & Management 65(5), Framework for Comparing Ecosystem Impacts of Developing Unconventional Energy Resources on Western US Rangelands, 2012, with permission from Elsevier).

upshot is that monitoring conditions on the land—both ecological and social/economic—gives managers their best chance for informed adaptive management.

Overviewing the Northern Great Plains[9]

The Great Plains (Fig. 1a) transitions from a semi-arid climate in the west to a mesic, sub-humid climate in the east, and ranges from cooler temperatures in the north to warmer temperatures in the south (Fig. 2). Cool-season C_3 grasses dominate northern latitudes, giving way to warm-season C_4 grasses at central to southern latitudes, and drought-resistant shrubs in portions of the southern reaches (Terri and Stowe 1976, Epstein et al. 1997, Joyce et al. 2001) The growing season for the Northern Great Plains is approximately 110 d. Approximately 80% of the land area in the Great Plains is used for agriculture, with over half contributed by rangelands and pasture (Ojima et al. 2002). Average temperatures have increased in the region with fewer “cold” days, more “hot” days, and increased precipitation over much of the area (Karl et al. 2009). Annual precipitation is predicted to increase in the Northern Great Plains (Fig. 2b), though extreme events such as drought and intense precipitation events are expected to become more common (Karl et al. 2009). Temperature is predicted to continue to rise, with increases being greater in the northern reaches (Fig. 2c) (Christensen et al. 2007, Karl et al. 2009).

We summarize some of the more critical concerns that will likely impact the Northern Great Plains rangelands:

1. Climatic shifts are predicted to alter the competitive balance among plant species leading to species changes, including potential increases in invasive plants—the net effect of these predicted changes is unknown.
2. An altered balance of plant species is expected to alter critical wildlife habitat.
3. Increases in temperature along with rising CO_2 may enhance forage production in the Northern Great Plains.

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[9] For both the Northern Great Plains and the Desert Southwest, the general trends and projections reported here from the 2009 National Climate Assessment (Karl et al. 2009) are largely unchanged in the 2014 National Climate Assessment (Melillo et al. 2014). Because small changes in timing and magnitudes do not affect the arguments in this paper, we have chosen not to update what we reported.

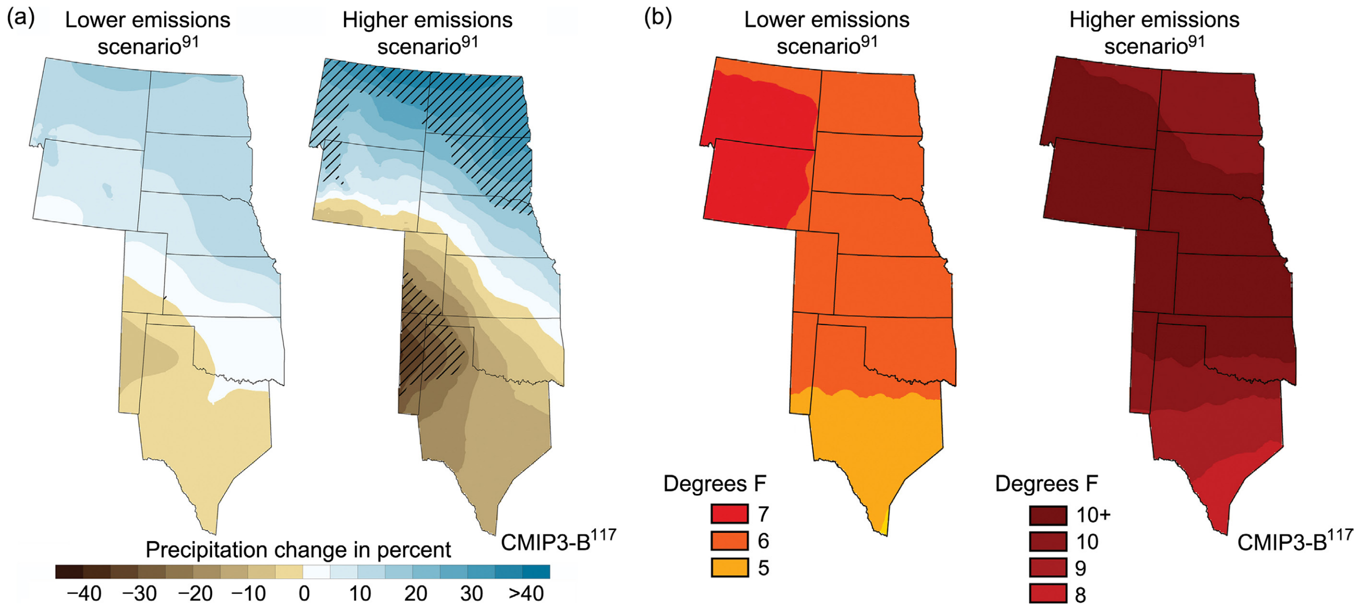

Fig. 2. Projected climatic conditions in the Great Plains. (a) Spring precipitation changes projected for 2080–2090s in the Great Plains for lower and higher emissions scenarios. Northern areas of the Great Plains are projected to experience a wetter climate by the end of this century, while southern areas are projected to experience a drier climate. The change in precipitation is compared with a 1960–1979 baseline. Confidence in the projected changes is highest in the hatched areas. And (b) summer temperature change in the Great Plains projected for 2080–2099 for lower and higher emissions scenarios. Temperatures in the Great Plains are projected to increase significantly by the end of this century, with the northern part of the region experiencing the greatest projected increase in temperature.(Source: Karl et al. 2009; Image credits: U.S. Global Change Research Program; www.globalchange.gov).

4. Increases in temperature, evaporation, and drought frequency are expected.
5. Warmer temperatures could enhance the spread of some plant and animal pests northward.

All of the above are likely to influence land-use change as cities and rural agriculture continue to compete for limited water resources. While precipitation may not be the limiting factor for rangeland productivity in the Northern Great Plains, rising temperatures will affect the timing of water availability as increased precipitation will influence the dynamics of the hydrologic cycle. In areas where precipitation is primarily snowfall, rising temperatures could instigate earlier melting and runoff events.

Overviewing the Desert Southwest

Southwest landscapes are dominated by the Chihuahuan, Sonoran, and Mojave Deserts. Desert vegetation in this region gives way to more woody and forested vegetation at the higher altitudes of the Colorado Plateau, and montane areas throughout the region (Fig. 1b). Raising livestock and associated agriculture have been important features of this region since the 18th century (Guido 2009).

Warming in the past few decades has been higher in the Southwest than in other regions of the United States and is predicted to continue (Karl et al. 2009). Annual precipitation is predicted to decline over almost all of this region for the remainder of this century (Fig. 3). Uncertainty remains an issue regarding the effect of climate as it influences the summer monsoonal precipitation pattern, responsible for delivering most of the region's precipitation. Given the region's fragile ecology, the following concerns are highlighted.

1. Water is expected to become increasingly scarce, though there is uncertainty regarding monsoonal responses. Severe drought has commonly occurred in the past and could be exacerbated in the future.
2. Increasing drought, temperature, wildfire, and species invasions will likely transform the landscape and render many rangelands less capable of supporting agriculture and wildlife.
3. A warmer, drier environment will likely reduce the effectiveness of restoration measures and/or their probability of success on degraded lands.
4. Intense precipitation events will likely decrease water-use efficiency, increase erosion and flooding potentials, and increase risks to people and animals.
5. More severe weather will decrease the region's attractiveness to tourism and recreation.

The issue of precipitation change and its implications for society are more critical and uncertain for the Southwest than for the Northern Great Plains. Water is already a scarce resource; any alterations in precipitation patterns are likely to have strong effects on plant production and community composition of the region (Smith et al. 2014). While there is consensus this region is headed toward a

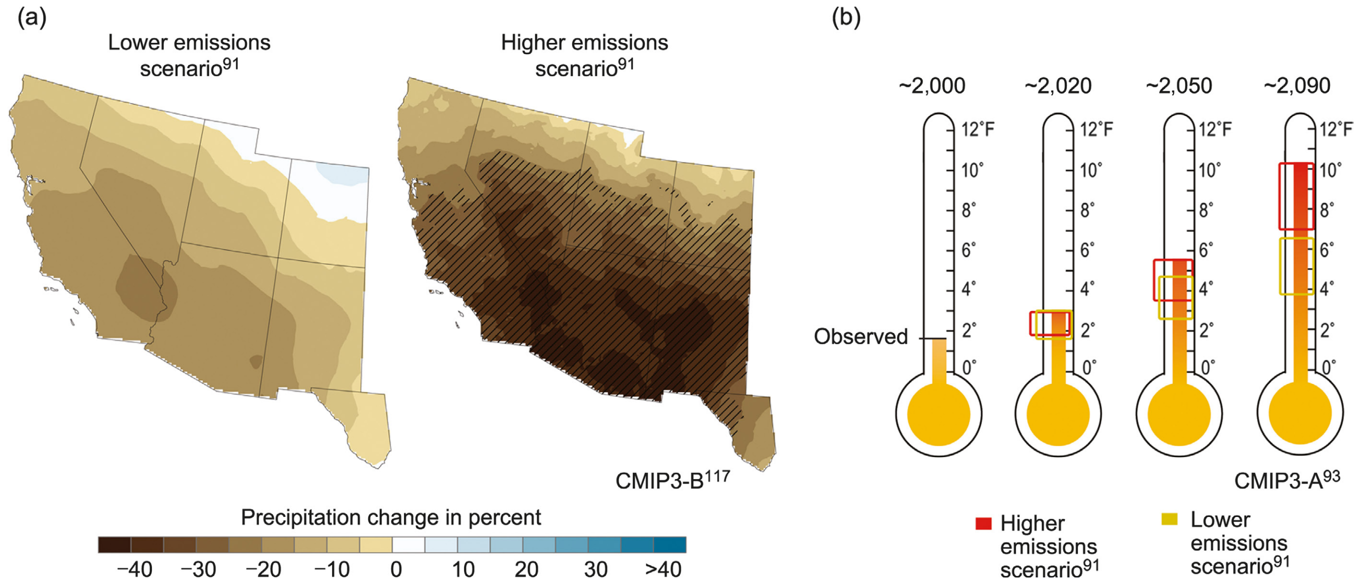

Fig. 3. Projected climatic conditions in the Desert Southwest. (a) Percentage change in March–April–May precipitation projected for 2080–2099 compared to 1961–1979 for lower and higher emissions scenarios. Percentage change in March–April–May precipitation for 2080–2099 compared to 1961–1979 for a lower emissions scenario[91] and a higher emissions scenario[91] (right). Confidence in the projected changes is highest in the hatched areas. And (b) projected average annual temperature, 2000–2090. Brackets on the thermometers represent likely ranges of model projections under higher and lower emissions scenarios. The average temperature in the Southwest has already increased roughly 1.5°F compared to a 1960–1979 baseline period. By the end of the century, average annual temperature is projected to rise approximately 4–10°F above the historical baseline, averaged over the Southwest region. The brackets on the thermometers represent the likely range of model projections, though lower or higher outcomes are possible.(Source: Karl et al. 2009; Image credits: U.S. Global Change Research Program; www.globalchange.gov).

drier future, uncertainty regarding the effects of climate change on the monsoonal dynamics complicates such predictions.

Addressing Uncertainty Regarding Climate Change and Rangeland Sustainability

Uncertainty as to how climate change will impact agroecosystems complicates efforts to develop appropriate management and mitigation strategies. There is no consensus on whether the answer is more scientific research or immediate policy action (Congressional Budget Office 2005). Potential consequences of irreversible decisions made under uncertainty are just one of the tradeoffs between waiting for better information that may never come and taking action that has some probability of mitigating adverse effects (Ingham et al. 2007).

In the case of climate change where both probability of occurrence and consequences of changes are highly uncertain, it may be useful to reframe the discussion in terms of vulnerability of rangeland systems to climate change. Vulnerability is the extent to which a system or system component is likely to experience harm due to exposure to a hazard or threat (Turner et al. 2003*a*). It involves characteristics inherent in a system that create a potential for harm to occur, but are not dependent on the risk of a particular event (Sarewitz et al. 2003). What is essential is to assess vulnerability as an integral part of the causal chain of risk and to appreciate that altering vulnerability is one effective risk management strategy (Kasperson et al. 2005).

The concept of resilience-based management has been proposed to aid rangeland managers in their ability to sustain desirable ecosystem states and ecosystem services in a changing and uncertain climate, and provide greater opportunities to incorporate adaptive management (Briske et al. 2008). Gradual changes in climate can trigger abrupt shifts (as if crossing a threshold) in vegetation to undesirable states from which recovery is impractical, if not impossible (Briske et al. 2005, 2006, Bestelmeyer et al. 2009). Thresholds are important in understanding how resilient ecosystems are to shifting to alternate states, and so indicate whether and when intervention might be necessary (Standish et al. 2014). Some evidence suggests loss of resilience can act as a precursor to shifts to alternate states (Scheffer et al. 2001), and managing for biodiversity can increase the resilience of desired ecosystem states (Elmqvist et al. 2003).

A focus on vulnerability implies a simultaneous focus on resilience. Turner et al. (2003*b*) predicated their vulnerability framework on the notion that vulnerability resides in the response capacities and system feedbacks to hazards encountered in the coupled human–environmental system. Whereas vulnerability reflects the susceptibility to harm, resilience reflects the ability to recover from harm (Standish et al. 2014).

It is important to consider ways in which ecosystems may amplify or attenuate the impacts of a hazard (Kasperson et al. 1988, Mitchell et al. 1989, Martine and Guzman 2002). Hazards or disturbances can lead to behavioral responses which, in turn, result in secondary impacts (Kasperson et al. 1988). Those secondary impacts can then have a cascading effect over time (Peters et al. 2007). Social and economic factors (poverty, loss of economic activity following disasters) and environmental factors (inappropriate land use, deforestation, erosion) interact to compound this vulnerability (Martine and Guzman 2002).

A framework of risk focuses on accruing more accurate predictions about the impacts of an event or series of events. Such a focus can be problematic in cases such as climate change where there is little to no experience with the phenomena being predicted. Understanding the uncertainties and incorporating them into management may become impossible (Sarewitz et al. 2003). Vulnerability involves characteristics inherent in a system which are often observable and therefore able to be monitored and better managed to increase resilience. The difference, in the end, might be subtle. But it puts managers into a proactive posture, based on things they can observe and act on, rather than trying to react to changes that may or may not occur.

Interactions Between Biophysical and Socio-Economic Systems and Management

Adaptive capacity may be described as the ability of a system to modify or change its characteristics or behavior so as to better cope with external stresses. Reductions in vulnerability arise from an understanding of a system's behavior and characteristics that enhance its ability to cope with external stresses (Brooks 2003). While climate change occurs globally, adaptive strategies are local or regional in nature and must consider the ecological, social, and economic drivers and responses of rangeland systems (Scheffer et al. 2015). Clark and Dickson (2003:8059) asserted that "… the multiple movements to harness science and technology for sustainability focus on the dynamic interactions between nature and society, with equal attention to how social change shapes the environment and how environmental change shapes society." The Integrated Social, Economic, and Ecologic Conceptual (ISEEC) Framework (Fox et al. 2009) built on those lines of thought by proposing ecosystem goods and services as the operative bridge between society and the environment. That is, the way in which climate change (and ecological change in general) becomes apparent to society is through changes in the functioning of environmental/ecosystem goods and services, which then evokes a societal response that further affects the functioning of ecosystem goods and services, thereby affecting the ecological realm of the ecosystem and triggering another iteration of feedback and response.

The ISEEC Framework complements a focus on vulnerability by highlighting linkages between system components and social, economic, and ecological states and processes. Initially, the framework depicts the current state and condition of the biophysical ecosystem along with the current state and condition of the socio-economic system (Fig. 4). Ecological and socio-economic processes, represented by the large vertical arrows between the "current" and "new" states/conditions, act on the states and conditions in the current time period, resulting in new states and conditions in the next time period. Perturbations and responses within the system differentially occur iteratively over time, thus incorporating a dynamic element. Changes in ecosystem goods and services are the means through which socio-economic systems and processes affect and are affected by ecological systems and processes. Socio-economic responses to ecological changes result in further changes in the delivery of ecosystem benefits that provide feedback to core ecological processes resulting in changes to the state and condition of the ecosystem. Assessment of sustainability occurs through interpretation of how and why changes occur between time periods.

A Rangeland Illustration

Once considered primarily for grazing and livestock production, rangelands are proving to be a complex set of ecosystems requiring a sophisticated approach to land management (Joyce 1989, Mitchell 2000). Energy production on rangeland ecosystems is increasing with the rise of unconventional energy sources such as shale oil/gas, wind, solar, and biofuels (Pletka and Finn 2009, Kreuter et al. 2012). Beyond the energy extraction itself, expanses of rangeland are impacted by energy transmission corridors and other energy-associated infrastructure. These activities can exacerbate issues associated with soil erosion, ecosystem fragmentation, water quantity/quality, and other ecological functions that produce ecosystem goods and services. Recreational uses of off-highway vehicles have amplified previously unconsidered concerns with increasing tourism demand for rangeland ecosystems (Wulfhorst et al. 2006, Ouren et al. 2007). Sheridan (2007) described the complex interactions between traditional uses of rangeland and the protection of threatened and endangered (T&E) species that rely on those systems. The Endangered Species Act can limit livestock grazing and other commodity uses of rangeland. These expanded, and potentially conflicting, rangeland uses further underscore the need to assess, monitor, and understand rangeland ecosystems.

Consider domestic livestock grazing as one extensive use of western rangelands. Rangelands provide habitat, food, and clean water to support livestock. The products of these operations (e.g., beef) are, in turn, used by humans. As more outputs are produced, economic theory predicts prices will respond in a downward direction and induce an increase in quantity demanded. As quantity of beef demanded increases, beef prices begin to rise,

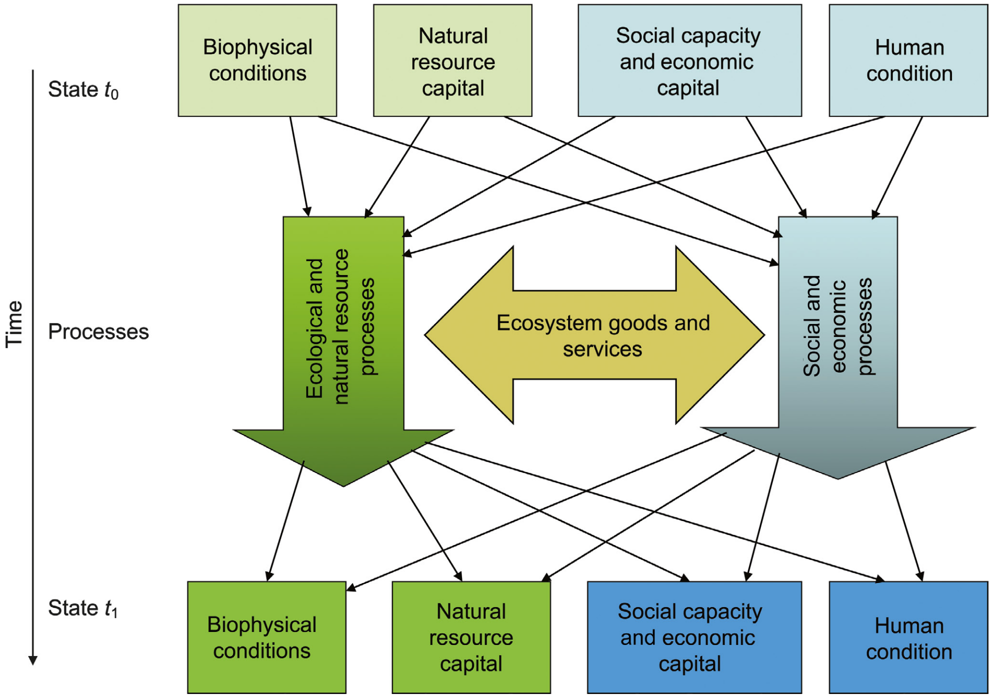

Fig. 4. Integrated Social, Economic, and Ecologic Conceptual Framework. Adapted from Fox et al. (2009). (Reprinted from Society and Natural Resources 22(7), An Intergrated Social, Economic, and Ecological Conceptual (ISEEC) Framework for Considering Rangeland Sustainability, 2009, with permission from Taylor & Francis).

signaling managers to increase output. In both the short and long terms, ranchers adjust their herd sizes based on expectations of forage supply that can be balanced with their herd size and expectations of prices. Decreases in herd size in response to either price or changes in forage availability or quality can be done fairly quickly through brood stock sales. Increases in herd size in response to those same factors often take longer, as most ranchers expand their herds through retained breeding stock rather than purchases.

Where rangeland assessment indicates overutilization of land by livestock, resulting in lower forage productivity and less output produced, there may be feedback time lags such that some effects are realized sooner than others. A change in productivity due to a drought might occur over a season or two, whereas a change in forage availability due to a T&E species can occur almost immediately. Nonetheless, producers are signaled that changes are needed. Observation of decreased rangeland productivity will trigger compensatory management responses such as reduced herd size, increased use of other pastures, or supplemental feeding. The assessment cycle continues through time and thereby iteratively provides a stream of information to managers. Incorporating simultaneous effects of climate change into this framework increases complexity, as does consideration of alternative land uses (Peters et al. 2004, 2007, Kéfi et al. 2007). Elevated atmospheric CO_2 resulting from climate change may affect the nutritive value of forage, thereby further affecting land productivity for livestock production (Owensby et al. 1993). It could also affect the mix and diversity of forage species supported by the rangeland.

Changes in climatic conditions evoke biophysical responses in rangeland ecosystems. These biophysical changes, in turn, lead to corresponding responses in socioeconomic systems. In areas of reduced precipitation, land managers might need to provide additional forage or supplements to support their operation which increases their cost of production, or reduce output to match available resources, resulting in reduced income. If land managers decide to leave livestock on rangeland for longer periods of time to provide additional forage, there will be increased stress on the land creating risk of degradation, thus prompting further ecological response. In areas where increased forage production results from climate change, ranchers may choose to increase herd size to take advantage of that forage, resulting in additional economic activity.

Besides those direct costs or benefits to ranchers as climate change effects unfold, livestock management will affect the quality and quantity of other benefits produced by rangeland ecosystems. For example, a hotter, drier climate in the Desert Southwest could lead to irreversible ecosystem transformations. Changes in vegetation composition will affect wildlife habitat, aesthetics, and other values people place on rangelands. Accelerated erosion could have similar effects, but also potentially affect water quality.

(Adaptive) Management and social responses, such as restoration of degraded rangelands, opening additional rangeland for grazing, or restricting livestock grazing can mitigate adverse effects. Increased competition for water between agricultural uses and human uses will intensify as conditions become warmer and drier. These changing conditions and reactions cause feedback responses cycling iteratively over time. Monitoring and assessing these response factors, including levels of ecosystem services, is a critically important component of adaptive management for rangeland sustainability.

Management Considerations in the Northern Great Plains

Land managers on the Northern Great Plains will likely have more opportunities to proactively mitigate effects of climate change because its effects are expected to be less deleterious. Some indicators to consider are provided in Table 1. These are adapted from the Sustainable Rangelands Roundtable national indicators (Mitchell 2010). Table 1 also indicates the direction of change expected for each indicator as a result of predicted climate change and identifies the linkage (numbered arrows) shown in the more detailed ISEEC Framework (Fig. 5), which shows some of the specific socio-economic and ecological processes that were collapsed into the vertical arrows in Fig. 4. Anticipated changes and effects, indicated by the +, −, and 0 symbols, are based on judgments by the authors for illustration. They are not assessments of expert opinion or empirically measured effects. In some cases, this kind of qualitative consideration may be sufficient to inform management. In other cases, further analyses and formal empirical measures may be needed. Both qualitative and quantitative measures can be incorporated into a monitoring protocol.

The predicted increase in precipitation and longer growing season in the north, along with continued rising of atmospheric CO_2, points to an increase in forage production (depicted by the + sign on Table 1, associated with Arrow 1 in Fig. 5). While ranchers may increase the number of livestock on rangelands as a result, it is likely that the amount of land available for grazing will not change (Table 1, Arrow 4). In the short term, more livestock on the land would induce a further ecological response (Table 1, Arrows 1 and 3).

Due to the increase in productivity, the rate of return on investment in the ranch and the proportion of total income from ranching would increase (Table 1, Arrow 4). Since forage is predicted to be more abundant, its value would decrease (Table 1, Arrow 5), while the value of other products is indeterminate. Recreation is predicted to increase over time (Bowker et al. 1999, Cordell et al.

Table 1. Indicators to detect expected effects on rangelands from changes in climatic conditions.

		Expected climate change effects‡	
Arrow†	Indicator(s)	Northern Great Plains	Desert Southwest
1	Precipitation	+	−
	Rangeland annual forage production	+	−
2	Increase in the frequency and duration of surface no-flow periods in rangeland streams	+	+++
	Extent and condition of riparian systems	0	−−
3	Area and percent of rangeland with a significant change in extent of bare ground	0	+++
	Integrity of natural fire regimes on rangeland	0	−−
	Number of domestic livestock on rangeland	+	−−
4	Rate of return on investment for range livestock enterprises	+	−
	Level of dependence on livestock production for household income	+	−
	Percent of available rangeland grazed by livestock	0	−
	Number of domestic livestock on rangeland	+	−−
5	Value of forage harvested from rangeland by livestock	−	+
	Value of production of non-livestock products produced from rangeland	+/−	+
6	Area and percent of rangeland with a significant change in extent of bare ground	−	++
	Area of infestation and presence/absence of invasive and non-native plant species of concern	0	+
	Area and percent of rangeland with accelerated soil erosion by water and wind	0	++
	Fragmentation of rangeland and rangeland vegetation communities	0	+
	Density of roads and human structures	+	+
	Presence and density of wildlife functional groups on rangeland	0	−−
7	Number of visitor days by activity and recreational land class	+	+
	Value produced by recreation industry as percent of total economy	+	−
8	Value of investments in rangeland, rangeland improvements, and infrastructure	0/+	−−−
	Expenditures (monetary and in-kind) on restoration activities	0	+
9	Value of investments in recreation/tourism infrastructure	+	++
10	Economic policies and practices	0	+
	Public information and public participation	+	++
	Professional education and technical assistance	+	++

† Arrow numbers refer to the linkages (arrows) in the detailed Integrated Social, Economic, and Ecologic Conceptual Framework (Fig. 5).
‡ "+"indicates a positive change; "−"indicates a negative change; "0" indicates no change; strength of change is denoted by the number of symbols.

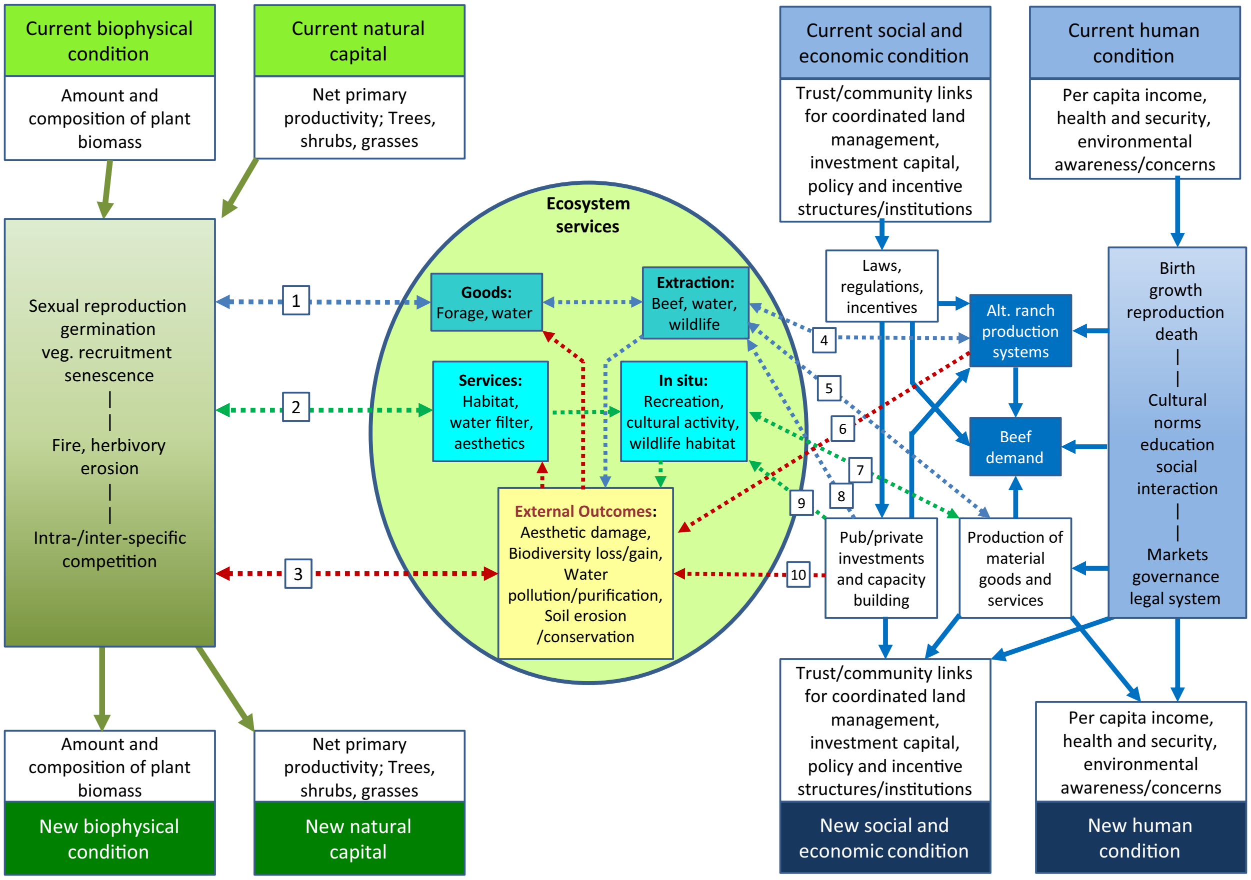

Fig. 5. Integrated Social, Economic, and Ecologic Conceptual Framework in greater detail with highlighted interactions. Adapted from Kreuter et al. (2012). (Reprinted from Rangelands 31(3), SRM Center for Professional Education and Devlelopment: Wildfires and Invasive Plants in American Deserts, 2009, with permission from Elsevier).

1999, 2009, Cordell and Betz 2008) and the value produced by recreation will increase (Table 1, Arrow 7). At the same time, there will be impacts, both positive and negative, on the ecosystem. The density of roads and human structures are expected to increase, while the extent of bare ground (erosion potential) may be expected to decrease (Table 1, Arrow 6). In this scenario, other effects on the ecosystem are expected to be negligible.

As these changes are occurring, it is plausible to expect investment in rangeland improvement practices to remain static or increase slightly due to higher returns on investment (Table 1, Arrow 8). Investments to restore rangelands may stay static or decrease as increased precipitation may make existing restoration actions more effective, thereby negating the need for more interventions (Table 1, Arrow 1). As demand for recreation opportunities increases, we can expect more investment in recreational facilities and infrastructure (Table 1, Arrow 9).

As a result, under the predicted conditions in the Northern Great Plains, there may be little incentive to change economic policies to assist the ranching sector. Any increased public involvement in land-use laws and policy would result in the need for further education and technical assistance to address these emerging issues (Table 1, Arrow 10).

Management Considerations in the Southwest

Southwestern rangelands are generally limited by precipitation. Annual precipitation is bimodal, characterized by a highly variable winter and early spring period and monsoonal rains in July and August (Swetnam and Betancourt 1998). The winter precipitation is important for recharging soil moisture; however, it is the summer rainfall that primarily controls rangeland productive capacity (Table 1, Arrow 1) and provides forage (Table 1, Arrow 4) for grazing animals (Paulsen and Ares 1961). Managers can anticipate relatively wet or dry winters based on predicted El Niño and La Niña events, respectively (Sheppard et al. 2002), but the summer monsoon remains less predictable.

Livestock herd adjustments (Table 1, Arrow 4) offer the primary rangeland management tool in the Southwest (Torell et al. 2010). Stocking rates depend on both present productivity and residual biomass (Table 1, Arrow 5) remaining from the previous year's utilization (Paulsen and Ares 1961). During extreme droughts (Table 1, Arrow 1), it can become necessary to remove nearly all livestock from affected rangelands (Table 1, Arrow 4). An ecological response to removing the livestock would then occur (Table 1, Arrow 3).

Shrub encroachment into desert grasslands (Table 1, Arrows 3 and 6) is driven, in part, by precipitation (Swetnam and Betancourt 1998), and in some locations may be promoted over the long term by rising CO_2 (Polley 1997, Morgan et al. 2007) and temperature (Shaw et al. 2000). Because shrubs can dramatically reduce forage production and cause accelerated erosion (Table 1, Arrows 1, 3, and 6), control of non-desirable shrubs is best attempted at an early stage of infestation, requiring managers to better understand how different states and transitions apply to their local ecological sites. State-and-transition models serve as tools to better understand how landscapes might respond to climate variability and organize options for responding (Bestelmeyer et al. 2004).

Forage quality is a factor affecting rangeland management in all regions. In the Southwest, forage quality (Table 1, Arrows 1 and 5) is correlated with precipitation (Cable and Shumway 1966). Land managers can take advantage of forage quality during critical periods of calving and prior to weaning by adjusting the timing of calving season (Vavra and Raleigh 1976). Winter calving, at the time of winter forage growth, is possible in the Southwest because of the mild weather generally present at that time. As temperatures increase over time and growing seasons lengthen, winter calving becomes even more feasible (Table 1, Arrow 4).

Given climate model predictions that the Southwest will become increasingly arid and hotter during this century (Seager et al. 2007), land managers must plan on droughts becoming more intense, if not more frequent (Table 1, Arrow 2). Recent research has also shown that, at broad scales, economic returns significantly decline with increasing annual temperatures (Burke et al. 2015). Management that reduces vulnerability, and thereby ecological and financial risk, will be essential to any planning framework (Table 1, Arrows 4, 5, 7, 8, and 9). Although little research to date has focused on the synthesis of ecological and economic sustainability under a varying climate (Craine et al. 2010, 2012, Ritten et al. 2010, Torell et al. 2010), science has shown that optimal (profit maximizing) stocking rates for economic returns may be lower than stocking rates that maximize livestock production (Workman 1986). This future points toward a subset of indicators related to economic and social interactions. Livestock prices, livestock product demand, cost of alternative feedstock and supplements, local labor market conditions such as unemployment and wage rates, local community, and economic stability could be considered useful assessment indicators (Table 1, Arrows 5–10).

General Comments on Rangeland Management

Table 1 and Fig. 5 illustrate interactions between ecological systems and social/economic systems, and iterations that would occur as changes and responses take place. The illustration is simplistic, but one can see how interactions between ecological factors and social/economic factors could extend and amplify, and sometimes attenuate, effects of possible changes due to climate. Consideration of energy, recreation, and other uses of rangelands further complicates the manager's job. Managers are asked to promote ecological and economic resilience in the face of climate change and other disturbances. Information provided by monitoring and understanding how systems interact and feedback on each other will not necessarily make their job easier but it will allow managers to make better informed decisions.

Projections such as those discussed in relation to the Northern Great Plains and Desert Southwest can suggest the kinds of changes that might be anticipated—a starting point for managers. Monitoring and evaluating observable conditions over time can point to those parts of the ecosystem (whether they be ecological or social/economic) that are likely to be vulnerable to changes related to climate. Acknowledging the importance of both realms (biophysical/ecological and social/economic) of the total ecosystem, and their dependence on each other, is critical to whatever degree adaptive management is possible. Interaction between the two realms in an iterative feedback and response mechanism underscores the dynamic nature of changes to the ecosystem, and how both realms contribute to ecosystem response to a perturbation. Further, it suggests the potential to approach management with multiple different actions, possibly leveraging their effects. Monitoring observable conditions on the land provides information regarding the rates and magnitudes of changes occurring in the ecosystem, which can inform and guide managers on potential adaptation and mitigation strategies. State-and-transition models are a useful tool for using those rates and magnitudes of change to signal the possible approach of a threshold of transitional change. Adaptation is undertaken to achieve mitigation.

Regardless of region, informing and diversifying management plans can help to more effectively reduce vulnerability (and increase resilience) to climate change, and increase flexibility to adapt to changes and cycles in conditions. Rangeland health and productive capacity for ecosystem goods and services are key. Identifying and monitoring vulnerabilities, and focusing adaptive management on those vulnerabilities to increase resilience of rangeland systems, is one way managers can respond to changing conditions in spite of uncertainty.

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