**Pasturelands, Rangelands, and Other Grazing Social-ecological Systems**

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## 1. Abstract

Grazing systems are globally extensive, heterogeneous, sensitive to climate, and managed by humans to support livestock production that provide an essential source of food in many parts of the world. The intensity of grazing system management can be broadly categorized into rangelands (natural grazing lands) and pasturelands (improved grazing lands). Whereas rangeland management approaches focus on reversing land degradation and restoring overgrazed ecosystems, pastureland management involves interventions (i.e., applying fertilizer, intercropping leguminous plants) that can increase the amount of forage produced and the number of cattle supported on the landscape. The management of grazing social-ecological systems faces numerous challenges including climate change, land degradation, nutrient loss, compaction and food insecurity. Grazing management for the provision of ecosystem goods and services beyond supply of food and fiber is required to support the sustainability of global grazing lands in the coming decades. As we balance the challenges of food security, climate change, and environmental sustainability, it is of critical importance to understand the social-ecological processes that govern the management of grazing lands, an under-studied element of global land use.

## 2. Introduction

Approximately 26% of Earth's land (excluding Antarctica) is occupied[1] by grazing systems, making them the largest non-forest land use on the planet (FAO 2011, Erb et al. 2017). A defining feature of livestock production is that ruminants (e.g., bovines, sheep, and goats) spend at least some of their lifetime grazing, however, there are several terms used to refer to large grassy areas depending on the intensity of use: grasslands, rangelands, pasturelands, and grazing lands. Practitioners and researchers usually distinguish among natural grazing lands (also called rangelands) and improved grazing lands (also called pasturelands) (Allen et al. 2011, Garnett et al. 2017). While the term grasslands describes ecological communities that are dominated by grasses, the term grazing lands refers to the potential or realized use of grasslands to humans. Rangelands are dominated by natural vegetation whose species composition has not been altered to boost livestock productivity (Allen et al. 2011, Garnett et al. 2017) (Fig. 1.1 b). Rangelands can be characterized as grasslands, shrub steppe, shrublands, savannas, and deserts that are managed to provision ecosystem services to benefit human well-being. Pasturelands, on the other hand, are more intensively managed by planting nutrient rich grasses and legumes, or by using fertilizer and other amendments (Allen et al. 2011, Garnett et al. 2017) (Fig. 1.1 a). Heretofore, we refer to rangelands and pasturelands together as grazing lands or grazing systems.

[1] Though the land occupied for grazing may include multiple non-grazing uses as well, just as grazing may occur in areas not primarily devoted to livestock production.


Figure 1.1 Examples of (a) pastureland (i.e., intensively managed planted grassland), (b) rangeland (i.e., extensively managed natural grassland), (c) silvo-pastoral system, and (d) integrated crop-livestock system.

## 3. Ecosystem services provided by grazing systems

There are four different categories of ecosystem services: provisioning, regulating, supporting, and cultural (MA 2005, Sala et al. 2017). Because grazing systems are heterogeneous, they provide numerous ecosystem services in addition to provisioning feed for livestock, and food and fiber for the world's pastoralists (Sala et al. 2017). In the case of grazing lands, *provisioning services*, which are the products that can be directly harvested and have market value, are freshwater and forage for livestock to produce meat, milk, wool, and leather (Sala and Paruelo 1997, Sala et al. 2017). The main ecosystem *regulating service* in grasslands is soil carbon sequestration. *Supporting services* enable the production of all other ecosystem services such as nutrient cycling, conservation of soils, habitat and biodiversity (MA 2005, Sala and Paruelo 1997). Lastly, *cultural services*, which are the nonmaterial benefits that humans obtain from grazing lands, include social status, traditional lifestyles, and tourism (Sala et al. 2017). From local-to-global scales, ranchers, commercial entities, and the public sector all benefit from the ecosystem services that are provided by grazing lands.

### 3.1 Provisioning services

Grasslands are a key feed resource, accounting for close to 50% of feed use in livestock production systems globally (Herrero et al. 2013). While in many parts of the world grassland provisioning services are directly traded in markets, in other places pastoralists depend on provisioning services for their livelihoods. Specifically, the livestock sector provides income for approximately 1.3 billion people worldwide and food for approximately 800 million food-insecure people (Herrero et al. 2013). Globally, the livestock sector produced approximately 586 million tons of milk, 59 million tons of beef, and 11 million tons of small ruminant meat in 2000 (Herrero et al. 2013). Although most rangeland-based systems occupy less productive lands compared to pasturelands, they provide a key source of livelihood for pastoralists in regions that rely on extensive livestock production. Indeed, rangeland-based systems account for the majority of small ruminant meat production, for local production of beef in Latin America and Oceania, and for small ruminant milk production in Sub-Saharan Africa (Herrero et al. 2013).

### 3.2 Regulating services

Grassland soils contain one third of the terrestrial soil organic carbon pool because they are geographically extensive and have relatively high per unit area carbon storage (White et al. 2000, Garnett et al. 2017). However, the ability of grasslands to sequester carbon is limited due to variability in many factors (e.g., soil type, nutrient availability) that determine if organic matter is converted to stable belowground carbon. Planting deep rooted grasses and legumes, adding manure to soils, stimulating forage productivity, and changing the timing and intensity of grazing can potentially increase the rate of soil carbon sequestration (Batjes, 2014, Garnett et al. 2017). Good grazing management at the right stocking rate can maintain or even increase soil carbon sequestration by stimulating plant growth, which can lead to an increase in the proportion of organic matter that's partitioned belowground (Batjes, 2014, Garnett et al. 2017). Although soil carbon stocks can quickly increase after an improvement in management, especially in degraded grazing lands, the rate of increase progressively declines as the system approaches an equilibrium (Smith 2014). As a result, while managing for land-based carbon sequestration in grazing systems is useful, it only plays a minor role in offsetting greenhouse gas emissions to which the livestock sector itself is a significant contributor.

### 3.3 Supporting services

#### 3.3.1 Wildlife habitat and biodiversity

Maintaining biodiversity in grazing systems is key not only to sustaining grassland flora and fauna but also to delivering all other ecosystem services. Managing for grassland structural heterogeneity, for example, can improve forage availability, enhance ecosystem functionality, and increase habitat availability for different plant, insect, bird, and mammal species (Fuhlendorf et al. 2017, Tews et al. 2004, Fuhlendorf et al. 2006). There are two aspects of biodiversity that appear to be critical for provision of ecosystem services and resilience to environmental change: functional-group diversity and functional-response diversity (Folke et al. 2004, Elmqvist et al. 2003). While functional-group diversity refers to groups of organisms that perform different functions in an ecosystem (i.e., graze, fix nitrogen), functional-response diversity refers to the ability of species from the same functional-group to respond differently to environmental change (i.e., rainfall, grazing). Loss of both types of functional diversity can cause dramatic alterations in ecosystem functioning (Chapin et al. 1997, Duffy 2002, Jackson et al. 2001).

#### 3.3.2 Soil conservation and nutrient cycling

Globally, grassland soils are very diverse and their characteristics and functions are critical determinants of the ecosystems services that grazing systems can provide. Grassland soil structure and biogeochemical cycles are controlled by three major functional groups of organisms: vascular plants, biological soil crusts, and soil microbial communities (Evans et al. 2017). In addition, soil biogeochemical cycles (i.e., water, carbon and nutrients) vary as a function of precipitation, phenology, disturbance regimes, and management practices (Evans et al. 2017). Rangelands, in particular, are a critical component of global biogeochemical cycles because they are globally extensive and sensitive to changes in resource availability caused by ecosystem drivers (Donohue et al. 2013, Poulter et al. 2014). In grazing lands, the quality and productivity of forage and, in turn, livestock are determined by the efficiency of these nutrient cycles. Managing these ecosystems for soil conservation and nutrient cycling involves controlling livestock density to minimize soil compaction and overgrazing, maintaining plant diversity, planting legumes, and incorporating manure and fertilizers to the soil according to a comprehensive nutrient management plan (Bellows, 2001).

### 3.4 Cultural services

While the provisioning, regulating, and supporting services that grazing lands provide often translate into material benefits to farmers (i.e., food and income), many land use choices are driven by the non-material benefits these systems provide (Garrett et al. 2017). The degree to which different non-material outcomes result in improved well-being is related to cultural preferences. Many farmers choose grazing systems as a livelihood due to the low and less seasonal labor demands relative to most systems of crop production (Hecht 1993, Muchagata and Brown 2003), a desire to pursue a lifestyle independent of markets and governments (Skaggs 2008, van der Ploeg 2010) and as a status symbol ( Walker, Moran, and Anselin 2000, Hoelle 2011). For example, the persistence of low income cattle ranching in the Brazilian Amazon and Cerrado has been linked to its cultural importance as a source of social status and a tranquil lifestyle (Garrett et al. 2017, Wilcox 2017b). Grazing lands and the biodiversity they harbor also provide aesthetic and spiritual values, including a sense of place, to both inhabitants and visitors (Knight 2002). These cultural values are reflected in the value of tourism activities and land prices, which often exceed the income provided by livestock rearing (Skaggs 2008).

It is important to note that while grassland ecosystems provide cultural services, cultural traditions also shape ecosystem services by determining land use diversity and intensity. In the Swiss Alps, for example, Romanic, German, and Walser villages exhibit very different land use configurations resulting in different levels of plant diversity within similar types of grazing systems (Maurer et al. 2006). Among Old Order Amish farmers in the United States cultural preferences toward autonomy, social controls on the introduction of new technologies (e.g., synthetic inputs, heavy machinery), and a refusal of government assistance, such as subsidized insurance (Stinner et al. 1989), have helped protect grazing systems within increasingly homogenized cropland landscapes (Garrett et al. 2020, Parker 2013).

## 4. Management of grazing systems

Climate is a major driver of ecosystem structure and function in grasslands, with near-term precipitation being the dominant climatic control and antecedent precipitation being secondary (Knapp and Smith 2001, Sala et al. 2012, Wu et al. 2015). As a result, the timing and amount of precipitation are key factors that limit soil moisture availability and annual vegetation productivity, and subsequently constrain grazing livestock density (Sala et al. 2012, Wilcox et al. 2017a, Sloat et al. 2018). Changes in water availability due to drought, for example, have negative impacts on the provision of grassland ecosystem services, with especially profound response in soils where microbial activity, nutrient availability, and soil carbon sequestration depend on soil moisture (Evans et al. 2017).

In addition to climate variability, vegetation dynamics and productivity in *rangelands (i.e., extensively managed systems)* are also driven by livestock density (Gaitán et al. 2014, Sala et al. 2012, Wilcox et al. 2017a, Ellis and Swift, 1988, Briske et al. 2003). Specifically, while grazing primarily affects the long-term structure and composition of rangelands, precipitation variability primarily affects yearly plant production and forage availability (Ellis and Swift, 1988, Briske et al. 2003, Fernandez-Gimenez and Allen-Diaz, 1999). In many regions of the world, continuous, unconstrained grazing (i.e., overgrazing) on rangelands with already poor soils or in climates with long dry seasons has led to degradation (decreased water infiltration and surface organic material leading to a loss of soil structure, nutrients, and water availability, and encroachment by invasive species) (King and Hobbs 2006, Perkins and Thomas 1993). Recent sustainable rangeland management approaches have focused on reversing land degradation and restoring overgrazed ecosystems (Briske et al. 2008, Bestelmeyer et al. 2012). Specifically, resilience-based rangeland management aims to maintain desirable ecological states (i.e., grasslands) in order to avoid ecological thresholds that lead to less desirable ecological states (i.e., desert shrubland) (Bestelmeyer et al. 2012, Elmqvist et al. 2003, Briske et al. 2008).

In *pasturelands (i.e., intensively managed systems)*, climate is also a major driver of productivity. Yet, human interventions such as irrigation, rotational grazing (frequently moving cattle through smaller paddocks to avoid grazing beyond an optimal threshold), applying soil correctives and fertilizer, and intercropping leguminous plant species (e.g., forage peanut) are mechanisms that can outweigh climatic effects on grass productivity while also improving animal nutrition (Valentim and Andrade 2005, Nobilly et al. 2013, Condrone et al. 2014). Grazing duration and intensity can also be managed to optimize productivity and economic returns. Other important improved grassland systems include integrated crop-livestock systems (planted pastures that are rotated with cropland) (Fig. 1.1 d) and silvo-pastoral systems (planted or natural pastures that are intercropped with tree species) (Fig. 1.1 c). These systems rely on synergies between the cropland, tree, and grazing land uses to increase nutrient availability and improve soil structure when livestock are kept at low to moderate grazing intensities (Lemaire et al. 2014, Carvalho et al. 2014, Ryschawy et al. 2017). These synergies can reduce needs for external inputs while maintaining or increasing productivity and profitability (Schiere et al. 2002, Garrett et al. 2017, Gil et al 2018). While mixed and integrated crop-livestock production systems are common in sub-Saharan Africa and Southeast Asia (Robinson et al. 2011), they remain very rare in the Global North and other important grazing regions (Garrett et al. 2020).

Collectively, these management decisions can substantially increase the amount of forage produced, as well as the number of cattle that can be supported, while decreasing the amount of time it takes the cattle to achieve slaughter weight. In Brazil, for example, existing ranching management practices in Brazilian Cerrado are highly extensive and the current productivity of these pastures is only 32-34% of its potential (Strassburg et al. 2014). Studies have shown that introducing rotational grazing can double the amount of protein produced per hectare, while integrated crop and livestock systems can increase the amount of protein produced by nearly 700% (Gil et al 2018).

Traditional approaches to grazing system management have focused on the provision of food and fiber but have often been inadequate in guiding the provision of other ecosystem goods and services (Sala et al. 2017). For example, despite management efforts, rangelands have remained vulnerable to accelerated soil degradation, which impairs their ability to provide both regulating and supporting ecosystem services (Sala et al. 2017). At different temporal and spatial scales, climate variability, land degradation, and the feedbacks between these two processes can reduce the ability of grazing systems to maintain ecosystem services.

## 5. Challenges in grazing systems

Quantifying the susceptibility of grazing systems to climate variability and land degradation is critical for anticipating grassland feed shortages and for monitoring regions that are vulnerable to desertification and woody encroachment. However, modeling the response of these ecosystems to climate variation, for example, is challenging because they are actively grazed by livestock and managed by humans, which means that their dynamics are influenced by grazing, soil amendments and precipitation at multiple spatial and temporal scales. The interacting dynamics of climate variability, land degradation, and management shape the demand and provision of ecosystems services of grazing social-ecological systems (Fig. 5.1).

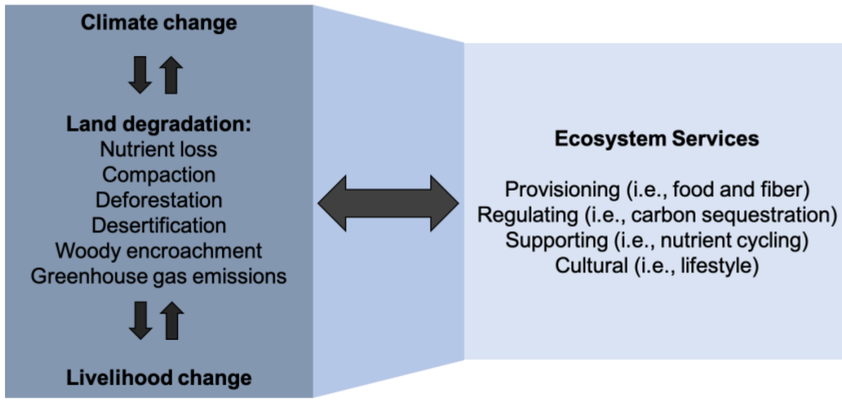


Figure 5.1 Generalized diagram of ecosystem services and challenges in grazing social-ecological systems. Humans and the environment interact to shape the demand and provision of ecosystem goods and services.

## 5.1 Climate change

In the coming decades, the response of ecosystem processes to changes in the frequency and intensity of drought are likely to be exacerbated by rising temperatures (Polley et al. 2017, Huang et. al. 2016). Recent studies suggest that up to 66% of global land areas are experiencing drying, and precipitation events in arid and semi-arid regions are forecast to become shorter, less frequent, and less widespread (Huang et. al. 2016, Reeves et al. 2014). When combined with overgrazing, a warmer and drier climate can ultimately result in decreased productivity and directional shifts in the cover and composition of plant communities in grazing systems (Polley et al. 2017). If realized, then these changes pose a significant threat to the sustainability of these systems, especially in arid and semi-arid regions.

## 5.2 Desertification

Twenty to thirty-five percent of the world's pastures are in poor condition and show signs of degradation, especially when compared to natural grasslands (non-pasture) where direct human impacts are limited (Garnett et al. 2017, Conant, 2010). Dryland ecosystems are especially vulnerable to degradation due to multiple biophysical and social stressors that exert pressure at different temporal and spatial scales: climate, land use, economic and institutional factors, national policies, and population growth (Reynolds et al. 2007, Geist and Lambin 2004). When degradation is characterized by severe reductions in biological activity and by a persistent state change, a regime shift, it is also known as desertification. Desertification often happens when poor management practices such as depletion of water resources and overgrazing are compounded by exploitative and distant economic and political systems (Bestelmeyer et al. 2015, Reynolds et al. 2007). Most dryland livelihoods depend closely on highly variable biophysical drivers such as precipitation, which means that there is great uncertainty in detecting thresholds of state change and maintaining the sustainability and future of these social-ecological systems.

### 5.3 Woody encroachment

In drylands, woody encroachment is often an example of desertification because continuous grass cover is replaced by patchy vegetation cover with increased proportion of bare soils, which leads to increased water and wind erosion, and nutrient loss for the soil in plant interspaces (Barger et al. 2011, Evans et al. 2017, D'Odorico et al. 2012). Encroachment is likely to result in degradation of value for cattle and sheep production, but does not necessarily result in degradation of structural and functional capacities of the ecosystem (Eldrige et al. 2011). The drivers of woody encroachment are complex and vary greatly by region and ecological zone but often reflect an interaction among climate (i.e., intensity and frequency of precipitation), land use (i.e., grazing), atmospheric chemistry (i.e., $CO_2$ concentrations), soil properties (i.e., texture and depth), and disturbance regimes (i.e., fire frequency and intensity) (Briggs et al. 2005, Archer et al. 2017). Robust generalizations about the importance of the different drivers remain unavailable due to context dependent factors that co-occur and interact to promote or constrain woody cover (D'Odorico et al. 2012, Archer et al. 2017). In the past few decades, brush management of woody encroachment has focused on reversing the directional shifts in vegetation with the goal of improving livestock production (Archer et al. 2017).

### 5.4 Poverty and food insecurity

Grazing systems are the most common forms of agricultural production in the developing world, in terms of both the total land area and the number of people supported (Herrero et al. 2012). In Africa, for example, livestock production systems cover 73% of the land area (Thornton 2014). Since livestock provide a critical source of income and food in livestock dependent communities, interactions between land degradation and climate change that reduce grazing land productivity are an existential threat to many of the world's poor (HLPE 2012). There are various adaptation strategies that can help reduce livestock dependent communities' vulnerability to climate change, including improved grazing, soil, and nutrient management (Thornton 2014). Yet, existing institutional and household asset constraints typically limit farmers' abilities to pursue these activities and lock farmers into the extensive practices that contributed to land degradation in the first place. These social-ecological dynamics create what are known as "resource degradation poverty traps", whereby human behaviors erode natural capital and reduce land productivity, food production, and income, leading to further constraints on the range of behaviors possible, further degradation, and greater poverty (Barrett 2008).

### 5.5 Nutrient loss due to runoff, leaching and erosion

In grasslands, rainwater and snowmelt can remove nutrients from soils via runoff, leaching, and erosion (Bellows 2001). Runoff and erosion transport either dissolved nutrients or nutrients attached to soil particles over the soil surface to streams, rivers, and lakes. Leaching, on the other hand, is the downward transport of dissolved nutrients through the soil profile, out of reach of plant roots and into groundwater (Bellows 2001). Leaching is more likely to happen when the number of cattle herd exceed the assimilative capacity of the land (Billota et al. 2007). All three processes are detrimental to livestock production and environment health because they deplete nutrients that could be used for forage production and contaminate water bodies (Bellows 2001). High nitrate levels in drinking water can cause health problems for animal and human infants, while high phosphorous levels in streams and lakes can lead to eutrophication.

Maintaining adequate livestock density, planting deep-rooted and prostrate vegetation and keeping plant residue cover can enhance water infiltration and provide good protection against nutrient loss (Billota et al. 2007, Bellows 2001). In addition, maintaining a healthy and diverse population of soil organisms helps incorporate nutrients into soil, reducing the risk of runoff, leaching, and erosion. Finally, protection of riparian areas surrounding streams and rivers is essential to minimizing broader ecosystem pollution (Osborne 1993, Dosskey et al. 2010).

### 5.6 Compaction

Soil compaction reduces the ability of nutrients, water, and roots to move through the soil (Bellows, 2001). Soil compaction is caused by animals or equipment continuously moving across the soil, pressing down on the soil and squeezing soil pore spaces together. The likelihood of compaction increases as soil moisture, animal weight, animal numbers, and the duration of grazing increase (Billota et al. 2007). Soil compaction makes vegetation susceptible to disease, restricts root growth, reduces nutrient availability for plant uptake, increases the potential for runoff and erosion, and reduces forage yields (Bellows 2001). The likelihood of compaction can be reduced by: i) maintaining a diverse population of soil organisms that burrow in the soil and form soil aggregates, ii) not grazing animals on wet or poorly drained soils, and iii) decreasing the number of animals and/or the time they spend in each paddock (Bellows 2001).

### 5.7 Greenhouse gas emissions and deforestation

Regardless of whether they are “conventional” or grass fed, most ruminants spend a majority of their life grazing and a relatively short period at the end of their life in a forage or feed-based finishing system. Consequently, a majority of their emissions from digestion (i.e., enteric fermentation) are associated with grazing. For example, a study in Alberta, Canada found that across the entire cattle production life-cycle, the reproduction and grazing period associated with calf-cow production contributed 80% of the greenhouse gas emissions for each finished steer (Beauchimin et al. 2010). Consequently, these authors recommend that interventions to reduce the greenhouse gas footprint of beef production from enteric fermentation should focus on improving forage quality within cow-calf grazing systems. Conversely, extending the amount of time that cattle spend grazing, i.e., in fully grass-fed systems, would substantially increase the amount of greenhouse gas emissions associated with beef production (Hayek and Garrett 2018).

Grazing on lower productivity rangelands and grasslands, including degraded systems, lowers animal weight gain. The longer it takes to raise a ruminant for slaughter, the more methane it will produce over its lifetime as part of its normal digestive processes. Land degradation can also contribute to greater greenhouse gas emissions via deforestation. When lands become degraded, they may be abandoned, leading farmers to clear new land that has more fertile soil (Balbino et al. 2011, Walker, Moran, and Anselin 2000, Dias-Filho 2014). This is a major sustainability challenge throughout much of Latin America. In the Brazilian Amazon, for example, pastures accounted for 59% of the cleared forest area in 2012 and 22% of these areas were in some degree of degradation (INPE 2012). Improved pasture management, including better grass varieties, rotational grazing, and integrated systems, can reduce deforestation and spare land for biodiversity by increasing production on existing cleared lands (Cohn et al. 2014, Strassburg et al. 2014, Gil et al. 2018). Since land cover change is one of the leading sources of greenhouse gas emissions (Houghton et al. 2012) improved pasture management can be an effective way to mitigate climate change (Strassburg et al. 2014), so long as it is coupled with stringent conservation policies (Garrett et al. 2018).

## 6. Major knowledge gaps in grazing systems

Despite the fact that livestock grazing is the largest land use activity on the planet (Erb et al. 2017, Herrero et al. 2013), and that it is important in tackling climate change and improving food security, quantitative global analyses of the spatial patterns and dynamics of grazing are rare (Kuemmerle et al. 2013, Erb et al. 2017). While there is some knowledge on the biogeochemical and biophysical aspects of livestock management, there is a lack of robust global datasets on the extent and intensity of grazing systems and associated management practices (Erb et al. 2017). Spatially explicit, consistent, and comprehensive global grazing data are crucial for doing social-ecological research. Data gaps are largest in developing countries, which are currently experiencing rapid land use change that is likely to accelerate in the coming decades.

Aside from spatially explicit information on grazing area and management and associated biomass production and use, there are many additional knowledge gaps related to fundamental processes and outcomes in grazing social-ecological systems. Very little is known about animal outcomes, including welfare, behavior, genetics, reproduction, and health under different management and environmental conditions. While much progress has been made in measuring ecosystem services and livelihood outcomes in grazing systems, there has not been sufficient study of landscape scale outcomes across these two interrelated sets of factors to understand how grazing systems can be improved to achieve more win-wins (and fewer tradeoffs). These knowledge gaps become even more prominent when considering the complex ways that climate change may alter both human management and ecological responses in grazing systems. Finally, greater social research is needed to better understand the multiple livelihood and community uses and resulting social values of grazing systems.

## 7. Conclusions

Grazing systems are extensive and heterogeneous; they provide numerous ecosystem services in addition to provisioning feed for livestock, including carbon sequestration, habitat for diverse species, regulation of biogeochemical cycles, and maintenance of traditional lifestyles. While livestock rearing has important cultural significance and provides income and nutrition in areas that cannot support any other livelihoods, the livestock production sector poses some challenges to the sustainability of our planet as a result of deforestation, habitat and land degradation, water pollution and greenhouse gas emissions. Ensuring food security, satisfying increased demand for meat and dairy, and protecting grassland ecosystems in an era of climate change are significant scientific and societal challenges. Given the complex and multi-dimensional social-ecological processes that shape grazing systems, there is an urgent need to improve our understating of the biophysical and biogeochemical aspects, and spatially explicit dynamics of grazing in order to devise and apply sustainable management practices.

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