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Knowledge and tools to enhance resilience of beef grazing systems for sustainable animal protein production

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Ruminant livestock provides meat and dairy products that sustain health and livelihood for much of the world's population. Grazing lands that support ruminant livestock provide numerous ecosystem services, including provision of food, water, and genetic resources; climate and water regulation; support of soil formation; nutrient cycling; and cultural services. In the U.S. southern Great Plains, beef production on pastures, rangelands, and hay is a major economic activity. The region's climate is characterized by extremes of heat and cold and extremes of drought and flooding. Grazing lands occupy a large portion of the region's land, significantly affecting carbon, nitrogen, and water budgets. To understand vulnerabilities and enhance resilience of beef production, a multi-institutional Coordinated Agricultural Project (CAP), the "grazing CAP," was established. Integrative research and extension spanning biophysical, socioeconomic, and agricultural disciplines address management effects on productivity and environmental footprints of production systems. Knowledge and tools being developed will allow farmers and ranchers to evaluate risks and increase resilience to dynamic conditions. The knowledge and tools developed will also have relevance to grazing lands in semiarid and subhumid regions of the world.

Keywords: climate change; greenhouse gases; grasslands; rangelands; enteric methane; soil carbon; meat and milk production

Introduction

Ruminant livestock production on the world's grazing lands constitutes an important component of the global food system, providing high-quality protein meat and dairy products. Grazing lands are the largest global land-cover type and are an important part of agricultural and natural ecosystems across a wide range of potential productivity conditions on every continent (Fig. 1).[1] In many regions of the world, lands suited to some level of grazing (grassland, woodland, open forest, and deserts) predominate. Ruminant livestock grazing is often the only viable form of agricultural production on these lands.[2] In the world's lower-income countries, grazing by ruminants of grassland and woodland is proportionally more important than other land uses, compared to middle- and high-income countries.[2] Grazing lands provide a wide range of ecosystem services, including provision of food,

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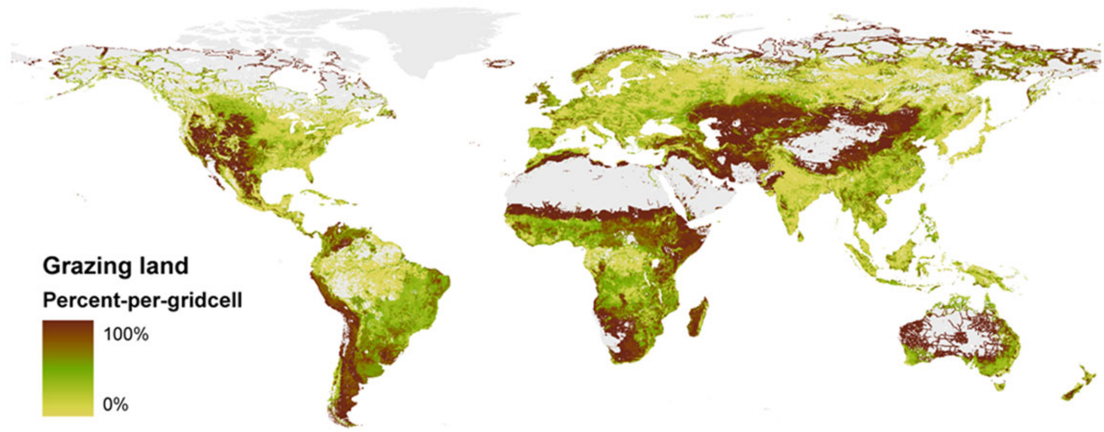

Figure 1. Global distribution of grazing land in the year 2000. Adapted from Ref. 1.

livelihoods, biodiversity, habitat, carbon sequestration and storage, soil erosion control, water filtration, and others.[3–5] The role of grazing lands as net sinks or sources of greenhouse gases (GHG) is poorly understood, limited by sparse data regarding management impacts on the flux of carbon, nitrous oxide, and methane in these complex landscapes. In grazing lands, soil quality and integrity of the plant and faunal communities are intrinsically intertwined, and both are affected by grazing.[2]

Grasslands in the Great Plains of North America are among the world's major ecosystems, extending from central Canada to southern Texas and spanning subhumid to semiarid climate zones. In the southern Great Plains, beef cattle production is a dominant part of the agricultural sector. Beef cattle production is based on combinations of annual and perennial vegetation, including native prairie, a variety of introduced pasture and hay species, grazing of winter wheat crops during the winter, and grazing of a variety of summer forages or stover remaining after the harvest of grain crops. Agriculture in this region is subject to a highly dynamic climate with extremes of heat and cold, as well as extremes of drought and flooding.[6] Climate pressures are intensifying with increasing temperatures, particularly minimum temperatures and increased incidence of the more extreme events.[7–10] Because a large portion of land in this region supports beef grazing, production systems on these lands have a large impact on water, carbon, and nitrogen cycles of the region. Management practices that result in efficient and sustainable use of grazing land resources are needed, but quantitative understanding of the environmental effects of beef grazing is sparse.

Beef cattle enterprises include cow-calf production, weaned stocker grazing, and finishing operations. Different phases of the animal's life cycle may be spent in different geographic areas and, often, under control of different owners. Grazed ecosystems support many ecosystem services in the Great Plains of the United States. Most of the remaining noncultivated ecosystems in the region are used for beef cattle grazing but also provide habitat for native flora and fauna. Well-managed, grazed ecosystems also sustain soil resources and support nutrient cycling and hydrologic function in the landscape. However, many opportunities remain to improve management to enhance positive environmental impacts and mitigate negative impacts of grazing on the environment. Animal science research has focused considerable attention on the finishing phases of beef production, which in the United States is predominantly conducted in large, confined animal feeding systems (i.e., feedlots), but the majority of the life cycle of beef cattle, and their consumption of nutrients, occurs in grazed ecosystems on farms and ranches distributed throughout the country.

Beef cattle production systems in the southern Great Plains also function within a socioeconomic context, which includes larger structural trends (e.g., demographic change, market imperatives, and regulatory frameworks) and regional and local factors (e.g., local institutions, household-level decisions). These factors, both macro and micro, interact in various ways that influence and shape agricultural production in the region. Put another way, the biophysical and socioeconomic systems of the region are in a constant process of interaction in which they are mutually shaped over time.[11] Socioeconomic factors can be a source of both vulnerability and resilience in an integrated system. For example, declining population and the concomitant loss of key social institutions can introduce long-term vulnerability. At a more micro level, producer knowledge, attitudes, and behaviors can become vulnerabilities if they present barriers to the adoption of practices designed to mitigate the impacts of climate variability. At the same time, socioeconomic factors can also contribute to system resilience. Social capital, knowledge exchange networks, and institutional support (e.g., Extension Service) can all be resources that help households, communities, and production systems be more resilient to traumatic events, be they biophysical (extreme weather events) or social (loss of local institutions).

To address sustainability of the system as a whole, integrative research and extension in soil, plant, and animal sciences; ecology; climatology; hydrology; sociology; and economics are needed. This paper introduces a multi-institutional, Coordinated Agricultural Project (CAP), the "grazing CAP," which was established in 2013 to better understand the vulnerabilities and enhance resilience of forage-based beef production through diversified forages, improved management, strategic drought planning, and improved decision-support systems to strengthen production and ecosystem services while mitigating GHG emissions. While some parts of the world use irrigation on grazing and forage production lands, in the southern Great Plains grazing lands are predominantly rainfed, so the focus of the grazing CAP project is on rainfed systems.

Ecosystem services provided by forage-based beef production

All ecosystems, including agroecosystems, provide a wide range of services that have been categorized as provisioning, supporting, regulating, and cultural.[12] Agricultural ecosystems are often thought of in relation to their provisioning services, which in the case of grazed ecosystems include provision of high-protein meat and dairy products along with leather and other by-products of livestock production. Additionally, many grazing lands sustain biodiversity of endemic flora, fauna, and microbial species. Appropriate grazing management and other practices can be used to enhance ecosystem services, for example, by minimizing habitat fragmentation and reducing invasive or encroaching species that pose a threat to biodiversity within the landscape.[13,14]

Grasslands composed of perennial plants provide strong supporting services such as soil formation, nutrient cycling, and primary production. Agricultural management practices greatly affect the efficiency and sustainability of these supporting services. Because grasslands are a dominant land cover, both globally and in the southern Great Plains, they play critical roles in regulating hydrologic processes that are essential to sustain clean and adequate water supplies. Finally, grasslands are culturally important and they often contribute to human well-being through spiritual, aesthetic, recreational, ecotourism, and educational benefits. Where grasslands are the dominant land-cover type, they contribute to people's sense of connection to place and their cultural identity.

Grazing CAP

The grazing CAP project, funded by the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture, focuses research, extension, and education efforts toward diverse management practices that can enhance and sustain ecosystem services from the southern Great Plains forage-based beef-production systems. The collaborative team includes 34 coinvestigators and numerous students and postdoctoral research associates located at Oklahoma State University, Kansas State University, the University of Oklahoma, Tarleton State University, the Samuel Roberts Noble Foundation, and the USDA Agricultural Research Service at El Reno, Oklahoma, and Bushland, Texas. The project is structured around on-going long-term research at the partner institutions to quantify seasonal and annual primary productivity and carbon, nitrogen, water, and energy budgets, along with centralized, intensive field campaigns conducted to develop improved understanding of interactive processes (Fig. 2). Survey and interview data from both Extension Service educators and producers will be analyzed to better understand barriers to the adoption of best management practices. Research and extension efforts are coordinated and linked through on-farm research projects that highlight

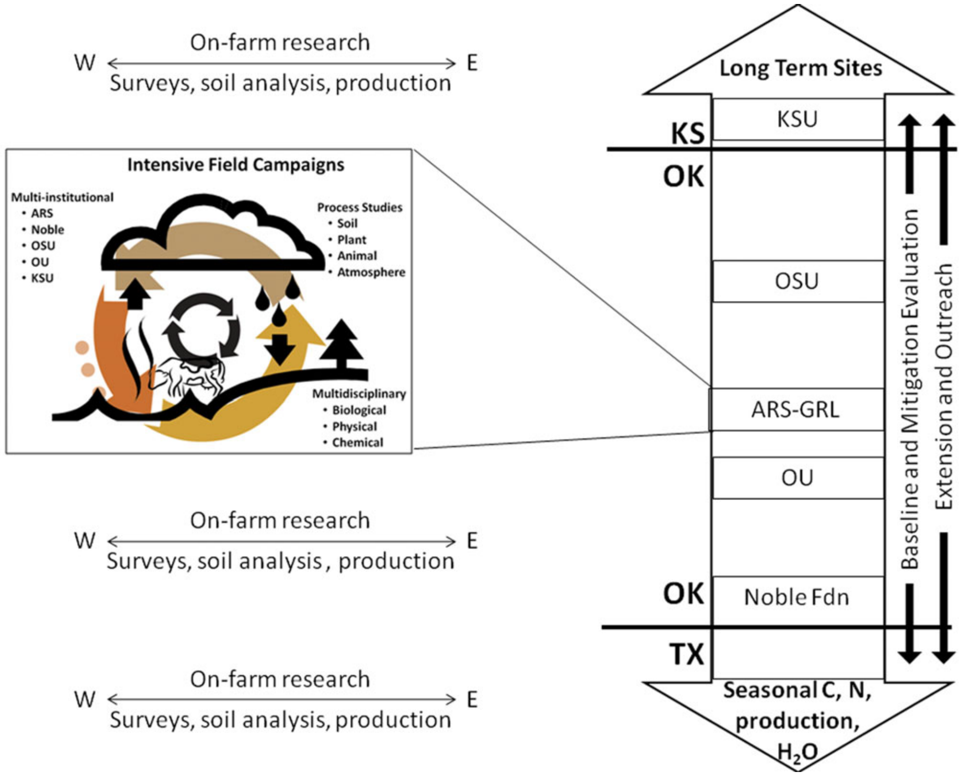

Figure 2. Grazing CAP research framework addressing multiple interactive processes at multiple scales that affect beef-grazing impacts on the environmental footprints of carbon, nitrogen, water, and energy.

successful systems of early innovators, develop better understanding of processes within the systems, and demonstrate to other farmers and ranchers new and innovative practices within productive and profitable systems.

The research and extension efforts address how management practices and systems affect the environmental footprint of forage-based beef-production systems. Particularly important questions to be addressed include how the rate, form, and timing of fertilization of wheat and introduced perennial forage species affect soil nitrous oxide emissions; how forage and feed quality affect enteric methane emissions for livestock classes (cow, calf, stocker, heifer[a]); and how agronomic management of crops and pastures (tillage, rotation, fertilization, stocking density, duration, and timing) affect soil organic carbon, species diversity of pastures, management of invasive species, water availability, and water quality (Table 1).

Field research is expected to provide data to improve and validate models that address different parts of the beef-production system at different scales. The models are linked within a framework to evaluate function and interactions of the system

[a]Key classes of beef cattle include the cow herd, in which the animals generally spend their life span on one farm and must have year-round sustenance and where economic return is associated with feed efficiency and reproductive efficiency; calves depend on the cows for sustenance through weaning, with increasing sustenance from forages and may be retained on the same farm or moved to another farm and/or owner after weaning. After weaning, sustenance for "stocker" animals is provided primarily from forage, and weight gain is rapid, requiring high-quality forage or feed supplements. To maintain the size of the cow herd, female calves may be retained as heifers to replace aging cows. Nutritional requirements and reproductive monitoring are higher for these young breeding animals than for mature cows.

Table 1. Synopsis of management practices, research, and education and extension goals to achieve desired outcomes of the grazing CAP of the southern Great Plains

Desired outcomes	Management practices	Research topics	Education and extension goals
Enhance agricultural productivity and profitability	• Animal genetics • Weaning time • Feed supplementation • Shift in forage type • Patch burning • Forage legumes • Grazing management • Soil management	• Impacts of forage quality parameters on enteric methane emissions • Selective grazing impacts on quality of forage consumed • Emissions as affected by livestock class (cow, calf, stocker, heifer)	• Recommended practices for forages and flexible production practices matched to environment
Enhance water quality and quantity	• Grazing management (stocking density, duration, timing) • Fertilization (rate, form, timing) • Conservation tillage, rotations, cover crops	• Impacts of grazing management on channel stability and riparian vegetation • Water-use efficiency of alternative systems • Erosion and nutrient losses affected by management	• Recommendations for soil, plant, and grazing management matched to environment • Recommendations to decrease loss of water to nonproductive uses (evaporation, runoff)
Mitigate carbon dioxide and enhance soil health	• Grazing management (stocking density, duration, timing) • Fertilization (rate, form, timing) • Conservation tillage, rotations, cover crops	• Management impacts on carbon and nitrogen cycling • Management impacts on soil health indicators (aggregate stability, biological activity, biodiversity)	• Recommendations to enhance soil health and increase soil organic carbon storage, increase system diversity, extend period with growing vegetation on field, and keep soil covered
Mitigate soil nitrous oxide emissions	• Fertilization (rate, form, timing): winter wheat and perennial pastures	• Climate and management impacts on GHG emissions • Background emissions from unfertilized prairie • Predictive models of soil GHG emissions	• Planning tools for fertility management
Mitigate enteric methane emissions	• Forage quality • Livestock genetics Livestock nutrient utilization	• Selective grazing impacts on quality of forage consumed • Impacts of forage quality on enteric methane emissions • Emissions as affected by livestock class (cow, calf, stocker, heifer) • Improve predictive models	• Recommendations for forage and grazing management • Recommendations on livestock genetics that match environment

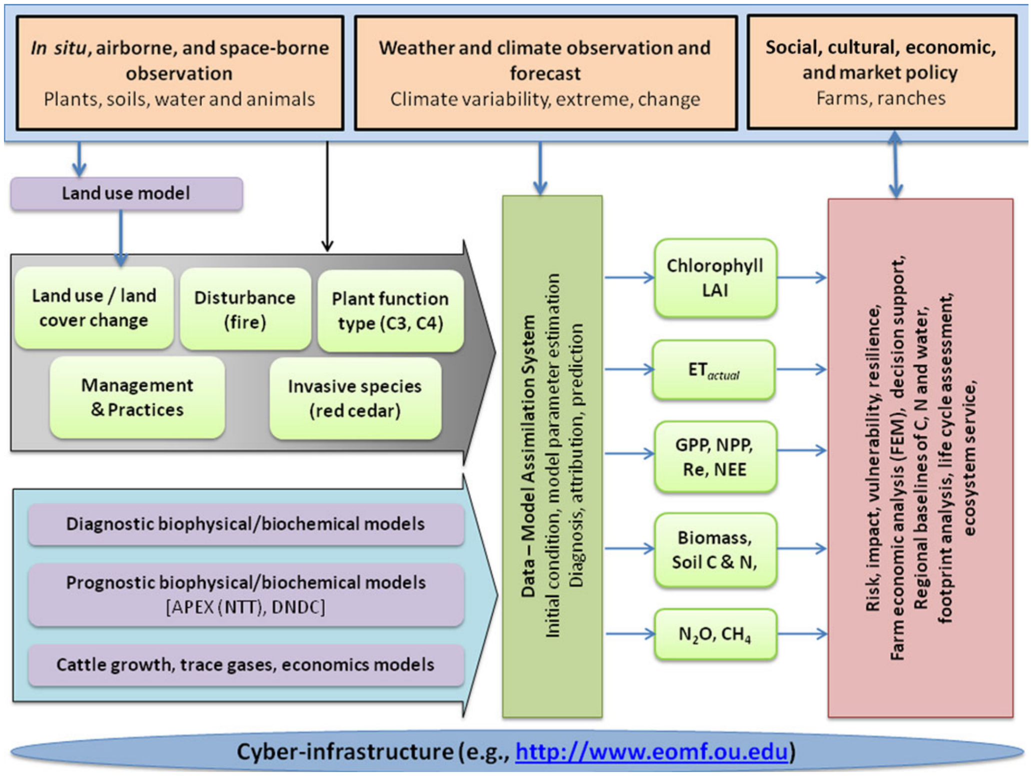

Figure 3. A linked observation-modeling framework to assess vulnerability, risks, and resilience of beef grazing systems. LAI, leaf area index; ET, evapotranspiration; NPP, net primary productivity; GPP, gross primary productivity; Re, respiration; NEE, net energy exchange; APEX, agricultural policy/environmental eXtender model; DSSAT, decision support system for agrotechnology transfer; NTT, nutrient tracking tool model; DNDC, denitrification decomposition model; FEM, farm economics model). Institutions: Kansas State University (KSU), Oklahoma State University (OSU); USDA-Agricultural Research Service, Grazinglands Research Laboratory (ARS-GRL); University of Oklahoma (OU); Samuel Roberts Noble Foundation (Noble Fdn).

as a whole, to develop regional maps of the environmental footprint, and to conduct life-cycle analysis of forage-based beef production (Fig. 3). The life-cycle modeling and data framework will provide a tool for future assessments, such as to evaluate the impact of drought depending on, for instance, if the drought is regional or national in scale; the impact of sustained (long-term) warming on vulnerability and resilience of the system; or the impacts of competing enterprises such as increased demand for land and cellulosic vegetation for biofuel production.

Extension teams are developing improved climate content for Extension Service programs, decision-support tools for beef cattle producers, and delivery of science-based information, including best management practices and technology for producers as well as for consumers. On the basis of a systematic assessment of available Extension Service programming materials, the team identified critical gaps in the available Extension Service materials that could be filled with existing or emerging data and knowledge (Table 2). The strategy of the Extension Service team is to deliver products through existing outreach networks using "train the trainer" initiatives; partnering with early innovators for on-farm demonstration and outreach efforts; developing case study results (stories of innovators along the supply chain); and engaging with key influencers in the region, including leadership of producer organizations, universities, state and federal agricultural and conservation agencies, certification programs, and consumer sectors who provide input and feedback to the project. In addition, an Extension Service program targeted at consumers has surveyed consumers about their preferences regarding beef

Table 2. Key gaps in Extension Service programming materials that must be filled to enhance resilience and minimize the environmental footprint of the southern Great Plains beef-grazing systems under dynamic climate and market conditions

Extension material gap	Goal
Initiate internal dialogue on best management practice (BMP) influence on resilience and environmental footprint. Identify social constraints to adopting science-based recommendations (e.g., matched cattle genetics to environment, stocking rate decisions, soil testing, forage testing) to increase resilience and reduce GHG emissions.	Adaptation and mitigation
Value to soil fertility from feed supplements via cattle urine and feces (i.e., offsets to N&P commercial fertilizer)	Mitigation
Heat stress and water use of cattle	Adaptation
Provide probabilistic estimates of forage growth on the basis of historical climate data and plant-available soil water. Information about water use by different forage crops.	Adaptation
Enterprise flexibility. Improve cow-herd flexibility to adapt to increasing variability in forage growth and extremes in weather. Help producers to conserve brood cow herds.	Adaptation
Matching wheat system management to changing climatic conditions.	Adaptation
Information about footprint of current production systems for GHG, life-cycle analysis.	Mitigation
Water requirements of cattle by breed, class, age, production phase, etc. and by environment (especially, hotter and drier climate).	Adaptation
Weather and climate—basic information for producers to inform them of the range of conditions in the past and what to prepare for in a highly variable climate.	Adaptation
Educate consumers, students, and Extension Service educators on the impact of climate on the availability/quality of beef they eat.	Education

products and their level of awareness of environmental impacts of beef production. The results of the survey are guiding development of consumer-targeted extension programs that will be conducted through fairs, 4-H activities, and other public venues.

Conclusion

The overarching objective of this multifaceted project is to increase resilience and sustain productivity of beef cattle systems through improved grazing management, including improved production efficiency, mitigation of GHG, increased water-use efficiency, diversified forage sources, multiple marketing options, strategic drought planning, and improved decision support for sustainable production of protein for human consumption. Additional institutional objectives are to build capacity and strengthen collaboration at the regional scale and to train and educate the next generation of farmers, ranchers, Extension Service educators, and researchers to collectively address challenges facing agriculture in the context of a growing world population. Success of such a complex project requires focused leadership, engagement of all participants, seamless communication, sustained funding, and leveraging of diverse resources of the partner institutions. In the grazing CAP of the southern Great Plains, the project directors work with a management team that includes institutional and disciplinary leaders to monitor, support, and communicate progress from research and Extension Service teams tasked with key responsibilities within the project. Project-wide communication, collaboration, and data sharing occur through regular teleconferences, face-to-face working meetings, quarterly newsletters, and a web-based shared work space. The project engages an external advisory group of key regional leaders in the agricultural, research, extension, industry, and consumer sectors that provide feedback on the project approaches and open doors to deliver grazing CAP findings to key stakeholders. As the team progresses from the current early stages through the planned 5-year project, success will be judged by contributions to sustainable rural economies under variable and changing climate, market, and policy environments. Knowledge and tools developed will also have relevance for adaptation to other grazing lands in semiarid and subhumid regions of the world.

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Conflict of interest

The authors declare no conflicts of interest.

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