Response to Request for Information (RFI) – ARS Long-term Agro-Ecosystem Research Network

<u>The Central Plains Experimental Range (CPER)</u>

By

Rangeland Resources Research Unit, Cheyenne, WY; Fort Collins, CO; Nunn, CO

David Augustine, Ecologist

Jack Morgan, Plant Physiologist

Dana Blumenthal, Ecologist

Justin Derner, Research Leader

Terry Booth, Rangeland Scientist

Background:
The Central Plains Experimental Range (CPER) has served as a key research site for livestock grazing and grassland ecosystem dynamics in the central Great Plains since it was established in 1937. The collaborative partnership from 1937 to present with Crow Valley Livestock Cooperative, Inc., the oldest grazing association in the US, has been instrumental in conducting research that is relevant for land managers and livestock production in the shortgrass steppe. For example, research at CPER during the 1940's–1960's led to the development of grazing management strategies that sustain forage and livestock production in the region (Bement 1969) and continue to influence the management of semiarid rangelands from Iceland to Africa. CPER became part of the International Biosphere Program in the late 1960's with Colorado State University as the primary research collaborator, and this collaboration extended from 1982 to current with the Shortgrass Steppe Long-term Ecological Research (SGS-LTER) project. This collaborative effort has supported ecological process-based research that substantially advanced our understanding of the structure and function of semiarid rangeland ecosystems. New collaborations with the National Ecological Observatory Network (NEON) through CPER being the core site for Domain 10 will provide an exciting frontier in the collaboration potential with additional scientific investigators. The shortgrass steppe exemplifies the ongoing challenges faced by semiarid rangelands around the world to simultaneously sustain livestock production, conserve native biodiversity, and restore soils and hydrological functions in the face of global climate change. The Rangeland Resources Research Unit requests that CPER be affiliated with the ARS Long-term Agro-Ecosystem Research (LTAR) network given the capacity of our scientific and technical personnel, collaborators and existing infrastructure that can accommodate multi-scale (plot to landscape) research programs that build upon the long history of applied and ecological research to address emerging challenges in semiarid rangeland ecosystems.

Productivity:
The Rangeland Resources Research Unit is recognized as a world leader in research addressing management of semiarid rangelands and effects of global change on these rangeland ecosystems. The Unit has five scientists with expertise in range management and ecology, invasive species, monitoring and global change. These scientists have published 89 peer-reviewed journal articles and 14 book chapters in the past five years (2007-2011, see www.rrru.ars.usda.gov for listing by scientist and pdfs of publications). Unit scientists have published in the upper echelon of scientific (*Nature*, *Science*, *Frontiers in Ecology and the Environment*, *Global Change Biology*, *Journal of Ecology*, *Ecology*, *Ecology Letters*, *Proceedings of the National Academy of Sciences*, *Oecologia*, *Trends in Ecology and Evolution*, *New Phytologist*) and applied journals (*Rangeland Ecology and Management*, *Journal of Applied Ecology*, *Ecological Applications*, *Journal of Wildlife Management*, *Journal of Soil and Water Conservation*). Unit scientists have authored several synthesis papers on topics including: grazing systems (Briske et al. 2008, 2011), grazing efficiency (Smart et al. 2010), carbon storage and sequestration (Derner and Schuman 2007; Morgan et al. 2010), carbon fluxes (Svejcar et al. 2008; Polley et al. 2010 a,b), plant invasions (Blumenthal 2005; Blumenthal et al. 2009; Bradley et al. 2010), and application of livestock grazing for multiple ecosystem goods and services (Derner et al. 2009; Toombs et al. 2010). Collectively, the Unit's current research focuses on the interface between livestock production and conservation in semiarid rangelands (215 National Program project) and the interactive influence of multiple components of global climate change and mitigation/adaptation strategies on semiarid rangelands (212 National Program project). Unit scientists have a diverse set of research skills and interests which are collaboratively applied to both research emphases.

Dr. David Augustine's research interests include plant-herbivore interactions, the ecology and management of semi-arid rangelands, and conservation biology. His current research examines interactions among cattle, prescribed fire, and prairie dogs in shortgrass steppe, and the effects of these disturbance processes on vegetation heterogeneity and native grassland birds.

Dr. Dana Blumenthal's research aims to develop durable weed control strategies for rangeland ecosystems by identifying underlying mechanisms of invasion. Current research examines how plant traits, disturbance and climate change interact to drive invasion.

Dr. Terry Booth's research encompasses rangeland monitoring/remote sensing using Very Large Scale Aerial (VLSA) imagery which has a resolution of <1 mm / pixel ground sample distance (GSD). Current research focuses on applying this imagery and associated software tools for application in multiple natural resource monitoring needs.

Dr. Justin Derner's research ascertains the effects of livestock as ecosystem engineers, alone or in combination with fire and prairie dogs, to influence livestock production, vegetation heterogeneity and modify states of vegetation and affect resilience of the northern mixed-grass prairie and shortgrass steppe. His work also addresses how grazing intensity interacts with weather/climate dynamics to influence livestock weight gains and soil carbon storage for adaptation strategies for global change.

Dr. Jack Morgan's research interests are in photosynthesis, plant/soil water relations, and physiological plant ecology of rangelands. His major two areas of research are understanding the effects of global climate change on western US rangelands, and evaluating the impacts of management practices on the health of rangelands, particularly in regards to C cycling.

Unit scientists have been successful in obtaining grant funding to leverage with ARS resources for expanded research experimentation. These grants collectively total over $8 million dollars over the past five years, and have been from funding sources including: USDA CSREES (now USDA NIFA), DOE, National Science Foundation, USDA Western SARE, USDI Bureau of Land Management, State of Wyoming, USDA Forest Service, and the US Fish and Wildlife Service.

Infrastructure Capacity:

The CPER encompasses 15,500 acres of shortgrass steppe characterized by domination of C_4 (warm-season), grazing-resistant shortgrasses such as blue grama (*Bouteloua gracilis)* and buffalograss (*Buchloe dactyloides;* Fig 1). Major drivers of livestock and forage production, as well as ecosystem structure and function, include drought, fire and grazing by large and small herbivores.

Figure 1. Upland shortgrass steppe at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER).

CPER is located on the western edge of the North American Great Plains, which are characterized by a precipitation gradient from dry areas in the northwest to the wettest areas in the southeast, and a temperature gradient from cold areas in the north to warmest areas in the south (Fig 2). Ecologically, CPER occurs at the center of this vast temperature gradient and at the western (driest) end of the precipitation gradient. Mean annual precipitation at CPER is 340 mm (13.4 inches) with the majority of the precipitation occurring as rainfall in the summer months (Fig 3). Mean average temperature is 8.6°C (47.5°F).

Vegetation at CPER is dominated by blue grama on Loamy Plains ecological sites (Fig 4, lower left panel), with land management practices (very heavy spring targeted grazing) reducing this domination (Fig 4, upper left panel). Other areas on the CPER have Overflow and Saline ecological sites which contain the perennial shrub saltbush (*Atriplex canescens*) (Fig 4, upper right panel) and Sandy Plains ecological sites which have a larger composition of perennial C3 (cool-season) grasses such as needle-and-thread (*Hesperostipa comata*) (Fig 4, lower right panel).

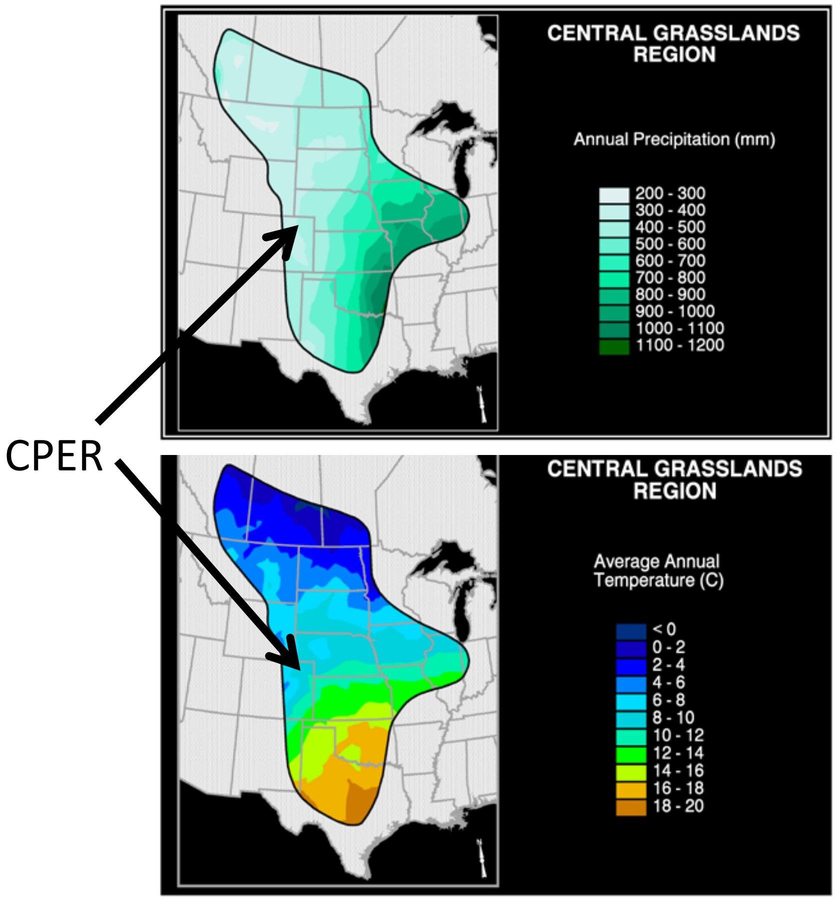

Figure 2. The North American Great Plains exhibit precipitation gradients (east-west) and temperature gradients (north-south), with the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER) located on the western edge. The location of CPER is highly advantageous for gradient studies addressing both temperature and precipitation influences.

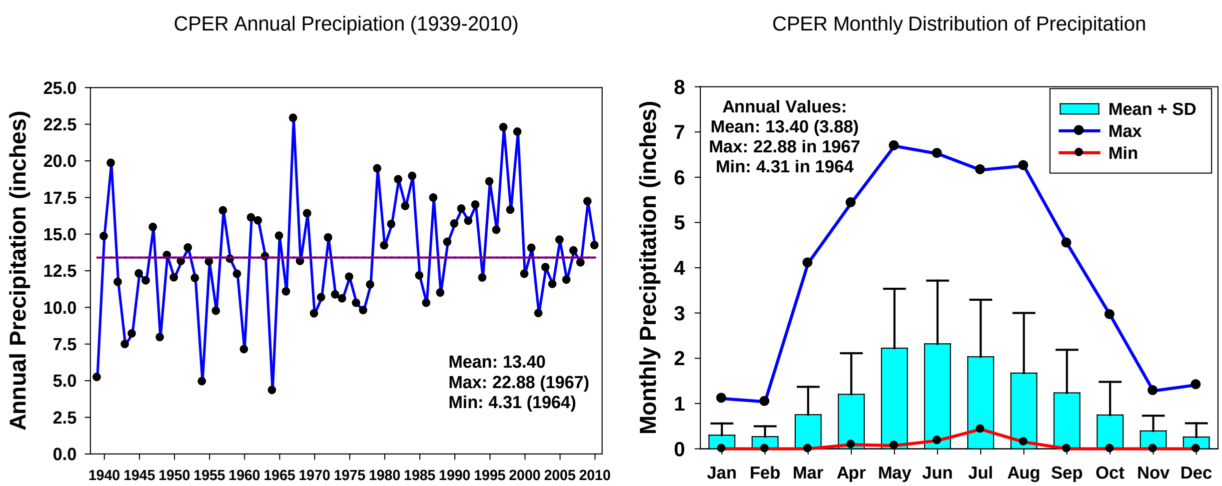

Figure 3. Annual (Jan-Dec) precipitation at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER) from 1939 to 2010 (left panel) and monthly (mean, max, min) distribution of precipitation (right panel).

Figure 4. Vegetation heterogeneity found at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER) with areas of high bare ground and limited plant cover (upper left), blue grama-dominated vegetation on Loamy Plains ecological sites (lower left), saltbush-dominated vegetation on Overflow and Saline ecological sites (upper right) and needle-and-thread dominated vegetation on Sandy Plains ecological sites (lower right).

CPER is contiguous with the 200,000 acre Pawnee National Grassland, which is administered by the US Forest Service (Fig 5). The larger landscape encompasses about 500,000 acres of private, state and federal lands within the boundaries of the Pawnee National Grassland. The CPER was established in 1937 on land taken over by the Forest Service after drought, overgrazing and dust storms forced abandonment of ranches and farms in the area (Shoop et al. 1989). Forest Service scientists began a research program directed toward developing sustainable land management practices, with the main objectives being enhancing livestock and forage production. From the beginning, all livestock for research have been provided by the Crow Valley Livestock Cooperative, Inc., which is comprised of forty individual ranches. As a result, research at CPER has been developed in close collaboration and with strong support of the local ranching community. The first research project was initiated in May 1939 with a grazing intensity study that is still underway today. Livestock weights have been taken every four weeks during each grazing season. Additionally, twenty-seven 1 acre livestock exclosures were established in 1937 and remain intact today (Fig 6). The Agricultural Act of 1953 reorganized the USDA and transferred administration of the CPER from the Forest Service to the Agricultural Research Service.

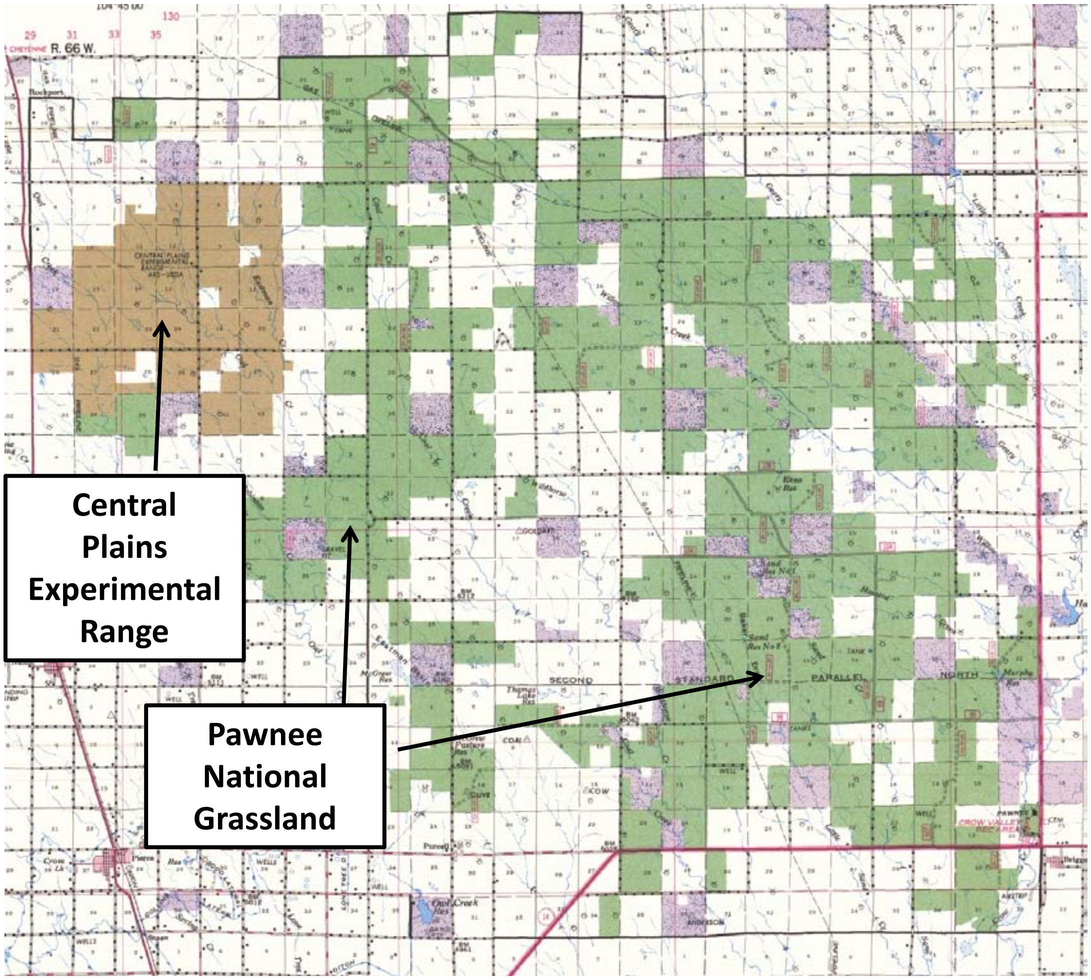

Figure 5. The USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER; brown shading) consists of 15,500 acres and is located on the western edge of the USDA Forest Service Pawnee National Grassland (green shading) which consists of 200,000 acres.

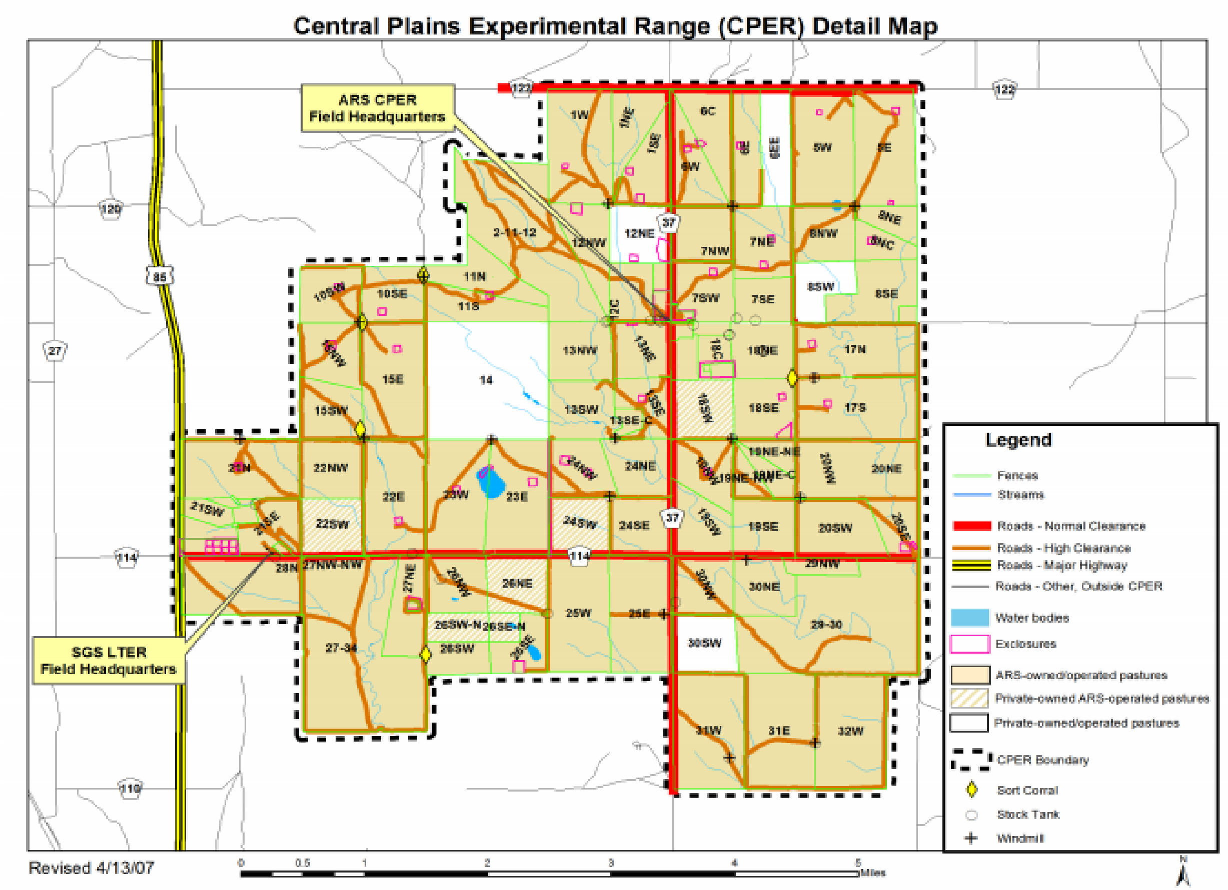

Figure 6. The USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER) consists of 15,500 acres, mostly divided into pastures of 160 and 320 acre sizes, with some larger parcels. There are twenty-seven 1 acre livestock grazing exclosures established in 1937, and the long-term grazing intensity study (pastures 15E, 23W and 23E) was initiated in 1939.

Early research determined critical relationships among stocking rate, forage production and livestock gain, along with reseeding, range improvements and plant-grazing interactions (Shoop et al. 1989, Fig 7). Foundational information from the long-term grazing intensity study was used for establishing recommended grazing practices (Bement 1969). This is one of the most widely used scientific findings from past research at the CPER, with livestock management decision-making based on ungrazed residue (Bement 1969, Fig 8). This information has been used to aid producers from Iceland to Africa.

Figure 7. Pictures showcasing early research efforts addressing livestock and forage responses at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER).

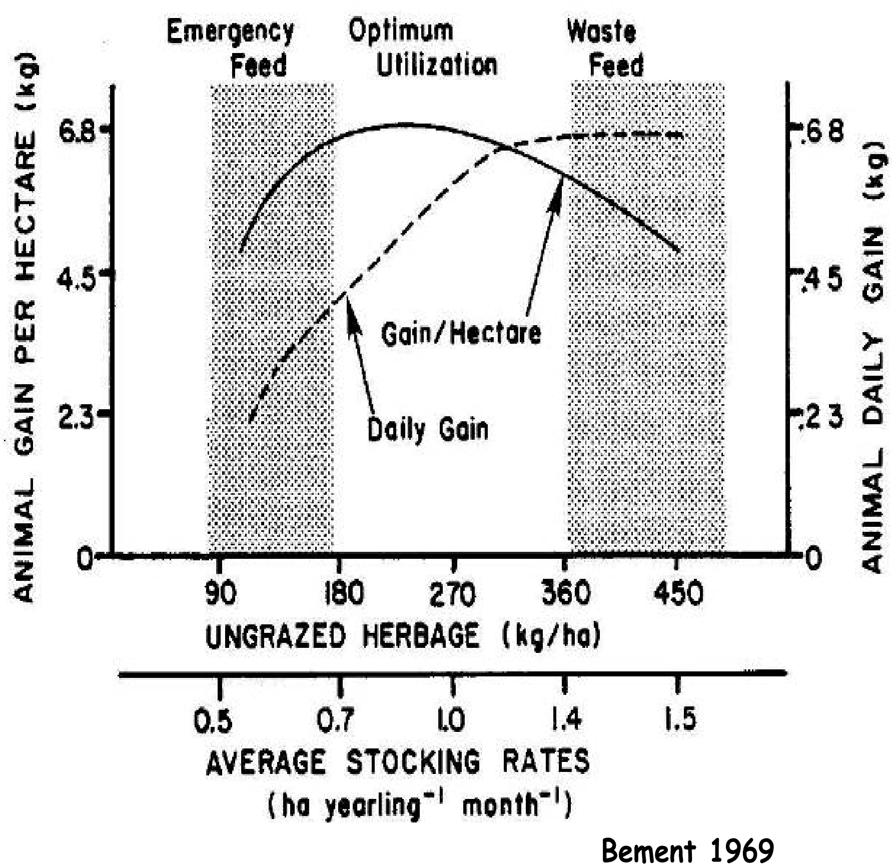

Figure 8. Relationship of livestock average daily gain and production (gain/hectare) at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER). The intersection of these response curves derived from long-term (since 1939) grazing intensity experiments depicts the optimum, sustainable stocking rate (1.2 ha/yearling/month or 16 acres/yearling/grazing season, mid-May to mid-October), and resulting ungrazed herbage residue target of 335 kg/ha or 300 pounds/acre.

Our current conceptual framework (Fig 9) views climate, disturbance regimes, and physiography as the key interacting factors that structure population and community processes and influence ecosystem states and services. Due to the semiarid climate, soil moisture is a key limiting factor controlling net primary productivity (Sala et al. 1988; Lauenroth and Sala 1992) and other fluxes of carbon and nutrients (Burke et al. 2008; Mosier et al. 2008). Climate change has also been shown to influence ecosystem dynamics through the effects of rising atmospheric CO_2 on soil moisture availability (Morgan et al. 2004). The role of disturbances is shaped by topographic controls on soil moisture and nutrient availability, and by the dramatic temporal fluctuations in weather conditions characteristic of the region. The shortgrass steppe evolved in the presence of grazing by large herds of bison. Present-day grazing by domestic cattle is a surrogate for this integral disturbance process, which favors native shortgrass fauna and flora, and limits the abundance of invasive, ruderal, or 'weedy' plant species. Studies have shown that plant species composition and productivity is relatively stable when subjected to wide range of cattle grazing intensities, more so than other grasslands worldwide (Milchunas et al. 2008). Furthermore, ungrazed plant communities are more likely to be invaded by exotic and native weedy species. The underlying mechanism for this response is posited to be increased basal cover by native grasses in grazed areas, resulting in a more uniform exploitation of above and belowground resources, and reduction in safe-sites for 'weedy' colonization (Milchunas et al. 2008). A recent global synthesis of plant traits, inspired by our understanding of plant traits in the shortgrass steppe, evaluated six conceptual models that may explain which plant traits become associated with each other under different combinations of climate and herbivore history (Diaz et al. 2007). Grazing history best explains the combinations of life history, plant type, and plant morphology of species found on grasslands worldwide (Milchunas et al. 1988; Milchunas and Lauenroth 1993).

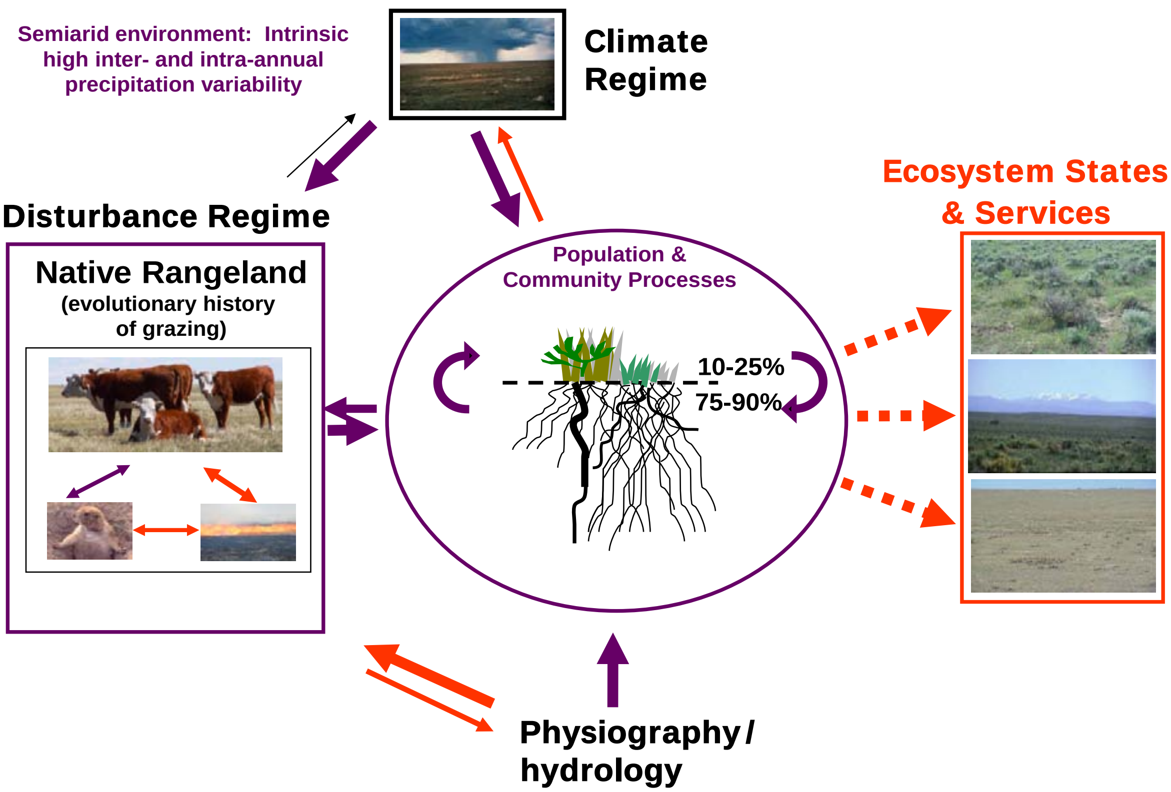

Figure 9. Conceptual diagram for research activities at the USDA-Agricultural Research Service Central Plains Experimental Range (CPER).

Because land use in the shortgrass steppe throughout the 1900's emphasized livestock production, elements of the natural disturbance regime that conflicted with this goal were suppressed, including prairie dogs and fires. A recent and ongoing development in grazing management is a transition from the single focus on beef production to attempts to balance production and biodiversity conservation (Derner et al. 2009). As a result, there is renewed emphasis on increasing natural disturbances of fire and black-tailed prairie dogs and interactions with livestock grazing. Current research experimentation is addressing production-conservation issues and associated tradeoffs with beef production when other ecosystem services are incorporated into management objectives (Fig 10). Recent studies at CPER have provided the most detailed analysis to date of the relationship between prairie dog occupancy and cattle grazing, revealing that cattle neither avoid or prefer prairie dog towns (Guenther and Detling 2003) and that prairie dogs only decrease cattle weight gain when they occupy more than 20% of the area within pastures (Derner et al. 2006a). Recent studies at the site have also shown that prescribed fire does not negatively affect forage production and can be compatible with livestock production objectives depending on the timing and spatial configuration of burns (Augustine and Milchunas 2009; Augustine et al. 2010). Other current studies focus on population and community responses to the interaction of climate and disturbance regimes within the landscape (physiography, ecohydrology) that result in sustaining or changing ecosystem states and services.

Figure 10. Current research experimentation at the USDA-Agricultural Research Service Central Plains Experimental Range (CPER) is addressing production-conservation issues and associated tradeoffs with beef production when other ecosystem services are incorporated into management objectives.

CPER has critical infrastructure present for research activities. Substantial investments have been made in state of the art low-stress animal handling facilities (designed by Temple Grandin), hydraulic livestock chutes and electronic weighing equipment (Fig 11), fencing and livestock watering supplies (windmills, tanks, pipelines), and IT capacity (T1 line).

Figure 11. Low-stress animal handling facilities designed by Temple Grandin and hydraulic chute located on the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER).

On-site buildings include a modern office with a dry laboratory and substantial storage room, equipment and vehicle storage, and a shop. Wet laboratory facilities for the Rangeland Resources Research Unit are located at the Crops Research Laboratory in Fort Collins, which has been recently remodeled and provides state-of-the art capacity. Also located on the CPER is the new Shortgrass Steppe Research and Interpretation Center (SGS-RIC, http://sgsric.colostate.edu/), built and operated by Colorado State University. This Center has a meeting/conference building (capacity of 100 persons, Fig 12) and available on-site lodging with three spacious houses (capacity of 30 persons total).

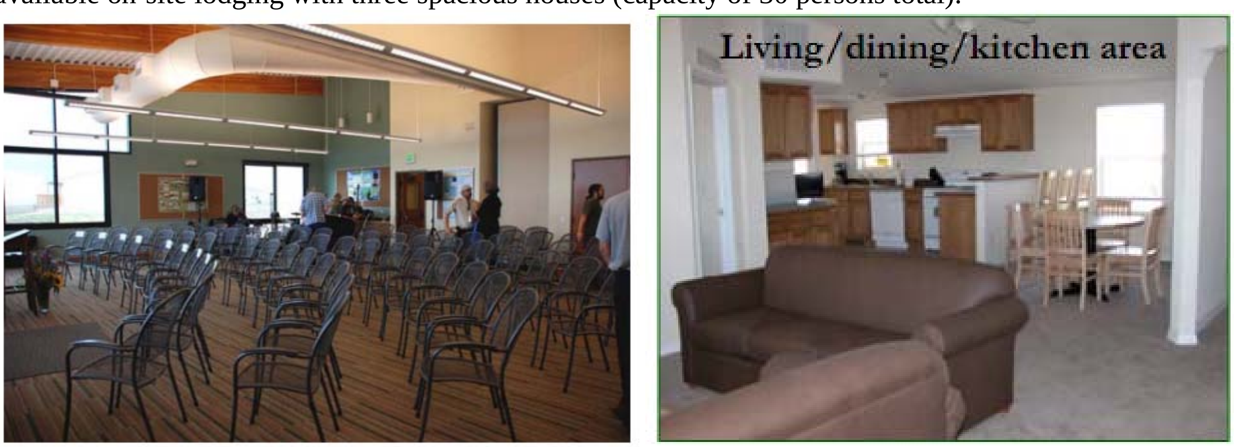

Figure 12. Pictures of the meeting room/conference facility (left) and housing (right) available at the Shortgrass Steppe Research and Interpretation Center located on the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER).

Additional infrastructural capacity for the CPER is the close proximity of the High Plains Grasslands Research Station, the headquarters of the Rangeland Resources Research Unit, at Cheyenne, Wyoming (30 miles northwest of CPER). This facility encompasses 2,800 acres of northern mixed-grass prairie, has paired experiments with the CPER (e.g., grazing studies), and is the location for the Prairie Heating and CO_2 Experiment (PHACE, http://www.ars.usda.gov/Research/docs.htm?docid=16754), which is the follow-up global change unit experiment to the initial Open Top Chamber (OTC) experiment which was conducted at CPER from 1999-2004.

Data Richness:
The CPER has a long history (> 70 years) of research on vegetation and livestock, and has emphasized consistency in data collection methods and storage for a core set of studies. Key datasets with >30 years of measurements include:

1) Aboveground net primary production: Forage production has been measured annually at three sites since 1939, and for varying decades at up to 12 sites (Lauenroth and Sala 1992; Milchunas et al. 1994; Lauenroth et al. 2008). Since the 1970's, forage production measurements were extended to include all aboveground net primary production (ANPP). Since 1982, ANPP has been measured annually in a network consisting of 12 moderately-grazed sites and 6 ungrazed sites that encompass the range of variation in soils and topographic positions within the shortgrass steppe (Lauenroth et al. 2008; Milchunas et al. 2008). ANPP under contrasting grazing intensities has been evaluated with spring precipitation more influential in plant communities with low grazing intensity than plant communities with a history of moderate and heavy grazing (Derner et al. 2008a). ANPP has also been measured annually since 2006 in two ongoing prescribed burning experiments at CPER.

2) Livestock weight gains: Livestock gains have been measured every four weeks during the grazing season on pastures with light, moderate and heavy stocking rates from 1939 to present. These data have been used in determination of grazing intensity effects on livestock gains (average daily gains and beef production, Bement 1969; Hart and Ashby 1998) and the differential effects of seasonal precipitation on livestock gains with grazing intensity treatments (Derner et al, in prep). Additional investigations will evaluate the influence of climatic extremes (precipitation events, drought) with this extensive data set.

3) Climate: Climatological data have been continuously collected at CPER since 1937. In addition, a network of twenty-seven rain gauges has been monitored during the growing season (May-September) each year since 1939, and provides a unique record of how precipitation varies spatially and temporally across the site (Augustine 2010).

4) Soil carbon: Soils have been sampled from the long-term grazing experiments (Derner et al. 1997, 2006b; Derner and Briske 2001; Reeder and Schuman 2002; Reeder et al. 2004) in 1994, 2004 and scheduled for another collection in 2014. Soil samples were also collected at all 26 long-term exclosures and paired grazed sites in 2011.

5) Carbon and trace gas fluxes: CPER was one of the main ARS Bowen Ratio network sites for rangelands, with measures of carbon and water balance conducted during 2001-2009, under varying grazing intensities. This network of sites has published several recent papers (Gilmanov et al. 2005; Svejcar et al. 2008; Alfieri et al. 2009; Polley et al. 2010 a,b) with site-specific papers forthcoming from CPER on temporal aspects of carbon flux and management influences (Parton et al. in press; Morgan et al. in prep). Studies of NO_x, N_2O and CH_4 emissions over the past two decades also provide baseline estimates of annual trace gas emissions for CPER (Mosier et al. 2008).

6) Hydrology: Multi-year data sets on surface runoff derived from available from rainfall simulation experiments at CPER are published and available (Frasier et al. 1995; Weltz et al. 2000).

7) Climate Change: A six-year experiment measured effects of elevated atmospheric CO_2 on grasslands at CPER using open-top chambers (Morgan et al. 2004, 2007; Nelson et al. 2004; Milchunas et al. 2005 a,b,c; LeCain et al. 2006; Dijkstra et al. 2008). Methods have been developed to directly compare these data with other sites, experiments and soil types based on the way elevated CO_2 influences soil moisture availability (Morgan et al. 2011).

8) Remote Sensing: Recent advances in very-large scale aerial imagery (Booth et al. 2006) have allowed for acquisition of aerial photography with pixel resolution up to 1 mm. VLSA imagery for all of CPER was in 2008, 2009 and 2011. This imagery has been used to determine grazing-induced changes in bare ground (Booth and Cox 2008), can be used to assess habitat for grassland birds of conservation concern (Augustine and Derner, in press), and is currently being used to evaluate the distribution and density of shrubs across the site (Augustine et al., unpublished data). Additional remote-sensing platforms will be tested at CPER by the NEON program, and can be used to evaluate the use of multiple satellite and airplane-based measurements to assess spatial and temporal variability in grassland structure and composition.

The CPER has an extensive history of partnering with Colorado State University from the late 1960s to current. First with the International Biological Program (IBP) and from 1982-current with the Shortgrass Steppe Long-Term Ecological Research (SGS-LTER) project. Although the SGS-LTER project will conclude in 2013, the collaborative research efforts have produced a process-based understanding of the structure and function of shortgrass steppe under light to heavy livestock grazing intensities (Lauenroth and Burke 2008). These archived datasets and published studies (Appendix A) provide a core background against which to evaluate the effects of more intensive grazing intensities, adaptive grazing management approaches, the restoration of fire and prairie dog grazing as key disturbance processes, altered precipitation regimes, and more extreme weather events in semiarid rangelands.

RRRU has also conducted parallel investigations regarding livestock gains and forage production at the High Plains Grasslands Research Station in Wyoming (Hart et al. 1993; Manley et al. 1995; Derner and Hart 2007; Derner et al. 2008b). These data have been important in cross-site comparisons of grazing effects at CPER and other long-term research sites in the Great Plains (Smart et al 2010), and have been used in conjunction with the ARS Agricultural Systems Research Unit for modeling efforts involving Great Plains Framework for Agricultural Resource Management, GPFARM; Andales et al. 2005, 2006). Climate change work has been focused on manipulation of water by rainfall shelters (Heisler-White et al. 2008) and atmospheric CO_2 (Morgan et al. 2004, 2007; Nelson et al. 2004; Milchunas et al. 2005a,b,c; LeCain et al. 2006; Dijkstra et al. 2008).

Data Availability (Accessibility):

Core data sets from experiments extending back to the start of CPER in 1937 are available through the SGS-LTER (see Appendix A). Spatially-related data sets are also available electronically through the SGS-LTER (See Appendix B). These data sets will remain accessible and available through the LTER network when the SGS-LTER is concluded in 2013.

Geographic Coverage at Various Scales:

The CPER is a key experimental site used in many north-south (CPER and Sevietta; Woodward, OK, CPER, and Miles City, MT) and east-west (e.g., CPER, Hays, Kansas and Konza Prairie) gradient studies addressing land management effects on livestock and forage production, and ecosystem structure and function. Currently, over seventy experiments are being conducted on the CPER with investigators from around the world, and using the CPER as a key site for cross-site research.

The CPER is located in the Mountain major ecosystem (http://www.usda.gov/news/pubs/factbook/002a.pdf) with the predominant land use being cattle production on native vegetation. Regarding the HUC-2 watersheds, CPER is located in the Region 10 Missouri watershed (http://water/usgs.gov/GIS/huc.html). For the NEON domains (http://www.neoninc.org/domains/overview), the CPER is the core site for Domain 10 (Central Plains). Infrastructure for building out this core site is scheduled to begin late fall 2011/early spring 2012. As already mentioned above, the CPER is also the location for the Shortgrass Steppe Long-term Ecological Research (SGS-LTER) project. This project has been functioning for thirty years (since 1982), but will conclude in 2013. The primary findings from this collaborative effort with ARS have been synthesized in the recent book Ecology of the Shortgrass Steppe: A long-term perspective (Lauenroth and Burke 2008).

Partnerships:
The CPER has a tremendous network of partnerships, both scientific and producer/customer related. The Crow Valley Livestock Cooperative, Inc., is the oldest grazing association in the US and has been a collaborative partner since the formation of CPER in 1937 (Fig 13). All cattle provided for research on CPER over the past 75 years have been from these forty ranches in the area. The Forest Service operated the CPER from 1937 to 1953, and remains a key partner with collaborations in research on CPER and the adjacent Pawnee National Grasslands. Colorado State University has been the leading scientific partner since the late 1960s beginning with the International Biological Program and continuing with the SGS-LTER. Current and/or planned research projects involve faculty from the following universities: Colorado State, University of Wyoming, Texas A&M, UC-Davis, Oklahoma State and University of Northern Colorado, as well as the Forest Service and the Natural Resources Conservation Service, Colorado Division of Wildlife, Environmental Defense Fund, The Nature Conservancy, in addition to ARS scientists from Jornada, Burns, Miles City, Mandan and Kimberly. Strengths of these partnerships include the stature of the researchers involved (e.g., David Briske, Daniel Milchunas, Bill Lauenroth, Ken Tate, Tony Svejcar, Brandon Bestelmeyer, Maria Fernandez-Gimenez, Karen Hickman, Lance Vermeire, April Leytem) and the diversity of land management agencies involved. Weaknesses of these partnerships include the lack of direct outreach involvement (e.g., extension) but the presence of the Shortgrass Steppe Research Interpretation Center on CPER provides an excellent avenue for both education and outreach activities, largely through Colorado State University and the Society for Range Management. Additional outreach possibilities include the development of an online prescribed grazing decision support tool and forum that is being designed to foster and facilitate additional communications among producers. In addition, the CPER is a key site in the following networks: Nutrient Network (NutNet, coordinated by Eric Lind, University of Minnesota, http://nutnet.science.oregonstate.edu/), Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet, led by Ron Follett, ARS-Fort Collins, http://www.ars.usda.gov/research/programs/programs.htm?np_code=204&docid=17271) and the NSF-funded National Ecological Observatory Network (NEON, led by David Schimel, http://www.neoninc.org/).

Figure 13. Partnership pictures with the Crow Valley Livestock Cooperative, Inc., and the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER) from 1937 to present. The Crow Valley Livestock Cooperative, Inc., is the oldest grazing association in the US and has provided all the livestock for research studies at the CPER.

Institutional Commitment:
The CPER has been, is currently, and will be, the flagship research location for the Rangeland Resources Research Unit with the benefits of a large land base (15,500 acres), an ability to conduct plot, pasture and landscape level experiments with a multitude of highly productive collaborators, and the infrastructural commitment by ARS (e.g., investment in state-of-the-art low-stress animal handling facilities) and CSU (the Shortgrass Steppe Research and Interpretation Center). National Science Foundation has also made a thirty year commitment with choosing the CPER as the core site for Domain 10 (Central Plains).
CPER is instrumental in existing (and planned) research for both CRIS projects. For NP215, CPER has been the site for extensive research on the production-conservation tradeoffs associated with managing for multiple ecosystem goods and services. The planned next five year project (2013-2018) for this NP will involve a large-scale, adaptive management grazing experiment involving the entire CPER with collaborations from Miles City and Mandan, and University of California-Davis (Ken Tate), Texas A&M (David Briske) and Colorado State University (Maria Fernandez-Gimenez). For NP212, CPER served as the primary location for the Open Top Chamber experiment and the soil carbon work associated with mitigation and adaptation is located here. Additionally, Dr. Will Blackburn, Director for the Northern Plains Area, has provided a letter of support for the Rangeland Resources Research Unit's request for the Central Plains Experimental Range (CPER) to be affiliated with the ARS's Long-Term Agro-Ecosystem Research (LTAR) network.

Literature Cited

Alfieri, J., P. Blanken, J.A. Morgan, and D.P. Smith. 2009. Concerning the measurement and magnitude of heat, water vapor, and carbon dioxide exchange from a semiarid grassland. Journal of Applied Meteorology and Climatology 48:982-996.

Andales, A.A., J.D. Derner, L.R. Ahuja, and R.H. Hart. 2006. Strategic and tactical prediction of forage production in northern mixed-grass prairie. Rangeland Ecology and Management 59:576-584.

Andales, A.A., J.D. Derner, P.N.S. Bartling, L.R. Ahuja, G.H. Dunn, R.H. Hart and J.D. Hanson. 2005. Evaluation of GPFARM for simulation of forage production and cow-calf weights. Rangeland Ecology and Management 58:247-255.

Augustine, D.J. 2010. Spatial versus temporal variation in precipitation in a semiarid ecosystem. Landscape Ecology 25:913-925.

Augustine, D.J. and D.G. Milchunas. 2009. Vegetation responses to prescribed burning of grazed shortgrass steppe. Rangeland Ecology and Management 62: 89-97.

Augustine, D.J., J.D. Derner, and D.G. Milchunas. 2010. Prescribed fire, grazing, and herbaceous plant production in shortgrass steppe. Rangeland Ecology and Management 63:317–323.

Bement, R.E. 1969. A stocking rate guide for beef production on blue-grama range. Journal of Range Management 22:83-86.

Blumenthal, D. 2005. Interrelated causes of plant invasion. Science 310:243-244.

Blumenthal, D., C.E. Mitchell, P. Pyšek, and V. Jarošík. 2009. Synergy between resource availability and pathogen release in plant invasion. Proceedings of the National Academy of Sciences 106:7899-7904.

Booth, D.T., and S.E. Cox. 2008. Image-based monitoring to measure ecological change on rangelands. Frontiers in Ecology and the Environment 6 doi:10.1890/070095

Booth, D.T., S.E. Cox, and R.D. Berryman. 2006. Precision measurements from very large scale aerial digital imagery. Environmental Monitoring and Assessment 112:293-307.

Bradley B.A., D.M. Blumenthal, D.S. Wilcove, and L.H. Ziska. 2010. Predicting plant invasion in an era of global change. Trends in Ecology and Evolution 25:310-318.

Briske, D.D., N.F. Sayre, L. Huntsinger, M. Fernandez-Gimenez, B. Budd, and J.D. Derner**.** 2011. Origin, persistence, and resolution of the rotational grazing Debate: Integrating human dimensions into rangeland research. Rangeland Ecology and Management 64:325–334.

Briske, D.D., J.D. Derner, J.R. Brown, S.D. Fuhlendorf, W.R. Teague, K.M. Havstad, R.L. Gillen, A.J. Ash, and W.D. Willms. 2008. Rotational grazing on rangelands: Reconciliation of perception and experimental evidence. Rangeland Ecology and Management 61:3-17.

Burke, I.C., A.R. Mosier, P.B. Hook, D.G. Milchunas, J.E. Barrett, M.A. Vinton, R.L. McCulley, J.P. Kaye, R.A. Gill, H.E. Epstein, R.H. Kelly, W.J. Parton, C.M. Yonker, P. Lowe, and W.K. Lauenroth. 2008. Soil organic matter and nutrient dynamics of shortgrass steppe ecosystems. In: W.K. Lauenroth and I.C. Burke (EDS.). Ecology of the Shortgrass Steppe: A Long-term Perspective. New York, New York: Oxford University Press. p. 306-341.

Derner, J.D., and D.D. Briske. 2001. Below-ground carbon and nitrogen accumulation in perennial grasses: A comparison of caespitose and rhizomatous growth forms. Plant and Soil 237:117-127.

Derner, J.D., and R.H. Hart. 2007. Grazing-induced modifications to peak standing crop in northern mixed-grass prairie. Rangeland Ecology and Management 60:270-276.

Derner, J.D. and G.E. Schuman. 2007. Carbon sequestration and rangelands: a synthesis of land management and precipitation effects. Journal of Soil and Water Conservation 62:77-85.

Derner, J.D., J.K. Detling, and M.F. Antolin. 2006a. Are livestock weight gains affected by black-tailed prairie dogs? Frontiers in Ecology and the Environment 4:459-464.

Derner, J.D., T.W. Boutton, and D.D. Briske. 2006b. Grazing and ecosystem carbon storage in the North American Great Plains. Plant and Soil 280:77-90.

Derner, J.D., D.D. Briske, and T.W. Boutton. 1997 Does grazing mediate soil carbon and nitrogen accumulation beneath C4 perennial grasses along an environmental gradient? Plant and Soil 191:147-156.

Derner, J.D., B.W. Hess, R.A. Olson, and G.E Schuman. 2008a. Functional group and species responses to precipitation in three semi-arid rangeland ecosystems. Arid Lands Research and Management 22:81-92.

Derner, J.D., R.H. Hart, M.A. Smith, and J.W. Waggoner Jr. 2008b. Long-term cattle gain responses to stocking rate and grazing systems in northern mixed-grass prairie. Livestock Science 117:60-69.

Derner, J. D., W.K. Lauenroth, P. Stapp, and D.J. Augustine. 2009. Livestock as ecosystem engineers for grassland bird habitat in the western great plains of North America. Rangeland Ecology and Management 62:111–118.

Diaz, S., S. Lavorel, S. McIntyer, V. Falczuk, D. Milchunas, F. Casanoves, H. Clark, C. Skarpe, G. Rush, M. Sternberg, I. Noy-Meir, J. Landsberg, J. Zhang, H. Clark, and B.D. Campbell. 2007. Plant trait responses to grazing-a global synthesis. Global Change Biology 13:313–341.

Dijkstra, F.A, E. Pendall, A. Mosier, J. King, D. Milchunas, and J.A. Morgan. 2008. Long-term enhancement of N availability and plant growth under elevated CO_2 in a semiarid grassland. Functional Ecology doi:10.1111/j.1365-2435.2008.01398.x.

Frasier, G.W., R.H. Hart, and G.E. Schuman. 1995. Rainfall simulation to evaluate infiltration/runoff characteristics of a shortgrass prairie. Journal of Soil and Water Conservation 50:460-463.

Gilmanov, T.G., L.L. Tieszen, B.K. Wylie, L.B. Flanagan, A.B. Frank, M.R. Haferkamp, T.P. Meyers and J.A. Morgan. 2005. Integration of CO_2 flux and remotely sensed data for primary production and ecosystem respiration analyses in the Northern Great Plains: Potential for quantitative spatial extrapolation. Global Ecology and Biogeography 14:271-292.

Guenther, D.A., and J.K. Detling. 2003. Observations of cattle use of prairie dog towns. Journal of Range Management 56:410–17.

Hart, R.H., and M.M. Ashby. 1998. Grazing intensities, vegetation, and heifer gains: 55 years on shortgrass. Journal of Range Management 51:392-398.

Hart, R.H., S. Clapp, and P.S. Test. 1993. Grazing strategies, stocking rates, and frequency and intensity of grazing on western wheatgrass and blue grama. Journal of Range Management 46:122-126.

Heisler-White, J.L., A.K. Knapp and E.F. Kelly. 2008. Increasing precipitation event size increases aboveground productivity in a semi-arid grassland. Oecologia 158:129-140.

Lauenroth, W.K. and O.E. Sala. 1992. Long-term forage production of North American Shortgrass Steppe. Ecological Applications 2:397-403.

Lauenroth, W.K., and I.C. Burke (EDS). 2008. Ecology of the Shortgrass Steppe: A long-term perspective. Oxford University Press, New York. 522 p.

Lauenroth, W.K., D.G. Milchunas, O.E. Sala, I.C. Burke, and J.A. Morgan. 2008. Net primary production in the shortgrass steppe: A long-term perspective. In: W.K. Lauenroth and I.C. Burke (EDS.). Ecology of the Shortgrass Steppe: A Long-term Perspective. New York, New York: Oxford University Press. p. 270-305.

LeCain, D.L., J.A. Morgan, D.G. Milchunas, A.R. Mosier, J.A. Nelson and D.P. Smith. 2006. Root biomass of individual species, and root size characteristics after five years of CO_2 enrichment on native shortgrass steppe. Plant and Soil 279:219-228.

Manley, W.A., R.H. Hart, M.J. Samuel, M.A. Smith, J.W. Waggoner Jr., and J.T. Manley. 1997. Vegetation, cattle, and economic responses to grazing strategies and pressures. Journal of Range Management 50:638-646.

Milchunas, D.G., and W.K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs 63:327-366.

Milchunas, D.G., J.R. Forwood, and W.K. Lauenroth. 1994. Productivity of long-term grazing treatments in response to seasonal precipitation. Journal of Range Management 47:133-139.

Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y. King and J.Y. Nelson. 2005a. Root production and tissue quality in a shortgrass steppe exposed to elevated CO_2: Using a new ingrowth method. Plant and Soil 268:111-122.

Milchunas, D.G., A.R. Mosier, J.A. Morgan, D.R. LeCain, J.Y King and J.A. Nelson. 2005b. Elevated CO_2 and defoliation effects on a shortgrass steppe: forage quality versus quantity for ruminants. Agriculture, Ecosystems and Environment 111:166-184.
Milchunas, D.G., J.A. Morgan, A.R. Mosier and D.R. LeCain. 2005c. Root dynamics and demography in shortgrass steppe under elevated CO_2, and comments on minirhizotron methodology. Global Change Biology 11:1837-1855.
Milchunas, D.G., W.K. Lauenroth, I.C. Burke, and J.K. Detling. 2008. Effects of grazing on vegetation. In: W.K. Lauenroth and I.C. Burke (EDS.). Ecology of the Shortgrass Steppe: A Long-term Perspective. New York, New York: Oxford University Press. p. 389-446.
Milchunas, D.G., O.E. Sala, and W.K. Lauenroth. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. American Midland Naturalist 132:87-106.
Morgan, J.A., A.R. Mosier, D.G. Milchunas, D.R. LeCain, J.A. Nelson and W.J. Parton. 2004. CO_2 enhances productivity, alters species composition, and reduces forage digestibility of shortgrass steppe vegetation. Ecological Applications 14:208-219.
Morgan, J.A., D.G. Milchunas, D.R. LeCain, M.S. West and A. Mosier. 2007. Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. Proceedings of the National Academy of Sciences 104:14724-14729.
Morgan, J.A., J.D. Derner, D.G. Milchunas, and E. Pendall. 2008. Management implications of global change for Great Plains rangelands. Rangelands 30:18-22.
Morgan, J.A., R.F. Follett, L.H. Allen, Jr., S.D. Grosso, J.D. Derner, F. Dijkstra, A. Franzluebbers, R. Fry, K. Paustian, and M.M. Schoeneberger. 2010. Carbon sequestration in agricultural lands of the United States. Journal of Soil and Water Conservation 65:6A-13A. doi:10.2489/jswc.65.1.6A
Morgan, J.A., D.R. LeCain, E. Pendall, D.M. Blumenthal, B.A. Kimball, Y. Carrillo, D.G. Williams, J. Heisler-White, F.A. Dijkstra, and M. West. 2011. C_4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. Nature 476:202-206.
Mosier, A.R., W.J. Parton, R.E. Martin, D.W. Valentine, D.S. Ojima, D.S. Schimel, I.C. Burke, E.C. Adair, and S.J. Del Grosso. 2008. Soil-Atmosphere exchange of trace gases in the Colorado shortgrass steppe. In: W.K. Lauenroth and I.C. Burke (EDS.). Ecology of the Shortgrass Steppe: A Long-term Perspective. New York, New York: Oxford University Press. p 342-372.
Nelson, J.A., J.A. Morgan, D.R. LeCain, A.R. Mosier, D.G. Milchunas, and B.A. Parton. 2004. Elevated CO_2 increases soil moisture and enhances plant water relations in a long-term field study in semi-arid shortgrass steppe of Colorado. Plant and Soil 259:169-179.
Polley, H.W., J.A. Morgan and P.A. Fay. 2010a. Application of a conceptual framework to interpret variability in rangeland responses to atmospheric CO_2 enrichment. Journal of Agricultural Science 149:1-14.
Polley, H.W., W. Emmerich, J.A. Bradford, P.L. Sims, D.A. Johnson, N.Z. Saliendra, T. Svejcar, R. Angell, A.B. Frank, F.L. Phillips, K.A. Snyder, and J.A. Morgan. 2010b. Physiological and environmental regulation of interannual variability in CO_2 exchange on rangelands in the western United States. Global Change Biology 16:990-1002.
Reeder, J.D., and G.E. Schuman. 2002. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environmental Pollution 116:457-463.
Reeder, J.D., G.E. Schuman, J.A. Morgan, and D.R. LeCain. 2004. Response of organic and inorganic carbon and nitrogen to long-term grazing of the shortgrass steppe. Environmental Management 33:485-495.
Sala, O.E., W.J. Parton, L.A. Joyce, and W.K. Lauenroth. 1988. Primary production of the central grassland region of the United States. Ecology 69:40-45.
Shoop, M., S. Kanode, and M. Calvert. 1989. Central Plains Experimental Range: 50 years of research. Rangelands 11:112-117.
Smart, A.J., J.D. Derner, J.R. Hendrickson, R.L. Gillen, B.H. Dunn, E.M. Mousel, P.S. Johnson, R.N. Gates, K.K. Sedivec, K.R. Harmoney, J.D. Volesky, and K.C. Olson. 2010. Effects of grazing

pressure on efficiency of grazing on North American Great Plains rangelands. Rangeland Ecology and Management 63:397–406.
Svejcar, A.J., R.F. Angell, J. Bradford, W. Dugas, W.E. Emmerich, A.B. Frank, T. Gilmanov, M.R. Haferkamp, D.A. Johnson, H.S. Mayeux Jr, P. Mielnick, J.A. Morgan, N. Saliendra, G.E. Schuman, P.L. Sims, and K.A. Snyder. 2008. Carbon fluxes on North American rangelands. Rangeland Ecology and Management 61:465-474.
Toombs, T.P., J.D. Derner, D.J. Augustine, B. Krueger, and S. Gallagher. 2010. Managing for biodiversity and livestock -A scale-dependent approach for promoting vegetation heterogeneity in western Great Plains grasslands. Rangelands 32:10-15.
Weltz, L, G. Frasier, and M. Weltz. 2000. Hydrologic responses of shortgrass prairie ecosystems. Journal of Range Management 53:403-409.

Appendix A. Core data sets that are available electronically at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER), in conjunction with the Shortgrass Steppe Long-Term Ecological Research (SGS-LTER) site.

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**
Annual Net Primary Production under different grazing regimes	1940	none	ANPP (1940-present, sampled annually)	Hart, Ashby: *Milchunas et al. 1994*
Ecosystem Stress Area Studies (ESA)	1969	none	Plant species basal and canopy cover and plant species density (treatments sampled annually 1971-72, 75-77, 82-91, biannually 1991-2007, then every 5 years 2009 on). ANPP on control plots (1983-present, sampled annually); small mammal abundance (1995-present, sampled every 3-5 years); plant tissue chemistry (1991)	Milchunas, Lauenroth: *Milchunas and Lauenroth 1995, Suding et al. 2005, Vinton and Burke 1995*
Standard Meteorological Measurements	1969	none	Air Temperature, precipitation, wind speed and direction, relative humidity, solar radiation, soil temperature (1969- present, 1986-present on CR21X sampled every fifteen minutes to daily)	Lauenroth and Parton: *Laptian and Parton 1996, Schimel et al. 1991*
Breeding Bird Survey	1970	none	Avian abundance (1970-present, sampled during breeding season)	Ryder, Lauenroth: *Porter and Ryder 1974, Sauer et al 1997, Robbins et al 1986*
Christmas Bird Count	1972	none	Avian abundance (1972-present, sampled once in Dec annually)	Ryder: *Braun 1994*
Recovery from White Grub	1977	none	Plant cover and density, ANPP (1977-present, sampled every 5-10 years)	Lauenroth, Laycock: *Coffin et. al 1998*
National Atmospheric Deposition Program	1979	none	Precipitation, wet Nitrogen and other deposition (1979-present, sampled daily)	Van Bowersox: *Lynch et al. 1996*

Study Title	Start Date	End Date	Information on Variables Measured and Sampling Frequency	Principal Investigator(s): References for Methods
Long-term ANPP	1983	none	ANPP, N concentration BOGR+BUDA and All-Other (1983-present, sampled annually; 2009 and on sampled by BOGR, BUDA, and each functional group; soil water by neutron probe from a catena site, 1984-1993, sampled bi-weekly), Seasonal plant N concentrations. BOGR, SPCO, GUSA (1990 - present, sampled monthly during growing season)	Milchunas, Lauenroth: *Lauenroth et al. 1986, Lauenroth and Adler 2008, Singh et al. 1996*
Long-term monitoring of the historical grazing strip	1984	none	Plant basal cover and density, soil C and N fractionations, soil organic matter (1984 – present, sampled every 2-10 years)	Milchunas, Lauenroth: *Milchunas and Lauenroth 1989, Milchunas et. al 1989, Milchunas et al 1998*
Soil Water by Neutron Probes	1984	none	Soil water by neutron probe (1984-1993, sampled bi-weekly)	Lauenroth: *Singh et. al 1998*
Use of C14 to measure root productivity	1985	none	C14 in belowground soil, roots, crowns and aboveground litter, standing vegetation (C14 labels applied in 1985, sampled 8-10 years following treatment). Short-term measures of exudation, labile-fiber components	Milchunas, Lauenroth: *Milchunas 2009, Milchunas and Lauenroth 1992, Milchunas and Lauenroth 2001, Milchunas 2009*
Seasonal Root Biomass	1985	2009	Seasonal root biomass in cores to 20cm depth (1985 - 2008, sampled monthly during the growing season)	Milchunas, Lauenroth: *Milchunas and Lauenroth 1992, Milchunas and Lauenroth 2001*
Seed production by *Bouteloua gracilis*	1989	2008	*B. gracilis* seed production (1989 - 2007, sampled annually)	Lauenroth: *Coffin and Lauenroth 1989*
Patterns and controls of N2O and CH4 fluxes	1990	none	Soil atmosphere exchanges of N_2O, CH_4, CO_2, and NO (1990 – present, sampled weekly)	Mosier, Valentine, Schimel, Parton, Martin: *Mosier et. al 1991*
Monitoring of area of prairie dogs towns	1981	none	Status and active area, in ha, of prairie dog towns on CPER and PNG, measured annually in summer or early fall	Antolin: *Stapp et al. 2004*

Study Title	Start Date	End Date	Information on Variables Measured and Sampling Frequency	Principal Investigator(s): References for Methods
CPER Soil Survey and Paleopedology Study	1990	none	Soils were mapped using 1:12000 (8.3 cm/km) color infrared aerial photos as basemaps: soil texture, organic C, total N, dithionate-citrate extractable Fe, Mn and Al, CEC, bulk density, soil water, and sand, silt and clay mineralogy. (1990 – present)	Kelly: *Blecker et al. 1997, Kelly et. al 1998, Yonker et al. 1988*
Recovery of soils on abandoned cultivated fields	1990	none	Soil texture, plant species basal cover, plant density (1990 – 1994, sampled annually)	Burke: *Burke et al. 1995, Ihori et al. 1995a, Ihori et al. 1995b*
Chart Project by Pantograph	1992	none	Chart project by pantograph (1997-present, sampled annually)	Lauenroth: *Peters and Lauenroth 2008*
Grazing Reversal – Large Mammals	1992	none	Belowground food web, nematodes, soil texture, soil C and N fractionations, soil compaction, litter C and N, soil total C and N, soil available resin N, plant species area plots, plant species density, ANPP, residual biomass on grazed treatments, herbivore selectivity by bite counts by belt transect, plant species basal and canopy cover, plant N concentrations on clip quadrats for BOGR+BUDA and All-Other, (1992-present) most variables sampled annually; soil water (2001-present) sampled monthly, Root ingrowth donuts to be added long-term in 2010; GU and UG treatments to be dropped near future after convergence)	Lauenroth, Burke: *Bakker et al. 2009, Milchunas et al. 2008a, Moore et al. 2008*
Rabbit Abundance	1994	none	Rabbit abundance (1994-present, sampled seasonally)	Stapp, Lindquist, Lauenroth: *Stapp 1996 (PhD. Dissertation), Stapp et al. 2008*
Canid Abundance	1994	none	Relative abundance of mammalian carnivore (coyotes, swift foxes, 1994-present, sampled seasonally)	Lindquist, Stapp Lauenroth: *Stapp 1996 (PhD. Dissertation), Stapp et al. 2008*

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**
Grazing Reversal – Small Mammals	1996	none	ANPP, plant species basal and canopy cover, plant N concentrations on clip quadrats for BOGR+BUDA and All-Other (1997-present, sampled annually). Short-term associated data see Grazing Reversal – Large Mammals above.	Milchunas: *Bakker et al. 2006*, , *Milchunas et al. 2008b*, *Bakker et al. 2009*
Monitoring abundance of small mammals, prey species and habitat structure	1994	none	Abundance of arthropods (sampled monthly, May-Sep) and vegetation composition and structure (1998-present, sampled annually), abundance of small mammals (1994 -present, sampled semi-annually), abundance of ground squirrels (1999-present, sampled semi-annually)	Stapp, Lindquist, Lauenroth: *Stapp 1996 (PhD. Dissertation), Stapp and Lindquist 2007, Higgins and Stapp 1997, Stapp et al. 2008*
Cross-site Fertilization Study	1995	none	ANPP, plant species density and basal cover (1998-present, alternatively sampled biennially); soil temperature and soil water by TDR (2001-2005, sampled daily); soil C and N fractionations, soil compaction, litter C and N, soil total C and N, soil available resin N (1995-present, sampled every five years)	Lauenroth, Burke: *Cleland et al. 2008*

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**
Responses to Elevated CO2 in Open Top Chambers	1995	2009	ANPP, ANPP by species, gas exchange for major species, gas exchange under different light levels, trace gas flux, leaf carbon isotopes, leaf water potential, soil texture, plant C, N and carbohydrates, seedling germination, plant size and density of STCO, plant cover, volumetric soil water content, root production/tissue quality, forage quality (N, fiber fractionations, ruminant digestibility), root biomass (1995-2009, sampled at different frequencies), nematodes, soil enzymes and microorganisms, soil C and N	Mosier, Morgan: *Morgan et al*. 2001a, *Mosier et al*. 2002, *Mosier et al* 2002, *Morgan et al*. 2004, *LeCain et al. 2006, Milchunas et al. 2005a,bc Morgan et. al 2001a, b, Morgan et al. 2007, Nelson et al. 2004, Ayres et al. 2008, Kandeler et al. 2006, King et al. 2004*
Responses to removal of BOGR, a dominant species	1996	2015	Plant species density and basal cover (1998-present, sampled annually)	Lauenroth, Burke, Coffin: *Munson 2009 (PhD. Dissertation), Munson and Lauenroth 2009*
Responses to drought	1996	2016	Plant species density and basal cover (1998-present, sampled annually)	Murphy, Burke: *Sala and Lauenroth 1982, Sala et al. 1982*
Phenological stages of various species of plants	1995	none	Plant phenological stages (1995 - present, sampled weekly during the growing season)	Lauenroth: *Dickinson and Dodd 1976*
Historic Ecosystem Stress Area Study plots treated with humus	1997	none	Plant species basal and canopy cover and plant species density (1997-present, sampled annually)	Burke, Lauenroth: *Lowe et al. 2002*
US Forest Service Burns, Impacts on vegetation	1997	2004	Plant N concentrations of BOGR, SPCO, and GUSA (1998-2004, sampled monthly during growing season); OPPO and shrub mortality, ANPP by species (1997-2004, sampled annually)	Milchunas: *Augustine and Milchunas 2009*

Study Title	Start Date	End Date	Information on Variables Measured and Sampling Frequency	Principal Investigator(s): References for Methods
U.S. Climate Reference Network	2002	2015	Air temperature, soil temperature, soil moisture, soil salinity (2, 4, 8, 20 and 40 inches), precipitation, wind speed and direction, surface temperature, solar radiation (2002- present, sampled hourly) and relative humidity (2004 - present, sampled hourly)	Helfert, Lindquist: *Owen et al. 2004*
Grazing seasonality and intensity	2004	2014	Abundance of arthropods (2003, 2004, 2006, sampled monthly May-Aug), density of bird nests (2004-2009, sampled monthly May-Jul), plant density and cover (2004 - present, sampled annually), ANPP (2004 - present, sampled annually), vegetation structure (2008-present), soil erosion instrumentation (2008-present)	Derner, Stapp, Lauenroth: *Derner et al. 2009*
Grazing of Conservation Reserve Program Land	2006	none	Annually:ANPP, plant species basal and canopy cover, consumption visual caged vs uncaged. Periodically: root biomass, soil C&N.	Milchunas, Munson, Lauenroth: *Milchunas et al. 2005,*
Plot size burning on Central Plains Experimental Range	2006	2016	ANPP, plant cover (2006 - present, sampled annually), vegetation structure (2008-present) plant density (2006-2008)	Derner, Augustine, Knapp: *Scheintaub et al 2009*
Patch size burning on Central Plains Experimental Range	2006	2026	ANPP, plant cover (2006 - present, sampled annually), vegetation structure (2008-present), plant density (2006-2008), grasshopper sampling (2009-present)	Derner, Augustine, Morgan: *Scheintaub et al 2009*

References for methods:

Augustine, D.J. and D.G. Milchunas. 2009. Vegetation responses to prescribed burning of grazed shortgrass steppe. *Rangeland Ecol Manage*. **62**: 89 - 97

Ayres, E., D. H. Wall, B. L. Simmons, C. B. Field, D. G. Milchunas, J. A. Morgan, and J. Roy. 2008. Belowground nematode herbivores are resistant to elevated atmospheric CO_2 concentrations in grassland ecosystems. *Soil Biology and Biochemistry* **40**:978-985

Bakker, E.S., J.M.H. Knops, D.G. Milchunas, M.E. Ritchie, and H. Olff. 2009. Cross-site comparison of herbivore impact on nitrogen availability in grasslands: the role of plant nitrogen concentration. *Oikos*. **118**: 1613 – 1622

Bakker, E.S., M.E. Ritchie, H. Olff, D.G. Milchunas, and J.M.H. Knops. 2006. Herbivore impact on grassland plant diversity depends on habitat productivity and herbivore size. *Ecology Letters*. **9**: 780 - 788

Braun, C.E. 1994. Ninety-fourth Christmas bird count, Nunn, CO. *National Audubon Society*. **48**: 765

Blecker, S., C.M. Yonker, C.G. Olson, and E.F. Kelly. 1997. Indicators of Holocene Climate Variations: Pedogenic Characterization of Shortgrass Steppe Soils, Colorado. *Geoderma*. **76**: 113 - 130

Burke, I.C., E.T. Elliot, and C.V. Cole. 1995. Influence of macroclimate, landscape position, and management on nutrient conservation and nutrient supply in agroecosystems. *Ecological Applications*. **5**: 124 - 131

Cleland, E. E. C. M. Clark, S. L. Collins, J. E. Fargione, L. Gough, K. L. Gross, D. G. Milchunas, S. C. Pennings, W. D. Bowman, I. C. Burke, W. K. Lauenroth, G. P. Robertson, J. C. Simpson, D. Tilman, and K. N. Suding. 2008. Species responses to nitrogen fertilization in herbaceous plant communities, and associated species traits. *Ecology*. **89**: 1175 - 1175

Coffin, D. P., W. A. Laycock, and W. K. Lauenroth. 1998. Disturbance intensity and above- and belowground herbivory effects on long-term (14y) recovery of a semiarid grassland. *Plant Ecology*. **139**: 221 – 233

Coffin, D.P. and W.K. Lauenroth. 1989. The spatial and temporal variability in the seed bank of a semiarid grassland. *American Journal of Botany*. **76**: 53 - 58

Derner, J.D., W.K. Lauenroth, P. Stapp, and D.J. Augustine. 2009. Livestock as ecosystem engineers for grassland bird habitat in the western Great Plains of North America. *Rangeland Ecology and Management*. **62**: 111 – 118

Dickinson, C.E. and J.L. Dodd. 1976. Phenological pattern in the shortgrass prairie. *American Midland Naturalist*. **96**: 367 - 378

Higgins, L.C., and P. Stapp. 1997. Abundance of thirteen-lined Ground Squirrels in Shortgrass Prairie. *Prairie Naturalist*. **29**: 25 - 37

Ihori, T., I.C. Burke, and P.B. Hook. 1995a. Nitrogen mineralization in native, cultivated, and abandoned fields in shortgrass steppe. *Plant and Soil*. **171**: 203 - 208

Ihori, T., I.C. Burke, W.K. Lauenroth, and D.P. Coffin. 1995b. Effects of cultivation and abandonment on soil organic matter in northeastern Colorado. *Soil Science Society of America Journal*. **59**: 1112 - 1119

Kandeler, E., A. R. Mosier, J. A. Morgan, D. G. Milchunas, J. Y. King, S. Rudolph, and D. Tscherko. 2006. Response of soil microbial biomass and enzyme activities to the transient elevation of carbon dioxide in a semi-arid grassland. *Soil Biology and Biochemistry* **38**:2448-2460

Kelly, E.F., S.W. Blecker, C.M. Yonker, C.G. Olson, E.E. Wohl, and L.C. Todd. 1998. Stable isotope composition of soil organic matter and phyoliths as paleoenvironmental indicators. *Geoderma*. **82**: 59 - 81

King, J. Y., A. R. Mosier, J. A. Morgan, D. R. LeCain, D. G. Milchunas, and W. J. Parton. 2004. Plant nitrogen dynamics in shortgrass steppe under elevated atmospheric carbon dioxide. *Ecosystems* **7**:147-160

Lapitan, R.L. and W.J. Parton. 1996. Seasonal variabilities in the microclimate factors and evapotranspiration in a shortgrass steppe. *Agricultural and Forest Meteorology*. **79**: 113 - 130

Lauenroth, W. K., and P. B. Adler. 2008. *Demography of grassland plants: Survival, life expectancy, and lifespan.* J Ecol. ***96****:1023-1032.*

Lauenroth, W.K., H.W. Hunt, D.M. Swift, and J.S. Singh. 1986. Estimating aboveground net primary production in grasslands: A simulation approach. *Ecological Modeling*. **33**: 297 - 314

LeCain, D.R., J.A. Morgan, D.G. Milchunas, A.R. Mosier, J.A. Nelson, and D.P. Smith. 2006. Root biomass of individual species, and root size characteristics after five years of CO2 enrichment on native shortgrass steppe. *Plant and Soil*. **279**: 219 – 228

Lowe, P.N., W.K. Lauenroth, and I.C. Burke. 2002. Effects of nitrogen availability on the growth of native grasses and exotic weeds.. *Journal of Range Management*. **55**: 94 - 98

Lynch, J.A., V.C. Bowersox, and J.W. Grimm. Trends in Precipitation Chemistry in the United States, 1983-1994: An Analysis of the Effects in 1995 of Phase I of the Clean Air Act Amendments of 1990, Title IV. U.S. Geological Survey, USGS 96-0346, Washington, DC, June 1996.

Milchunas, D. G. 2009. Estimating root production in shortgrass steppe: Comparison of 11 methods in shortgrass steppe and review of biases. *Ecosystems* **12**:1381-1402.

Milchunas, D.G., J.R. Forwood, and W.K. Lauenroth. 1994. Productivity of long-term grazing treatments in response to seasonal precipitation. *Journal of Range Management*. **47**: 2133 – 139

Milchunas, D.G. and W.K. Lauenroth. 1989. Three-dimensional distribution of a plant biomass in relation to grazing and topography in the shortgrass steppe. *Oikos*. **55**: 82 - 86

Milchunas, D.G. and W.K. Lauenroth. 1992. Carbon dynamics and estimates of primary production by harvest, C14 dilution, and C14 turnover. *Ecology*. **73**: 593 - 607

Milchunas, D.G. and W.K. Lauenroth. 1995. Inertia in plant community structure: state changes after cessation of nutrient enrichment stress. *Ecological Applications*. **5**: 452 - 458

Milchunas, D.G. and W.K. Lauenroth. 2001. Belowground primary production by carbon isotope decay and long-term root biomass dynamics. *Ecosystems*. **4**: 139 - 150

Milchunas, D. G., W. K. Lauenroth, and I. C. Burke. 1998. Livestock grazing: animal and plant biodiversity of shortgrass steppe and the relationship to ecosystem function. *Oakes* **83**:65-74

Milchunas, D. G., W. K. Lauenroth, I. C. Burke, and J. K. Detling. 2008. Effects of grazing on vegetation in the shortgrass steppe. Chapter 16 pages 389-446 *In:* Ecology of the shortgrass steppe: a long-term perspective (W. K. Lauenroth and I. C. Burke, eds.). Oxford University Press, New York.

Milchunas, D.G., W.K. Lauenroth, P.L. Chapman, and M.K. Kazempour. 1989. Effects of grazing, topography, and precipitation on the structure of a semiarid grassland. *Vegetation*. **80**: 11 - 23

Milchunas, D.G., A.R. Mosier, J.A. Morgan, D. LeCain, J.Y. King,and J. A. Nelson. 2005. Root production and tissue quality in a shortgrass steppe exposed to elevated CO2: Using a New Ingrowth Method. *Plant Soil*. **268**: 111 - 122

Milchunas, D.G., M.W. Vandever, F. Knopf, and A.W. Allen. 2005. Refining Conservation Reserve Program management to meet regional objectives: Evaluation of limited grazing on succession and stability of CRP grasslands in shortgrass steppe of eastern Colorado, pp.158-162. *In* A.W. Allen and M.W. Vandever (eds.). The Conservation Reserve Program - Planting for the Future, Proceedings of a National Symposium, Fort Collins, CO, June 6-9, 2004. US Geological Survey, Biological Resources Division, Scientific Investigations Report No. 2005-4145, 248 pp.

Moore, J.C., J. Sipes, A.A. Whittemore-Olson, H.W. Hunt, D.W. Wall, P.C. de Ruiter, and D.C. Coleman. 2008. Trophic structure and nutrient dynamics of the belowground food web within the rhizosphere of the shortgrass steppe. Chapter 11, pp. 248-269, *In* W.K. Lauenroth and I.C. Burke (eds.), Ecology of the Shortgrass Steppe: A Long Term Perspective. Oxford University Press, New York, NY.

Morgan, J. A., A. R. Mosier, D. G. Milchunas, D. R. LeCain, J. A. Nelson, and W. J. Parton. 2004. CO_2 enhances productivity but alters species composition and reduces forage quality in the Colorado shortgrass steppe. *Ecological Applications* **14**:208-219

Morgan, J. A., D. G. Milchunas, D. R. LeCain, A. R. Mosier. 2007. Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. *Proceedings of the National Academy of Science* **104**:14724-14729

Morgan, J.A., D.R. LeCain, A.R. Mosier, and D.G. Milchunas. 2001a. Elevated CO2 enhances water relations and productivity and affects gas exchange in C3 and C4 grasses of the Colorado Shortgrass Steppe. *Global Change Biology*. **7**: 451 - 466

Morgan, J.A., R.H. Skinner, and J.D. Hanson. 2001b. Re-growth and biomass partitioning in forages under nitrogen and CO2 regimes: differences among species of three functional groups. *Crop Science*. **41**: 78 - 86

Mosier, A.R., D.S. Schimel, D. Valentine, K. Bronson, and W.J. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Nature*. **350**: 330 - 332

Mosier, A. R., J.A. Morgan, J.Y. King, D. LeCain, and D. G. Milchunas. 2002. Soil-atmosphere exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado shortgrass steppe under elevated CO_2. *Plant and Soil* **240**:201-211

Munson, S.M. and W.K. Lauenroth. 2009. Plant population and community responses to removal of dominant species in the shortgrass steppe. *Journal of Vegetation Science*. **20**: 224 - 232

Nelson, J.A., J.A. Morgan, D.R. LeCain, A.R. Mosier, D.G. Milchunas, and W.J. Patron. 2004. Elevated CO2 increases soil moisture and inhances plant water relations in a long-term field study in sami-arid short grass steppe of Colorado. *Plant and Soil*. **259**: 169 – 179

Owen, K.S. 2004. US Climate Reference Network. *In* NOAA's National Climatic Data Center, Protecting the past, revealing the future. Annual Report 2004.

Peters, D.P.C. and W.K. Lauenroth. (2008). Simulation of disturbances and recovery in shortgrass steppe plant communities. Chapter 7, pp. 119-131, in: W.K. Lauenroth and I.C. Burke (eds.), Ecology of the Shortgrass Steppe: A Long Term Perspective. Oxford University Press, New York, NY.

Porter, D.K. and R.A. Ryder. 1974. Avian density and productivity studies and analyses on the Pawnee site in 1972. US/IBP Grassland Biome Technical Report No. 252. 77p.

Robbins, C.S., D. Bystrak, and P.H. Geissler. 1986. The breeding bird survey: its first fifteen years, 1965-1979. - U.S. Fish and Wildlife Service Resource Publication 157, Washington, D.C.

Sala, O.E. and W.K. Lauenroth. 1982. Small rainfall events: An ecological role in semiarid regions. *Oecologia (Berl.)*. **53**: 301 – 304

Sala, O.E., W.K. Lauenroth, and W.J. Parton. 1982. Plant recovery following prolonged drought in a shortgrass steppe. *Agricultural Meteorology*. **27**: 49 - 58

Sauer, J.R., J.E. Hines, G. Gough, I. Thomas, and B.G. Peterjohn. 1997. The North American Breeding Bird Survey Results and Analysis. WWW-Version 96.4. Patuxent Wildlife Research Center, Laurel, MD.

Scheintaub, M.R., J.D. Derner, E.F. Kelly, A.K. Knapp. 2009. Response of the shortgrass steppe plant community to fire. *Journal of Arid Environments*. **73**: 1136-1143

Schimel, D.S., T.G.F. Kittel, and W.J. Parton. 1991. Terrestrial biogeochemistry cycles: global interactions with the atmosphere and hydrology. *Tellus*. : 188 - 203

Singh, J.S., P. Bourgeron, and W.K. Lauenroth. 1996. Plant species richness and species-area relations in a shortgrass steppe in Colorado. *Journal of Vegetation Science*. **7**: 645 – 650

Singh, J. S., D. G. Milchunas, and W. K. Lauenroth. 1998. Soil water dynamics and vegetation patterns in a semiarid grassland. *Plant Ecology*. **134**: 77 - 89

Stapp, P. 1996. Determinants of habitat use and community structure of rodents in northern shortgrass steppe. Ph. D. Dissertation. Colorado State University, Fort Collins.

Stapp, P., M.F. Antolin, and M. Ball. 2004. Patterns of extinction in prairie dog metapopulations:plague outbreaks follow El Nino events. *Front. Ecol. Environ.* **2**: 235 – 240

Stapp, P. and M.D. Lindquist. 2007. Roadside foraging by kangaroo rats in a grazed shortgrass-prairie landscape. *Western North American Naturalist*. **67**: 368 – 377

Stapp, P., B. Van Horne, M.D. Lindquist. 2008. Ecology of mammals of shortgrass steppe. Chapter 8, pp.132-180, ***In:*** W.K. Lauenroth and I.C. Burke (eds.), Ecology of the Shortgrass Steppe: A Long Term Perspective. Oxford University Press, New York, NY.

Suding, K.N., S.L. Collins, L. Gough, C. Clark, E.E. Cleland, K.L. Gross, D.G. Milchunas, and S. Penings. 2005. Functional- and abundance-based mechanisms explain diversity loss due to N fertilization. *Proceedings of the National Academy of Science*. **102**: 4387 – 4392

Vinton, M.A., and I.C. Burke. 1995. Interactions between individual plant species and soil nutrient status in shortgrass steppe. *Ecology*. **76**: 1116 – 1133

Yonker, C.M., D.S. Schimel, E. Paroussis, and R.D. Heil. 1988. Patterns of organic carbon accumulation in a semiarid shortgrass steppe, Colorado. *Soil Science Society of America Journal*. **52**: 478 – 483.

Appendix B. Spatially-related datasets available at the USDA-Agricultural Research Service (ARS), Central Plains Experimental Range (CPER), in conjunction with the Shortgrass Steppe Long-Term Ecological Research (SGS-LTER) site.

Central Plains Experiment Range (CPER) GIS Datasets:

Dataset Name	**Description**	**Source**
cper-bdy	Boundary of CPER	USGS quads
cper-building	Buildings within the CPER	Aerial Photos and USGS quads
cper-elev_contours	Elevation Contours of CPER	Based on 10M DEM
cper-exclosures	Exclosures in CPER	GPS
cper-fences	Fence lines in CPER	USGS PLSS and other sources
cper-lakes	Lake boundaries in CPER	USGS 1:24000
cper-landforms	Landform in CPER	USGS 1:24000
cper-landmark	Landmarks in CPER (tanks, corrals, windmills)	GPS
cper-pastures	Pasture boundaries in CPER	USGS PLSS and other sources
cper-pipelines	Pipelines in CPER	Various sources
cper-pls	Public Land Survey boundaries in CPER	USGS PLSS 1:24000
cper-roads	Roads in CPER	USGS, GPS and other sources
cper-soils	Soil boundaries in CPER	Special NRCS soils survey
cper-streams	Stream lines within CPER	USGS 1:250000
cper-vegibp	IBP Vegetation within CPER	IBP Species Composition
cper_metstations	Meteorological Station s in CPER (recorded weather data can be joined and mapped)	GPS
cper_studysites	Study sites within CPER	GPS
cper_dem	Digital Elevation Model (raster)	USGS 10M DEM
cper_pdog (97 to 09)	Prairie Dog Town Boundaries (1997 to 2009)	GPS by CSU
cper_chart (97-09)	Permanent square meter plots	Pantograph
cper_PhotoIndex	Aerial Photo Indices of CPER – 1937, 1941, 1977, 1982	
cper_wildfire_june06	June 2006 Wildfire boundary	GPS by CSU
cper_pasture_treatments	CPER pasture treatments 1991-2009	ARS

Pawnee National Grassland (PNG) GIS Datasets

Dataset Name	Description	Source
png_boundary	Boundary of PNG	USGS and USFS
png_exclosures	Exclosure boundaries in PNG	GPS
png_geology	Geology boundaries in PNG	USGS
png_landuse_weld	Landuse in PNG	Weld County
png_ownership	Land Ownership in PNG	Weld County
png_pls	Public Land Survey Boundaries in PNG	USGS
png_roads	Road lines with PNG	USGS 1:250000
png_soils	Soil boundaries with PNG	NRCS Weld County Soil Survey
png_streams	Stream lines in PNG	USGS 1:250000
png_dem	Digital Elevation Model (raster)	USGS 10M DEM
png_pdog (81 to 08)	Prairie Dog Town Boundaries (1981 to 2008)	GPS by USFS
png_watersheds	Major watershed boundaries in PNG	USGS 10M DEM

CPER Miscellaneous Map Imagery

Dataset Name	Description	Comments
Photos	Aerial Photos and Indices - 1937, 1941, 1977, 1982	Indices are digital. Photos are hard copy images (1977 has been scanned to digital images)
Root Diagrams	Root Diagrams - scanned images in CPER	scanned and vectorized by CSU for analysis of root distribution by depth.
Burn Areas	Burned areas 1960 - 1999	From aerial photos and GPS
Cultivated Fields	Cultivated Fields 1954 - 1999	
Management Methods	Fields with Management Methodologies 1937 – 1999 of CPER	
Grazing Intensity	Grazing Intensity by Field	
Protected Areas	Protected Areas of CPER/SGS	
Power Lines	Power Lines of CPER	
Trails	Trails of CPER	

Central Grasslands Miscellaneous Map Imagery

Dataset Name	Description	Comments
Absolute Production of C3 and C4 Grasses	Absolute Production of C3 and C4 Grasses derived from NRCS Range Site Data	
Absolute Production Grasses by Species	Absolute Production Grasses by Species (24) derived from NRCS Range Site Data	
Duration of Greenness	Duration of Greenness - NDVI derived	
Grain Carbon Change	Grain Carbon Change (1995-1950-1900)	
Onset of Greenness	Onset of Greenness - NDVI derived	
Peak of Greenness	Peak of Greenness - NDVI derived	
Relative Production of C3 and C4 Grasses	Relative Production of C3 and C4 Grasses derived from NRCS Range Site Data	
Relative Production of Grasses by Species	Relative Production of Grasses by Species (24) derived from NRCS Range Site Data	
Soil Carbon Change	Soil Carbon Change (1995-1950-1900)	
Steady State Soil Carbon	Steady State Soil Carbon (1900)	
Precipitation	Precipitation - 20-year mean annual contours	
Temperature	Temperature - 20-year mean annual contours	
Weather Stations - 20-year mean	Weather Stations - 20-year mean-monthly and mean-annual data (points)	