Shortgrass Steppe LTER VI: Examining Ecosystem Persistence and Responses to Global Change 2010-2014 Proposal

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Project Summary

<u>Intellectual Merit:</u> The Shortgrass Steppe Long-term Ecological Research (SGS-LTER) program focuses on how grassland ecosystems function and persist or change in the face of global change. Our conceptual framework asserts that ***climate***, ***physiography***, ***grazing, fire*** and ***land-use,*** operating over different spatial and temporal scales, are the dominant determinants of the structure, function, and persistence of the SGS. Using the shortgrass steppe (SGS) ecosystem of the North American Great Plains as a model, we seek to (1) identify the ecological attributes of grasslands that historically have resulted in their persistence and (2) understand these attributes in ways that will allow us to identify area of vulnerability and better forecast the future of grasslands in the face of global change. Given its geographic extent and history, the SGS encapsulates many of the features of a system driven by social-ecological interactions and the vulnerabilities of semi-arid grasslands to global change. Our overarching question is:

How will structure and function of the SGS respond to expected changes in climate, management, and land-use, and what will be the consequences?

Our program is organized around four major themes based on the key determinants and our desire to forecast change. The major themes and guiding questions are:

A. Climate: *How has climatic variation shaped the structure and function of SGS, and how will projected climate change influence processes in the future?*

B. Physiography: *To what extent are SGS dynamics and responses to global change contingent on physiography?*

C. Grazing, Fire and Land-use: *How will land-use changes that alter grazing, fire and grazing-fire interactions modify the structure and function of SGS?*

D. Synthesis and Projections/Forecasting: *How do climate, grazing, and land use influence the SGS over multiple spatial and temporal scales?*

We will include traditional and state-of-the-art approaches and methodologies over multiple temporal and spatial scales, including increased use of molecular techniques to study microbial and invertebrate communities, gas flux measurements, and novel modeling approaches. For synthesis and forecasting, data drawn from our monitoring and experimental activities will be used to parameterize simulation and theoretical models to study phenomena operating at multiple temporal and spatial scales. Our interdisciplinary approach includes team members from the physical sciences, biological sciences, social sciences, and education. This melding of the traditional ecology, the social sciences, and education has the potential to be transformational as a model as envisioned in the LTER Decadal Plan.

<u>Broader Impact</u> The SGS-LTER is committed to promoting environmental literacy through basic research in student learning, direct engagement with K-12 teachers and students, and curriculum reform. We will offer research internship and professional development workshops for students and K-12 teachers. Our education research is focused on the development of an Environmental Science Literacy Framework by identifying key ecological concepts and assessing the current state of knowledge of teachers and students in these core areas, and understanding the scaffolding of science and mathematics concepts required to reach the desired level of understanding. We will research the development of learning progressions (descriptions of increasingly sophisticated ways of reasoning about topics) from grades 6-12 focusing on preparing students for STEM careers and environmentally responsible citizenship. These learning progressions are organized around three key science strands (carbon, water, and biodiversity) and a mathematical strand (quantitative reasoning and the mathematics of modeling); all of which are aligned with the research focus of the SGS-LTER.

Section 1. Results from Prior Support

We present our results from SGS-LTER V (2002-2008) and the first 1.5 years of SGS-LTER VI (2008-present). Since its inception in 1983, the Shortgrass Steppe Long Term Ecological Research program (SGS-LTER) has made significant advancements in our understanding of grassland ecology and general ecological principles through the development of a comprehensive program of core ecological research across multiple spatial and temporal scales, complemented by intensive short- and extensive long-term experiments. Following the probation decision in 2008, we thoroughly revised our program in ways that build on our past strengths while addressing the shortcomings identified by the last review. We have trimmed experiments, integrated our work, revised our management structure, invited in a new cadre of scientists, and re-affirmed the university's commitment to the program.

Through the years, the SGS-LTER program has identified ***climate, grazing, physiography, land use, and biotic interactions*** as key determinants (forcing factors) responsible for the structure and functioning of this ecosystem with research emphasizing subsets of these determinants during different funding cycles. In SGS-LTER V, we focused on the vulnerability of SGS to environmental change, particularly with respect to the five determinants and their interactions. We (1) evaluated the long term effects of grazers (historically important biotic drivers now mostly under human control) on SGS ecosystem dynamics, (2) continued experiments on climate change, and human and natural disturbances, (3) initiated new experiments evaluating the influence of fire and land use, (4) expanded our research program with new cross site, international, and synthesis activities, and (5) updated our research approach to include new methods of trace gas monitoring, and molecular techniques to characterize microbial communities, gene function, and soil enzyme activity.

<u>Research Productivity and Quality:</u> Peer-reviewed publications, invited book chapters, books and scientific presentations increased substantially during this funding cycle. The SGS-LTER produced approximately 263 (plus 25 submitted) journal articles (including papers in *Nature, Science,* and *PNAS*), 3 books, 66 book chapters, 38 dissertations and theses, and many abstracts from national and international meetings (Table S1). Most of these involved multiple authors, reflecting the collaborative spirit and interdisciplinary nature of the SGS-LTER research program. We are pleased to report that SGS-LTER lead scientists spearheaded completion of the site synthesis volume entitled *Ecology of the Shortgrass Steppe: A Long-Term Perspective* (Lauenroth and Burke 2008). This comprehensive synthesis combines the research and expertise of 23 primary authors, and has served as a springboard for future research.

<u>Information Management:</u> We made significant changes to our Information Management System by revising the relational database management system to more efficiently organize, relate and deliver information, data and metadata. The Information Management System of the SGS-LTER program makes >250GB of information available to researchers inside and outside the SGS-LTER program. Besides requests for publications, SGS-LTER maintains 133 data sets that are available electronically, 70 of these are downloadable (Table S2.1-S2.4) with EML level 5 metadata. The use of these data sets by non-SGS-LTER scientists is substantial: 76% of requests are from outside users (Table S2.5).

<u>Education and Outreach:</u> SGS-LTER scientists and staff actively mentor students and young scientists, and work within the K-12 community. During this funding cycle, we supported 57 graduate students with stipends, travel, supplies or facility access, 93 undergraduate students, 13 Research Experience for Undergraduate (REU) students, and 6 post-doctoral fellows. Our Education and Outreach component grew significantly by increasing the number of partnerships with regional school districts, professional development and training for K-12 teachers, research internships for teachers and minority high school students, and cross-site education and outreach programs among 9 LTER sites (see Section 5). These activities; supported with SLTER supplements and funding from state and federal sources, generated 5 journal publications and 2 book chapters. Additionally, SGS-LTER contributed to the development of a network-wide LTER education plan as part of the LTER Planning Grant activities.

<u>Research Findings:</u> We highlight our major syntheses of long-term data and new discoveries from this most recent 6-yr cycle funding. Additional results from SGS-LTER V-VI are presented in other parts of the proposal where they are relevant to our proposed research activities. A full accounting of our research accomplishments and details of experimental procedures can be found in our research summaries in our *Progress Reports* submitted to NSF (2003 to 2009) (sgslter.colostate.edu/ProgressReports/proposal.htm).

Impacts of Grazing and Land-use: Grazing by large herds of bison and low precipitation were historic drivers in the development of the current-day SGS. These convergent selective forces resulted in a system with a large proportion of plant biomass belowground, where competition for soil water and nutrients dominates over competition for light in the sparse canopy (Milchunas et al. 1988, Burke et al. 1998) and belowground consumers dominate food webs (Lauenroth and Milchunas 1992). The SGS is thus unique among LTER sites in the degree of resistance to aboveground disturbances such as livestock grazing and fire (Milchunas et al. 2008).

Overall, we have found that aboveground grazing and fire have relatively small and often stabilizing effects on SGS plant communities, while disturbances that affect the belowground system or shift allocation patterns away from the belowground realm can have large and long-lasting effects. Our long-term grazing studies show modest shifts in plant community and belowground community composition and plant productivity following a shift from grazed to ungrazed. Further, native and exotic opportunistic "weeds" are more abundant under ungrazed conditions (Milchunas et al. 2008, Rebollo et al. 2005), due to more uniform exploitation of belowground resources by roots (Milchunas and Lauenroth 1989) and reductions in safe-sites for colonizers (Milchunas et al. 1992, 2008). Fire has relatively small effects on SGS plant community composition or productivity (Augustine and Milchunas 2009, Schientaub et al. 2009). Fire enhances nesting habitat for the mountain plover by reducing standing dead vegetation and increasing bare soil (Svingen and Giesen 1999), increases rates of prairie dog colony expansion (Augustine et al. 2007) and improves habitat for swift fox (Thompson et al. 2008). Long-term cattle exclosures and prairie dog colonies moderately grazed by cattle increased the abundance and diversity of small mammals (Newbold et al. *submitted*) due to the additional cover provided by taller vegetation in exclosures and the burrows in colonies. In contrast, no significant treatment effects were seen for beetles, spiders or grasshoppers. We recently provided the most detailed analysis to date of interactions between prairie dogs (*Cynomys ludovicianus*) and cattle grazing in SGS. Unlike in mixed-grass prairie, where cattle graze preferentially on colonies, we found that cattle neither avoid nor prefer prairie dog towns in SGS (Guenther and Detling 2003, Stapp et al. 2008a).

During the 20th century, conversion of native grassland to dry cropland was the most common human disturbance at the SGS. Now, land previously plowed and replanted to grassland under the Conservation Reserve Program (CRP) comprises about 10-15% of the local landscape. Studies of different aged CRP fields (Milchunas et al. 2008, Munson and Lauenroth, *in prep*) document long periods for recovery of native perennial grasses and loss of early-seral weedy annuals. Net primary production has increased with time since re-seeding, with 18- and 20-year-old fields being similar to native shortgrass steppe.

Urbanization is a rapidly expanding disturbance along the western edge of SGS. Measured C fluxes, N cycling and soil microbial community structure in urban lawns differed strongly from irrigated corn and dryland wheat, and unmanaged SGS grassland (Kaye et al. 2004, 2005). ANPP in urban ecosystems was 4-5 times greater than wheat or SGS, but significantly less than corn. Soil respiration and belowground C allocation in urban ecosystems were 2.5-5 times greater than other land-use type (Kaye et al. 2005).

Consumer-Disease Interactions: Prairie dogs alter nutrient and water dynamics, productivity and plant community composition; provide habitat for burrow-dependent species; and are prey for numerous predators (Whicker and Detling 1988, Stapp et al. 2008a). Prairie dogs are extremely susceptible to plague; a disease caused by the introduced bacterium *Yersinia pestis*. Plague leads to the extinction of entire prairie dog towns and creates a novel metapopulation structure (Antolin et al. 2006). Long-term surveys of towns revealed that plague outbreaks are relatively common during El Niño years (Stapp et al. 2004), and uncommon during hotter and drier years. Increased town connectivity, cooler-wetter summers, and soils with high moisture retention predict the timing and location of outbreaks (Savage 2007). Field-parameterized modeling (Webb et al. 2006), lab experiments (Eisen et al. 2006, Wilder et al.

in press a,b) and field surveys (Salkeld and Stapp 2008, Stapp et al. 2008b, Stapp et al. 2009, Tripp et al. 2009) examined the role of fleas and other rodent hosts in driving plague outbreaks. Rodents or fleas serve as short-term reservoirs for the pathogen. Mammalian carnivores (Salkeld and Stapp 2007, Salkeld et al. 2007, Boone et al. 2009) or prairie dogs (Stapp et al. 2004) may be long-distance vectors of fleas from one town to another. The exact mechanism of persistence of plague remains unresolved.

Several recent studies have also demonstrated strong responses of other species to the mosaic of habitats generated by prairie dog population dynamics. Characteristics differ between occupied towns; recently extirpated towns; older towns where burrows have collapsed and vegetation has recovered; and newly recolonized towns. Differences among these habitat types are found in swift foxes (*Vulpes velox*; Lebsock 2009), burrowing owls (*Athene cunicularia*; Conrey et al. 2009), rodents (Stapp 2007a), pollinators (Hardwicke 2006), harvester ants (Alba-Lynn 2006), belowground microbial communities (Quirk 2006) and plant communities (Hartley 2006, Stapp 2007a). Plague has caused local trophic cascades by removing prairie dogs, with effects felt throughout the SGS ecosystem (Stapp 2007b).

The SGS and Global Change: Increases in CO_2 and other trace gases in the atmosphere are predicted to increase global temperatures 3°C by the end of the century (Meehl et al. 2007). In contrast to the relative insensitivity that plant communities have exhibited to grazing and fire (Hart and Hart 1997, Milchunas et al. 2008), the SGS is more sensitive to experimental manipulations of CO_2, temperature, water and N additions, and is responsive to climate as observed in our long-term monitoring. Overall, this suggests that there is strong potential for global change to push this historically stable ecosystem to states that differ significantly from recent historical and contemporary versions.

We recently manipulated precipitation in the SGS with rainout shelters and direct watering. In a 3-year experiment, plots received the long-term average growing season precipitation, distributed as 4, 6, or 12 events following seasonal patterns for May-September (Heisler-White et al. 2008). The treatments were designed to push the system with a rainfall regime that was outside the historic range of variability (mean = 14 events, minimum = 9 events in years with average total precipitation). Plots receiving fewer, but larger events had higher ANPP (30% increase above the long-term mean) compared to plots receiving more frequent rainfall. Larger events led to greater soil water content and permitted moisture to penetrate deeper in the soil profile. These results indicate that SGS can respond immediately and substantially to forecast shifts in rainfall regimes. In 2009 we erected rainout shelters to study the short-term (7 day) response of SGS to 1-cm and 2-cm wetting events (von Fischer et al. 2009b). Daily sampling confirmed rapid and staggered responses of plant growth, biota, soil respiration, and soil enzyme activity in a manner consistent with the pulse-dynamics paradigm (Noy-Meir 1973, Collins et al. 2008).

An open top chamber experiment that doubled CO_2 concentration over present levels increased aboveground biomass of native SGS vegetation an average 41% over 5 years (Morgan et al. 2004a). Results from similar experiments suggest that semi-arid grasslands may be especially responsive to CO_2 due to increased plant water use efficiency (Morgan et al. 2004b). Over 5 years of CO_2-enrichment C_3 grasses (e.g., *Stipa comata*), and the sub-shrub *Artemisia frigida* (common to other North American and Asian grasslands) exhibited substantial increases in productivity. Most strikingly, aboveground biomass of *A. frigida* increased 40-fold (Morgan et al. 2007). Shifts in species and reduction in tissue N concentration that occurred under CO_2-enrichment reduced forage quality (Milchunas et al. 2005b). For SGS, models show that rising CO_2 leads to minor reductions of soil organic N (Parton et al. 2007), thereby constraining any CO_2-induced stimulation in plant growth and C sequestration (Luo et al. 2004). However, Dijkstra et al. (2008) determined that increases in plant N uptake in plants exposed to double ambient CO_2 concentrations (King et al. 2004) was due to greater soil N mineralization. Further, N deposition may counter such CO_2-induced soil N limitations. These results and those from our N-addition experiments highlight the uncertainty about the fate of SGS soil N in future CO_2-enriched conditions.

Responses of SGS to temperature changes are likely to be contingent on soil water content, with higher temperatures enhancing production in wet to normal years, and decreasing production in dry years (Parton et al. 2007). Warm-season C_4 grasses will likely benefit at the expense of cool-season C_3 grasses (Epstein et al. 1997). The interaction of plant responses to increased temperature and CO_2 are presently being explored in the Prairie Heating and CO_2 Enrichment Experiment. After 3 years of experimentation, combined warming and CO_2 enrichment are enhancing ANPP, with no clear differences yet emerging between C_3 and C_4 perennial grasses (Morgan et al. 2007).

Finally, we investigated controls on methane oxidation by SGS soils, an important sink for this greenhouse gas. von Fischer et al. (2009a) quantified the physical vs. biological controls that generate the hump-shaped response to variation in soil moisture, thus improving our ability to model this process.

Cross-Site Studies, Synthesis and Contributions to Theory: In a global synthesis of plant traits (from197 sites representing all the major grazing regions on Earth) known to respond to grazing by large herbivores, we evaluated six conceptual models that explain which plant traits become associated with each other under different combinations of climate and herbivore history (Diaz et al. 2007). Grazing history, as proposed by the SGS model (Milchunas et al. 1988, Milchunas and Lauenroth 1993), best explains the combinations of life history, plant type, and plant morphology of species found on grasslands worldwide. As part of a LTER cross-site synthesis project in North America and Europe, we investigated how interactions between large and small mammalian herbivores influence plant community structure and diversity. Herbivore impacts on plant species richness depended on site primary production changing from negative to positive as primary production increased (Bakker et al. 2006). Species richness of the SGS was negatively affected by both herbivore sizes, with small selective herbivores that consume ~3 % of plant biomass having as much effect as large generalist ones that consume 40%. We also participated in a cross-site synthesis on plant diversity responses to N fertilization, which found that diversity declined with increasing NPP due to the loss of native, perennial species (Suding et al. 2005, Pennings et al. 2005).

With the support of the LTER Network Office, in 2007 we initiated cross-site analyses of long-term patterns of rabbit and rodent populations at 3 LTER sites (SGS, SEV, JRN) and 1 ILTER site (Mapimi) in Mexico, where similar data on the populations, food resources and predators were collected for >12 years. The analyses focused on effects of drought and wet years on rodent diversity. We found strong affinities between the desert sites, but also a consistent effect of shrub cover as a determinant of rodent communities. We compared taxa among the sites and gained a clearer understanding of the effects of climate change on animal communities throughout the region. The studies led to a Symposium at the 2007 Mammalogists Meeting and a special issue of *Journal of Mammalogy* is forthcoming.

Other research has increased our understanding of food webs and the way in which they are studied. This work 1) incorporated biogeochemical processes into the study of trophic dynamics, 2) integrated detritus and donor-controlled dynamics, and 3) led to techniques to apply empirically-derived data to test theory, and to study the "dynamics of dynamics" encompassing changes in population sizes, strengths of interactions, and dynamic states of food webs in space and time (Moore et al. 2003, Moore et al. 2004, de Ruiter et al. 2005a,b, Rooney et al. 2006, 2008).

SGS-LTER has been a leader in data synthesis for the most extensive cross-site LTER study – the Long-term Intersite Decomposition Experiment Team (LIDET). The 10-year decomposition data from 21 sites (seven biomes) found that litter decomposition is the primary source of mineral N for biological activity in most terrestrial ecosystems, and that net N release from leaf litter is primarily driven by initial tissue N concentration and mass remaining, regardless of climate, edaphic conditions, or the biota (Parton et al 2007). Arid grasslands exposed to high UV radiation were an exception, where net N release was insensitive to initial N. The fundamental constraints on decomposer physiology lead to predictable global-scale patterns in net N release during decomposition (Adair et al. 2008). SGS-LTER students summarized patterns of decomposition that occur across all grassland sites (Bontti et al. 2009).

Additionally, the SGS is involved in a cross-site (CDR, SGS, SEV) study addressing the role of UV over a productivity gradient, building upon an earlier field study at SGS where UV effects were evident primarily under dry, low production conditions (Brandt et al. 2007). Finally, the SGS is the only location in the world where all but one method of root production have been tested, allowing a comparative-approach synthesis of biases for estimating this important C and N input (Milchunas 2009).

The SGS LTER Social Science research participated in the LTER network wide study, *"Maps and Locals (MALS): A Cross-Site LTER Comparative Study of Land-Cover and Land-Use Change with Spatial Analysis and Local Ecological Knowledge*." This initiative led to our rethinking how we approach the human dimensions of changes in land-use on the SGS ecosystem (see section D3 of our proposal).

Finally, the SGS-LTER site, representing native SGS ecosystems in the western Great Plains, was selected as the first candidate core site to be built as part of the National Ecological Observatory Network (NEON). The network is designed to help researchers over the next 30 years to understand and forecast the impacts of contemporary global changes, including climate change, land-use change and invasive species, on the ecology of ecosystems as diverse as grasslands, deserts and forest. The state-of-the art monitoring equipment and measurements that NEON offers will greatly increase our research capabilities, while the ~30-year record of measurements at this SGS-LTER site, as well as ongoing and planned new studies (described in section 2) will be a major benefit to NEON.

Project Management, Human Capital, Infrastructure, and Institutional Commitment: In the first 1.5 years of LTER VI, there have been significant changes in the management of the SGS-LTER program and a significant increase in the level of institutional support from Colorado State University. In 2009 M. Antolin passed the leadership role for this proposal to J. Moore. Furthermore, in response to career moves and the need to reinvigorate our program, J. Derner (USDA ARS) and N. Kaplan (SGS IM Manager) have joined our leadership team as member of the SGS Executive Committee, reflecting the leadership role each have demonstrated and our commitment to our core partners and the importance of IM to the SGS-LTER (see section 3).

We made a consistent effort to expand the number of scientists in our program. During SGS-LTER V we recruited six scientists to strengthen the project in needed areas: Drs. David Augustine (fire ecology), Dana Blumenthal (invasive species), Cynthia Brown (invasive species), Justin Derner (range ecology), Alan Knapp (plant ecology and ecophysiology), and Joseph von Fisher (microbial ecology). For SGS-LTER VI we recruited twelve new scientists: Drs. Amy Angert (evolutionary plant ecology), Randall Boone (human–grazing systems), Richard Conant (biogeochemistry), Noah Fierer (microbial ecology), Kathy Galvin (anthropology), Niall Hanan (land-atmosphere), Catherine Keske (natural resource economics), Julia Klein (range ecology), Patrick Martin (landscape ecology), Heidi Steltzer (plant ecology), Matthew Wallenstein (microbial ecology), and Colleen Webb (modeling and synthesis).

The SGS-LTER leadership secured funding from NSF, Colorado State University and the University of Northern Colorado to construct a new field station and interpretive center at the SGS site. The complex includes a central building that serves as meeting area (capacity of 100) with spectacular views of the SGS, breakout rooms, and advanced cyberinfrastructure, and four adjacent housing units (total capacity of 30). The effort literally required an act of congress to allow for the lease between CSU and the USDA and for the construction to proceed. Plans for additional housing and new laboratory space are in the works.

Finally, the CSU administration views our current probationary status as an opportunity to strengthen the SGS-LTER program, and broaden its scientific and leadership base. We now have a commitment to search for a new faculty member (Associate or Full Professor) in Global Change Ecology. The expectation is that this scientist will bring new expertise to our research program and will assume a leadership role in the SGS program in the future (see letter of support, supplementary documents). Furthermore, CSU has assumed the utilities and maintenance costs of the new field station, and 0.5 FTE of the station manager salary. In the current fiscally challenging times that the State of Colorado faces, this represents a remarkable commitment to the SGS-LTER program and one that has truly re-invigorated the extant cadre of SGS scientists.

Section 2. Conceptual Framework and Research Plan

"Knowing trees, I understand the meaning of patience. Knowing grass, I can appreciate persistence."
Hal Borland – 20th century author from the Great Plains

Understanding how ecosystems function, and persist or change in the face of global change is a fundamental area of research in ecology (Smith et al. 2009) and the Shortgrass Steppe Long-term Ecological Research (SGS-LTER) program has embraced this challenge for grasslands. Persistence in its broadest sense is an ecosystem structural and dynamic state characterized by regularity in the species that are present, the interactions they engage in, the biogeochemical processes that emerge from the interactions, and in the responses of the system to external drivers over large spatial and long temporal scales. Forecasting persistence or potential transitions of complex systems requires the study and understanding of the defining dominant (numerically abundant) species such as grasses, as well as other key species that may be fewer in number but act as important ecosystem engineers. These species control the structure and function of the ecosystem through their physical presence, their physiological and genetic responses to abiotic factors, their trophic and competitive interactions with other species, and their feedbacks to the physical environment. In grasslands, linkages between plants and soil organisms at the root-soil interface (*aka* rhizosphere) are particularly important, as persistence is dependent on the patterns of multi-species interactions and nutrient exchanges. The persistence of grasslands also depends on landscape-level processes defined by physiography (the mosaic of soils, landscape position and landforms). As with most ecosystems, this historic persistence is being challenged by unprecedented rates and magnitudes of global changes (Vitousek et al. 1997, IPCC 2007). With this background and our past work at the SGS, the overarching question that guides our research is:

How will structure and function of the SGS respond to expected changes in climate, management, and land-use, and what will be the consequences?

Conceptual Framework

Our conceptual framework (Fig. 1) asserts that ***climate***, ***physiography***, ***grazing, fire*** and ***land-use,*** operating over different spatial and temporal scales, are the dominant determinants of the structure, function, and persistence of the SGS. The SGS-LTER program, using the SGS ecosystem of the North American Great Plains as a model, seeks to (1) identify the ecological attributes of grasslands that historically have resulted in their persistence and (2) understand these attributes in ways that will allow us to identify areas of vulnerability and better forecast the future of grasslands in the face of global change. Given its geographic extent and its history, the SGS encapsulates many of the features of a system driven by social-ecological interactions (ISSE 2007) and the vulnerabilities of semi-arid grasslands to global change worldwide. The SGS is a grassland ecosystem dominated by the low stature C_4 and C_3 grasses, blue grama (*Bouteloua gracilis*) and western wheatgrass (*Pascopyrum smithii*). The stature and dominance of these species is likely due, historically, to low annual precipitation with extensive periods of drought (within and across years), wide seasonal temperature fluctuations, low aboveground productivity and fire frequency, and locally intensive grazing by a suite of migratory herbivores (bison and antelope) and colonies of prairie dogs (Lauenroth and Burke 2008). Changes in land-use and cover, changes in regional climate, the introduction of novel species and encroachment by humans have altered the system in critical ways. In the late 19th and early 20th centuries, ranchers replaced bison with cattle and introduced tillage agriculture. These changes and the associated management practices drove a shift from migratory grazing impacts to resident grazing, removal of marginal croplands to the Conservation Reserve Program (CRP) and almost complete elimination of fire (Fig 2). Today, the SGS is shaped by this legacy with the recent added influence of exurban development.

Our conceptual framework recognizes that understanding and forecasting the structure and functioning of the SGS ultimately depends upon our understanding of the abilities of the dominant species, and on multi-species (community-level) interactions they engage in locally and regionally, to respond to natural and increasingly anthropogenic perturbations. Studying the SGS from a social-ecological perspective will require an understanding of the populations and communities of key species, interactions among these

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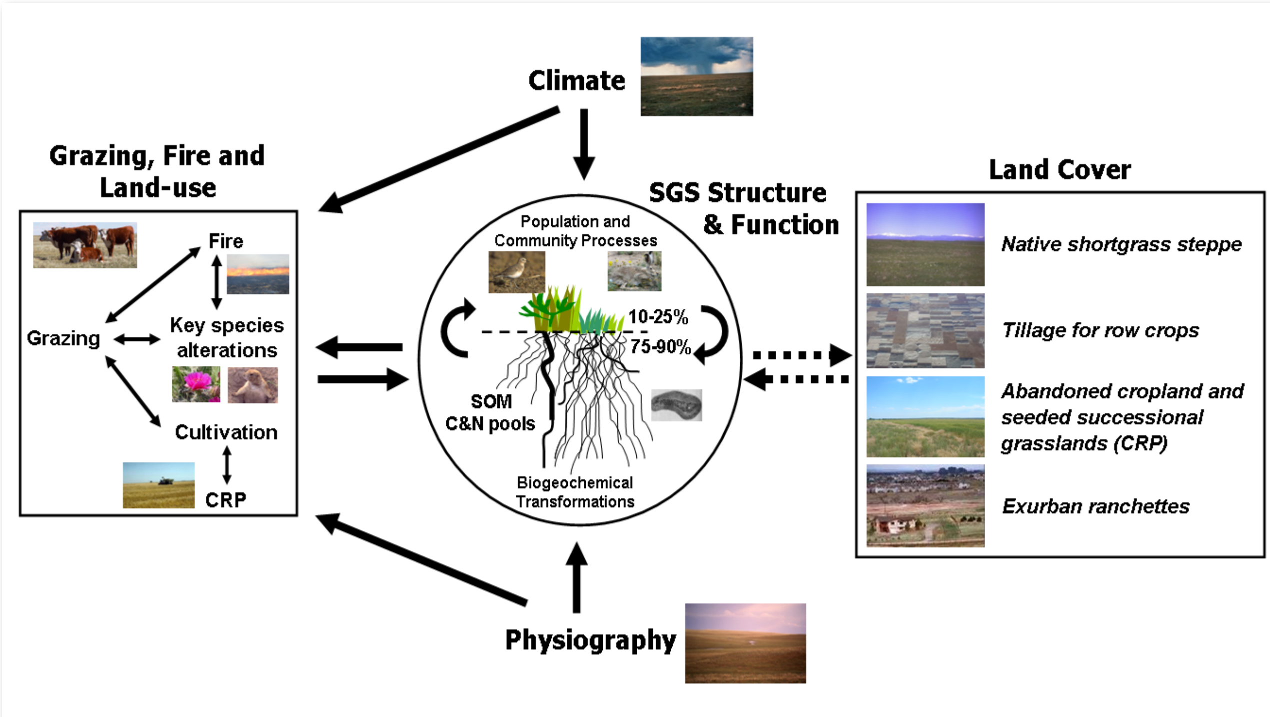
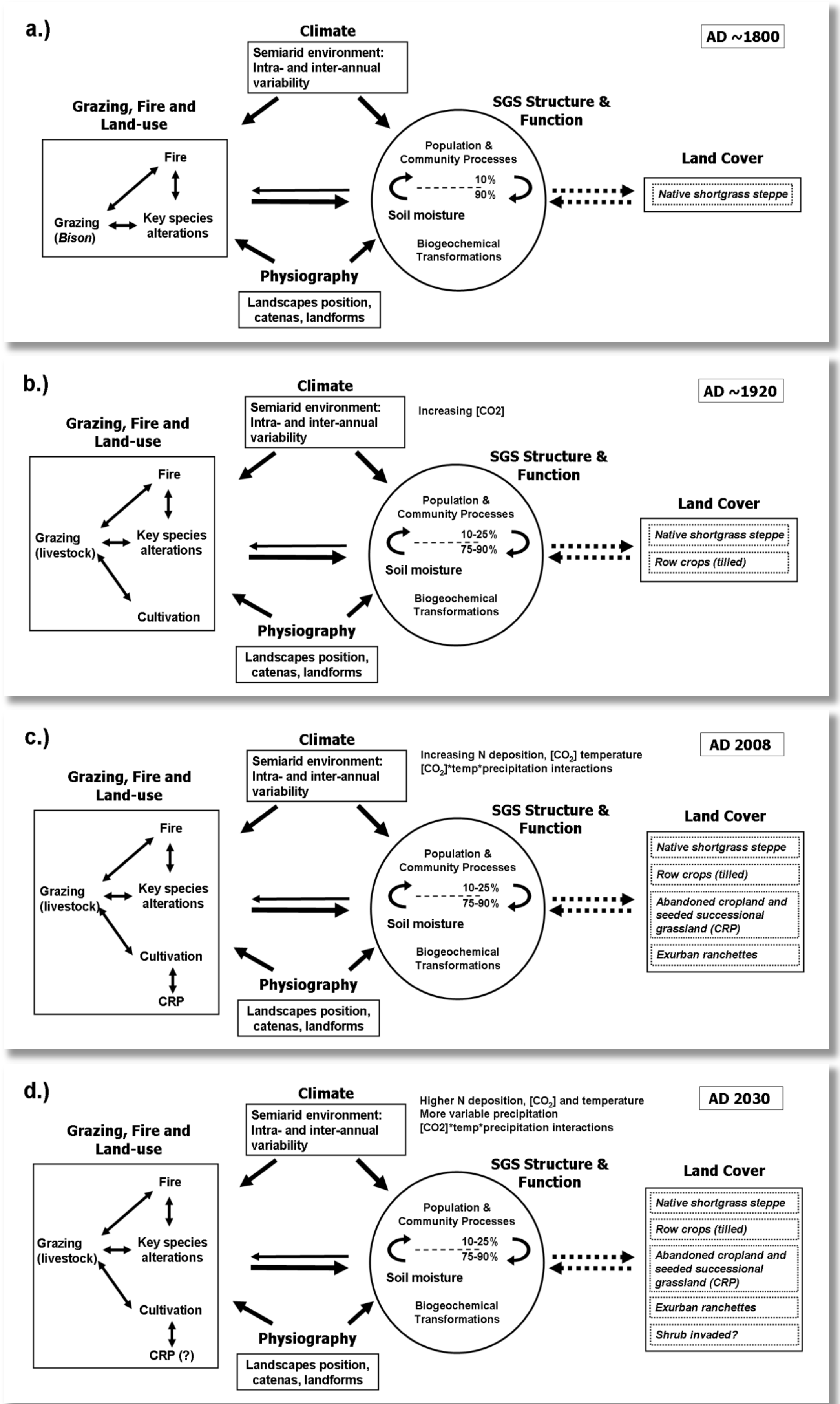


Fig. 1. The conceptual framework of SGS-LTER research depicting three key contemporary determinants (Climate; Physiography; Grazing, Fire and Land-Use) of SGS structure and function (center circle) and their interactions. The interplay of biotic, abiotic and anthropogenic factors ultimately determine the ecological trajectory at a given location, resulting in a range of possible ecosystem states or types (here, exurban development, cultivated row crops, native SGS, and seeded grasslands) that co-occur at landscape and regional scales. The spatial arrangement of these different ecosystem types can affect the states of adjacent types, or organisms that operate over large spatial scales. Hence, understanding the interaction depicted in the center circle at multiple points across the landscape and in response to changes in the three determinants is critical. As a social-ecological system, changes in land-use, policy and management decisions, or economic factors on the SGS can rapidly change the mosaic of ecosystem types over the landscape. SGS SGS-LTER researchers combine experimental and comparative approaches with long-term monitoring, cross-site studies and modeling to understand the interactions among these components and forecast responses of SGS structure and function to regional and global change. This work informs our cross site (SGS, BES, KBS, SBC, and LN) environmental literacy initiative (Section 5).

Fig. 2 (next figure page). A historical view of the primary determinants of structure and function of the SGS ecosystem: Climate; Physiography; Grazing, Fire and Land-Use. The figure illustrates the social-ecological interactions that have transformed the SGS over the past 150 years have involved changes in grazing, fire and land-use. a) Before European settlement during the 1800s, grazing by herbivores (bison and prairie dogs) was the dominant determinant of the SGS ecosystem structure and function. The extent to which fire also influenced the effects of grazing and key species interactions is less well known. b) European settlers removed bison and replaced them with livestock, and began cultivation and tillage for agriculture. Recurring droughts, especially in the 1910s, 1930s, and 1950s led to development of irrigation systems and the unset of irrigated agriculture along the front range and riparian areas in conjunction with dryland framing. Fire is infrequent and largely suppressed. c) The current state(s) of the system, with return of tilled lands to grassland, with 10% of Weld County planted and managed under the Conservation Reserve Program (CRP) in part to conserve soil. Fire is used as a management tool. The ecosystem currently exists as a mosaic of land uses. d) With global change, temperatures have begun to rise, and changes in the timing and intensity of precipitation are expected. Interactions between CO_2 concentrations, temperature, and precipitation may lead to several alternative states in the future. Forecasting these changes are an important focus of the current SGS-LTER program.


a.)
Climate
Semiarid environment: Intra- and inter-annual variability
AD ~1800
Grazing, Fire and Land-use
Fire
Grazing (*Bison*)
Key species alterations
SGS Structure & Function
Population & Community Processes
10%
90%
Soil moisture
Biogeochemical Transformations
Land Cover
Native shortgrass steppe
Physiography
Landscapes position, catenas, landforms
b.)
Climate
Semiarid environment: Intra- and inter-annual variability
Increasing [CO2]
AD ~1920
Grazing, Fire and Land-use
Fire
Grazing (livestock)
Key species alterations
Cultivation
SGS Structure & Function
Population & Community Processes
10-25%
75-90%
Soil moisture
Biogeochemical Transformations
Land Cover
Native shortgrass steppe
Row crops (tilled)
Physiography
Landscapes position, catenas, landforms
c.)
Climate
Semiarid environment: Intra- and inter-annual variability
Increasing N deposition, [CO_2] temperature
[CO_2]*temp*precipitation interactions
AD 2008
Grazing, Fire and Land-use
Fire
Grazing (livestock)
Key species alterations
Cultivation
CRP
SGS Structure & Function
Population & Community Processes
10-25%
75-90%
Soil moisture
Biogeochemical Transformations
Land Cover
Native shortgrass steppe
Row crops (tilled)
Abandoned cropland and seeded successional grassland (CRP)
Exurban ranchettes
Physiography
Landscapes position, catenas, landforms
d.)
Climate
Semiarid environment: Intra- and inter-annual variability
Higher N deposition, [CO_2] and temperature
More variable precipitation
[CO2]*temp*precipitation interactions
AD 2030
Grazing, Fire and Land-use
Fire
Grazing (livestock)
Key species alterations
Cultivation
CRP (?)
SGS Structure & Function
Population & Community Processes
10-25%
75-90%
Soil moisture
Biogeochemical Transformations
Land Cover
Native shortgrass steppe
Row crops (tilled)
Abandoned cropland and seeded successional grassland (CRP)
Exurban ranchettes
Shrub invaded?
Physiography
Landscapes position, catenas, landforms

species, their responses to changes in biotic and abiotic factors, and key biogeochemical processes and the mechanisms that underpin them at the molecular to landscape scales. Humans and land-use are important component of the calculus as they affect the structure and function of the SGS directly and the spatial mosaic of ecosystem components that it depends on. Hence, changes to SGS will affect not only the natural system, but also alter the relationship between the natural system, humans and land-use. Finally, efforts to enhance environmental literacy are critical to this social-ecological perspective (see Section 5).

Research Approach

Research conducted under the SGS-LTER program (1983-present, corresponding with SGS-LTER I through VI) has generated a deeper understanding of the processes and principles that govern the dynamics and functioning of the SGS, and grassland communities and ecosystems in general. We draw the following conclusions from our recent work, which will guide our new research:

- Climate, grazing and fire remain important drivers of the SGS in maintaining current-day structure and function. Many aspects of the SGS ecosystem are resistant to the effects of grazing and fire, but some facets of function are highly responsive to variation in seasonal and annual precipitation. Short-term responses of the SGS to precipitation are consistent with those of the pulse-dynamic framework (Noy-Meir 1973, Collins et al. 2008). Changes in magnitude and timing of climatic variables or anthropogenic inputs of nutrients that alter resource allocation above- vs. belowground have the potential to significantly alter the structure and function of the SGS.
- The SGS is acutely vulnerable to any disturbance that disrupts the belowground system. Recovery occurs slowly or not at all in cases where soils are severely altered. The composition and physiography of the SGS landscape is changing rapidly in terms of the contributions of native, agricultural and urban elements, each of which have different effects on belowground resources, and may alter the distribution and flow of energy, nutrients, water and organisms across the landscape.
- Changes in climate, CO_2, land-use or other factors will have profound effects across multiple trophic levels and ecosystem processes given their impacts on the vegetation structure of the SGS. Increases in the aboveground canopy will likely increase the importance of grazing and fire in SGS, as fuel loads increase and grazing-mediated plant competition for light increases.
- Because of the importance of belowground system in SGS, biotic, geological and geochemical processes that drive the development of soils over tens to hundreds of thousands of years must be understood. These processes have shaped the development and degradation of soils, the structure and biological dynamics of landscapes and the hydrological functioning of the ecosystem. Understanding how these biological and geochemical processes interact, and understanding their vulnerability is key to quantifying how physiography may regulate ecosystem responses to global change.

Given the above, it is clear that the current structural and functional characteristics of SGS are vulnerable to change when confronted with conditions predicted by global climate models and projected shifts in land use. But the nature and pace of this change, the particular global change factors that are likely to be most important, and the most vulnerable attributes of the SGS that will be altered are unresolved. SGS-LTER VI will focus on ***climate***, ***physiography,*** and ***grazing, fire*** and ***land use*** as key determinants of SGS structure and function, with a new emphasis on providing the tools and data necessary to ***forecast*** how the SGS may change under projected global changes. We propose an integrative approach of monitoring, manipulative experiments and modeling to investigate the mechanisms underlying current structure and function at multiple spatial and temporal scales (Fig. 3.).

Research Themes

Our program has four major themes based on the key determinants and our desire to forecast change. In the sections that follow we provide the background and rationale for our research priorities and a synthesis section that discusses the significance of the research in terms of the past, current, and future state of the SGS. The major themes and guiding questions are:

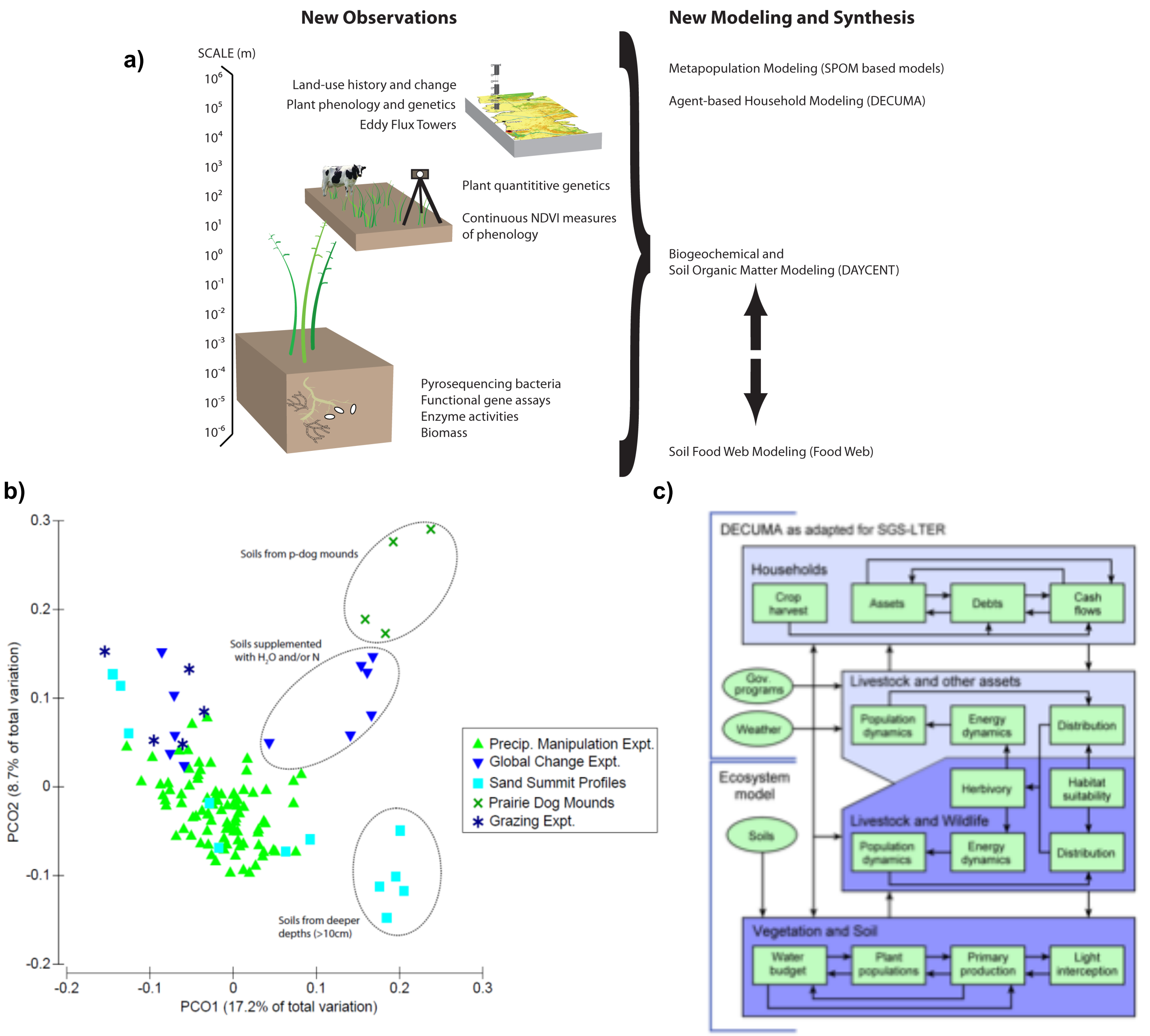


Fig. 3. Summary illustrating the integration of multiple scales of measurement outlined in our social-ecological research approach. **a)** New activities proposed include work at the regional/landscape, plot and microbial scales. **b)** An illustration of data collected at the microbial scale. At the plot and microbial scales we will employ traditional methods to determine plant growth (roots and shoots), diversity and biomass of microbes and invertebrates, N and C cycling, trace gas fluxes, along with modern molecular techniques to assess microbial diversity and enzyme activity. Presented here are the results of a bacterial pyrosequence survey among soils as a function of landscape position, soil depth and experimental treatment. Grazing, Physiography, and precipitation are clear determinant so of microbial diversity. **c)** The SGS-LTER has a long history of using models in analysis and synthesis. For SGS-LTER VI, system level responses to alterations in climate regime, grazing, fire, and land use will be evaluated using models of C and N cycling (DayCent), models of trophic interactions (Food Web), metapopulation models, and agent-based models (DECUMA). The models can be parameterized using a common currency and linked to address processes that operated at different scales. For example, DECUMA is an agent-based model that when linked to an ecosystem model can address the impacts of changes in policy, economics or management decisions on households on SGS, and in turn how decisions by households may affect basic components of the SGS. The results of our research are critical to our environmental literacy initiative and our education research on learning progressions and planned teacher professional development activities (Section 5).

A. Climate: *How has climatic variation shaped the structure and function of SGS, and how will projected climate change influence processes in the future?* The climate is semi-arid with a mean annual temperature is ~ 8 ^{0}C and precipitation regimes (mean annual of ~340mm) characterized by high inter- and intra-annual variability, with few large events and many events too small to infiltrate soils and alleviate chronic plant water stress. Like most grasslands, evapotranspiration far exceeds precipitation during much of the growing season, and so the system appears to follow a pulse-response dynamic (Noy-Meir 1973, Collins et al. 2008). The primary emphasis of our climate research will be to study how changes in precipitation regimes affect soil moisture regimes, above- and belowground community structure and interactions, aboveground trophic and disease interactions, nutrient dynamics, plant phenology, and plant genotypic structure.

B. Physiography: *To what extent are SGS dynamics and responses to global change contingent on upon physiography?* Physiography (e.g., soil developmental phase, landscape position and landforms) defines the geologic and pedologic template for the ecosystem and modifies the relationship between precipitation and soil moisture content, thereby affecting soil microbes, invertebrates, biogeochemical processes, and communities of plants and animals. Thus, we will study ecohydrological and pedological controls on water distribution within and among landscape features and how landscape variability influences ANPP, species composition, processes, and sensitivity of SGS to forecasted climatic change.

C. Grazing, Fire and Land-use: *How will land-use changes that alter grazing, fire and grazing-fire interactions modify the structure and function of SGS?* The SGS ecosystem evolved with and has adapted to grazing by large herbivores, with native migratory bison replaced by managed resident livestock. Human land-use has been and continues to be a major determinant of large-scale structure and function. Human land-use during the latter half of the 20th century was designed to better integrate with the natural functioning of the SGS than land uses during the first century of European settlement. Grazing by large herbivores and fire, are now highly managed or suppressed with decisions informed by the current climate regime and land use practices. Given this, we will continue to study the sensitivity of the SGS to different climates, grazing regimes and management practices, fire management, and other disturbances.

D. Synthesis and Projections/Forecasting: *How do climate, grazing, and land use influence the SGS over multiple spatial and temporal scales?* Forecasting how the SGS will respond to global change depends on identifying which key determinants of ecosystem structure and function will change, and how the organisms and processes within the ecosystem responds to them (Carpenter et al. 2001, Kerkhoff and Enquist 2007, Grime et al. 2008). To accomplish this, we will improve model-data synthesis at landscape scales by incorporating land-use and physiography into spatially explicit variations of our current models (DayCent and Food Web), and new meta-population models that incorporate historic and predicted land-use change. Data collected from our monitoring and experiments will be used to parameterize the models. At the SGS, changes in climate and shifts in land-use may not only affect the natural system but also alter the relationship between the natural system, humans and land-use. In this sense, the SGS is similar to other LTER sites like SEV, JRN, and KBS that are at the interface between natural and human-managed systems. We will model the interactions of precipitation regime, grazing and other management decisions to the social-ecological system with our household agent-based model DECUMA linked to DayCent to address questions of resilience of both the human economic and ecological systems.

The research from SGS-LTER I-V, and the changes we have made during the first 1.5 years of SGS-LTER VI provides both continuity for maintaining key long-term data collection and experiments and the research platform for our new initiatives. The baseline data support both long-term and short-term experimental studies, our modeling and synthetic efforts, and as the basis for documenting and evaluating temporal changes at the SGS-LTER site (Fig. 4 and sgslter.colostate.edu). This being said, we will end several studies, modify the sampling frequency of ongoing studies, and initiate new activities in order to

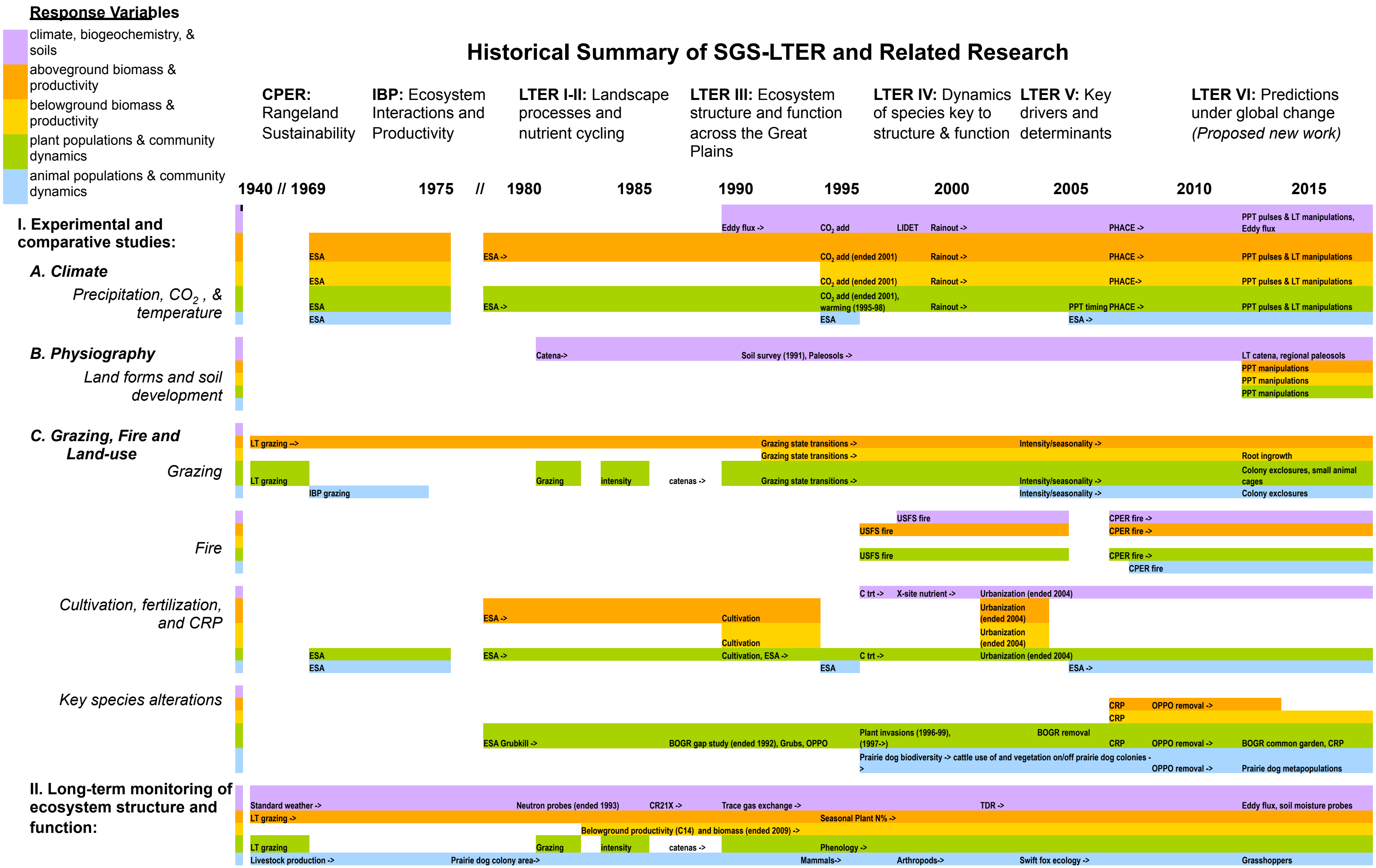


Fig. 4. A summary of historic studies relevant to SGS-LTER VI, with research programs along a timeline on top, and organized around our conceptual framework (see Fig. 1) on the left. Proposed activities in LTER VI are to the right. Studies here represent core (usually lasting > 2 years) and key supplementary research and monitoring (Table 2.1-2.3). Studies labeled with arrows (->) are ongoing and will continue for the 2010-2014 cycle. Because of their synthetic and inter-disciplinary nature, important modeling or cross-site efforts are not displayed in detail here but are described elsewhere. Studies trimmed from our program are not included in this figure.

free time and resources for new research (Fig. 4, see Table S2.1-S2.5). We will include traditional and state-of-the-art approaches and methodologies over multiple temporal and spatial scales (Fig. 3), including increased use of molecular techniques to study microbial and invertebrate communities, gas flux measurements, and novel modeling approaches. For synthesis and forecasting, data drawn from our monitoring and experimental activities will be used to parameterize simulation and theoretical models to study phenomena operating at multiple temporal and spatial scales. We begin with a brief description of the SGS-LTER site and our research history, followed by detailed descriptions of our proposed activities.

Site Description and Research History

The SGS-LTER site is typical of the semi-arid grasslands that encompass a major portion of the Colorado Piedmont of the western Great Plains (Fig. 5). Most of the previous research of the SGS-LTER project has been carried out at the Central Plains Experimental Range (CPER), a 6,280-ha site managed by the USDA Agricultural Research Service (ARS). The CPER, in operation since 1937, maintains a series of pastures under different long-term grazing treatments (Fig. 6). These grazing treatments, along with small plots and entire pastures subjected to different fire frequencies serve as the backbone of an experimental design that includes an extensive array of long-term sites at various topographic positions. In 1996 we extended the SGS-LTER site beyond the CPER to include an additional 78,129 ha of the Pawnee National Grasslands (PNG), a mosaic of land-use that includes federal, state and private lands managed by the USDA Forest Service. This expansion allowed us to extend our measurements to a broader range of climatic, geologic, topographic and land-use conditions within the Colorado Piedmont.

The SGS-LTER site is not only well-positioned within the LTER network to address the themes and questions outlined above but also serves as one of several sites in the spectrum of resource (water) limited “low productivity” sites within the LTER network (Fig. 7). The SGS-LTER site is situated at the climate-determined boundary between SGS and northern mixed prairie, which may facilitate detection of shifts in plant and consumer communities in response to global change. In addition, because the SGS is primarily a managed system that includes rangelands and both dryland and irrigated crops, it has direct societal value for food production and other ecosystem services (e.g., carbon sequestration, biodiversity, and water and air quality) that are likely to increase in importance under global change. As a result, our research foci span a continuum from basic sciences to the applied questions that are relevant for local and regional land managers, policy makers, and educators.

Continuing and Proposed Research

Below we elaborate on our research themes and provide more detail regarding the questions we will address and the studies we propose to continue and initiate over the next four years. Our environmental literacy initiative and education research efforts are presented in Section 5.

A. Climate*: How has climatic variation shaped the structure and function of SGS, and how will projected climate change influence processes in the future?*

Background: The climate of the SGS is characterized by low precipitation, periodic water deficits, and large inter-annual and inter-seasonal fluctuations. Most (70%) of the annual precipitation at SGS is derived from the Gulf of Mexico and falls during the warm season between April and September. Annual evaporative potential exceeds precipitation at the SGS by more than three-fold. Water deficits across the region are most common in mid-summer or later, though for any given year the frequency, intensity, and duration of water deficits varies substantially from place to place. Inter-annual variation in precipitation is very high, with a coefficient of variation around 30%. As with all North American grasslands, the total precipitation and the timing of precipitation are key controls of primary production (Lauenroth 1979, Sala et al. 1988, Derner and Hart 2007, Derner et al. 2008b). Annual precipitation amount accounts for most inter-annual variation in ANPP (Lauenroth and Sala 1992) and much of its spatial variation across the Great Plains (Epstein et al. 1996). However, we have demonstrated a strong sensitivity of temperate grassland ecosystems to more extreme growing season rainfall regimes, with responses of ANPP contingent on mean soil moisture content for a particular grassland type (Heisler-White et al, 2009). Thus changes in precipitation are likely to have significant impacts on most ecosystem processes in SGS.

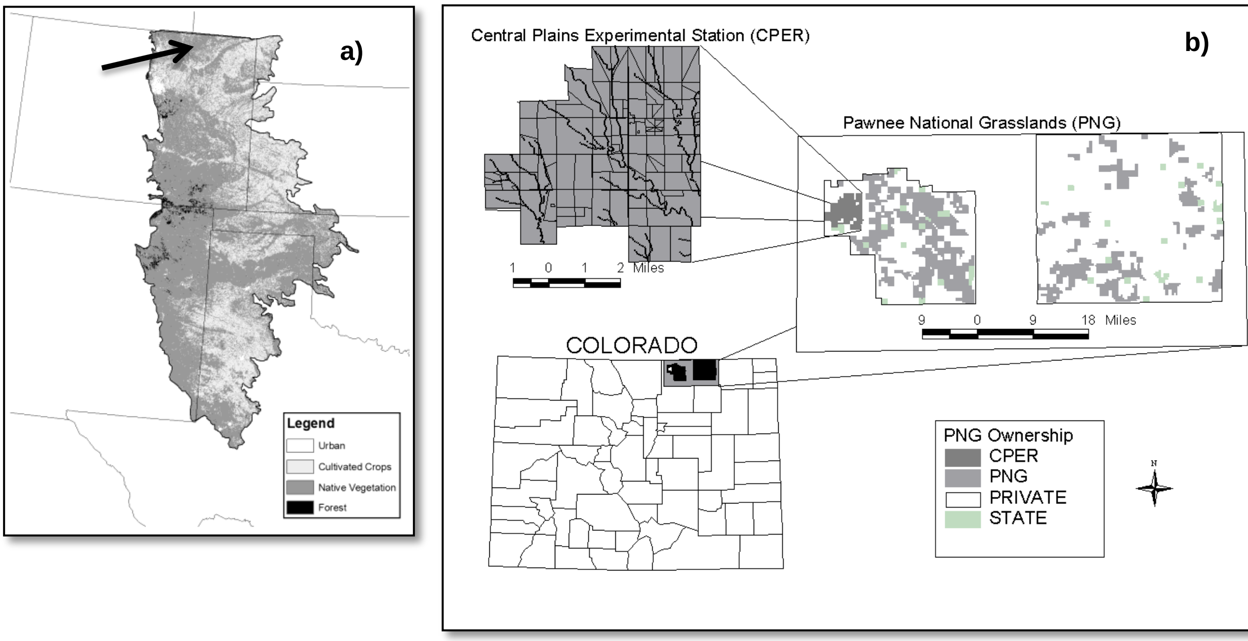


Fig. 5. a) Extent and land use of the SGS ecosystem in the Great Plains of the United States. Location of the SGS-LTER site is shown by the arrow. **b)** Map of the SGS-LTER site, composed of the Central Plains Experimental Range, administered by the USDA-Agricultural Research Service, and the Pawnee National Grassland, administered by the USDA-Forest Service. The map shows the mosaic of ownership and land use that fragments the landscape.

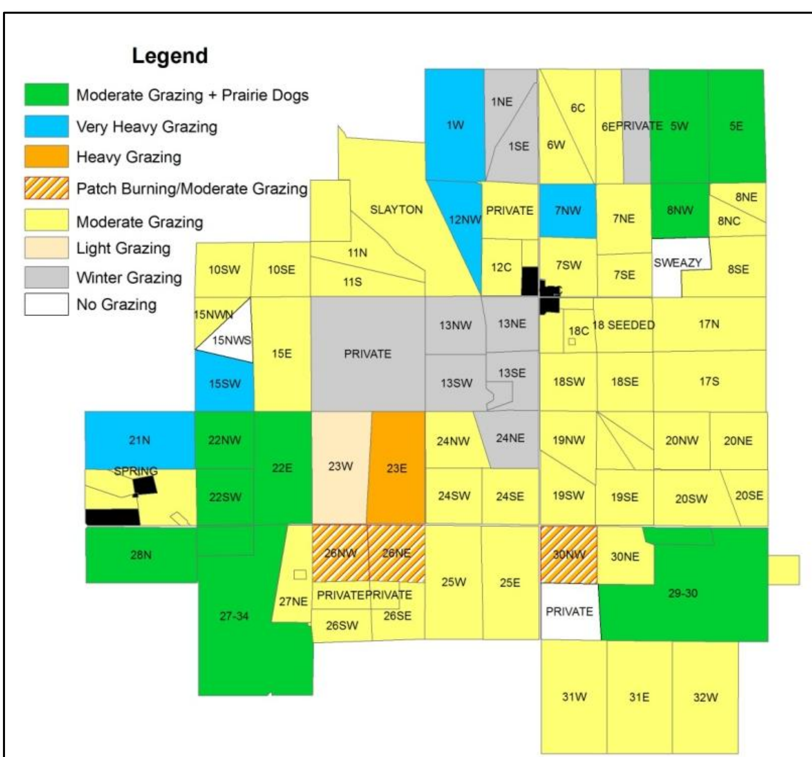


Fig. 6. Following European settlement of the plains, Bison were replaced by cattle. During the 20th century grazing by large migratory herbivores gave way to grazing by large resident (pastured) herbivores. Management practices under study since 1937 at the CPER have focused on grazing regimes (rates and season) and the movement of cattle from one pasture to another, much as migratory herbivores would have done.

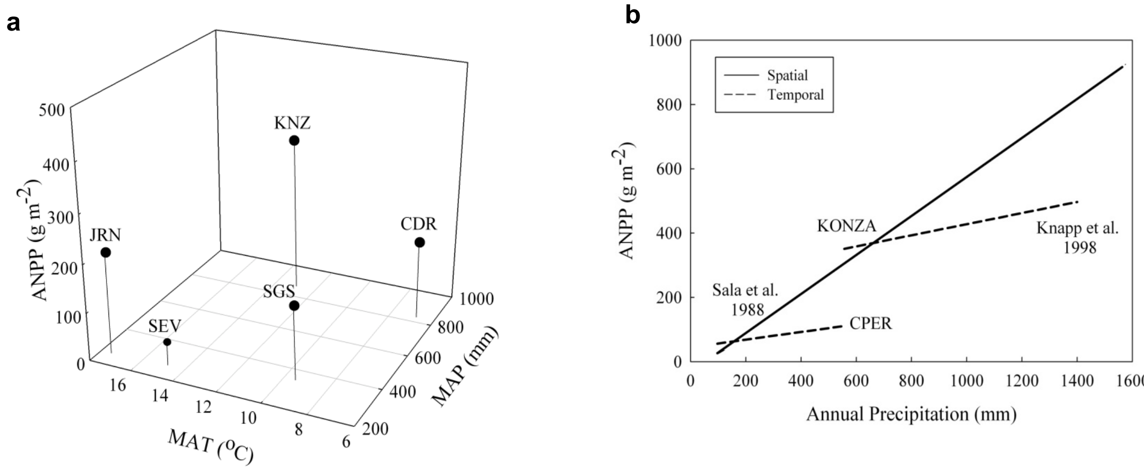


Fig. 7. **a)** In the climate space defined by mean annual temperature (MAT) and mean annual precipitation (MAP), the SGS-LTER is a cold, dry grassland with low aboveground net primary production (ANPP) and fills a unique climatic envelope relative to other LTER sites (JRN= Joranda Basin; SEV = Sevilleta; KNZ = Konza Prairie; CDR = Cedar Creek Reserve; SGS = Shortgrass Steppe). **b)** Precipitation is a primary control on grassland ANPP, but the response of ANPP to variation in precipitation differs when sampling across the Great Plains (solid line) vs. repeated sampling within a site (dashed lines).

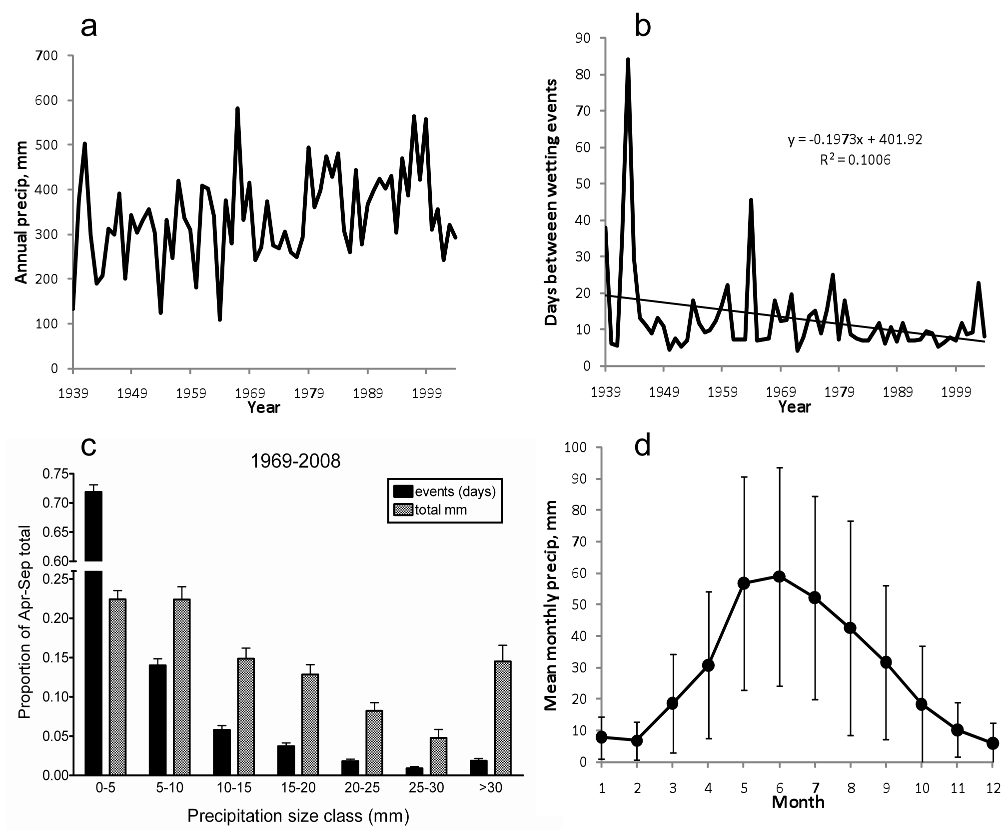


Fig. 8. New analysis of the SGS-LTER climate data highlight features of the precipitation regime and temporal trends. **a)** Annual precipitation record from the USDA ARS CPER headquarters. Precipitation readings have been taken manually each day at 08:00 hr since 1939. The long-term average is 340mm (+/- 115 mm SD), maximum (581mm) in 1967 and minimum (109 mm) in 1964. Regression is significant ($p<0.006$). **b)** Days between late growing season (July – September) "wetting events" when daily precipitation > average potential evapotranspiration for that day. Regression remains significant when 1939, 1942 and 1964 outliers are excluded. **c)** 74% of the precipitation events in the Apr-Sep growing season are <5 mm and these events contribute 23% of total precipitation during the growing season. Large events (>20 mm) comprise only 4% of the events but contribute 25% to the seasonal total. **d)** Most of the SGS-LTER precipitation falls during the growing season (April – September) but interannual variability in monthly precipitation is very high (error bars are 1SD), making extended dry periods relatively common.

A.1 How are climate and soil moisture changing?

Rationale: Our climate record indicates that during the last 30 years annual precipitation has shown no temporal trend in magnitude, but the LTER years have been wetter than in the decades of the 1940's – 1970's (Fig. 8a). Similarly, temperatures have been slightly cooler during the period of our LTER data set compared to previous decades. During summer, the size of precipitation events has not changed, but the size and timing of wetting events (when daily precipitation > daily potential evapotranspiration) has increased by 0.08 mm yr^{-1} (Fig. 8b), with a significant decrease in the number of days between wetting events. Associated with these changes in precipitation, some temperature indices have decreased modestly (~ 0.07 °C yr^{-1}). Global circulation models predict that global warming will accelerate the hydrologic cycle across temperate North America, and drive both larger precipitation events and a greater number of dry days between storm events (IPCC, 2007). However, while some models predict the SGS will experience 4°C warming and 5-10% reduction in Jun-Aug precipitation (IPCC 2007), inter-model agreement on these predictions is poor and observed trends to date are inconsistent. It is likely that climate change will eventually drive increased potential evapotranspiration on the SGS, but it is unclear how this increase will interact with changes in the precipitation regime. Further, our experiments indicate that effects of temperature and precipitation will be modulated by changes in soil moisture and altered water use efficiency of C_3 vs. C_4 plants with rising atmospheric CO_2 concentrations (Morgan et al. 2007). To quantify climate and soil moisture trends, we will maintain our current array of micro-met stations and expand our monitoring of evapotranspiration, water use efficiency and soil moisture.

(A.1.1) Evapotranspiration, C-flux and Water Use Efficiency at Landscape Scales: Eddy flux (EF) instrumentation provides the best integrated method for measuring water and energy balances at the landscape scale (Baldocchi 2003). We will deploy EF instrumentation (already available to the project) as a new long-term observation to bridge our research themes relating to climate variability and change (this section), physiography (section B), and grazing and land-use (section C), while also providing data for modeling the contemporary and future dynamics of the shortgrass steppe (section D). Four EF stations, with associated meteorological and soil measurements, will be deployed in contrasting landscape positions (upland grasslands and lowland shrublands) and in pastures where prairie dog colonies are present or absent (2 landscape treatments x 2 prairie dog treatments = 4 sites). These landscape-scale (>50 ha) measurements will be situated in pastures where other plot-scale observations and experiments take place and will provide system-level measurements to integrate and scale up the fine-scale. We will use these measurements to quantify ecosystem-scale fluxes of carbon and water and their variability in time (response to rainfall events, wet and dry periods, seasonality and inter-annual variability) and in space (contrasting responses related to physiography). Each site will be equipped to measure temperature, humidity, wind-speed, incoming and reflected PAR, shortwave and long-wave radiation, soil heat flux, soil temperature and soil moisture profiles. These data will also provide context information for the fine-scale experimental work in the same pastures, while on-going measures of vegetation production, leaf area and dynamics will inform our understanding of and ability to model the measured fluxes.

(A.1.2) Expanding Measurements of Soil Moisture: Soil moisture is a master variable that integrates climatic and ecosystem function for several reasons: 1) it is important for understanding dynamics of the system spanning the ecological hierarchy (individuals to ecosystems across landscapes), 2) it is expected to change in the future, and 3) it can be manipulated in relatively inexpensive ways that will permit inferences to be made with regard to the wide array of global changes likely to impact most terrestrial ecosystems. However, we have limited long-term measures of soil moisture, and these measures are not distributed to sample the heterogeneity of the SGS landscape. To correct this, we will install Decagon soil moisture probes at each micro-met station and at each of our proposed experimental sites.

A.2. How does precipitation magnitude and timing affect SGS ecosystem structure & function?

Rationale: Climate is a fundamental driver of grassland ecology (Fig. 7), yet the mechanisms by which ecological patterns emerge from climate regimes remains critically uncertain. The SGS LTER experiences periods of time where biological activity is triggered by precipitation in a pulsed manner. Inter-annual variation of precipitation is high – since 1939 the recorded range was from 32% to 170% of the long-term annual average (95% CI: 139 to 542 mm-yr^{-1}). Intra-annual variation, summarized by the sizes of wetting events and the duration between them (when daily precipitation > daily potential evapotranspiration), underlies this pattern: events < 5 mm comprise more than 70% of the total during the growing season (Fig. 8c). Because potential evapotranspiration greatly exceeds precipitation over the course of the year, water from small precipitation events has contingent ecological impacts (Sala and Lauenroth 1985) that depend on the season (e.g. physiological state of plants and microbes), soil moisture content, time since the previous event, and the time of day when rains fall (Sala and Lauenroth 1985, Heisler-White et al. 2009). The potential is high for long periods of time between wetting events, and when coupled with high potential evapotranspiration, the SGS-LTER experiences periods of time where biological activity is very low until triggered or "pulsed" by individual precipitation events.

Results from a 3-year deployment of EF towers on the SGS revealed that most of the ecosystem C accumulation occurred during the early growing season (April – June), while C exchange was near zero during the late growing season (July – September) when heat and dry conditions drove plants to senesce. Although large rain events in the late season induced pulses of soil respiration followed days later by net C uptake, smaller events induced only respiration. In addition, plant and microbial emergence from dormancy was slower after longer drought periods, but maximum plant activity was larger following wet springs. These findings were not predicted by our DayCent ecosystem model (see section D) revealing weakness in our understanding of plant and soil microbial responses to precipitation events. We conducted an integrated, multi-investigator rainfall pulse experiment on the SGS In July 2009 wherein we simulated 1cm and 2cm rain events and measured a suite of biological responses over 7 days following the water addition. Despite an absence of precipitation for 3 weeks (a common duration in SGS climate), we observed rapid biogeochemical and plant physiological responses, surprisingly high variations in soil microbial enzyme levels, but no detectable changes in the community composition of soil fauna or soil bacterial community (von Fischer et al. 2009b).

(A.2.1) Short-Term Precipitation Manipulations: We have several small-scale experiments in place to address how changes in precipitation magnitude and timing affect SGS structure and function (Fig. 9). The studies include a cross-site component with plots at the SGS-LTER, southern Colorado and northern New Mexico, and central and eastern Kansas, and reveal the capacity of the SGS to respond over 2-3 year time scales. The studies target specific features of the climate regime (drought, precipitation event size) to capture short-term responses of plant communities (species composition, cover, above- and belowground productivity), biogeochemistry, soil biota (microbes, protozoa and invertebrates), and enzyme activity. We will maintain these experiments for an additional two growing seasons. The results will improve the predictive capacity of our DayCent and Food Web models (see Section D).

(A.2.2) Long-Term Precipitation Manipulations - Seasonality: To better understand responses to precipitation at seasonal to decadal time scales, we will establish a new long-term precipitation manipulation experiment to magnify the temporal variations in precipitation (detailed in Fig. 9). The experiment uses a 2-factor design; factor 1 is seasonality of precipitation (early growing season vs. late growing season), while Factor 2 is size of precipitation events (-50%, ambient, +50%). We will run these in a full factorial experiment with n=5 replicates per treatment (45 experimental units). Reduced precipitation will be achieved with Sala shelters that intercept and divert 50% of incoming rainfall. Elevated precipitation will be achieved by adding the water from the -50% treatments onto the +50% plots. Plots will be 2m x 2m, with trenched edging to minimize run-on/run-off and root foraging. We will structure our sampling to align with the response times of different ecosystem components. Biogeochemical parameters will be measured bi-weekly. Plant, soil fauna and microbial community composition, and soil enzyme activity will be characterized in June and September. In May and August of each year, we will conduct an opportunistic sampling following a natural rain event, when we will measure CO_2 exchange and soil N levels at 24-hour intervals for 5 days. System level responses alterations in climate regime will be evaluated using the DayCent and Food Web models (section D).

(A.2.3) Long-Term Precipitation Manipulations – Physiographic Variability: As we detail in section B below, the system response to precipitation events also depends on soil properties of the local system.

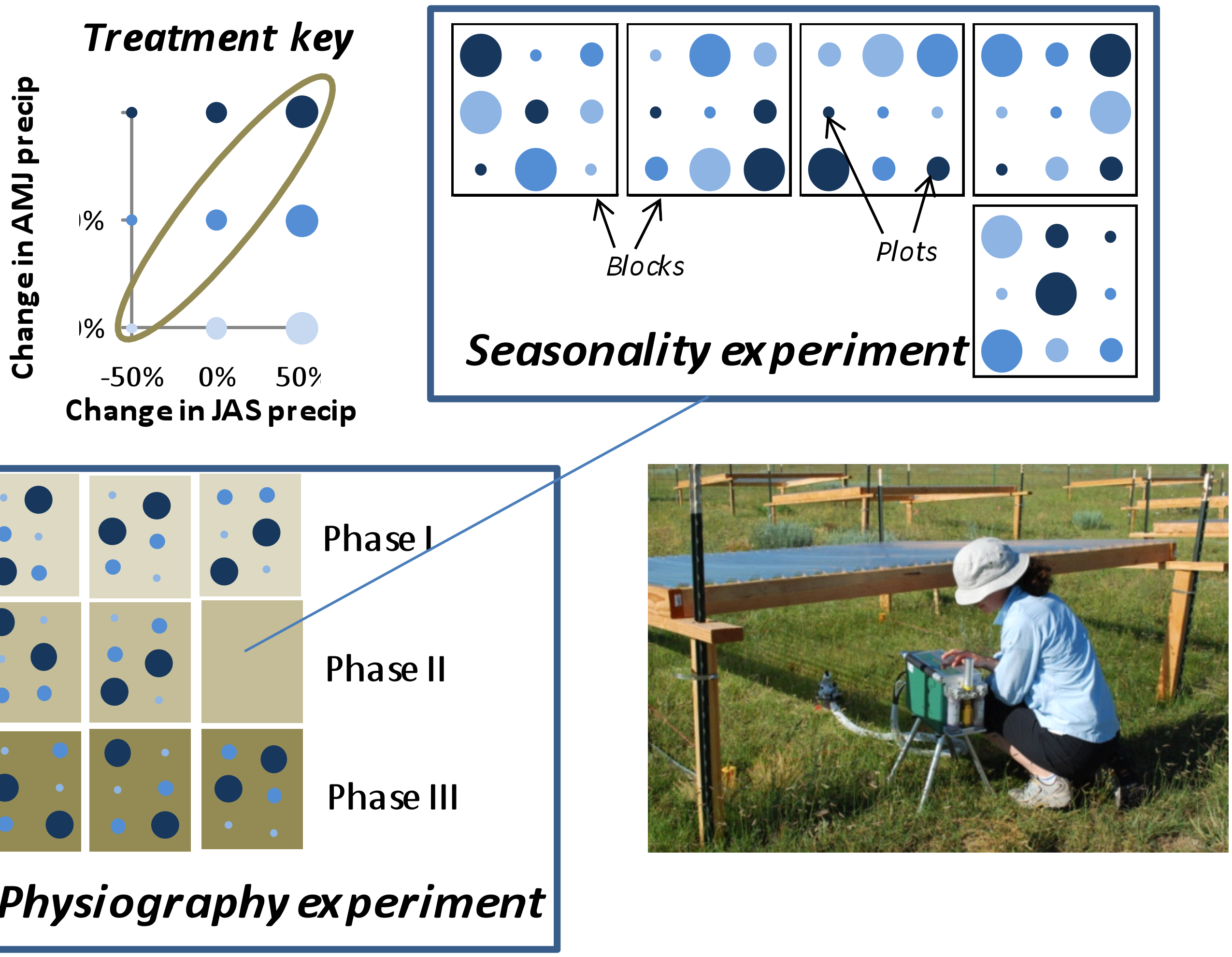


Fig. 9. Schematic of the new, long-term precipitation manipulation experiments to alter the magnitude of precipitation events. This design magnifies the natural, inter-annual variability in precipitation by sheltering some plots from precipitation, while supplementing others. The Seasonality experiment investigates the timing of precipitation; early growing season is in April, May and June (AMJ) and the late growing season is in July, August and September (JAS). The Physiography experiment manipulates the annual magnitude of precipitation (treatments circled along diagonal of Treatment Key) on different soil types. Phase I are the youngest and least weathered soils, while Phase III are most highly weathered (See Section B). The seasonality experiment will be conducted on a Phase II soil, which has the greatest water holding capacity, and is the most common soil type on the SGS. Each experimental plot is 2x2m. Plots treated at -50% will have half of the incoming precipitation captured and diverted to a container. Plots treated at +50% will receive supplemental precipitation during each precipitation event, pumped from the container to the plot by micro-irrigation system. Plots will be trenched and edged to 30cm to limit root foraging and prevent water run-on/off. Although the experiments will be exclosed from cattle grazing, patchy clipping, 3x during growing season will simulate grazing, and with end of season harvest will record ANPP. Decagon soil moisture probes will be installed in 3 reps of each treatment, and calibrated gravimetrically. We will structure sampling to align with response times of different ecosystem components. Biogeochemical parameters measured bi-weekly include: ecosystem respiration, gross primary production and net ecosystem exchange (gases from permanent collars, 20cm diameter),exchangeable NH_4^+ and NO_3^- (2M KCl from soil cores 0-10 and 10-20cm). Plant, soil fauna and microbial communities' composition will be characterized in June and September. In May and August of each year, we will conduct an opportunistic sampling following a natural rain event, when we will measure gas exchange and soil N levels at 24 hour intervals for 5 days.

To better understand the interaction between precipitation and physiography, the product of which are landscape-scale patterns in plant productivity, we will extend this precipitation experiment across the SGS landscape (Fig. 9). This landscape-level experiment uses a 2-factor design; factor 1 is magnitude of growing season precipitation (-50%, ambient, and +50%), and factor 2 is phase of soil development (Phase I, II, and III; see Fig. 13 section B). We will run these as a full factorial experiment, with true replication (n=3 per treatment) at the field scale. Soil phase replicates will be placed on separate soil units, at least 5km apart. Biogeochemical parameters will be measured monthly. The community composition of plants, soil invertebrates and microbes will be characterized in June and September. System level responses will be evaluated using DayCent and Food Web (see section D).

(A.2.4) Ecosystem Stress Areas (ESA) Studies: Changes in precipitation regime can have large and long-lasting effects. We have the opportunity to study these legacy effects by sampling an experiment initiated in 1971 that involved water and/or nitrogen additions for 5 years (ESA I), and a parallel study initiated in 1998 that involved similar treatments with reduced treatment magnitude (ESA II). The composition of the plant and bacterial communities within the water and N treatments of the ESA experiments were altered (see Fig 3b). We will sample the ESA plots in concert with the Long-Term Precipitation Manipulations – Physiographic Variability study discussed above (section A.2.3).

A.3 How does climate shape the phenology and the genetic structure of key plant populations?

Rationale: Understanding the phenological responses and the genetic structure of the dominant species within SGS plant communities in relation to climatic conditions is critical if we are to forecast persistence and potential transitions. Dominance of key species at the SGS is attributed to their abilities to withstand stresses such as drought and grazing while also being able to respond rapidly to favorable conditions via phenological and physiological plasticity. Plastic responses to climate variability may manifest themselves through changes in total ANPP, the timing of ANPP over the growing season and in the length of the growing season. Observations from across the northern hemisphere over the past several decades have shown an increase in the length of the frost free growing season and an advance in the emergence of green leaves and first flowers (e.g., Schwartz et al. 2006). SGS plant-phenology data, collected weekly for 22 species since 1995, show a similar pattern. Our most important (in terms of biomass and cover) C_4 and C_3 grasses, *Bouteloua gracilis* and *Pascopyrum smithii*, show advancement in the dates of first green leaf (6-7 days per decade) and first flower (10-20 days per decade) (Fig. 10a). We will continue to monitor ANPP, plant phenology and soil moisture at the landscape and plot scales to further document this change and assess the ecological consequences.

However, future climate change scenarios are also likely to force SGS populations into novel environmental conditions that may exceed their ability to respond with phenotypic plasticity, instead requiring genotypic adaptation and/or migration for species persistence. To provide needed information on both the phenotypic plasticity and genotypic variability of the dominant SGS plant species, we propose initiating a new common garden experiment to examine genetic variation within and among populations of the dominant species, blue grama (*B. gracilis*). Blue grama is well-suited for this type of study as it is long-lived and recruits infrequently (Lauenroth et al. 1994, Lauenroth and Adler 2008). Blue grama has a broad geographic distribution and occupies dry environments that vary in soil moisture availability. Reciprocal transplants of blue grama genotypes between SGS and KNZ have demonstrated potential local adaptation of the populations via genetic differences in phenology and biomass allocation (Fig. 10b). To expand on these results, we will increase sampling of blue grama genotypes at two spatial scales: 1) among sites within the SGS that vary in physiography and grazing history, and 2) among sites in the central plains that extend from mesic tallgrass prairie to arid southwestern grasslands (Fig. 10). The SGS common garden will foster future complementary projects (e.g., transplants to other sites, greenhouse studies to pinpoint physiological response mechanisms, and development of neutral genetic markers to characterize variation within and connectivity among populations).

(A.3.1) ANPP and Plant Phenology Responses to Climate Variation and Change: Measurements of ANPP were initiated in 1940 by the ARS, expanded in the 1970's by the IBP, and expanded across

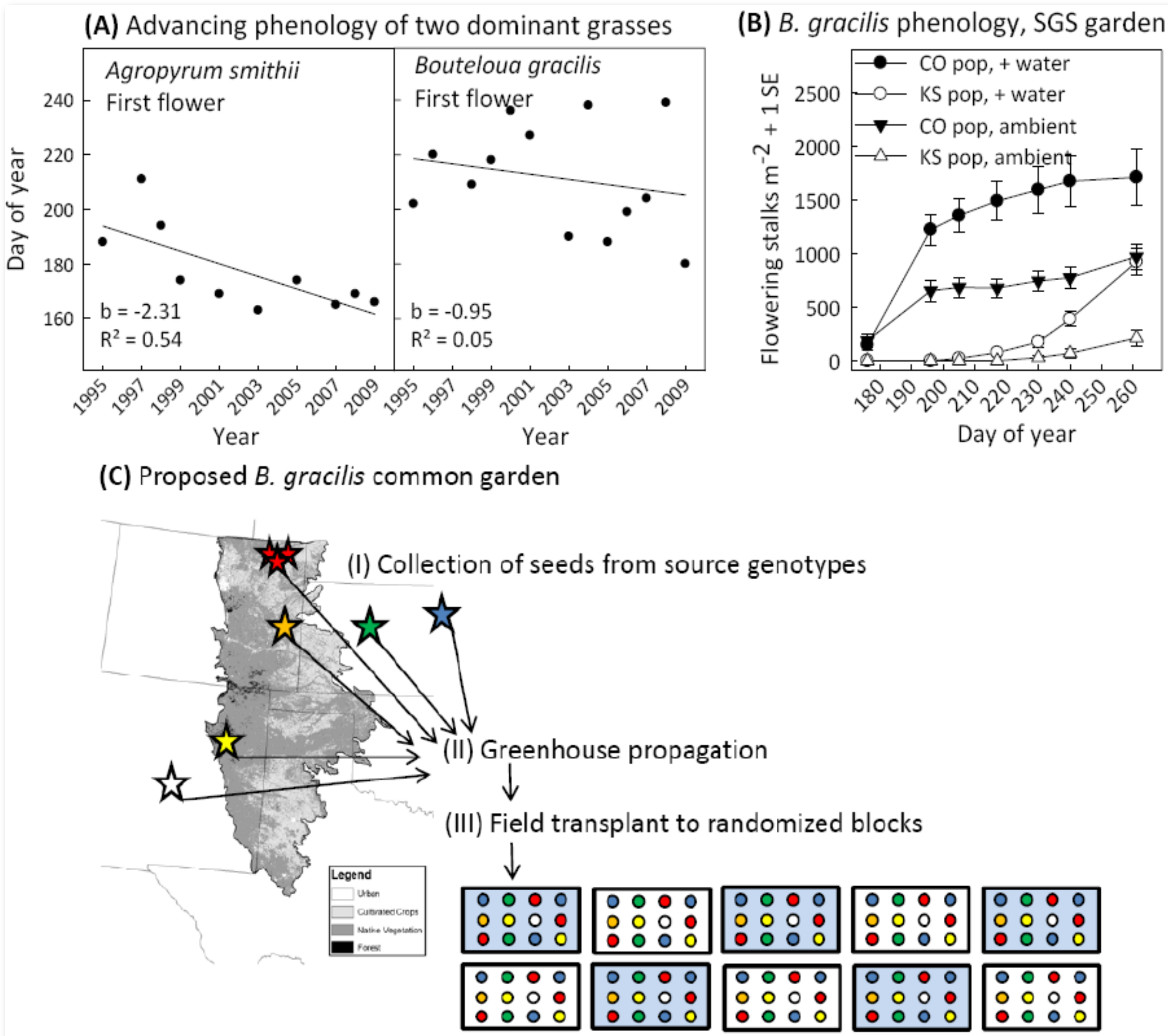


Fig. 10. (A) Advancing date of first flower for *Bouteloua gracilis* and *Agropyron smithii.* In recent years *B. gracilis* also shows high variance in flowering onset. **(B)** Reproductive phenology of *B. gracilis* genotypes from SGS and KNZ in a common garden at SGS. Native genotypes flowerd earlier and had greater reproduction in both ambient and supplemented water plots (Lease and Knapp, unpub. data). **(C)** Cartoon of proposed *B. gracilis* common garden. (**I**) Seeds from source genotypes have been collected at two spatial scales. Within SGS (red stars), we have seeds from 30 plants across each of ten sites that vary in physiography (e.g., toe slope and drainages versus uplands) and grazing history. Additionally, we have seeds from five sites in the Great Plains and southwestern US (Sand Creek, CO - orange star; Las Vegas, NM - yellow, Sevilleta LTER – white, Hayes, KS - green, and Konza LTER - blue). (**II**) We will --minimize maternal effects by greenhouse propagation prior to transplant, following established methods for germination and pollination (Nason et al. 1987). In fall 2011, greenhouse-generated seeds will be sown in the greenhouse and then transplanted to the field as small seedlings. (**III**) Plants will be grown in a fully randomized, complete block design. Within each of 10 blocks, two seedlings per maternal family will be planted at 0.5 m intervals. Prior to planting, existing vegetation will be removed without soil disturbance by placing black plastic along the planting grid and then raking off dead vegetation (Angert and Schemske 2005). Weeding will be as necessary to maintain cleared areas around each individual. All plots will be watered for several weeks following transplant to aid establishment. After establishment, half will receive only ambient precipitation (white blocks) and half will be watered to alleviate mid-season water stress (blue blocks). Response variables and analysis are described in sections A.3.1 and A.3.2.

landscape positions in 1982 during SGS-LTER I (see Fig. 4). We will add NDVI sensors to transects where ANPP is currently being measured so that seasonal patterns in greenness can augment ANPP measures based on end of season plant clipping. We will also continue our continuous monitoring of canopy development on the SGS initiated in 2001. In previous years, two Skye 1800 2-channel radiometers (red 630 nm and near-infrared (NIR) 862.5 nm) were installed, one in a grazing exclosure and one in the adjacent grazed pasture. The radiometers were polled every minute and averaged and the data stored hourly. Additionally, soil water monitoring at both of the sites was initiated using time domain reflectometery (TDR) at 3 soil depths, 0-10 cm, 10-20 cm, and 20-30 cm, polled hourly and stored daily. A tipping bucket gauge was installed to record 24-hour precipitation totals. Data are downloaded from the data logger every two weeks and uploaded to the SGS-LTER data management system. From these data we calculate a greenness index based on the Normalized Difference Vegetation Index (NDVI) for the noon hour reflectance average. For each treatment and each year we will fit a double logistic function of time to the greenness data (Fischer 1994a,b) to provide information on when the vegetation is active and how its dynamic responses to rainfall and soil moisture vary during the growing season. These data will help to provide mechanisms that explain changes in future productivity.

(A.3.2) Responses of blue grama genotypes: We will investigate genotypic variation within and among blue grama populations in a common garden experiment (Fig. 10). At SGS, we have collected seeds from 30 maternal plants across each of ten sites with varied physiography and grazing history, the same sites where long-term blue grama seed harvest has been conducted. Additionally, we have seeds collected from a total of seven sites in the central plains (see details in Fig. 10). Tissue from maternal plants will be collected for karyotyping. Seedlings will be transplanted in a fully randomized, complete block design and watered generously for several weeks following transplant. After establishment, half will receive only ambient precipitation and half will be watered to alleviate mid-season water stress. We will census at monthly intervals throughout the growing season to record survival and reproductive phenology and make additional physiological measurements on a subset of individuals (e.g., leaf greenness, gas exchange). At the end of each growing season, we will measure size (basal cover, tiller number) and fecundity (number of inflorescences, average seeds per inflorescence). We will use failure time models to test for differences in survivorship among populations. Date of peak flowering and end-season fecundity of reproductive plants will be analyzed by linear models including fixed effects of population and random effects of block and maternal family nested within population. To test for differences in growth rates, we will use repeated measures analysis of variance on size measures.

A.4. How does climate structure the interactions between organisms and their resources?

Rationale: Native consumer populations and introduced diseases have profound effects on plant communities and ecosystem processes at the SGS. Variation in temperature and precipitation affects consumer populations directly through survival and reproduction and indirectly, by altering the quality and availability of habitat and resources. Because most of the small vertebrates are omnivorous and responsive to changes in vegetation structure, changes in the production of arthropod prey and seeds and the cover of shrubs and taller, cool-season grasses are likely to have the greatest effect on abundance and species composition. In the context of global climate change, these changes are likely to be particularly relevant at the SGS-LTER site, which is at the boundary between SGS and northern mixed prairie. Specifically, decreases in temperature and increases in early growing season precipitation may increase the importance of cool-season grasses and shrubs that are more common in northern mixed prairie. Alternately, an increase in aridity is likely to decrease plant cover and favor species typically associated with southern SGS. In the mid-late 1990s, we began tracking populations of representative consumer populations on the SGS-LTER site, including rodents, rabbits, mammalian carnivores, as well as abundance of arthropod prey, vegetation structure, plant species composition, and cover of invasive plants. These efforts revealed dramatic effects of the 2000-02 drought on the abundance of multiple mammal taxa (Fig. 11). Changes in these taxa may have important ecosystem consequences: pocket gophers and prairie dogs are the most important causes of soil disturbance, black-tailed jackrabbits are the most significant small browsers of shrubs, and Ord's kangaroo rats, which became numerically dominant, are major seed predators. Importantly, some of these changes have persisted for several years after the end of the drought, suggesting a possible shift in favor of more xeric-adapted fauna.

Prairie dogs are ecosystem engineers (*sensu* Jones et al. 1997, Stapp et al. 2008a) whose activities significantly modify vegetation, nutrient dynamics and habitat for other species. The introduction of plague has altered the spatial dynamics of prairie dog populations, resulting in a metapopulation structure in which large colonies are prone to plague and where proximity to large colonies increase risk of plague extirpation (Stapp et al. 2004). Interestingly, in an analysis of long-term data on the status of colonies on the SGS between 1981 and 2001, we found that the probability of plague extirpation increases following El Niño (ENSO) years, when winter-spring temperatures are milder and spring precipitation tends to be higher than in non-ENSO years (Stapp et al. 2004). This pattern appears robust, as it has persisted during recent years (Fig. 12). The ecological mechanism is not yet clear as mild winters may increase host (prairie dog) population densities or survival of flea vectors. However, recent work suggests that outbreaks of plague may also be driven by the abundance of another small mammal host, the northern grasshopper mouse *Onychomys leucogaster*, an insectivorous mouse common on prairie dog colonies that is capable of spreading plague among prairie dog burrows and across social boundaries of prairie dog populations (see Fig. 12; Stapp et al. 2009).

(A.4.1) Monitoring Consumer Responses to Climate Variation and Change: We will continue monitoring all small mammal populations, their prey (grasshoppers, ground-dwelling arthropods) and mammalian and avian predators, with changes in methods and sampling intensity to reflect what we have learned and to fill important gaps. For example, we have modified our sampling methods for tracking changes in abundance of grasshoppers, which are the important insect herbivores and key prey for both birds and mammals. Our new protocols, which have been calibrated against our old methods, follow those used by the USDA-ARS at other northern rangeland sites, permitting cross-site comparisons in the future. We will conduct sweep-net surveys to estimate species composition of grasshopper communities throughout the growing season to assess grasshoppers associated with different plants with changes in climate and plant species composition, e.g., cool- season versus warm-season grasses.

(A.4.2) Monitoring Effects of Climate on Disease: We will monitor the size and status of prairie dog colonies on the SGS-LTER in collaboration with CPER and PNG staff. Each year, colonies are surveyed to map the extent of the area occupied by prairie dogs (see Fig. 4). The data represent a ~30-year record of the distribution and relative size of regional prairie dog populations in response to climatic variability, disease and land use, and serve as the foundation for comparative studies and additional modeling efforts to 1) better understand the mechanisms driving extinction-colonization dynamics in prairie dog metapopulations, including climatic factors, physiography and landscape configuration (spatial GIS and SPOM models, see D.2.1 below) and 2) develop predictive niche-based models to describe historical and current habitat suitability for prairie dogs and species of conservation concern in SGS.

B. Physiography: *To what extent are SGS responses to global change contingent on upon physiography?*

Background: Our previous work has found specific components of physiography (the mosaic of soils, landscape position, and landforms) are key factors for understanding the contemporary structural and functional features of the SGS including ANPP (Singh et al. 1998), prairie dog activity (Stapp 1998), N and P availability (Burke et al. 1999, Hook and Burke 2000, Ippolito et al. *in press*), and microbial community structure (McCulley and Burke 2004). The major physiographic features in the SGS emerged from a complex geomorphological and pedological history (Blecker et al. 1997). The features vary spatially (from 0.1-100 km), have provided the template for many of our field studies, and remain critical to scaling exercises necessary to forecast the ecosystem responses to global change. Our physiography research goals are to understand how ecosystem structure, function, and dynamics at the plot scale vary across these physiographic features, how interactions among the mosaic of communities that result across a landscape contribute to the persistence of SGS, and how land-use may alter these relationships.

To accomplish these goals we focus on key features that capture the variation described above. In our current efforts to scale up from the plot to the landscape (10's to 100's of km) scales, we rely on the spatially explicit soils and landform data, which were derived from detailed soil inventories (Peterson and Kelly 1994) and long term pedological research (Kelly et al. 1998, Blecker et al. 1997). However, the level of detail provided by this information is also overwhelming from a practical perspective. For example, soil surveys have identified more than 70 unique soil series across our study area, and that key properties such as water holding capacity and inorganic nutrient content are quite variable among soils ranging in age from 5,000 YBP to 600,000 YBP. Fortunately, our most recent work suggests that we can broadly categorize soil development into three phases based on landscape age and the associated systematic variations in the degree of soil development (Vitousek et al. 1997, Kelly et al. 2008; Fig. 13). When this approach is coupled with our traditional sampling focused on topography (e.g., catenas), the synthetic categorization needed for scaling results (Loadholt 2002). Combined, the three phases cover >90% of the SGS (with erosional surfaces, floodplains and parent material comprising the remaining 10%) and their distributions are well known and mapped. We anticipate that the hydrologic limits of the ecosystem are linked directly to the stage of soil development and we plan to conducted experiments across these pedologic gradients. In short, by stratifying or studies along these phases of soil development we can make connections among ecohydrology (soil water content and dynamics), grazing, fire and land-use and ecosystem response in an objective way at the landscape scale.

Although future research may indicate that additional phases need to be added, we will begin with these three because they appear to capture a significant amount of variation, and they allow for tractable experiment design at the landscape scale. In an effort to refine this concept, we will also use our long-standing approach, taking advantage of topographic (e.g., catenas) and soil development (soil chronosequences) gradients within the SGS. In addition, we will use paleo-environmental data derived from paleosols (ancient buried soils) to identify the ancient limits (e.g., range and variability of ancient climatic and biological conditions) of the SGS region. Our plan is to use these data as a baseline to compare ancient and current conditions and then design both long and short term manipulative experiments (e.g. water additions or removals) across contemporary physiographic gradients (e.g., catenas and chronosequences). We will continue our long-term investigations of topographic controls on ecosystem structure and function by expanding our studies of catenary sequences. We will also continue our investigations of soil development and ancient conditions at the SGS and, by augmenting climatic studies described in section A.2, include a physiographic dimension to assess the degree to which soils at different stages of development "dampen" or "reinforce" the effects of changing precipitation regime. The design and sampling of the new experiments are described previously in sections A.2.2 and A.2.3. Based on the nature of the responses measured, we will be able to quantify the degree of vulnerability of landscapes within the SGS ecosystem to global change, and use the experimental findings in our modeling and upscaling efforts (see Section D).

B.1. How does soil moisture influence community structure and function across stages of soil development and landscape position?

<u>Rationale:</u> Organizing soils on a landscape scale is a necessary prerequisite for an extrapolation of plot-level experiments and measurements to greater areas (upscaling) for ecological forecasting. In this respect the catena concept continues to provide a very useful model to decipher soil patterns and related regular trends in ecosystem structure and function on the landscape scale. We will test the hypothesis that the key abiotic variable controlling soil community structure and biogeochemical processes (primary productivity and nutrient turnover and trace gas exchange dynamics) is water availability but that the degree of control varies with key soil properties (soil texture and depth) associated with topographic position. Our long-term dataset reveals significant differences in the greenhouse gas methane (CH_4) emissions and oxidation rates among physiographic units (Fig. 14). In a cross-site comparison of uptake rates at the SGS, Konza and Sevilleta, we found significant differences in rates of CH_4 oxidation, methanotroph community composition, and in enzyme kinetics, supporting the idea that community composition does matter for rates of CH_4 oxidation (Fig. 14). Moreover, previous work by our group

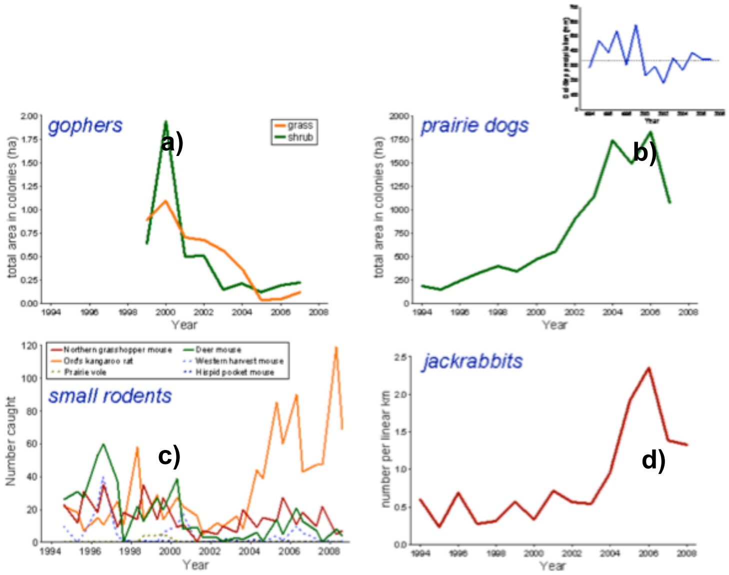
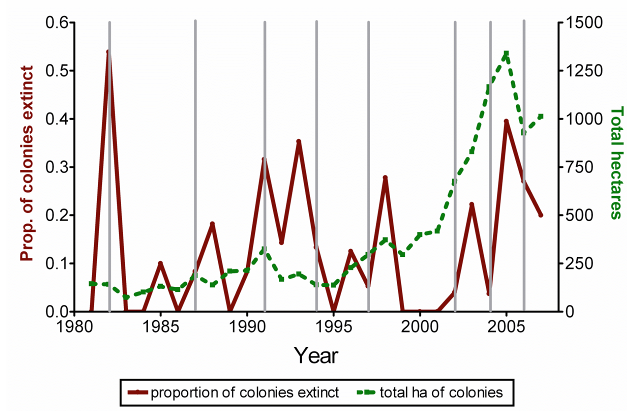


Fig. 11. Persistent shifts following the 2000-02 drought in ; **a)** the area disturbed by pocket gophers; **b)** the total area encompassed by prairie dog colonies; **c)** relative abundance of small mammal species in saltbush trapping webs, and **d)** the relative abundance of jackrabbits. Inset at top right shows Oct-Sep annual precipitation from 1994-2008. Horizontal line represents the long-term mean.

Fig. 12. Although acreage of black-tailed prairie dog colonies on the Pawnee National Grasslands has grown exponentially over the past 28 years, plague-related extinctions of colonies are common and tend to occur after El Niño Southern Oscillation events (vertical gray lines). Updated from Stapp et al. (2004).



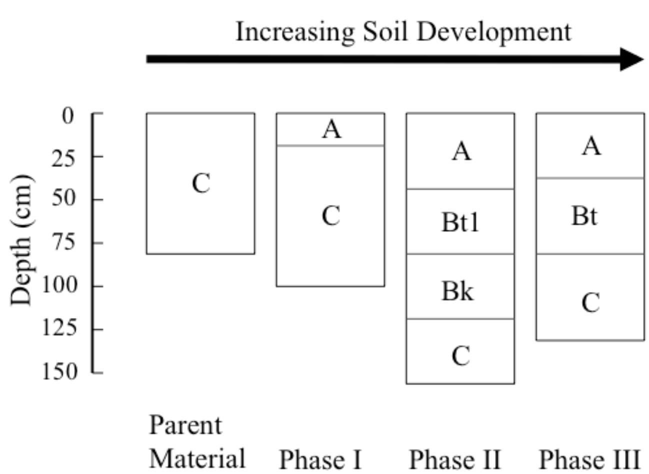


Fig. 13. Gradients of Soil development on the SGS. **<u>Phase I</u>:** Aggrading or Building Stages in which soil development begins with a new substrate. The soils are generally weakly developed and although mineral transformations have occurred the soil is genetically simple with little horizon differentiation and surface and subsurface materials being pedogenically and hydrologically similar. **<u>Phase II</u>**, Intermediate or Equilibrium Stage during which the formation and clay and $CaCO_3$ become dominate features in the soil profiles and there is significant pedological and hydrological differentiation between surface and subsurface horizons. **<u>Phase III:</u>** Degrading or Declining Stage in which the most weatherable primary minerals have been transformed into secondary forms. In this stage of development soils experience losses of clay (relative to soils in the intermediate stages of development) and complete removal of $CaCO_3$ is apparent.

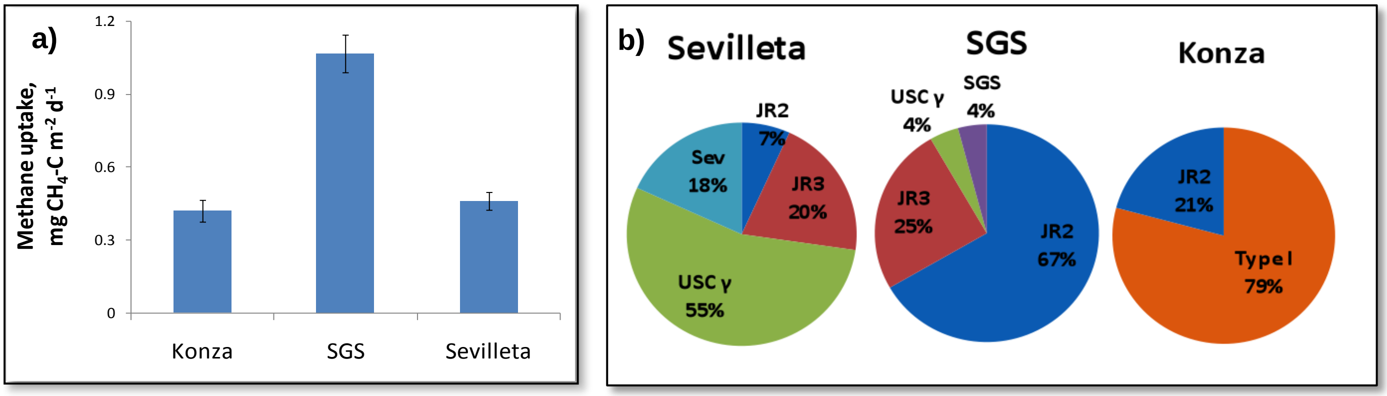
(Fierer and Jackson 2006) found pH to be a key control of bacterial community composition at the global scale, and we anticipate large differences in composition on the often acidic Phase III soils as compared to other SGS soils.

(B.1.1) Long Term Studies of Soil Catenas: We will expand field studies that were originally designed to separate the effects of soil texture and topography on net primary productivity and nutrient turnover dynamics. We examined three catenary sequences derived from diverse lithologies (e.g., sandstone, siltstone and shale) and within each catenary sequence, we identified and sampled at three different landscape elements that are delineated based on discordance in slope (e.g., summits, back slopes and footslopes). We have used this template to inform our biogeochemical measurements designed to assess the coupling and de-coupling of microbial and biogeochemical and other ecosystem processes (e.g., ANPP) across the topographic and lithologic gradients. In each location, we will now estimate *in situ* soil water content using calibrated Decagon TDR technology. This will allow us to identify the range and variability in the key biotic interactions mentioned above within catenas as a function of soil moisture and landscape position and among catenas as a function of soil moisture and texture. Additionally, we will characterize the soil microbial and invertebrate community, biogeochemistry, and trace gas fluxes as a function of soil development phase. We will continue monitoring CH_4 oxidation rates across catenas on different soil phases and add seasonal measures of methanotroph community composition and enzyme kinetics on these studies to quantify long-term changes in rates and controls of these rates. We will also extend our use of pyrosequencing of the bacterial community composition to characterize Phase I and Phase III catenas.

B.2. What can we learn from the ancient range and variability of climatic and biological conditions in the SGS region of the Great Plains and how can this help us forecast the future?

Rationale: Long-term monitoring of soil water from recent decades, including effects of topography and soil texture may not reflect the range of variability and trends over centuries or millennia. We will test two hypotheses, aimed at establishing relationships between contemporary (B.2.1) and paleo-environmental conditions (B.2.2). The first hypothesis is that soils of contemporary landscapes record the biogeochemical development and hydrological functioning of the SGS ecosystem. The second hypothesis is that soils of ancient buried landscapes record paleo-environmental conditions and may be used to establish the range and variability of past climatic and biotic conditions (dust deposition, temperature, precipitation, soil water distribution and content).

(B.2.1) Reconstructing Prehistoric Distribution of Soil H_2O: Soils of contemporary landscapes record the biogeochemical development and hydrological functioning of the SGS ecosystem (Kelly et al. 2008). We sampled over 50 pedons (from a total of 200) to date across gradients of topography, age and parent material. We use changes in chloride concentration in soil profiles to quantify patterns of water distribution within and among soils. The chloride (Cl) mass balance (CMB) technique (Allison and Hughes 1978, Tyler et al. 1996, Scanlon et al. 1999, Scanlon 2000) has received considerable attention as a potentially quick, reliable, and economical technique for estimating soil water movement. In essence, Cl undergoes no chemical transformations in soil and thus, measuring changes over time of total chloride in soil can provide an estimate of relative differences in water movement into and through soil during soil development. With these data, we will be able to establish the variations in long term hydrologic dynamics in soils as a function of the key attributes of physiography (e.g. soil texture, landscape position, and soil development) as show in Figure 15. These data depict longterm trends in water movement across different textures (Fig. 15a) and as a function of landscape position (15b). The backslope in this case receives very little water relative to the summit and toeslope positions suggesting that for landscape positions hydrological functioning is quite different over periods of time that extend beyond the scope of the historical LTER monitoring. When coupled with our measurements of biotic variables these data may provide us with a means of estimating the “within site” variability of biotic responses to global change and to identify which landscapes are likely most vulnerable to climate change.



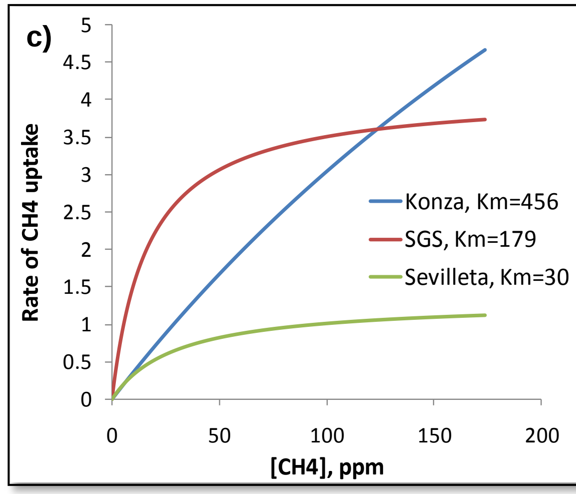


Fig. 14: a) Rates of methane oxidation differed significantly among sites. **b)** Methanotroph community composition based on clone libraries of soil DNA amplified with pMMO-specific primers (Kolb et al. 2003). The strains are identified by taxonomic affiliation, based on sequence similarity to other published works. USC is the "upland soil cluster." Clone library sizes are 44 to 48 sequences per site. **c)** Enzyme kinetics for methane oxidation from the 3 sites reveal significant differences in enzyme affinity.

a

b

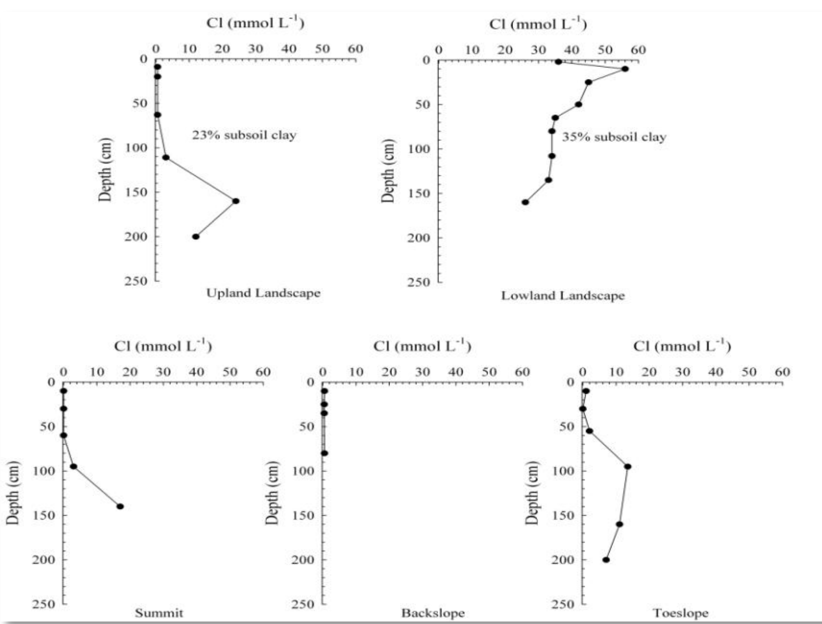


Fig. 15. The chloride mass balance model applied to different elements of the landscape: **a)** uplands versus lowlands with different clay contents in the subsurface Bt horizons and **b)** across the landscape elements of a centenary sequence (Kelly et al, 2008). The approach uses the change in concentration of chloride in the soil profile over time to estimate patterns of water penetration. Because chloride undergoes no chemical transformations in the soil, losses or gains of chloride from the soil profile may be assumed to be due to the movement of water containing dissolved chloride. Water penetrates deeper into the soil with lower amounts of clay in subsurface. Along the catena very little water enters the backslope position relative to the summit and toeslope.

B.2.2) Reconstruction of Ancient Biotic Conditions: We have demonstrated that soils of ancient buried landscapes record paleo-environmental conditions and can be used to establish the range and variability of past climatic and biotic conditions in the western Great Plains during the Holocene (<11,500 ybp) and provide key insights into ranges of ancient climatic variability in the SGS (Kelly et al. 1998). Climate and biota can by reconstructed by: 1) establishing isotopic records of SOC, $CaCO_3$ and phytoliths (identifiable fossils of plant species) from paleosols; 2) finding episodic pulses of dust associated with large changes in vegetation cover in loess/paleosol stratigraphic sequences; and 3) identifying key faunal and botanical remnants to create models of plant community composition. We initiated work during SGS-LTER V by describing and sampling the Old Wauneta site because, at six meters deep, it is arguably the thickest and most complete Holocene loess section on the western and central Great Plains (Jacobs and Mason 2005) (Fig. 16). Holocene Bignell loess at Old Wauneta contains as many as five buried A horizons. Soil horizons will be measured for a full suite of paleoclimatic indicators for the region, as outlined previously (Kelly et al. 1998, Blecker et al. 1997, Stevenson et al. 2005, Stevenson et al. *in press*). Our data point to dramatic shifts in the proportion of C_4 to C_3 vegetation for the region throughout the Holocene (Kelly et al. 1998). Phytolith data from the Brady Soil suggests a larger component of shrub like vegetation than we previously reported for this region (Kelly at al. 1998) and that the dominance of of blue grama appears to be driven by conditions present during the Holocene. By expanding our sampling to new locations we will be able to better assess the range and environmental conditions of ancient plant communities – many of which are dominated by plants that absent or only minor components of the contemporary SGS ecosystem.

C. Grazing, Fire and Land-use change: *How will land-use changes that alter grazing, fire and grazing-fire interactions modify the structure and function of SGS?*

Background: Grazing is an important determinant of the past and current structure and function of SGS. Indeed, many traits of the dominant SGS plant species are thought to be responses to a long evolutionary history of grazing, fire and drought (Coughenour 1985, Milchunas et al. 1988, Briske and Richards 1995). However, over the past 200 years, human activities have altered the nature of grazing across the SGS, while also managing the fire regime and inducing other land use changes (see Fig. 2). In the mid-1800s, the demise of bison herds and introduction of livestock led to the first large-scale transition in land use, from free-range native grazers to domesticated livestock confined to small land pastures and the associated control of fire. The Homestead Act in 1862 led to a large-scale transition to row crop agriculture (Hart 2008), which replaced diverse perennial native plant communities with monoculture crops and annual tillage practices. A major transition occurred with the 1985 Farm Bill, which created the Conservation Reserve Program (CRP) and allowed for the abandonment of millions of acres of marginal cropland within the SGS. These lands were reseeded with mixes of non-native and native mid- and tall-statured plant species, and policies have largely excluded grazing from these lands over the past 25 years. The latter two transitions markedly altered resource allocations above- and belowground, as well as disrupting biogeochemical processes of nutrient cycling, resulting in protracted recovery periods. The current landscape is a mosaic of native grassland, grassland on cropland abandoned during the Dustbowl (approximately 20-30% of the CPER/PNG area), ungrazed CRP grassland (950,000 ha in eastern Colorado), and cropland. Our research seeks to understand the effects of these historic transitions in SGS management for both the basic ecology and for ecosystem services provided by the SGS, in particular the maintenance of native biodiversity. We will study how managed-grazing interacts with prescribed fire, prairie dog populations regulated by plague, and grazing on restored grasslands influence SGS structure and function. These processes may serve as key stabilizing forces in the SGS under changing climate.

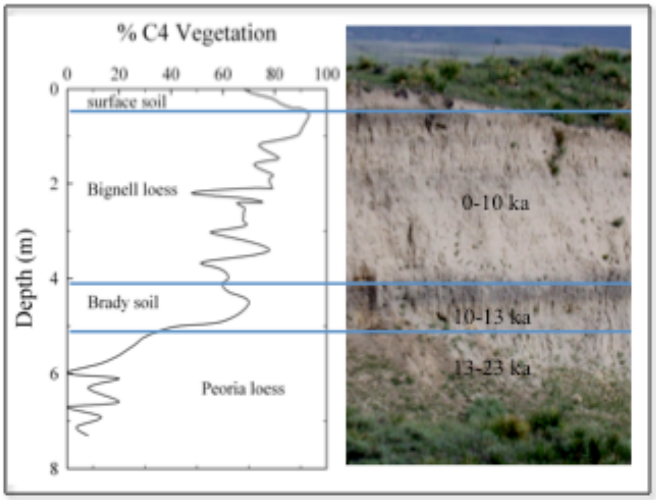
C.1. How do alterations of the type and intensity of grazing influence structure, function and biodiversity of the SGS, and influence transitions among vegetation states?

Rationale: Early research on type of grazer showed a high degree of similarity between bison and cattle grazing at the pasture scale (reviewed in Lauenroth and Milchunas 1992). Both are large generalist herbivores whose grazing patterns at the landscape scale differ historically primarily due to bison constraint by distance to water and cattle constraint by fencing. Our prior LTER focus was on livestock grazing at intensities that vary from 0 – 60% of ANPP (Bement 1969, Milchunas et al. 2008) with manipulations of grazing timing in response to climatic variation to optimize secondary (i.e., livestock weight gains) production (Hart and Ashby 1998, Hart and Derner 2008). Livestock grazing at these intensities has minor effects on ANPP and vegetation state transitions (Milchunas and Lauenroth 1993, Milchunas et al. 2008,) compared to other grazed ecosystems (Milchunas et al. 1988), and rotation of cattle among pastures has little effect compared to continuous grazing (Derner and Hart 2007).

Recent investigations of small herbivores suggest they can have greater influence than livestock on some aspects of the structure and function of SGS (Bakker et al. 2006; Fig. 17). Over the past 20 years, prairie dogs have increased dramatically in the SGS (Stapp et al. 2004, Derner et al. 2006), with research focused on their interactions with and effects upon other herbivores (Guenther and Detling 2003, Derner et al. 2006, Stapp 2007a). The cessation of prairie dog poisoning has allowed for long-term studies of spatiotemporal patterns in the disturbances caused by prairie dogs (Stapp et al. 2004, Augustine et al. 2008a), especially in relation to metapopulation dynamics induced by plague (Antolin et al. 2006). Sporadic plague outbreaks cause local extinctions of prairie dogs, with cascading effects on plant and faunal diversity (Stapp 2007a, Augustine et al. 2008b, Hartley et al. 2009). We will test a series of hypotheses in the following field experiments.

(C.1.1) States and Transitions under Large Mammal Grazing: We will study long-term interactions among large mammal grazing, plant communities, and climate. At moderate grazing intensities interactions between grazing and weather cycles influence the magnitude of fluctuations in plant community composition and diversity, productivity, and nitrogen content. Moreover, grazing at moderate intensities stabilizes system responses to climate change by suppressing exotic and opportunistic plant species and maintaining the dominance of belowground resource allocation by plants, which in turn has significant feedbacks to the configuration of the soil community and nutrient cycling. To test these hypotheses, we will continue to assess vegetation composition, diversity, ANPP, nitrogen content of key species, root production, nutrient cycling and soil communities in our long-term Grazing Reversal experiments that we initiated in 1991. In this experiment we opened existing long-term (since 1939) exclosures to grazing and new exclosures were constructed on long-term moderately grazed areas. Results indicate that ANPP of the SGS recovers rapidly after drought, regardless of livestock grazing treatment (Fig. 18a), and structure of trophic interactions within the belowground community is directly affected by grazing in ways that impact nutrient dynamics and stability (Moore et al. 2004, Rooney et al. 2006, 2008; see Fig 18b). Absent from all our previous research on grazing and root production is the combination of those two important processes. Therefore, we will add long-term estimates of root production in previously ungrazed and grazed treatments in LTER VI, using root ingrowth donuts (Milchunas et al. 2005c, Milchunas 2009).

(C.1.2) Large Mammal Grazing Seasonality and Intensity: We aim to test the limits of the SGS to grazing by altering both the seasonality and intensity of grazing. Grazing intensities outside the traditional boundaries of grazing intensity and seasonality can interact with physiography to induce changes in vegetation states. To test this hypothesis we will assess vegetation composition, ANPP, diversity and structure in an experiment that began in 2003 (Grazing Seasonality and Intensity). Since livestock can modify vegetation composition and structure to alter habitat and resources for other organisms (Derner et al. 2009), manipulations of the seasonality and intensity of grazing therefore may be used as a tool to create habitat for species of conservation concern. Two treatments involve manipulations of livestock grazing in spring and summer at very high (80%) grazing intensities. We propose to expand this study to examine potential interactions between seasonality and intensity of grazing and physiography by comparing livestock grazing treatments on uplands with moderately summer-grazed lowland pastures dominated by fourwing saltbush (*Atriplex canescens*) that, prior to 2008, were grazed during winter (Nov-Mar; Derner and Hart 2005). Vegetation sampling will focus on ANPP, residue, composition, cover, and structure (visual obstruction; Robel et al. 1970) to determine if treatments induce changes to vegetation



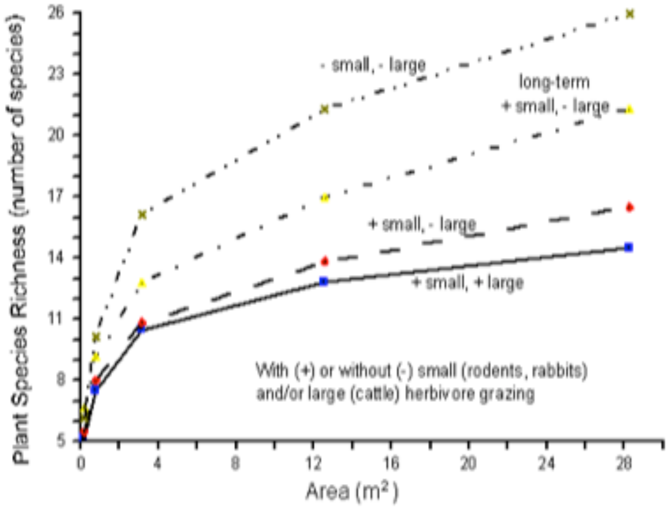
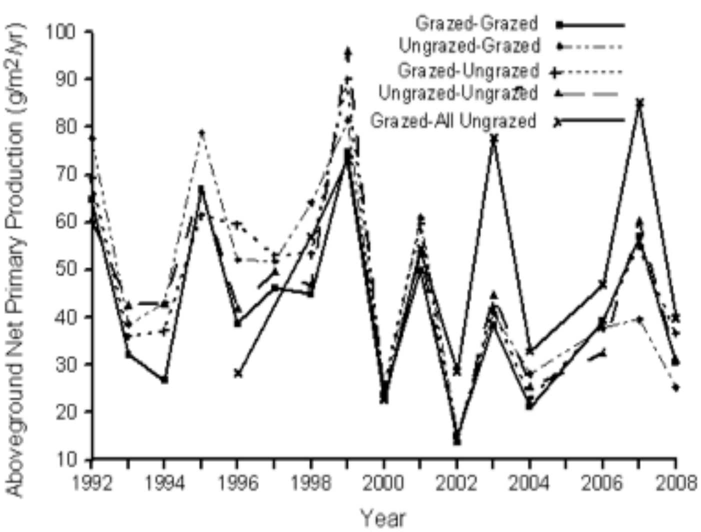


Fig. 16. Photograph of sequence of paleosols at Old Wauneta site eastern margins of the SGS Ecosystem. Paleosols were re-sampled in 2008-2009 for paleoclimatic studies and isotopic characterization. Photograph shows ages in 1000s yr BP, courtesy of Joe Mason (Miao et al., 2005). Percentage of C4 vegetation from C-13 values of SOC (data from Kelly and Busacca Unpublished). Note shift in abundance of C4 vegetation in late Holocene (0.5 to 2m depth) relative to early Holocene (6m depth).

Fig. 17. Plant community species richness (species-area-curves) in treatments grazed and ungrazed by combinations of large and small herbivores. Long-term treatments are from 1939, while short-term treatments are from 1994.



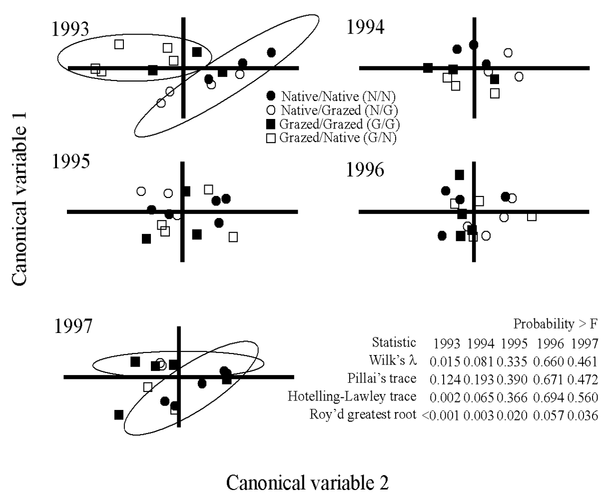


Fig. 18. a) Schematic of the Grazing Reversal Study. Half of old long-term exclosures were opened to grazing and new exclosures on long-term grazed areas were constructed, resutling in four treatments: UG-old Ungrazed, now Grazed, GG-old Grazed, still Grazed, GU-old Grazed, now Ungrazed, and UU-old Ungrazed, still Ungrazed. The fifth treatment (grazed- all Ungrazed) is our small mammal plus large mammal body-size exclosures built at 3 of the 6 replicates of the other treatments. **b)** Canonical Discriminant analysis of the long-term study on grazing at the shortgrass steppe comparing plots that had been under long term grazing (GG and GN) and from those that had not been grazed (NN and NG). The analysis used bacteria (CFU g-1 soil) and fungi (CFU g-1 soil), and the densities of Protozoa (nos. g-1 soil) as input variables. Pre-treatment, the communities in the grazed and ungrazed plots differed. Early in the study (1992-1997) the structures of microbial and protozoan communities within the manipulated plots shifted to their pre-treatment counterparts.

composition. Remote sensing and aerial photography will be used to provide estimates of bare ground and canopy cover, as well as shrub densities.

(C.1.3) Small vs. Large Mammal Grazing: The targeted feeding patterns and behaviors of small mammals (e.g., rodents and rabbits) may exert a greater influence on vegetation composition, diversity and structure than less selective large mammals, which consume greater amounts of dry matter. To test this hypothesis, we will assess vegetation composition, diversity, ANPP and structure in the Grazing Reversal experiment. In 1996, exclosures limiting access to both small and large mammals were constructed at three of the six replicates in the above study (Bakker et al. 2006, 2009). Small mammals including rodents and lagomorphs, but excluding prairie dogs, have been thought to primarily influence community structure through their small-scale activities (Peters et al. 2008), because gross consumption is about 3% of ANPP (Lauenroth and Milchunas 1992). Small mammals increase with decreased grazing intensity (Milchunas et al. 1998), suggesting an interaction with large herbivores that potentially masks effects observed in large herbivore exclosures that do not exclude small mammals. Large effects of altering small mammal populations have been observed in desert ecosystems (Brown and Heske 1990 a,b) because of the importance of large-seeded annuals plants. Results from the SGS showcase that when small mammals are excluded changes in plant diversity are similar in magnitude to those for large herbivore exclusions (Fig. 18a). Large-seeded annuals as well as shrubs respond to the additional removal of small herbivores. Removal of both large and small herbivore has a larger effect on ANPP than grazing by large herbivores alone (Fig. 18a). Building on these results and those of our long-term studies of jackrabbits and granivorous rodents, we will initiate a new experiment (Small Browser/Granivore Cages) using cage exclosures to separate the effects of rabbits and small rodents on plant diversity, ANPP and seed production in the context of the other larger-scale manipulations of grazing (moderate cattle grazing and prairie dogs). Cages that include and exclude small rodents (<150 g) will be placed on plots in and out of livestock exclosures, on and off prairie dog colonies (see C.1.4 below), in a factorial design to allow us to evaluate the relative importance and interactive effects of a full suite of herbivores.

(C.1.4) Prairie Dog Grazing Studies: Removal of large mammal grazing in prairie dog colonies may increase diversity and NPP of plants and consumers compared to area with no large mammal or prairie dog grazing. To test this hypothesis, we will construct 1-ha livestock exclosures on 4 prairie dog colonies and compare responses of plants and key consumer groups (e.g. grasshoppers, small mammals) to those in 1) moderately grazed prairie dog colonies; 2) exclosures in areas without prairie dogs; and 3) moderately grazed pastures without prairie dogs. Previous studies were conducted on sites grazed by livestock, making it difficult to separate the effects of prairie dogs from livestock (Stapp et al. 2008a, Hartley et al. 2009). Moreover, changes in plant community dynamics caused by plague-induced loss of prairie dogs followed by subsequent recolonization are contingent on physiography and colony age, and alter livestock behavior and weight gains. To test this hypothesis, we will assess vegetation composition, livestock behavior (via GPS collars) and livestock weight gains in one of our core monitoring studies (Prairie Dog Monitoring). Boundaries of all active prairie dog colonies are surveyed annually on CPER and PNG to provide a background for the evaluation of prairie dog effects on vegetation (see A.4.2 above). We initiated a long-term study of plant community dynamics on prairie dog colonies that became re-established on CPER during 1997-99, and expanded rapidly during the ensuing 7 years (Derner et al. 2006). Plant species composition and vegetation structure were monitored annually on the 5 largest colonies from 2004 to 2009, before, during and after these colonies were extirpated by local plague events in 2006. In 2007 we expanded vegetation monitoring to specifically encompass areas that were previously occupied by prairie dogs for 1-2 years, 3-4 years, 5-6 years, and ≥ 7 years before prairie dogs were removed by plague. These studies allow us to contrast rates of vegetation change following prairie dog establishment versus removal. Measurements of livestock behavior in these pastures will be evaluated with GPS collars on 3-4 steers/pasture during the grazing season. We will track livestock weight gains to determine if the reduction in gains associated with prairie dog presence (Derner et al. 2006) is altered by removal of prairie dogs by plague and their subsequent recolonization.

C.2 How do interactions among grazing, fire and land-use influence the structure, function and biodiversity of the SGS, and associated provision of ecosystem services?

Rationale: Human land-use has already altered the structure and function of SGS at landscape scales through suppression of fire, control efforts targeting non-forage species (e.g., prickly pear cactus, *Opuntia polyacantha*) to enhance livestock production, tillage for crop production, and the subsequent restoration of former croplands. Past research has focused on direct effects of the major disturbances on the SGS, but far less is known about how grazing interacts with other disturbances and land-use patterns.

Although historic fire return intervals in grasslands of the western Great Plains are controversial, fire has been acknowledged as an important component of these grasslands (Wright and Bailey 1982, Brockway et al. 2002, Erichsen-Arychuk et al. 2002). Some native plant and animal species exhibit adaptations to recover from or breed within recent burns (Svingen and Giesen 1999, Vermiere et al. 2001, Knopf and Wunder 2006). The re-introduction of fire to SGS may increase biodiversity, suppress unpalatable species such as cactus, and enhance plant nitrogen content (Brockway et al. 2002, Augustine and Milchunas 2009, Derner et al. 2009). Additionally, fire and grazing can strongly influence one another (Knapp et al. 1999, Fuhlendorf and Engle 2001), and likely have interactive effects on grassland dynamics.

Under long-term fire suppression, prickly pear cactus is the second dominant species in the SGS. Presence of cactus cladode clusters creates small biotic refugia throughout the landscape. These spiny refugia, often removed by land managers, alter grazing patterns, and thereby influence plant and consumer communities, and nutrient distribution and cycling (Rebollo et al. 2002, 2005, Stapp et al. 2008a). Our prior efforts have addressed removal of the dominant grass species (*B. gracilis*) and subsequent disruption in structure and function of SGS (Peters et al. 2008, Burke et al. 2008), but little is known about how the loss of refugia created by cactus may alter SGS structure, function and biodiversity.

Our studies addressing restoration of formerly cropped lands have shown that rates of plant succession and recovery are slow and highly variable. Soil C and ANPP differ from native grasslands suggesting that the SGS is not resilient to disturbances of large belowground root and SOM pools (Fig. 19; Burke et al. 2008, Peters et al. 2008), but these studies were conducted in the absence of grazing. Grazing on CRP lands could reduce weed invasion and accelerate succession (Milchunas et al. 1992, 2008), and by favoring native short-statured grasses, could also ameliorate changes in altered N and water availability caused by climate change (Heisler-White et al. 2009).

(C.2.1) Burn Experiments: The influence of fire on SGS structure, function and biodiversity may be linked to the grazing patterns large herbivores. The strength of this proposed fire-grazing interaction is a function of temporal weather fluctuations that determine fuel loads, mediating the effect of fires on soil moisture, soil temperature, forage quality and forage quantity. The fire-grazing interaction may have cascading effects on faunal communities by altering the spatial variation of vegetation structure at multiple scales. We will use two prescribed burn experiments will be used to test these hypotheses. The first (Small Plot Burns), initiated in 2006 during LTER V, uses replicated (n=4) small-scale (20 X 20 m) prescribed burns conducted in the absence of livestock grazing to assess direct effects of fire frequency (annual vs. 4 year) and seasonality (spring, fall) on ANPP and vegetation composition. Here, we will focus on linkages among fire effects on soil moisture, temperature, microbial (in particular nitrifiers and methanotrophs) and invertebrate community composition, soil inorganic N availability and trace gas fluxes, and vegetation dynamics. The second study (Patch Burn), initiated in 2008, examines fires implemented at sufficiently large spatial scales to evaluate interactions with livestock grazing and the responses of multiple faunal groups. Here, the structure, function and biodiversity of pastures receiving a patch burn treatment (25% of the pasture, or 16 ha, burned each year; cattle at moderate stocking rate) will be compared with control pastures (no burning; cattle at moderate stocking rate). Our study design will facilitate cross-site comparisons with completed studies in the tallgrass prairie (eastern Oklahoma and Kansas; Knapp et al. 1999, Fuhlendorf and Engle 2004, Fuhlendorf et al. 2006) and two recently initiated studies in mixed-grass prairie (western Oklahoma, eastern Montana; Fig 20). In addition to measures of soil moisture, soil temperature, ANPP and plant community composition, we will quantify livestock weight gains and use of patch-burned pastures at a fine temporal resolution [5 min sampling via satellite telemetry (GPS collars) of 3-4 steers/pasture] over the grazing season, as well as quantification of numbers of pronghorn antelop on burned and unburned areas three times weekly over the entire year. Spatial distribution of livestock will be examined in relation to tradeoffs between forage quality and quantity measured on/off burns, and in relation to temporal patterns of plant growth and senescence (i.e., precipitation pulses) measured with ground-based NDVI sensors, soil moisture probes, and precipitation gauges in each pasture. Patch-burn effects on vegetation heterogeneity will be quantified with ground-based measures of vegetation structure (vegetation visual obstruction; Robel et al. 1970) and vegetation composition within small-scale (1 ha) and large-scale (16 ha) grids of sampling locations distributed over experimental pastures, and with high-resolution (1 mm) remote sensing, aerial photography methods that have recently been validated for use in SGS and other grassland ecosystems (Booth et al. 2007). These measurements will be used to access faunal responses (largely densities of thirteen-lined ground squirrels), density and species composition of grasshoppers (modified from Branson 2005), and grassland bird density and species composition.

(C.2.2) Cactus Removal Experiment: Large-scale removal of prickly pear cactus (*O. polyacantha*) may have larger effects on vegetation structure and diversity than the small-scale differences inside vs. outside cactus clusters, which in turn may affect the diversity and densities of arthropod and small mammal communities. To test this hypothesis we established 8 pairs of 12 x 12 m plots in June 2009 within a 130 ha region slated for aerial herbicide spraying, half of which were covered with a tarp during application and plots of similar dimension in adjacent untreated pastures to include: 1) cactus removal plots in a landscape where most cactus clusters have been removed, 2) untreated (cactus present) plots areas where most cactus clusters have been removed, and 3) untreated (cactus present) plots in areas where cactus clusters have not been removed (Fig. 21). Pretreatment and annual post treatment measurements include plant cover by species, plant species-area curves, vegetation structure (visual obstruction; Robel et al. 1970), cactus density and flowering stalk production inside and outside cactus clumps annually, sample soil C and N, and arthropod and small mammal abundance.

(C.2.3) Restoration of Formerly Cropped Lands: Given that the SGS developed with large herbivores, the addition of grazing to formerly cropped lands may speed succession towards native SGS. We posit that herbivore will reduce the abundance of opportunistic, ruderal species and tall and mid grasses and promote short grasses. These changes would in turn shift plant biomass from relatively greater proportions aboveground to relatively greater proportions belowground, and increase carbon sequestration in SOM through greater belowground inputs from roots. We will assess annually vegetation composition, ANPP, root production and soil C and N (5 year increments) in two experiments (CRP and Seeded Pastures). The CRP experiment has grazing treatments (grazed, ungrazed) since 2007 following pretreatment sampling (Fig. 22). The Seeded Pasture study which has eight pastures (7.5–20 acres) that were plowed and seeded in 1994 with monocultures of non-native perennial grass species (Russian wildrye or crested wheatgrass) will receive a moderate spring grazing treatment with ungrazed areas established through exclosures.

D. Synthesis and Forecasting: *How do climate, grazing, and land use influence the SGS over multiple spatial and temporal scales?*

Background: Forecasting future states of the SGS ecosystem will require connecting our measurements of population, community, and biogeochemical processes at multiple locations, to documentation of past, current and future land-use. We have developed and implemented models as integral tools to study the structure and function of the SGS and for cross-site comparisons of ecosystems. Our use of models is best described as the melding of simulation and theoretical models informed by the data collected at the SGS. We have extensive experience using ecosystem and metapopulation models to guide research, interpret results from field experiments and use the models to extrapolate the impact of human management of ecosystems at the regional to global scale. Examples include efforts that have synthesized field data to understand regional gradients in grassland ecosystem dynamics (Burke et al. 1997), mechanisms underlying variation across multiple temporal scales interactive effects of temperature and atmospheric

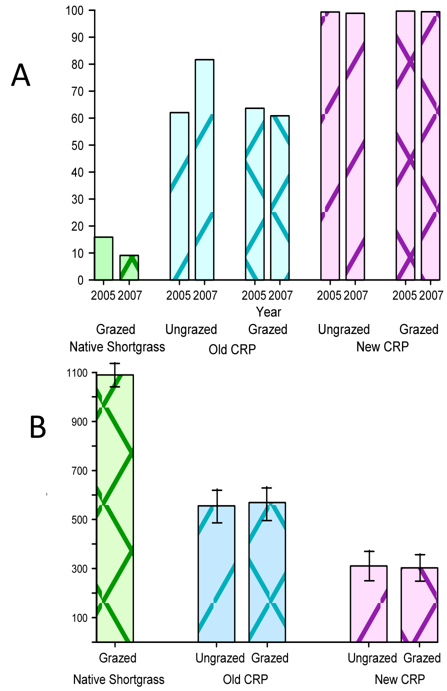


Fig. 19. Plant community species dissimilarity (% - Whittaker index of community association) of newly planted CRP (2003), old CRP (1989), and native SGS compared to SGS steppe (six replicates compared) in pre-grazing treatment year 2005 and the first year of grazing treatment 2007 (A), and root biomass (g/m^2) of the treatments in 2005 (B). New CRP plots are dominated by exotic annuals, while old CRP plots are a mix of mid-height and tall native grasses (some not native to the site) and mid-height exotic grasses.

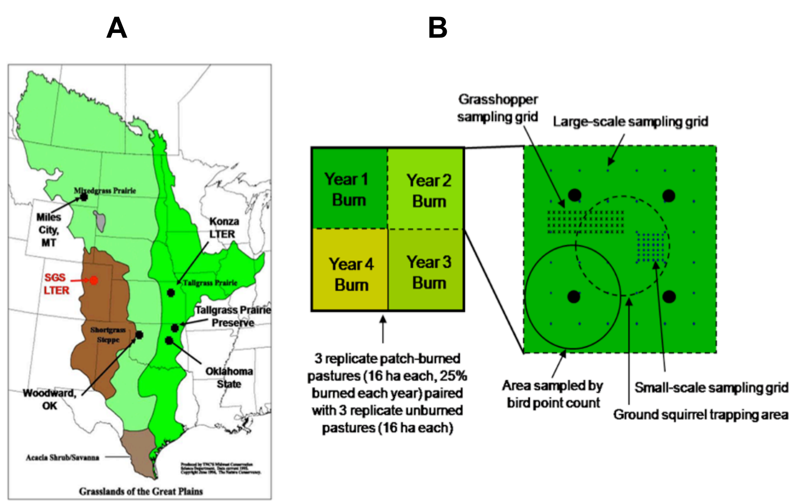


Fig. 20. Details of fire x grazing interactions studies. **A)** Locations of proposed and ongoing experimental studies of fire x grazing interactions in the Great Plains of the United States, **B)** and schematic showing the temporal distribution of burns in the proposed experiment at the SGS LTER, and the multi-scale sampling design in each quarter of the experimental pastures. Within the small-scale sampling grids we will measure soil moisture, soil temperature, ANPP, plant species composition, and vegetation structure. Within the large-scale sampling grids we will measure vegetation composition and structure, and relate these measures to the abundance of grasshopper species (grid of sampling hoops), grassland bird species (4 point counts per pasture quarter), and 13-lined ground squirrels (3-ha sampling web per pasture quarter).

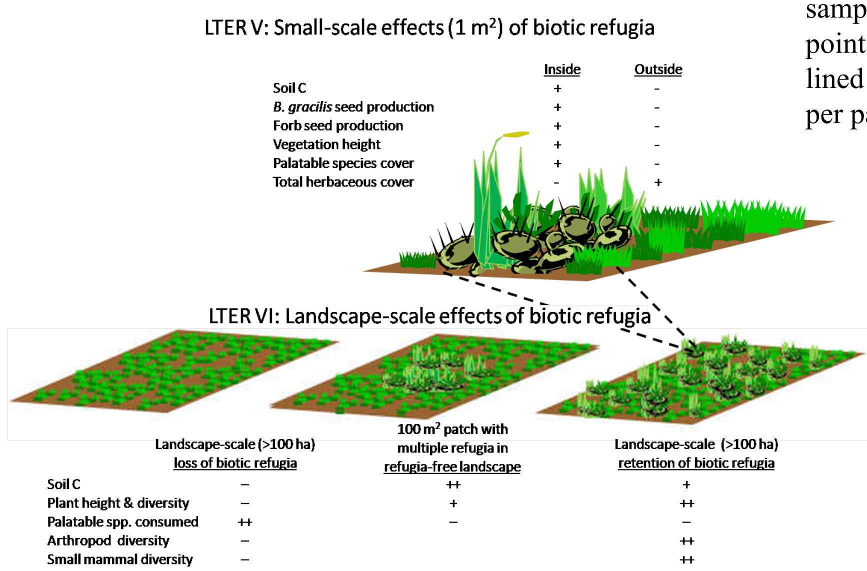


Fig. 21. Small-scale effects of biotic refugia created by *Opuntia polyacantha* in shortgrass steppe (Rebollo et al. 2002, 2005), and hypothesized landscape-scale effects of refugia to be evaluated during LTER VI.

[CO_2] under climate change (Parton et al. 2007) and the importance of metapopulation dynamics for landscape-scale patterns of disturbance imposed by prairie dogs (Antolin et al. 2006, Hartley et al. 2009).

Changes in the SGS structure and function and how humans value SGS ecosystem services can influence management decisions about land-use. We witnessed this in the 20th century and the first decade of the 21st century with the development of croplands and their eventual abandonment and placement into the CRP, boom and bust of corn ethanol, and as the populations and economies of cities along the Front Range grew and diversified, an increase in exurban development. A new ecosystem service of carbon sequestration in soil organic matter has emerged with the discussions of the development of carbon trading markets. Understanding how these factors influence stakeholder decisions will be critical to forecasting land-use patterns and the effects of these patterns on the SGS.

We will build upon these strengths and extend our syntheses of field experiments and modeling to encompass finer temporal resolution and broader spatial scales. First, we will use our proposed field studies manipulating intra-seasonal variation in precipitation to improve and validate models of pulse dynamics in this semiarid ecosystem, and utilize models to further our understanding of feedbacks among factors limiting plant and soil processes, and land and atmosphere exchanges across temporal scales from days to centuries. Second, we will extend our field study/model syntheses to broader spatial scales through the incorporation of landscape variation in physiography and land-use into our metapopulation models (including linkages with temporal variation in climate), and through the use of a spatially explicit version of DayCent (Parton et al. 1993) simulations guided by historic and projected patterns of land-use change in the SGS. Third, we will link an agent-based model (DECUMA) with ecosystem models (e.g., DayCent) to study the linkages between resources/ecosystem services and household land-use.

D.1. How can improved temporal resolution of ecosystem models guide our understanding of seasonal and annual ecosystem dynamics in pulse-driven, semiarid ecosystems?

Rationale: We will develop representations of our models of trophic interactions and processes (Fig 23) to include finer temporal scales (hrs to wks) associated with the impact of pulse driven precipitation events, grazing, fire and land use on ecosystem dynamics and the consequences for dynamics measured over longer time periods (e.g., seasons, years and decades).

(D.1.1) DayCent Model: The DayCent model (Parton et al. 1993, Parton et al. 2001) has been used to study soil formation; plant, soil biota and soil interactions; the impact of climatic and atmospheric CO_2 on soils; and changes in land use practices and land conversion on soil-atmosphere interactions, trace gas dynamics, and carbon sequestration at the SGS site and other grassland and forest sites around the world (Fig. 23a). DayCent simulates soil nutrients (N and P) and C dynamics, trace gas fluxes, plant production and nutrient uptake, and soil water and temperature dynamics. The model uses a plant production submodel (Kelly et al. 2000, Del Grosso et al. 2001), soil temperature and water content submodels (Eitzinger et al. 2000, Parton et al. 1998), and a nutrient and C cycling submodel (Parton et al. 1988). We will use DayCent to evaluate the impact of precipitation pulses (small vs. large rainfall events) on net carbon exchange and trace gas fluxes, assess the effect of the grazing treatments (moderate, heavy and prairie dog sites) on water loss rates, and study the ecosystem impacts of fire and land use.

(D.1.2) Food Web Model: The Food Web model parameterized with data from the SGS and elsewhere (Hunt et al. 1987, de Ruiter et al. 1993, Moore et al. 1996), has been used to study basics properties of ecosystem structure, function and dynamics, as a template for cross-site comparisons, and as a means to develop simpler abstract models for theoretical studies (Fig. 23b). Food Web depicts the trophic interactions among detritus, plant roots and soil biota in terms of C and N fluxes. During SGS-LTER V we elaborated on the importance of detritus to the structure and functioning of systems (Moore et al. 2004), the linkages and feedbacks that occur between the root-based and detritus-based pathways (Moore et al. 2003), and the compartmentalized structure to the stability of systems (de Ruiter et al. 2005b, Rooney et al. 2006, 2008). We studied the concept of a flexible and dynamic architecture to explore these spatial and temporal relationships among pathways. The pathways possess quasi-independent dynamics with the degree of separation being important to the food webs stability and to nutrient dynamics and

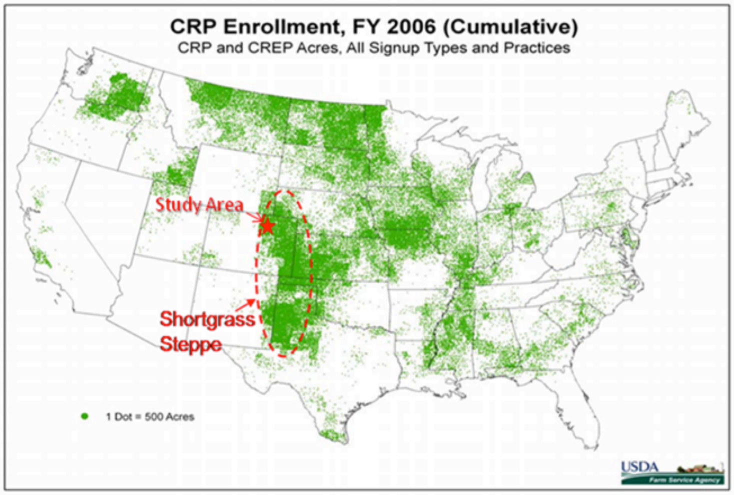


Fig. 22. Map of the CRP distribution within the US. Federal policy prohibits grazing on the lands. We propose to study the impacts of livestock grazing on CRP lands within the SGS to assess its impact on plant community development..

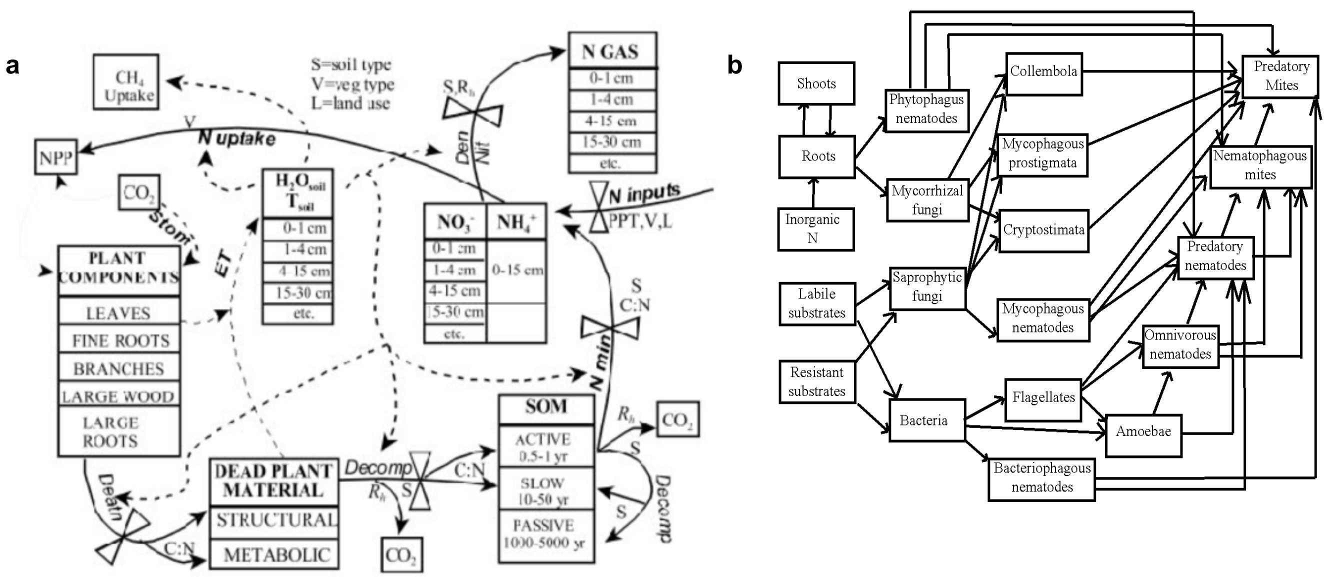


Fig. 23 **a**) Schematic of the DayCent Model (Parton et al. 1993). **b)** Schematic of the Food Web Model (Hunt et al. 1987). Both models estimate C and N fluxes among key components of soil ecosystems. DayCent provides greater resolution on the pools of organic materials, while Food Web provides greater resolution on the trophic interactions among functional groups of microbes, protozoa, invertebrates, and plant roots. The models require data on the pool sizes and the kinetics of the interactions between pools. For the pool sizes we will use our data (collected as outlined above) on plant litter and roots (amount and quality of the fractions), the invertebrates, decomposition and mineralization, and soil C and aggregates, supplemented with soil temperature and water data. The kinetics of the physical, chemical and invertebrate induced transformations will use current formulations (Eitzinger et al. 2000, Parton et al. 1998, de Ruiter et al. 1993). For the functional groups of microbes we will use a variant of the substrate-induced respiration (SIR) technique to measure their physiological capacity to utilize different substrates, reconciled with estimates of total microbial biomass obtained using SIR, and bacterial (direct counts and QPCR) and fungal biomass (direct counts and ergosterol). Under different temperature and moisture regimes we will add organic compounds at different concentrations to a fixed density of microbes and monitor their utilization. Functional responses for microbe-substrate utilization under different regimes will be used to model the kinetics of substrate transformations.

retention. Disturbances common to the SGS alter how the pathways were compartmentalized spatially and temporally (Moore et al. 2005, Moore et al. 2008). These concepts align well with the current SGS-LTER themes of persistence, change, and pulse dynamics. We will use Food Web to study how soil organisms and processes respond to changes in precipitation, and by evaluating the Jacobian matrix, the dynamic properties and potential state transitions of the system.

(D.1.3) Soil Food Webs and Pedogenesis: We will link elements of DayCent (Parton et al. 2001) and the Food Web (Hunt et al. 1987, Moore et al. 1996) to provide greater resolution in the C-substrate pools and microbial pool to simulate the impact of climate change on plant litter, roots and soil C (Fig. 23a). We will expand the litter, root, and carbon substrate submodels of DayCent to better reflect the types of plant communities at the SGS. The litter and root submodels will be partitioned into substrate types (cellulose, lignin, DOC, etc.) to better capture the dynamic with the microbial and invertebrate communities, while the substrate submodel will capture the byproducts of microbial and invertebrate activities (amino sugars, extracellular polysaccharides, fecal pellets, etc.). We will replace the decomposition rate function (Decomp R_k in Fig. 23a) with soil microbe and invertebrate submodels based on Food Web (Hunt et al. 1987) to capture the interactions among plants and soil biota within the rhizosphere. The submodels will allow us to discriminate the impacts of different enzymes and substrate-use efficiencies of bacteria and fungi, and the differences in the byproducts produced by microbes (e.g., cell walls, liquid excretions) and their consumers (e.g., fecal pellets, exoskeletons), on SOM formation and stabilization.

(D.1.4) Land-Atmosphere Interactions and Climate Change: We will characterize how arid and semi-arid ecosystems like the SGS will respond to elevated CO_2, warmer temperatures and precipitation variability, and to incorporate the short-term responses (hours to weeks) from manipulative plot-scale experiments into both ecosystem and coupled biosphere-atmosphere models for more accurate predictions of how these systems will operate in the future. We have over 30 site-years of long-term soil moisture, precipitation and aboveground biomass measurements in a small number of pastures at the SGS sites. We propose using the three-year SGS Bowen ratio, and long term soil moisture/precipitation and plant biomass data sets to test the DayCent model. We also plan on incorporating an energy balance approach from the General Energy and Mass transfer model (Chen and Coughenhour 1994) into DayCent, using the Bowen ratio and soil moisture/precipitation data to tune the model to site-specific conditions. We will then incorporate key plant and soil mechanistic responses (e.g. photosynthesis; water dynamics) from our manipulative global change experiments into DayCent to predict how such fluxes will be modified by rising CO_2 (data from SGS-LTER V), warmer temperature, and altered precipitation.

D2: To what extent do physiography and land-use change affect local and regional populations?

Rationale: Prairie dog towns on the LTER form metapopulations, defined as groups of subpopulations each with independent population dynamics subject to local extinction and subsequent re-colonization. We developed a set of stochastic patch occupancy models (SPOM; Hanski and Gaggiotti 2004) in order to better understand the dynamics of prairie dogs at the landscape level (George 2009). We found that since 1982, following the cessation of wide-scale poisoning, the prairie dog metapopulation in the western PNG has increased in patch occupancy to approximately 60%. Our current efforts link metapopulation dynamics to town size and connectivity. An assumption of traditional metapopulation models is that the habitat matrix that surrounds suitable patches is spatially homogenous in its effects on connectivity, and that the size and number of suitable habitat patches is known (see Magle et al. 2009). We will test these assumptions by incorporating spatial and temporal landscape variability into our metapopulation models.

(D.2.1) Metapopulation models: We seek to better understand mechanistic controls determining metapopulation occupation and the balance between local colonization and extinction. In this approach, colonization of prairie dog towns is determined by prairie dog dispersal and conforms to traditional metapopulation models with colonization as a function of connectivity determined by area and distance of subpopulations areas to surrounding patches. On the other hand, prairie dog town extinction is a function of landscape level plague transmission, as plague is the only contemporary factor known to cause extinction of prairie dog towns larger than 1-2 hectares in area (Stapp et al. 2004, Cully et al. 2006, Pauli et al. 2006). We generated alternative functions describing how plague is transmitted across the landscape. Using model selection (AIC), we found support for the hypothesis that plague spread is unstructured in comparison to prairie dog town connectivity (Fig. 24). A possible explanation for this result is that plague-resistant species, such as coyotes (*Canis latrans*), swift fox (*Vulpes velox*) and grasshopper mouse (*Onychomys lecogaster*), serve as alternative hosts for flea vectors that harbor plague and thus transport plague via the vectors to new prairie dog towns.

(D.2.2) Metapopulations - spatial and temporal aspects of habitat and climatic variation: Using the SPOM framework discussed above, we will adjust the colonization function by incorporating patch connectivity as a function of soils and other factors influencing the surrounding habitat matrix (Collinge et al. 2005, Savage 2007, Magle et al. 2009). We will also adjust the extinction function to incorporate climate effects known to influence plague transmission and persistence (Stapp et al. 2004, Savage 2007) and the movements of alternative vector hosts. We will integrate these efforts with GIS analyses of landscape structure to quantify connectivity among colonies based on (1) improved soils maps (see Physiography section), (2) indices of topographic complexity representing drainage patterns (topographic wetness index; Gomez-Plaza et al. 2001) and local variation in slope (topographic ruggedness index; Sappington et al. 2007), and (3) land-use maps incorporating vegetation structure associated with cropland, CRP, and cattle stocking rates. GIS layers help refine our prairie dog habitat suitability model, by identifying unoccupied patches of suitable habitat and evaluating how their presence may influence metapopulation stability in response to changing precipitation patterns and human land-use regimes.

D.3: What are the extent and consequences of Land Use and Land Cover changes on the SGS and Human Decisions and Future Management?

Rationale: Humans have been (see Fig. 2) and are important agents of change. We will use resilience approaches to bridge ecological and social sciences to understand the interactions between humans and the environment (Berkes et al. 2003). Resilience in ecosystems and in social systems is linked through the dependence of people and their economic activities on ecosystems (Reynolds et al. 2007, Galvin et al. 2006). Resilience refers to the buffer capacity or the ability of a social-ecological system to absorb perturbations or the magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables and processes that control behavior (Adger 2003, Nelson et al. 2007). Thus, we are interested here in how current and projected human land uses affect ecosystem structure and function (D2.1and D2.2), but also in the feedbacks to human economic state and decision-making (section D2.3; LTER Network Decadal Science Plan, http://www.lternet.edu/decadalplan/).

(D.3.1) Land Use and Land Conversion Analyses: We are quantifying historical changes in agricultural land use for Colorado and the Great Plains and using DayCent to evaluate the impact of these land use changes on regional ecosystem dynamics (Baron et al. 2004, Parton et al. 2005, DelGrosso et al. 2005). The studies show that the dramatic expansion of irrigated agriculture and animal feedlots from 1960 to 1980 has increased gross agricultural income, soil carbon storage, and soil N_2O emissions (>50%) due to increases in N fertilizer application. We used DayCent to evaluate the ecosystem impact of grazing on grasslands and converting agricultural land to lawns and golf courses (Conant et al. 2005, Bandaranayake et al. 2003, Qian et al. 2003). Our analyses of historic photographs from sites within the SGS show how land use patterns have changed since the 1930's. The photographic land use data will be combined with spatial data on the climate and soils within the SGS research site. Soil texture, climate and the access to irrigation water are the main factors that seem to control the patterns in land use. The three major traditional land uses in the region include dryland agriculture, irrigated cropping and grazing of native pastures (Fig. 25). In the past 20 years, acreage has been placed into the CRP. With the economic expansions that occurred during 1980-present, the population in Colorado has more than doubled with increasing exurban expansion into the SGS in the form of 35-acre ranchettes. The net result has been a land use pattern that is more diverse and fragmented.

We will document changes in land-use since European settlement and use DayCent to simulate the impact of these historical changes on net greenhouse gas fluxes for the SGS and the county level for all of the US Great Plains counties (Hartman et al. *submitted*). We will integrate spatial data bases, historic agricultural

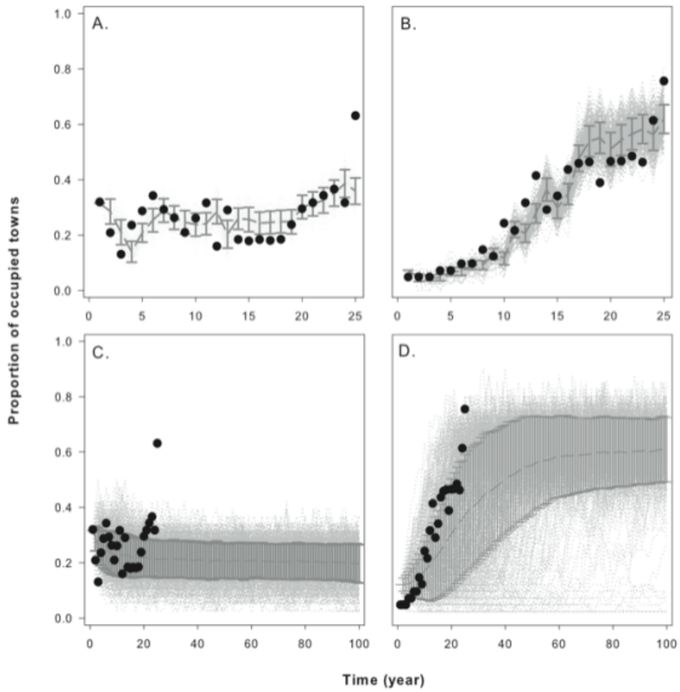


Fig. 24. The proportion of occupied towns through time for each metapopulation (eastern and western) in northern Colorado. Light gray dotted lines represent output from simulation runs. Dark gray lines represent the mean of simulation runs with 95% confidence intervals. Black dots represent the empirical data. **A)** western metapopulation, step-by-step simulation. **B)** eastern metapopulation, step-by-step simulation. **C)** western metapopulation, full simulation. **D)** eastern metapopulation, full simulation.

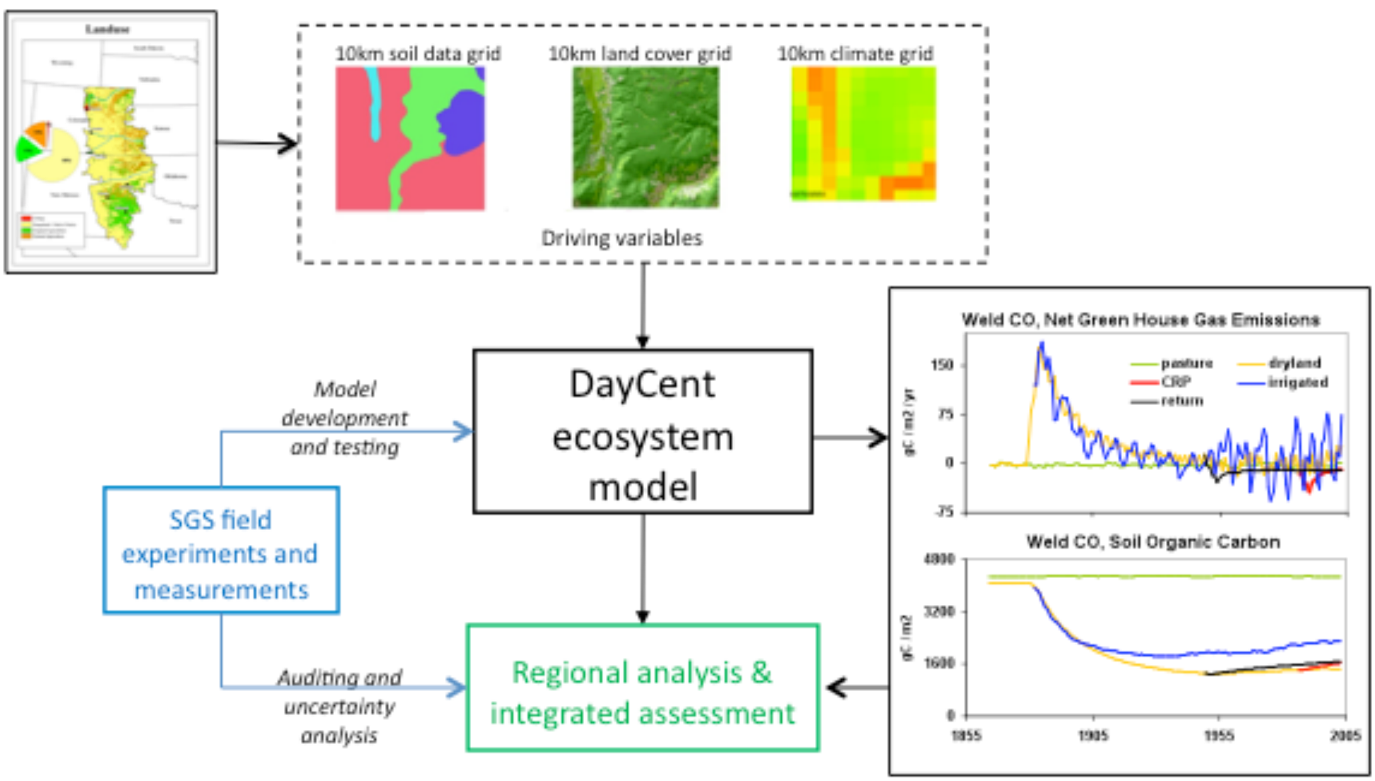


Fig. 25. Schematic of the way the observed SGS experiments and field data and DayCent are used in our regional analysis of land-use on ecosystem processes and characteristics. Regional data sets describing land use, climate, and soil texture are then used as inputs to the DayCent model which then simulates historical changes in ecosystem variables (soil carbon, N2O fluxes, plant production and nitrogen mineralization) . The results for Weld Co show large losses of soil carbon resulting from plowing out of native grasslands in the 1900-1020 time period which results in a large net greenhouse gas emission during that time period(Hartman et al , submitted). Land removed from plant production after 1950 stimulates soil carbon sequestration and a net negative greenhouse gas budget.

census data, and case study survey data from farmers and ranchers in order to determine how land use changes during the last 100 years have impacted the social-ecological systems near the SGS-LTER site. This approach will enable us to link the spatial, historic and case-study information discussed below with the data collected from our monitoring and major experiments included in the proposal. We will extrapolate the impact of future changes in the climate and CO_2 levels, with land use and conversion on SGS ecosystem dynamics. Apart from modifying DayCent, the major activities include: 1) linking US Agricultural Census data for Weld County (Parton et al. 2007; Fig. 25) with the analysis of historic photographs from the site which start in the 1930's, and 2) combining the observed land use change data with case study local farmer survey data (Bohren 1995). We will combine photographic land use change analysis and US Agricultural Census data for the last 100 years with farmer survey data to assess the combined social-economic-ecological factors which control historic patterns in land use change.

(D.3.2) Carbon Sequestration, Land Use and Land Conversion: The sequestration of carbon in soils is an important ecosystem service, and with proposed cap-and-trade legislation, may offer a new economic market to households and land managers at the SGS. Policies encouraging greenhouse gas emitters to mitigate emissions through terrestrial carbon offsets in the forms of carbon sequestration in soils or biomass are not possible unless changes in carbon stocks can be documented accurately. This is particularly challenging for changes in soil carbon stocks. Quantifying changes in soil organic carbon stocks rely upon a set of measurements that are extrapolated in various ways to represent a larger geographic area. The main challenge in documenting plot-level changes in soil carbon stocks is not with measuring soil carbon, but rather in designing an efficient, cost-effective sampling and soil carbon stock estimation system. Currently data on grassland management impacts on soil carbon stocks is sparse, limiting our ability to accurately estimate carbon sequestration given changes in land use/management. Collecting new data at the SGS-LTER as proposed in the climate and physiography sections, that employ robust sampling methods that maximize the ability to detect changes in soil carbon stocks over time will make a contribution to filling this data gap (Fig 25).

(D.3.3) Human Decision-making in the face of Global Change: Populations in agent-based models of social systems are represented as an aggregate of the responses of many individuals, emphasizing a bottom-up emergence of social organization and variability across individuals, rather than a mean population level responses or top-down forced organizations (Axelrod 1997, Bonabeau 2002). We will use empirical data on households and their decision-making collected from our proposed land-use and land conversion study (D3.1), and information on the carbon sequestration potential of the SGS (D3.2) to make realistic agents (Janssen and Ostrom 2006). We will use a spatially explicit household agent-based model, DECUMA (Fig. 26), (Decisions under Conditions of Uncertainty by Modeled Agents) linked to an ecosystem model, e.g., DayCent (Fig. 27), to understand how households may respond to change with the goal of understanding their resilience in the face of change (Boone et al. 2007, Thornton et al. 2007). We will address how and to what extent do ecosystem services (provisioning and supporting) influence households, how household wealth affects ecosystem services, whether household resilience/vulnerability imply ecological resilience/sustainability, and how closely coupled are the ecological and social systems.

Significance and Broader Impact

The proposed research addresses important questions in ecology and the ecology of grasslands from a social-ecological perspective. We focus on ***climate***, ***physiography,*** and ***grazing, fire*** and ***land use*** as key determinants of SGS structure and function, and the development of the tools and data to ***forecast*** how the SGS may change under projected global changes. We propose an integrative approach that includes traditional and innovative methods for monitoring, manipulative experiments and modeling to investigate the mechanisms underlying current structure and function at multiple spatial and temporal scales. Our interdisciplinary approach includes team members from the physical sciences, biological sciences, social sciences, and education. This melding of the traditional ecology, the social sciences, and education has the potential to be transformational as a model as envisioned in the ISSE 2007 and LTER Decadal Plan.

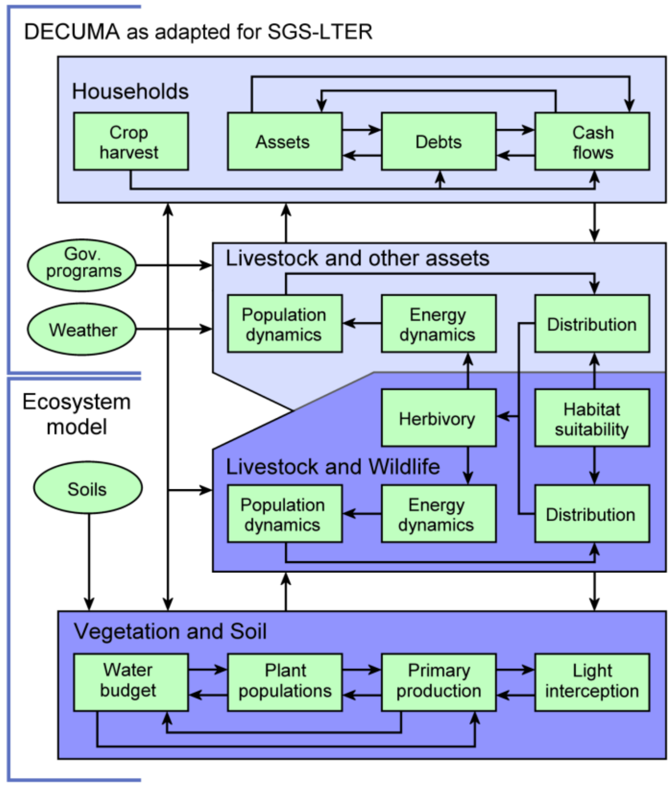


Figure 26. Information flows within the DECUMA model as adapted for SGS-LTER, and its linkage to a spatially explicit ecosystem model. The ecosystem model (bottom) simulates plant production using process-based methods, driven primarily by weather. Herbivory is simulated, as well as population dynamics for wildlife species. For livestock, the suitability of landscape patches for each species is used by households (agents) represented in DECUMA (top) to distribute their animals. These distributions are used by the ecosystem model to simulate herbivory, and DECUMA is informed of energy acquired. DECUMA then simulates livestock population dynamics, sales and purchases, crop harvesting, and asset (e.g., land, livestock) and debt (e.g., monetary, mortgage) management within households. Cash flows are then simulated for each household, and other decision making is simulated. For example, government programs, such as Conservation Reserve Program or carbon cap-and-trade efforts, may affect household decision making. The simulation repeats, with ecosystem linkages updated each week, and the states of households updated monthly.

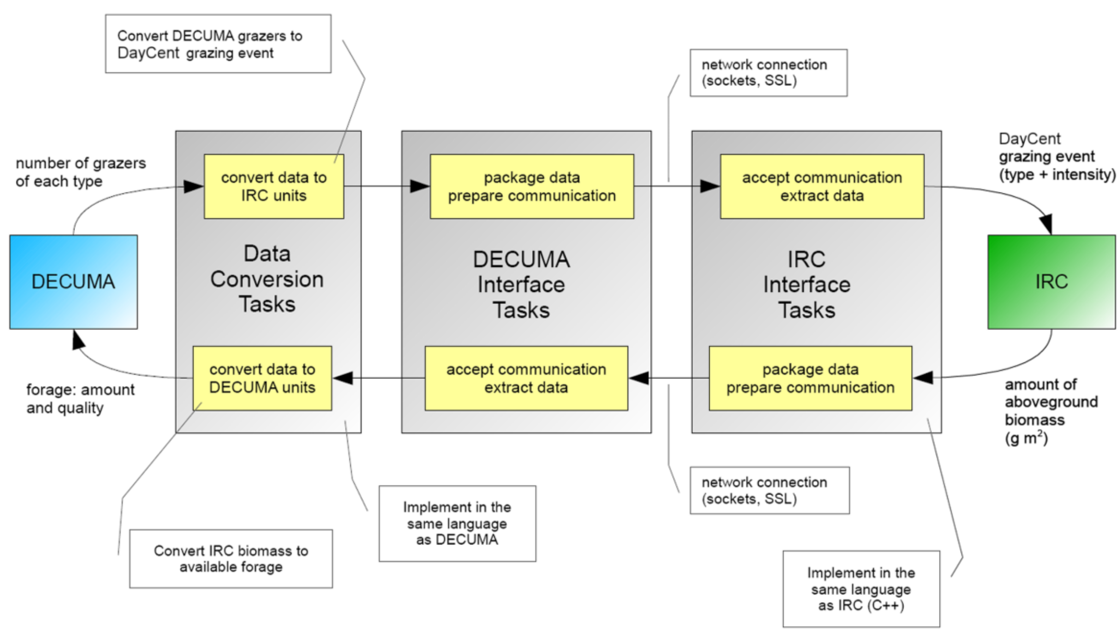


Figure 27. The linkages between DECUMA and instances of DayCent. DayCent is essentially aspatial; regions are represented using multiple simulation instances. IRC ("Integrated Research Challenges") manages those instances. Two interfaces will be used between the packages. One will summarize and convert data from forms suitable to DECUMA (e.g., household livestock holdings) to forms suitable for IRC and DayCent (e.g., stocking density in discrete grazing events), and vice versa. The second will be an interface that manages communication among the tools using MPI (Message Passing Interface). This modular structure and the use of data packet processing will allow simulations to be parallelized more easily than if there were hardwired linkages between the tools.

Section 3. Project Management

The management structure of the SGS-LTER (Fig 3.1) was developed in response to reviewer comments from mid-term review in 2005 and to improve project integration in response to panel comments from the probation decision in 2008. One of the original goals of the architects of the LTER Program was that long-term, site-based research programs with a relatively stable funding base would be managed to maintain continuity of long-term research in the face of the inevitable turnover of individual investigators and/or completion of scientific careers (Callahan 1984). The central premise of support for LTER sites is that many ecological processes occur or become apparent over decadal time scales. The SGS-LTER remains committed to these principles and has designed a management plan to ensure both continuity and renewed vision. We remain committed to a model of "developing new leadership" as younger scientists rise in rank, prove their commitment to the long-term goals of the program, and are willing to assume greater share of the scientific leadership and project management responsibilities. Additionally, the CSU central administration has committed to the hiring of a mid-career ecologist with expertise in global change ecology to work within the SGS-LTER community (see letter from Provost Rick Miranda).

SGS-LTER Leadership and Executive Committee: Our priorities for managing the SGS-LTER project are to ensure that we support a broad range of scientists and stimulate new ideas and participation within the context of stability and continuity of an integrated research program. During SGS-LTER V (2002-2008) Dr. Eugene Kelly (EFK) was lead PI and Dr. Mike Antolin (MFA) was the lead PI on the last submission (2008-2010). The current submission has Dr. John C Moore (JCM) as the lead PI.

Because we have a large group of participating senior scientists and collaborators, an executive committee (EC) is tasked with managing the scientific goals and progress of the project. The composition of the EC has changed since the last funding cycle. Although still engaged in the project scientifically Drs. William Lauenroth (WKL) and Ingrid C. Burke (ICB) accepted positions at the University of Wyoming and relinquished their roles on the executive committee. Scientists with the ARS Central Plains Experimental Range have a central role in the SGS LTER, and the EC previously included Dr. Jack Morgan (JAM) of the USDA-ARS, who has been replaced by Dr, Justin Derner. We intend that the mid-career scientist hired as Global Change Ecologist will participate in our mid term review (summer of 2011) and assume leadership for the project after the next submission.

The EC for the SGS-LTER VI includes the signatory PI's, who each have responsibility to coordinate research areas and the lead of IM (Fig. 3.1). Membership within research areas (Fig 3.1) overlaps broadly with many of investigators working under two or more research areas. By including leaders from each research area in our executive committee, we maintain a management structure that mirrors our reporting to NSF, ensures balance across our sub-disciplines, and facilitates information dissemination among all researchers. The EC meets monthly throughout the year.

SGS-LTER Scientists: Comments from our mid-term site review team led us to add depth in areas that are crucial to understanding the structure and function of the SGS ecosystem. During SGS-LTER V, we recruited six scientists to strengthen the project in needed areas: Drs. David Augustine (fire ecology), Dana Blumenthal (invasive species), Cynthia Brown (invasive species), Justin Derner (range ecology), Alan Knapp (plant ecology and ecopyhsiology), and Joseph Von Fisher (microbial ecosystem ecology). For SGS-LTER VI, we recruited twelve new scientists to participate on the project: Amy Angert (evolutionary ecology), Randall Boone (human ecology – grazing systems), Richard Conant (biogeochemistry), Noah Fierer (microbial ecology), Kathy Galvin (anthropology), Niall Hanan (land-atmospshere), Catherine Keske (natural resource economics), Julia Klein (range ecology), Patrick Martin (landscape ecology), Heidi Steltzer (plant ecology), Matthew Wallenstein (microbial ecology) and Colleen Webb (modeling and synthesis).

Resources allocated to each of these scientists are variable, but often include partial summer salary, logistical support for field work, travel to meetings to present results, participation in LTER Science Council meetings and workshops, and stipend/tuition support for graduate students, especially for summer field work. We continue to focus on increasing gender diversity in the SGS-LTER project through promotion and mentoring of researchers into greater leadership roles. Further, inclusion of Drs. Paul Stapp (Cal. State Univ-Fulleton) and Heidi Steltzer (Fort Lewis Coll., Colorado) ensures increase of diversity in our education and outreach, as both come from institutions primarily serving diverse students (Hispanic and Native American, respectively) that participate as REU and field crew during summer.

SGS-LTER Program Management: In practice lead PI JCM will serve as the responsible PI representing CSU to NSF and as Science Council Representative to the network and annual SC meetings (along with one other scientist on a rotating basis). For day-to-day financial and other project decisions, JCM will share responsibility and coordinate activities with the other EC members who guide research and IM with each area (Fig. 3.1). Interactions are fostered and scientific/programmatic information is disseminated as follows:

1) All investigators (at CSU, UNC, California State U Fullerton, U Colorado-Boulder and at USDA-ARS) are on e-mail listservs for distribution of information and requests for input. For example, LTER network office e-mail communications sent to "PI-list" are assessed by JCM, MFA and EFK for potential distribution to groups or the entire staff when appropriate. Further, the SGS-LTER web page now includes a "News and Events" ticker featuring both local and LTER network news.

2) The entire group of SGS-LTER participants (lead scientists, staff and graduate students) meets once a month for "science meetings" to disseminate ongoing results, plan and coordinate fieldwork, discuss project business, and to provide general announcements. Meetings currently are held on the second Wednesday of each month in a room equipped for video conferencing so that SGS-LTER scientists who are on travel or whose homes are not on the CSU campus have access. Some meetings feature research presented is by visiting scholars, graduate and undergraduate students, researchers from ARS and USGS, and SGS-LTER investigators. Meetings also serve to engage new researchers to meet SGS-LTER investigators and discuss new collaborations. Minutes are made available on the SGS-LTER web site.

3) We also hold once-a-month "nuts and bolts" meetings, currently scheduled for the fourth Wednesday of each month, where logistic issues related to the project are discussed. For instance, a regular meeting each year in April is mandatory for anyone using SGS-LTER vehicles and covers safety and "Rules of the Road" for navigating the SGS-LTER field sites.

4) We have initiated an annual local 'all scientists meeting', to be held for a day at our new field station in early January, to foster interactions among scientists within the project, to summarize our accomplishments from the summer field season, to prepare for the following year, and to plan proposals to develop new funding opportunities. Besides SGS-LTER scientists, staff, and students, we encourage attendance by our cooperators from the Pawnee National Grasslands, NEON, and scientists with interests initiating research at the SGS-LTER.

SGS-LTER employs a staff of 9-10 (Fig 3.1), supervised by the lead PI. Staff coordinate their efforts during weekly meetings, and during the once-monthly "nuts and bolts meetings". In addition, staff increase the visibility of the SGS-LTER program at our biennial public symposium (see Education and Outreach), and provide information to the public at events like Ag Day at CSU (football game) in the fall, and the Western Stock Show in Denver each January.

SGS-LTER Facilities Management: We made major facilities improvements in the past 5 years, with the construction of the comprehensive Shortgrass Steppe Research and Interpretation Center located adjacent to the long-time SGS-LTER field station. Currently the SGS-RIC has classroom/meeting space (including a computer room), and housing for up to 30 overnight visitors. It is our expectation that the new facilities will make the SGS-LTER site more attractive both to researchers from Colorado State and to new researchers from outside the current community, as well as, expand the educational and outreach opportunities. A new business model has been developed as the station is built out to capacity, in anticipation of broader use by outside researchers and classes from K-12 and Colorado State University. The SGS-RIC has become a CSU facility with its own director and staff, with a separate income stream from classroom, housing and laboratory fees, including those from the SGS-LTER (and possibly NEON) as principal clients.

Fig 3.1 . Organizational Structure of the SGS-LTER Project

Executive Committee
*Science Council Representative

John Moore (Lead PI) *, Mike Antolin , Eugene Kelly, Nicole Kaplan,
Justin Derner (USDA-ARS), Sallie Sprague (ex-offico)

SGS-LTER Staff

Suellen Melzer (Soils), Mark Lindquist (Site Manager), Judy Hendryx (Plants), Robert Flynn (IM), Sallie Sprague (Project Manager), Kim Melville-Smith (Education Coordinator), TBA (Field, Monitoring, and Data Manager)

SGS-LTER Research
**Leader

Climate

Amy Angert, David Augustine, Dana Blumenthal, Ingrid Burke, Cynthia Brown, Rich Conant, Niall Hanan, Gene Kelly, Julia Klein, Alan Knapp, Bill Lauenroth, Patrick Martin, John Moore, Jack Morgan
Bill Parton, Paul Stapp, Joe von Fischer**,

Physiography

Ingrid Burke, Rich Conant, , Julia Klein, Gene Kelly**, Alan Knapp, Bill Lauenroth, Patrick Martin, Joe von Fischer

Grazing, Fire, Land-use

David Augustine, Dana Blumenthal, Justin Derner**, Jim Detling (emeritus), Julia Klein, Bill Lauenroth
Dan Milchunas, Jack Morgan, Paul Stapp, Heidi Steltzer

Soil Molecular Ecology

Noah Fierer, John Moore**
Joe von Fischer, Matt Wallenstein

Social Science

Kathy Galvin**, Catherine Keske,

Synthesis/Modeling

Mike Antolin**, Bill Lauenroth, Jack Morgan, John Moore, Bill Parton, Colleen Webb

Cross Site Studies

Mike Antolin, Gene Kelly**, Alan Knapp, Bill Lauenroth, Patrick Martin, Jack Morgan, Heidi Steltzer, Paul Stapp

SGS LTER
Education, Outreach and Information Management

Education and Outreach

Gene Kelly, John Moore**,
Kim Melville-Smith
Mark Lindquist, Sallie Sprague

Information Management

Nicole Kaplan**
Bob Flynn

Section 4. Information Management System

Philosophy and Goals

The SGS Information Management System (IMS) is designed with the philosophy that a functional IMS must be accessible to the community, well organized and structured, yet nimble enough to support ecological research approaches that change with advances in technology (Stafford et al. 1986a,b). The flexibility and forward thinking we have applied to the design of the SGS IMS was described in the review from our 2008 proposal as “robust and continues to evolve to better support site and network science”. The SGS-LTER IMS was co-designed by SGS-LTER scientists and staff under the leadership by Co-PI Nicole Kaplan, Information Manager and Bob Flynn, Information Technology (IT) and Geographic Information System (GIS) Manager to meet the following goals:

- Manage and provide access to high quality data and metadata to support local, network, and community research, education and management efforts now and in the future.
- Employ IT tools, guidelines, and policies that facilitate management, discovery, and integration of information to support collaboration, research, and education.
- Participate and support the LTER Network Information System and share innovative approaches to IM.

Design and Implementation of the SGS Information Management System

Scope: The SGS IMS consists of over 200 tabular datasets, including LTER core, supplementary, and historical data (Tables S2.1-S2.3). The online component of our SGS IMS currently contains 133 non-spatial LTER datasets and dozens of spatial datasets (Table S2.4). Fifteen percent of our archive is legacy datasets, produced by work at the CPER and grassland researchers funded by IBP (Stafford et al. 2002). Our data stored offline include supplementary datasets, larger GIS data files, photographic and remotely sensed images, components of models, a few datasets that contain information regarding species of concern, and a database for our reference collection. All offline data are stored on the centralized SGS IMS, are inventoried in a data catalog, and are available upon request. Flynn has worked with our partners at the CPER to document historical grazing treatments and other physical attributes of the CPER and PNG within the GIS. Our document archive grows steadily and contains publications, including citations for journal articles, book chapters, and abstracts, as well as downloadable reports, proposals, and IBP technical reports. Citations can be queryied on date, author(s), keyword(s) and/or publication type (http://sgslter.colostate.edu/research_search.aspx). The amount of storage necessary for data increases dramatically each year and presents a challenge to staff and the existing IT infrastructure.

Design: Over LTER V-VI, we have moved into a more centralized and collaborative mode of operation from a cumbersome Network File System model spread over various Unix servers. The current SGS IMS includes a windows-based server, named Ascalon, with RAID technology (Redundant Array of Inexpensive Disks) that centralizes management of data, metadata and other information, while public accessible information is available from a web server maintained by CSU (Fig. 4.1). This set-up allows flexibility to migrate the system to other locations within CSU under any project leadership and administrative structure. Incremental back-ups are performed twice daily and full back-ups weekly. Everyone associated with the project is instructed to store data and other files on Ascalon so as to take advantage of the off-site backup system and facilitate real-time capture of SGS-LTER products. Anyone working off campus can still access the SGS IMS via the CSU Virtual Private Network. Personnel data and other sensitive data are protected against misappropriation and misuse by controlling permissions. We implemented video teleconferencing to support collaboration with people off campus and a blog to share ideas regarding our rainfall pulse experiments.

Web Site: The new SGS-LTER website (http://sgslter.colostate.edu), launched January 2009, is supported by an information architecture in a Relational Database Management System (RDBMS), MS Access, which contains multiple relationships between information that is served with Active Server Page technology, creating a more responsive system. Metadata and data are queriable and downloadable in a csv format for all of our core datasets, and some supplementary short-term and non-LTER datasets (Tables S2.1 and S2.2). The design and behavior of the SGS-LTER website is the result of a co-design effort between LTER staff, researchers, and web development professionals at CSU. The SGS-LTER website conforms to guidelines from the LTER Website Design Working Group (Kaplan 2005) and the LTER core data access template. Researchers contribute content regularly to new sections of the website, which were designed to share current events, accomplishments, and news items. The new maps section of the website contains various maps as PDFs for downloading and a new interactive mapping tool, ArcGIS, which runs on a Java compliant browser that allows users to view and print maps that they customize by making different layers visible (http://sgslter.colostate.edu/maps.aspx).

Other LTER sites have taken great interest in our navigation and information discovery functions; where searching and browsing produce "no dead ends". These new features create a more complete picture of the SGS-LTER research project from several facets. We also have implemented tools to collect and analyze information about end-users. A local registration form submitted prior to downloading datasets requires the purpose of the download (Table S2.5), while Google Analytics reports a broader overview of visitors to the website. Over the past 12 months we've had over 7,000 visitors to the new website. Most of our visitors are from Colorado, but we have visitors from every state in the United States, as well as from 103 other countries or territories. We also can see that people are visiting from different networks, including CSU and other Universities, as well as other institutions such as the US Forest Service, National Park Service, US Department of Agriculture and National Science Foundation.

Documentation: The architecture, procedures, and protocols for usage and back-up of the SGS IMS are documented in guidelines distributed to our users (http://sgslter.colostate.edu/visitors.aspx). We regularly review our roles and responsibilities to efficiently and effectively plan and delegate how critical tasks and projects will be accomplished. A current list of research projects on the CPER is maintained within the IMS for the ARS (http://sgslter.colostate.edu/ars/MapsandExperiments.htm), as well as a field crew calendar and crew manual that contains detailed methodologies and information on all current SGS-LTER core studies (http://sgslter.colostate.edu/fieldcrew.aspx).

Review of IM Team Roles: Kaplan and Flynn are responsible for the submission, management, and curation of data and metadata related to SGS-LTER research, and design and maintenance of a centralized work space for the SGS-LTER community and the SGS-LTER website. They work closely with SGS and other LTER site researchers and graduate students on data integration and synthesis, spatial analysis, as well as implementing technology to facilitate successful collaborations. In 2009, Kaplan joined the SGS-LTER Executive Committee and the current proposal team as a Co-PI. Kaplan has an MS in Rangeland Ecosystem Science from CSU. She conducted and supervised field sampling in the shortgrass steppe from 1996-2006 and has taken advanced coursework in database management and human-computer interactions. Kaplan works closely with Flynn, who has extensive experience in GIS and IT management, as well as programming in wide-ranging disiplines. The SGS-LTER Executive Committe meet to establish IM priorities and evaluate progress with a focus on quality and quantity of information and data served online. We are making progress toward integrating our non-spatial and spatial datasets, as recommended by past reviewers, as well as other related data types, such as images and documents.

SGS Information Management System Supports Site, Network, and Community Science

Site Science: All stages of project development are integrated into the SGS IMS including data collection, verification, entry, QA/QC, archiving, and publication (Brunt 2000) (Fig. 4.2). The guidelines for students and researchers for use of the SGS IMS exemplify an organizational structure of files that facilitates migration of data, metadata and related publications and other final products to the web server allowing researchers effective use of the system (Fig. 4.1).

Policies: All metadata, and most data are accessible on-line in accordance with the LTER Data Access and Use Policies (http://sgslter.colostate.edu/data_policy.aspx), as most data are entered following each field season. Researchers and students are made aware of policies that address public access to and use of

SGS-LTER data and metadata. The few data and metadata that have restricted access contain information regarding the location of species of concern or infectious diseases.

Metadata: Metadata are compliant to the standard adopted by the LTER Network, Ecological Metadata Language (EML) level 5, and LTER Best Practices are followed to ensure long-term usability of data (> 20 years) for our core datasets. We generate EML level 5 for machine-readable applications and harvest it to the LTER Metacat quarterly, and download metadata and data directly to users from the same RDBMS on the web server. We are in the process of documenting the additional content required for EML level 5 metadata for all 133 datasets within the RDBMS serving the online data access system. As of January 2010, we are more than half way through the process. Information required to meet higher-level EML for our legacy datasets is not always available. In the future, we would like to work with scientists who were associated with the IBP project to supplement the metadata from those historical datasets. In addition, we would like to explore methods to document metadata for models developed and utilized by SGS-LTER researchers.

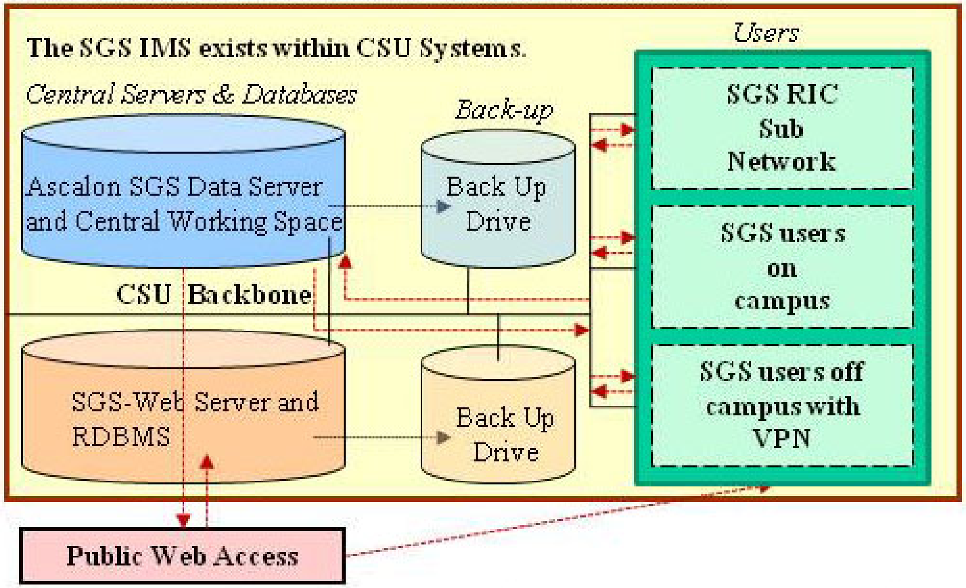
Data: We use a suite of QAQC programs called the Matrix on meteorological data for submission to CLIMdb (http://www.fsl.orst.edu/climdb/) and data tables produced by floral dynamics research that includes over 60 percent of our studies. We continue to work with researchers to develop tools to more efficiently process, quality check, integrate and publish their data with high integrity. This will be especially important as the flow of data increases with the proposed installation of additional sensors in the field and as data types and structures change with novel research directions in this proposal. Data downloads and requests are tracked in accordance with the LTER Data Access Policy using web forms to log intentions for data use and notify researchers (Table S2.5).

Contributions to LTER Network and Community Activities: Current SGS-LTER data have been uploaded to LTER databases as part of the Network Information System (Table 4.1). SGS-LTER participates in cross-site and other community driven IM activities. Such activities include attending annual meetings, and co-leading LTER IM community efforts such as the Website Design, IM Governance, and IM History Database Working Groups. Kaplan has served as a member of the IM Executive Committee from 2003 to 2006 and the Co-chair of the IM Committee from 2006 to 2009. Kaplan has co-authored an LTER white paper, and nine articles in the LTER Network and Data Bits Newsletters. Flynn is participating in two cross-site GIS projects, 'Comparative Analysis of Land Fragmentation', and 'Maps and Locals'.

Summary

SGS-LTER has a rich legacy of long-term research, and our datasets and metadata serve as a resource for the broader community, as well as future generations. The flow of data and metadata from the field to the IMS involves frequent communication between researchers, students, educators, and project managers to maintain the high integrity of our data and information. The essential components of our system support science and education, and include well-documented policies and guidelines, a centralized working space for co-developing data and other products, collaborative tools supporting coordination of research and project management efforts, and a well-integrated website allowing access to related data and other information from various facets of the system. We will continue to support integration of large cross-site datasets needed to support synthetic research that addresses broader scale ecological questions and contributes to the LTER IM community. We foresee that the SGS IMS and staff will be challenged by managing increasing quantities of data, samples, specimens and imagery, and propose to take on documenting and archiving complicated components of models as this represents a significant piece of the SGS-LTER accomplishments and current work. In addition, more sensors and new methods in microbial ecology and remote sensing will be used in the field, increasing the flow and complexity of our datasets. With this, we aim to be proactive and innovative in supporting research and collaboration between and among our scientists, educators, and managers.

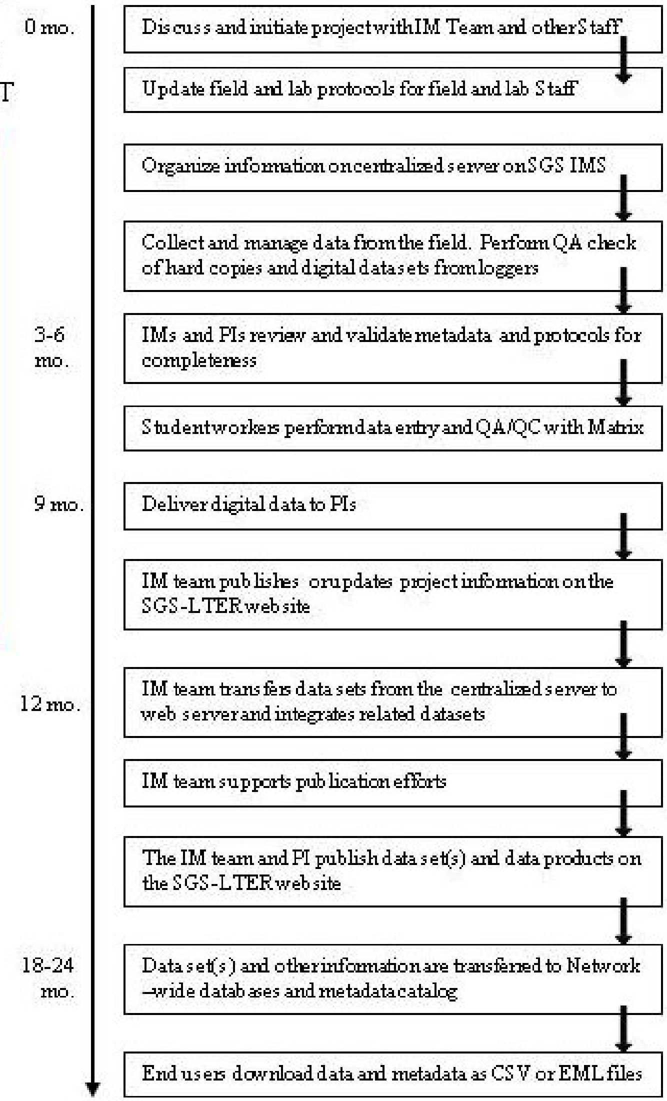
Figure 4.1. The SGS IMS is accessible to the SGS-LTER community on or off campus, and at the SGS Research and Interpretation Center as we operate on the CSU computing network and centralize our working and publishing spaces. We have guidelines that facilitate the flow of working drafts and data to final folders, areas for back-up, and publication to the SGS-LTER web site. Solid black lines represent the IT networks and dashed red lines the flow of data and information.



NIS Database	Latest Upload	Data Sets and Information
ClimDB	December 2009	1969-2009
PersonnelDB	September 2009	> 1000 participants
SiteDB	September 2009	Research and site history
All Site Biblio	February 2010	> 1100 citations
Metacat	February 2010	> 65 EML Data Packages

Table 4.1 SGS participation in LTER Network Information System.

Figure 4.2 Time line of collecting, verifying, archiving, and publishing data



Section 5: Education and Outreach

Education Plan

We will build upon goals established in our previous grant cycle, paying particular attention to fostering cross-site collaborations. From 2002-present, the SGS-LTER has secured over $18.9M to support education and outreach and cross-site collaborations (Table 5.1). Our program targets K-12 students, teachers, undergraduate and graduate students, with all aspects subject to external evaluation (see letter, Metrica, Inc.). The SGS-LTER is committed to promoting environmental literacy through basic research in student learning, direct engagement with K-12 teachers and students, and curriculum reform.

Goal 1: Provide interdisciplinary instruction, research experiences and professional development opportunities.

Goal 2: Promote interactions between higher education and K-12 through instruction, research experiences and professional development

Goal 3: Increase the participation of groups under-represented in STEM disciplines by working with under-served schools, providing research experiences for minority high school students, and by actively recruiting minority undergraduate and graduate students.

Goal 4: Conduct research on student learning and K-12 professional development models.

Graduate and Undergraduate Education: SGS-LTER scientists supported 57 graduate students from 2002-present with project funds with 16 in 2010 AY from other sources (Table 5.2). We will support and secure additional graduate assistantships through research grants, training grants (NSF IGERT: www.primes.colostate.edu), USDA NNF: http://www.nrel.colostate.edu/scholarships/227-education-eses-scholarship.html), and outreach grants (NSF GK-12, CDE MSP). SGS-LTER scientists supported 93 undergraduates from 2002-present on research experiences through REU fellowships, direct funding from the LTER and related grants, and university-wide initiatives designed to increase undergraduate involvement in STEM. The SGS-LTER leadership works with the CSU Key Academic Community (a freshman and sophomore cluster program), the CSU Summer Ecology Research Program and the CSU NSF-funded Undergraduates in Mathematics and Biology program (www.fescue.colostate.edu) to recruit students. We will continue to provide research experiences, professional development training, and work with the CSU student affairs programs to recruit and retain students from under-represented groups.

K-12 Outreach and Training: We will continue to provide high quality research experiences, workshops and courses for university credit leading to recertification, endorsements, and/or graduate degrees, and increase the participation of K-12 students from groups under-represented in STEM disciplines. Our K-12 efforts build on existing partnerships with CSU, the University of Northern Colorado, the University of Wyoming, and regional school districts (Table 5.3; 56 teachers from 24 schools in CO and WY; see letters of support). Our efforts will be funded using the Schoolyard LTER supplemental funds, as well as Federal, State and private foundation funds. Key elements of the SGS-LTER K-12 education plan include the following:

Professional Development (PD) Workshops: SGS-LTER scientists and graduate students will continue their leadership in the research, development and delivery of PD workshops for teachers designed to increase content knowledge, prepare teachers for field experiences, and transfer knowledge and experiences to the classroom. Current and past efforts include a partnership with BES, KBS, SBC, the development of the Summer Soil Institute (soilinstitute.nrel.colostate.edu) with a grant form the USDA, and the LNO through the NSF MSP grant, AND, CAP, JRN, LUQ through an NSF TPC grant, and a collaborative with KBS and MCR for IPY with funds from the Smithsonian Institute. Participants are provided funds to pay for two graduate credits through continuing education. Teachers may also enroll in a graduate degree program at CSU, including on-line courses, web-based activities and field experiences.

K-12 Professional Development (TiR, RET, Graduate Programs at CSU): The SGS-LTER provides research opportunities, graduate credit, fellowships, and funds for school resources for K-12 teachers. For example, we provide a $2,500 summer research stipend for teachers that have completed or are enrolled in the PD Workshops. Funding to support this effort will continue to come from the SLTER supplements, direct costs on other grants, and NSF Research Experience for Teachers (RET) supplements. In 2008, we established a Teacher in Residence (TiR) program with funding from our NSF MSP program wherein teachers are provided up to $50,000 to support sabbaticals at SGS, BES, SBC, and KBS. We currently support 3 TiR fellows. Apart from opportunities at the SGS-LTER site, we will continue to promote cross-site opportunities for our teachers as we have from 2006-present with the ARC LTER and the NSF ECOS project in Costa Rica (Table 5.1). Expectations include participation on a project, data collection, analysis, report writing, presentation and transference of these experiences to the K-12 classroom.

Graduate-K-12 Partnership: To promote greater interaction between higher education and K-12, and to provide continuity in the proposed K-12 PD activities, we support graduate student involvement in K-12 classrooms (Table 5.3). Following the NSG GK-12 model, SGS-LTER graduate students will be offered an augmentation to their research stipend ($2000 per semester) on a rotational basis to work in the K-12 classroom for one afternoon per week during the AY (~120 hrs). Graduate students will assist teachers with instruction and implementation of the modules that they jointly developed.

Research Experience for Minority High School Students (RAMHSS): The SGS-LTER has a long history of working with under-represented high school students through their partnerships with regional TRIO programs (Upward Bound, Upward Bound- Math and Science) and the NSF RAMHSS program. We will continue to support the students through NSF RAMHSS supplemental funding. Students will be selected from schools close to CSU with high numbers of minority students (primarily Hispanic in Colorado) that participate in either on-campus resident programs or non-residential programs (e.g., Upward Bound).

Education Research

The SGS-LTER has been actively engaged in educational research. Our efforts from 2002-present have generated 5 journal publications and 2 book chapters in the areas of student learning, classroom instruction, K-12 professional development, and student mentoring. Funded through the NSF Mathematics and Science Partnership program and involving 4 LTER sites (Table 5.1), our research is focused on the development of an Environmental Science Literacy Framework by identifying key ecological concepts and assessing the current state of knowledge of teachers and students in these core areas, and understand the scaffolding of science and mathematics concepts required to reach the desired level of understanding (lter.mspnet.org). We will research the development of learning progressions (descriptions of increasingly sophisticated ways of reasoning about topics) from grades 6-12 focusing on preparing students for STEM careers and environmentally responsible citizenship. These learning progressions are organized around three key science strands (carbon, water, and biodiversity) and a mathematical strand (quantitative reasoning and the mathematics of modeling); all of which are connected by the theme of education for citizenship. Each of these aspects is deeply embedded in state and national science and mathematics standards, and aligned with core LTER topics. Our multidisciplinary themes focus on the human impacts on land-use, ecosystem structure and ecosystem services offering rich experiences in science and mathematics that include atmospheric science, soil science, geology, agronomy, ecology, hydrology, computer science and systems modeling across locations and over time.

Outreach Plan

The SGS-LTER program will continue to engage the CSU campus and the surrounding community. We host the biennial Shortgrass Steppe Symposium (last hosted Jan. 2009) where we present our research to our colleagues, but also involve others who use and manage the SGS. Beyond our engagement of K-12, we have established a presence with the agricultural and ranching communities in Colorado, by staffing booths each year at large events like Ag Day at a Colorado State football game each fall, and the Western Stock Show in Denver each January. In our work we have also developed partnerships with the USDA-NRCS, USFWS, the Nature Conservancy, Rocky Mountain Bird Observatory, CO Division of Wildlife, the Crow Valley Grazing Association, and the Pawnee National Grassland (PNG).

Table 5.1: Funding sources for the SGS-LTER Education and Outreach Activities (2002-present)			
Funding Source	**Amount**	**Years**	**LTER Partner Sites**
NSF Math and Science Partnership	$12,500,000	2008-2013	SGS, BES, KBS, SBC, LNO
NSF GK-12 (2 awards)	$2,800,000	2001-2010	SGS
USDE Math Science Upward Bound	$1,200,000	2004-2009	SGS
NSF Undergraduate Biology Mathematics	$1,000,000	2007-2012	SGS
Colorado Department of Education	$409,819	2007-2010	SGS
USDA National Needs Fellowship	$234,000	2008-2011	SGS, KNZ
USDA AFRI	$150,000	2009-2012	SGS
NSF Teacher Professional Continuum	$135,000	2006-2010	AND, CAP, JRN, LUQ, SGS
NSF EdEn Venture Fund	$75,000	2005-2007	SGS, KBS, BES
NSF SLTER Supplements	$24,000-$27,000	Annually	SGS
Pharos Foundation-Bohemian Fund	$22,129	2007	SGS
NSF ARC LTER International Supplement	$20,000	2008-2010	ARC, SGS
NSF RET Supplement to ECOS	$15,000	2009-2010	SGS

Table 5.2: Undergraduate and graduate students associated with the SGS LTER 2002-present		
Academic level	# Students	College or University
Research Experience for Undergraduates	13 (7 female, 6 male)	Austin College , College of Wooster, Colorado School of Mines, Colorado State University (4), Earlham College, Front Range Community College, Middlebury College (2), University of California – Berkeley, University of Northern Colorado
Undergraduate research assistants	73 (42 female, 31 male)	California State University – Fullerton, Colorado State University, University of Northern Colorado,
Master's degree in progress	6 (4 female, 2 male)	California State University – Fullerton, Colorado State University, University of Copenhagen
Master's degree recipients	23 (15 female, 8 male)	California State University – Fullerton, Colorado State University, University of Copenhagen
Ph.D. degree in progress	10 (8 female, 2 male)	Colorado State University, University of Wyoming
Ph.D. degree recipients	18 (12 female, 6 male)	Colorado State University, University of Copenhagen
Foreign graduate students (research only, not enrolled in US institution)	7 (6 female, 1 male)	University of Copenhagen

Table 5.3: List of SGS-LTER Partner Schools supporting 56 teachers
School District
Greeley SD6 (28 teachers)
Bella Romero Elementary, Brentwood Middle School, Cameron Elementary, Chappelow K-8 Arts & Literacy Magnet, Dos Rios Elementary, Greeley West High School, Heath Middle School, John Evans Middle School, Maplewood Middle School, McAuliffe Elementary, Meeker Elementary, Poudre Learning Center, Union Colony Prep School, Winograd Elementary
Eaton RE-2 SD (2 teachers)
Eaton Middle School
Poudre SD (24 teachers)
Cache La Poudre Middle School, Fossil Ridge High School, Irish Elementary, Poudre High School, Preston Middle School, Riffenburgh Elementary, Rocky Mountain High School
Weld RE-4 SD (2 teachers)
Mountain View Elementary, Skyview Elementary

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Results from Prior Support Table S1: SGS-LTER Bibliography 2002-2009

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Journal Articles:

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Pielke, R.A., Sr. 2002. Planning for drought in Colorado. The City Club of Denver, Brown Palace Hotel, December 10, Denver, CO.

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Table S2.1 SGS-LTER Related Data Available Electronically.

Core Data: The collection, processing and curation of SGS-LTER core data is performed by SGS-LTER PIs, students, and/or staff. Most protocols are documented and published online in our field crew manual. These datasets are prioritized for publication on the SGS website and the LTER Network Information System databases. These datasets serve as the basis for documenting and evaluating temporal changes in representative taxa at the SGS-LTER site. Proposed in LTER VI, are the termination of some long-term measurements, modifications of the sampling frequencies, and/or implementation of new sampling techniques.

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**	**Notes on Sampling Changes to Core Studies**
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*	Vegetation sampling frequency decreased to every 5 years (except on control treatment which acts as long-term plant species monitoring, done every year)
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*	Deploy eddy flux instrumentation with soil moisture probes across the landscape
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*	Now conducted by Rocky Mountain Bird Observatory
Christmas Bird Count	1972	none	Avian abundance (1972-present, sampled once in Dec annually)	Ryder: *Braun 1994*	Conducted by Audubon Society and SGS-LTER volunteers

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**	**Notes on Sampling Changes to Core Studies**
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*	Wet chemistry performed at central NADP CAL lab
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*	New technique sampling vegetation by functional group, lab N analyses reduced to samples composited by transect and NDVI sensors added.
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*	New techniques including TDR (time domain reflectometery)
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*	A new root ingrowth technique will be initiated on grazing and CRP studies
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*	Terminated in 2009, replaced by ingrowth root production above

Table S2.1.118

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**	**Notes on Sampling Changes to Core Studies**
Seed production by *Bouteloua gracilis*	1989	2008	*B. gracilis* seed production (1989 - 2007, sampled annually)	Lauenroth: *Coffin and Lauenroth 1989*	Terminated in 2008
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*	New technologies using Eddy Flux Towers and part of Tragnet, US Trace Gas Network
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*	New techniques using all terrain vehicles to map perimeters
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*	New techniques using changes in chloride concentration , and establishing isotopic records of SOC, CaCO3, and phytoliths
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*	Data in Geographic Information System

Study Title	Start Date	End Date	Information on Variables Measured and Sampling Frequency	Principal Investigator(s): References for Methods	Notes on Sampling Changes to Core Studies
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 comvergence)	Lauenroth, Burke: *Bakker et al. 2009, Milchunas et al. 2008a, Moore et al. 2008*	New techniques to investigate the belowground, including TDR and root ingrowth donuts. ANPP reduced to functional groups, cactus production added, plant density dropped and canopy cover added to previous basal cover, selectivity dropped, lab N analyses composited.
Rabbit Abundance	1994	none	Rabbit abundance (1994-present, sampled seasonally)	Stapp, Lindquist, Lauenroth: *Stapp 1996 (PhD. Dissertation), Stapp et al. 2008*	Conducted by SGS-LTER volunteers
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*	Terminated winter scat survey 2009
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*	See Grazing Reversal – Large Mammals above

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**	**Notes on Sampling Changes to Core Studies**
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*	–Adopted USDA-ARS sampling frame design and added sweep net counts to estimate species composition
Cross-site Fertilization Study	1995	none	ANPP, plant species density and basal cover (1998-present, alternatively sampled biennually); 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*	Cross-site project with Hay, Kansas
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*	

Study Title	**Start Date**	**End Date**	**Information on Variables Measured and Sampling Frequency**	**Principal Investigator(s): References for Methods**	**Notes on Sampling Changes to Core Studies**
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*	Rain-out shelters for rainfall experiments redesigned for decrease in cost and ease of maintenance
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*	Techniques using NDVI will be explored
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*	Carbon treatments terminated, but vegetation sampling continues
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*	
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*	

Study Title	Start Date	End Date	Information on Variables Measured and Sampling Frequency	Principal Investigator(s): References for Methods	Notes on Sampling Changes to Core Studies
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,*	Root production to be added as in Grazing Reversal above
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*	

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Table S2.2 Supplementary data archived electronically on the SGS Information Management System and available upon request.

Supplementary data: The collection and processing of supplementary data are usually performed by SGS-LTER students for short-term studies and may be supported by grants other than LTER or outside collaborators. These data supplement the core data in the system and may be used as baseline or preliminary data for planning future studies. These data are being transferred to the new SGS-LTER website, but in most cases are offline and backed-up on our centralized server with access for the LTER community and the public upon request.

Study Title	**Start Date**	**End Date**	**Principal Investigator(s)**
Microhabitat selection, movement patterns and interactions between grasshopper mice and deer mice in SGS; Summary of pellet contents of great-horned owls	1993	1996	Stapp
Plant species effects on soil properties in shortgrass steppe; cross site study	1992	1992	Vinton, Burke
Defoliation effects on western wheatgrass in long-term protected and long-term grazed pastures	1992	1992	Atsedu
Effects of landscape factors, precipitation and individual plants on N mineralization	1992	1992	Hook and Burke
Response of mycotrophic C3 and C4 rangeland grasses to atmospheric CO_2 & H_2O	1992	1994	Morgan, Knight, Hunt
Idaho-Utah Study of biogeochemistry data, C & N mineralization, soil pH/electrical conductivity	1992	1992	Aguiar
The influence of soil texture on plant productivity in the central grasslands	1993	1994	Lane, Coffin
The role of roots in soil organic matter formation and maintenance	1993	1993	Kelly R., Burke
Phenology of grasses, forbs, and shrubs of CPER	1993	1993	Atsedu
Effects of plant mortality of the dominant species and other important species on the dynamics of a shortgrass steppe plant community	1994	1994	Martinez
Isotopic variation of H_20 in sgs	1994	1996	Welker, Kelly, Hook
Assessing nematode biodiversity in Colorado SGS natural and managed ecosystems	1994	1995	Huang, Freckman, Coffin
Effects of a methamidophos application on *Pasimachus elongatus LeConte (Coleoptera: Carabidae*): an update after six years. The effects of vegetational architecture on beetle movements	1994	1994	McIntrye
Soil Organic Matter under different SOM manipulations	1994	1994	Bisbee

Study Title	**Start Date**	**End Date**	**Principal Investigator(s)**
Temperature increase influences SGS plant communities	1995	1998	Alward, Detling
Plant species effects on temporal patterns of nitrogen cycling	1995	1996	Epstein
Effects of shrub density on soil water patterns and soil texture; decomposition on vegetation transects	1995	1996	Dodd, Lauenroth
Vectors of seed dispersal for *Bouteloua gracilis* and *Buchloe dactyloides*	1995	1996	Fraleigh, Coffin
Constraints on production and decomposition in temperate grassland	1995	2010	Lauenroth, Burke
Seed variation under prickly pear cactus	1995	1995	Bayless, Lauenroth
Ecophysiology of western wheatgrass and blue grama	1995	1995	Fahmstock
Comparative ecology of native and exotic plants, common gardens, and clone height	1996	1999	Kotanen, Burke, Berbelson
Grazing refugia and biodiversity	1997	1999	Milchunas, Salva, Rebollo
Fine scale spatial patterns in vegetative cover	1998	1999	Adler, Child
Cattle use of prairie dog towns; vegetation on and off towns, and on and off mounds	1998	2004	Guenther, Hartley, Farrar, Detling
Burrowing owl nesting patterns in NE Colorado	1999	2001	VanHorne, Woodard
Physiology and diet of black-tailed prairie dogs in SGS	1999	2003	Antolin, Kulbartz, Lehmer
Environmental controls on the abundance and distribution of entemopathogenic nematodes in grasslands	1999	2000	DeCrappeo, Wall
Effect of grazing, water, N and disturbance on the establishment of two exotic species	1999	2008	Lauenroth, Betz, Allhouse
Variations in decomposition, N mineralization and soil respiration rates x precipitation gradient in the Central Great Plains	1999	2002	McCulley, Burke
LIDET (Long-term Intersite Decomposition Experiment Team)	1998	2008	Parton, Burke
UV, abiotic and biotic components of production and decomposition on SGS: interactions with CO_2 enrichment	2000	2004	Milchunas, King
Biogeochemical dynamics of urban lawns	2000	2004	Kaye, Burke
P-dog genetics of metapopulations	1997	2010	Antolin, Savage, Roach, Harp
The influence of field research experiments with controversial species, black tailed prairie dogs, on high school students	2003	2004	Fox-Parrish, Jurin
Mediation of spatial organization in the swift fox (*Vulpes velox*)	2003	2006	Darden

Table S2.2.130

Study Title	**Start Date**	**End Date**	**Principal Investigator(s)**
Temporal variability in ANPP, species distribution. and climate in grasslands	2005	2010	Galeas, Heisler, Kelly, Knapp
Habitat use, survivorship, and mortality causes of Ord's Kangaroo Rats in disturbed and fragmented habitats	2005	2006	Ross, Antolin
Survey of SGS LTER CPER trace gas fluxes and associated microbial communities	2005	2010	Von Fischer, Burke
The role of photodegradation in surface litter decomposition across UV gradient in the Great Plains, USA	2005	2010	Brandt, King
Prairie dogs, ants as disturbance agents on the shortgrass steppe: implications for habitat heterogeneity	2005	2005	Alba, Detling
Estimations of composition and relative density of carnivore species on Pawnee National Grassland	2005	2010	Dabelsteen, Lindquist
Interactions between northern grasshopper mice and fleas in prairie dog colonies: implications for the spread of plague	2006	2007	Stapp, Kraft
Diets of three species of horned lizard in Colorado	2007	2012	Martin, Simmons, Newbold
Temporal effects of drought on semi-arid grassland ecosystems	2007	2010	Cherwin, Knapp
Granivore influence on plant population and plant community dynamics	2007	2010	Alba, Detling
Nut Net: Controls of nutrients and herbivory on grassland dynamics at the SGS, CO and mixed grass, WY	2007	2013	Klein, Brown, Blumenthal
PHACE (Prairie Heating and CO2 Enrichment)	2007	2017	Morgan, Blumenthal
Vegetation dynamics on plague-affected prairie dog colonies at CPER	2007	2017	Augustine, Derner
Climate change and plant species composition and structure in the Great Plains	2008	2011	Lauenroth, Byrne
Phenotypic differences between populations of *Bouteloua gracilis* (BOGR) and *Andropogon gerardii* (ANGE)	2008	2009	Knapp, Lease
Pulse response experiment: Linking carbon and water fluxes to population and community responses	2009	2010	Hannan, Von Fischer
Soil ecology responses to precipitation pulses	2009	2009	Von Fischer, Moore
Opuntia polyacantha (OPPO) Removal	2009	2009	Milchunas, Stapp, Augustine

Table S2.2.131

Table S2.3 Historical IBP data available electronically from SGS-LTER.

Historical data: The SGS-LTER inherited a legacy of historical data from the International Biome Program (IBP). These data are accompanied by published technical reports, which are available on-line as PDFs through the SGS-LTER website and Colorado State University library. The data and reports serve as a baseline for many students, visiting scientists and new collaborators who are planning research. One of our Information Management goals is to document EML compliant metadata for the IBP datasets.

<u>**Category/Dataset Title and Comments**</u>

Aboveground Herbage and Biomass

- 1978 aboveground herbage (epa)
- Aboveground herbage summary output
- *Ecological Stress Experiment: Nutrient Stress*
  - 1970 aboveground herbage (pawnee) biomass esa field data
  - 1970 aboveground herbage (pawnee) biomass esa summary data
  - 1971 aboveground herbage (pawnee) biomass esa field data-6 dates 4 dbl sampled
  - 1972 aboveground herbage (pawnee) biomass esa field data-9 dates
  - 1973 aboveground herbage (pawnee) biomass esa field data-8 dates 6 dbl sampled
  - 1974 aboveground herbage (pawnee) biomass esa field data-8 dates 3 dbl sampled
  - 1975 aboveground herbage (pawnee) biomass esa field data-5 dates 2 dbl sampled
  - 1976 aboveground herbage (pawnee) biomass esa field data-4 dates on 1st 3
  - 1977 aboveground herbage (pawnee) biomass esa field data-4 dates dbl sampled
  - 1978 aboveground herbage (pawnee) biomass esa field data
- *Grazing Intensity*
  - 1969 aboveground herbage (pawnee) biomass grazing intensity field data-10 dates
  - 1969 aboveground herbage (pawnee) biomass grazing intensity summary data-10 dates
  - 1970 aboveground herbage (pawnee) biomass grazing intensity field data-11 dates
  - 1970 aboveground herbage (pawnee) biomass grazing intensity summary data-11 dates
  - 1971 aboveground herbage (pawnee) biomass grazing intensity field data-5 dates
  - 1971 aboveground herbage (pawnee) biomass grazing intensity summary data-5 dates
  - 1972 aboveground herbage (pawnee) biomass grazing intensity field data-6 dates 1st dt no trt1
  - 1972 aboveground herbage (pawnee) biomass grazing intensity summary data-6 dates 1st dt no trt1
- *Network Comparison*
  - 1971 aboveground herbage (pawnee) biomass network comparison field data-12 dates
  - 1972 aboveground herbage (pawnee) biomass network comparison field data-8 dates 1st dt no trt1
  - 1972 aboveground herbage (pawnee) biomass network comparison summary data-8 dates 1st dt no trt1
- *C14- Photosynthesis*
  - 1977 aboveground herbage (epa) carbon 14 photosynthesis data
  - 1978 aboveground herbage (epa) carbon 14 photosynthesis data
- *Plant Growth*
  - 1977 aboveground herbage (epa) plant growth-only trt L & M
  - 1978 aboveground herbage (epa) AGSM plant growth-9 dates trts A-D
- *Aboveground invertebrates*
  - 1971 aboveground invertebrate (pawnee) insect-range plant association data
  - 1971 aboveground invertebrate (pawnee) pit trap invertebrate collection data

1971 aboveground invertebrate (pawnee) sweep net invertebrate collection data
1972 aboveground invertebrate (pawnee) bureau of sport fisheries
1972 aboveground invertebrate (pawnee) bureau of sport fisheries
1972 aboveground invertebrate (pawnee) insect-plant host data (v. yount)
1972-3 aboveground invertebrate (pawnee) grasshopper plot data and programs
1977 aboveground invertebrate (epa) grasshopper census data
aboveground invertebrate (pawnee)
aboveground invertebrate (pawnee) species code list

Density and Biomass

ESA field data

1971-1974 aboveground invertebrate (pawnee) density & biomass esa field data

ESA summary data

1972-1974 aboveground invertebrate (pawnee) density & biomass esa summary

Grazing Intensity

1970-1972 aboveground invertebrate (pawnee) density & biomass grazing intensity field data
1970 aboveground invertebrate (pawnee) density & biomass grazing intensity summary data
1972 aboveground invertebrate (pawnee) density & biomass grazing intensity summary data

Network comparison field data

1971-1972 aboveground invertebrate (pawnee) density & biomass network comparison field data
1972 aboveground invertebrate (pawnee) density & biomass network comparison summary data

Dung insects

Field data

1971-1972 aboveground invertebrate (pawnee) dung insects field data

Summary data

1971-1972 aboveground invertebrate (pawnee) dung insects summary data-# & mg per g of pat
1971-1972 aboveground invertebrate (pawnee) dung insects summary data-# & mg per g pat

Dung mites

Field data

1971-1972 aboveground invertebrate (pawnee) dung mites field data

Summary data

1971-1972 aboveground invertebrate (pawnee) dung mites summary data-# & mg per pat

Field data

1970-1972 aboveground invertebrate (cottonwood) field data
1970-1972 aboveground invertebrate (jornada) field data
1970-1972 aboveground invertebrate (osage) field data
1970-1972 aboveground invertebrate (pantex) field data
1971-1972 aboveground invertebrate (pawnee) field data
1972-1973 aboveground invertebrate (ale) field data
1972 aboveground invertebrate (bridger) field data
1973-1974 aboveground invertebrate (san joaquin) field data
1974-1976 aboveground invertebrate (epa) montana field data

Summary data

1970-1972 aboveground invertebrate (cottonwood) summary data

1970-1972 aboveground invertebrate (jornada) summary data
1970-1972 aboveground invertebrate (osage) summary data
1971 aboveground invertebrate (pawnee) summary data
1972-1973 aboveground invertebrate (ale) summary data
1972-1973 aboveground invertebrate (pantex) summary data
1973-1974 aboveground invertebrate (san joaquin) summary data
1974-1976 aboveground invertebrate (epa) montana summary data

Belowground Herbage

1975 belowground herbage
1978 belowground herbage

Field data

1970 belowground herbage (pawnee) field data
1971 belowground herbage (pawnee) field data-all dates trts
1972 belowground herbage (pawnee) field data
1973-1976 belowground herbage (pawnee) field data-all dates trts sample date codes
1975 belowground herbage (pawnee) site 13-field data-3 dates trts H-K
1976 belowground herbage (pawnee) site 13-field data-2 dates trts H-K
1977 belowground herbage (pawnee) field data
1978 belowground herbage (epa) field data-5 dates trts A-D

Summary data

1970 belowground herbage (pawnee) cores avg within quadrats summary data
1971 belowground herbage (pawnee) summary data-all dates trts
1972 belowground herbage (pawnee) summary data
1973-1974 belowground herbage (pawnee) summary data-cores avg within quadrat
1975 belowground herbage (pawnee) site 11-all cores avg within quadrats summary data
1975-1977 belowground herbage (pawnee) summary data
1976 belowground herbage (pawnee) site 13-summary data-2 dates trts H-K

Belowground Temperature

Combined field data

1971-82 belowground temperature (pawnee) combined field data

Field data

1971-1994 belowground temperature (pawnee) field data

Output summary data

1971-1994 belowground temperature (pawnee) output summary table

Summary data

1971-1994 belowground temperature (pawnee) summary data

Birds

1968-72 avian (pawnee) ryders' permanent plot pawnee data
1970-73 avian (ale cottonwood)
1973 avian (pawnee) ryder's permanent plot pawnee data
1974-75 avian boyd's bird field data
avian owl prey field data (marti robinson)

Diet Data

1968-72 avian (pawnee) baldwin bird diet data
1968-72 avian (pawnee) baldwin bird diet data
1970-71 avian (pawnee) lark bunting reformatted data diet data (baldwin)

Hawk data

1970-71 avian (pawnee) hawk data (ollendorf)
1971-73 avian (pawnee) hawk growth data

Int.-ext. collection

1970-71 avian (jornada) avian int. - ext. collection

1970-72 avian (cottonwood) avian int. - ext. collection
1970-72 avian (osage) avian int. - ext. collection
1970-72 avian (pantex) avian int. - ext. collection
1971-72 avian (ale) avian int. - ext. collection

Nesting field data

1970-1972 avian (pawnee) avian nesting field data

Road count

Field data

1968-90 avian (pawnee) avian road count field data
1970-72 avian (pantex) avian road count field data
1971 avian (ale) avian road count field data
1972 avian (jornada) avian road count field data
1972-74 avian (cottonwood) avian road count field data
1972-75 avian (osage) avian road count field data

Summary data

1968-73 avian (pawnee) avian road count summary data

Decomposition

Field data

1974 decomposition (epa) field data
1975 decomposition (epa) field data-cellulose
1975 decomposition (epa) field data-native litter
1976 decomposition (epa) field data

Summary data

1971-1972 decomposition (pawnee) summary data

Grub kill

1977-1980 plant recovery on grubkills (raw data)
1982 plant recovery on grubkills (raw data)
1990 plant recovery on grubkills (raw data)

Hygrothermograph

4hr intervals

1984 hygrothermograph (pawnee) data-4hr intervals (1- 6-84 to 16- 9-84)
1984 hygrothermograph (pawnee) data-4hr intervals (11-12-84 to 5- 2-85)
1984 hygrothermograph (pawnee) data-4hr intervals (17- 9-84 to 10-12-84)
1984 hygrothermograph (pawnee) data-4hr intervals (20- 2-84 to 1- 6-84)
1984 hygrothermograph (pawnee) data-4hr intervals (30-10-84 to 19- 2-84)
1985 hygrothermograph (pawnee) data-4hr intervals (2- 9-85 to 31-12-85)
1985 hygrothermograph (pawnee) data-4hr intervals (5- 2-85 to 7- 5-85)
1985 hygrothermograph (pawnee) data-4hr intervals (7- 5-85 to 2- 9-85)

Daily max and min

1983-85 hygrothermograph (pawnee) daily max and min (16-10-83 to 4- 2-85)
1985 hygrothermograph (pawnee) daily max and and min (5- 2-85 to 31-12-85)

Field data

1971 hygrothermograph (ale) field data
1971 hygrothermograph (osage) field data
1972 hygrothermograph (ale) field data
1972 hygrothermograph (bridger) field data
1973 hygrothermograph (ale) field data
1976-1981 hygrothermograph (pawnee) field data format as on form #150

Processed with program HYTHER

1975 hygrothermograph (pawnee) data processed with program HYTHER
1971 hygrothermograph (pawnee) data processed with program TWOHR

1973-1974 hygrothermograph (pawnee) data processed with program TWOHR

Uncorrected data (process with HYTHER or TWOHR)

1970 hygrothermograph (pawnee) uncorrected data (process with HYTHER or TWOHR)

Litter

Bridge set

Field data

1972 litter (pawnee) bridge set type 1 field data

Summary data

1972 litter (pawnee) bridge set type 1 summary data

Esa

Field data

1970-1976 litter (pawnee) esa type 1 field data

1973 litter (pawnee) esa type 3 field data

Summary data

1970-1976 litter (pawnee) esa type 1 summary data

1973 litter (pawnee) esa type 3 summary data

Field data

1977 litter (epa) field data

1978 litter (epa) field data

Grazing intensity

1971-1972 litter (pawnee) grazing intensity type 1 field data

1971-1972 litter (pawnee) grazing intensity type 1 summary data

Herbicide

1972 litter (pawnee) klm (herbicide) type 1 field data

1972 litter (pawnee) klm (herbicide) type 1 summary data

Insecticide

1972-1973 litter (pawnee) xyz (insecticide) type 1 field data

1972-1973 litter (pawnee) xyz (insecticide) type 1 summary data

Litter component data

1969-1970 litter (pawnee) litter component data

Network comparison

Field data

1971-1972 litter (pawnee) network comparison type 1 field data

1972 litter (pawnee) network comparison type 3 field data

Summary data

1971-1972 litter (pawnee) network comparison type 1 summary data

1972 litter (pawnee) network comparison type 3 summary data

Lysimeter

Field data

1972-1978 soil water - lysimeter (pawnee) field data

Neutron Probe

Field data

1983-1992 soil water - neutron probe (pawnee) lysimeter field data

Summary data

1972-1976 soil water - lysimeter (pawnee) summary data

Mammals

1975 small mammal

small mammal (pawnee)

Large herbivore activity

1972 small mammal (pawnee) large herbivore activity data

1973 small mammal (pawnee) swartz large herbivore activity data

- *Autopsy data*
  - 1972 small mammal (pantex) autopsy data
- *Esa*
  - 1972 small mammal (pawnee) esa autopsy data
- *Off-grid*
  - 1973-1974 small mammal (san joaquin) off-grid autopsy data
- *Diet data*
  - 1969-70 small mammal les flake - diet data & program
- *Field data*
  - 1971 small mammal (pawnee) field data
- *Live trap*
  - *Field data*
    - 1970 small mammal (bridger) live trap field data
    - 1970 small mammal (cottonwood) live trap field data
    - 1970 small mammal (dickson) live trap field data
    - 1970 small mammal (jornada) live trap field data
    - 1970 small mammal (osage) live trap field data
    - 1970 small mammal (pantex) live trap field data
    - 1971-1975 small mammal (pawnee) live trap field data
  - *Zippin analysis*
    - 1973 small mammal (pawnee) live trap zippin analysis
  - *Off-grid snap trap data*
    - 1971-1972 small mammal (pawnee) misc. off-grid snap trap data
  - *Pronghorn interaction*
    - small mammal (pawnee) rob deblinger's pronghorn interaction data
  - *Reproductive data*
    - 1969-70 small mammal les flake - reproductive data
- *Snap trap*
  - 1970 small mammal (bison) snap trap field data
  - 1970 small mammal (bridger) snap trap field data
  - 1970 small mammal (cottonwood) snap trap field data
  - 1970 small mammal (dickson) snap trap field data
  - 1970 small mammal (jornada) snap trap field data
  - 1970 small mammal (nevada) snap trap field data
- *Summary data*
  - 1971 small mammal (pawnee) summary data
- *Weight and reproduction*
  - 1970 small mammal (bridger) mammal wt & reproduction analysis
  - 1970 small mammal (cottonwood) mammal wt & reproduction analysis
  - 1970 small mammal (dickson) mammal wt & reproduction analysis
  - 1970 small mammal (jornada) mammal wt & reproduction analysis
  - 1970 small mammal (osage) mammal wt & reproduction analysis

Microarthropods

- 1971 soil microarthropods (pawnee) field data
- 1971 soil microarthropods (pawnee) summary data
- 1972 soil microarthropods (pawnee) deep sample (16 30 aug) field data
- 1972 soil microarthropods (pawnee) deep sample (16 30 aug) summary data
- 1972 soil microarthropods (pawnee) deep sample (23 26 may) field data
- 1972 soil microarthropods (pawnee) deep sample (23 26 may) summary data
- 1972 soil microarthropods (pawnee) deep sample (29 jun 6 july) field data
- 1972 soil microarthropods (pawnee) deep sample (29 jun 6 july) summary data

1972 soil microarthropods (pawnee) deep sample (5 14 apr) field data
1972 soil microarthropods (pawnee) deep sample (5 14 apr) summary data
1972 soil microarthropods (pawnee) esa nc
1972 soil microarthropods (pawnee) esa nc
1973 soil microarthropods (pawnee) deep sample (may) field data
1973 soil microarthropods (pawnee) deep sample (may) summary data
1973 soil microarthropods (pawnee) deep sample (winter) summary data
1973 soil microarthropods (pawnee) esa field data
1973 soil microarthropods (pawnee) esa summary data
1973 soil microarthropods (pawnee0 deep sample (winter) field data
1974 soil microarthropods (pawnee) esa field data
1974 soil microarthropods (pawnee) esa summary data
1975 soil microarthropods (pawnee) nematicide study analysis (0-5 5-10
1975 soil microarthropods (pawnee) nematicide study analysis trt H I (10-15
1975 soil microarthropods (pawnee) nematicide study analysis-combine trts H-J I
1975 soil microarthropods (pawnee) nematicide study data
1975 soil microarthropods (pawnee) nematicide study data with wts and trophics
1975 soil microarthropods (pawnee) nematicide study trophic summary by host (0-10cm)
soil microarthropods (pawnee)

Nematodes

1975 aboveground herbage (pawnee) nematode study-1 date trts H-K
1976 aboveground herbage (pawnee) nematode study-1 date trts H-K

Phenology

Field data

1970 phenology (cottonwood) field data - 12 dates condensed
1972 phenology (cottonwood) field data
1972-1977phenology (pawnee) field data

Montana field data

1975-1977 phenology (epa) montana field data1971-1972 soil macroarthropods (pawnee)

Esa field data

1970-1974 soil macroarthropods (pawnee) field data1971-1972 soil macroarthropods (pawnee)

Grazing intensity field data

1975 soil macroarthropods (pawnee) analysis of stanton ARFR data (nematicide study)
1975 soil macroarthropods (pawnee) analysis of stanton BOGR data (nematicide study)
1975 soil macroarthropods (pawnee) analysis of stanton nematicide study-special trophics
1975 soil macroarthropods (pawnee) data from stanton nematicide study-special trophics

Network comparison

Field data

1971-1972 soil macroarthropods (pawnee) network comparison field data

Summary data

1970-1974 soil macroarthropods (pawnee) summary data
1977 soil water - gravimetric (epa) different depths for frost block comparisons
1978 soil water - gravimetric (epa)1976 soil water - gravimetric (pawnee)

Esa field data

Field data

1970 soil water - gravimetric (cottonwood) field data - 12 dates trts 1
1971 soil water - gravimetric (cottonwood) field data - 11 dates trts 1

1972 soil water - gravimetric (cottonwood) field data - 9 dates trts 1
1977 soil water - gravimetric (epa) field data - 12 dates trts A-D
1977 soil water - gravimetric (epa) field data - 19 dates trts A-D

Nematicide study

1975 soil water - gravimetric (pawnee) nematicide study field data

Network comparison

1972 soil water - gravimetric (pawnee) network comparison field data
1976 soil water - gravimetric (pawnee) network comparison field data1969-1078 soil

Water - microwatershed (pawnee) field data

1971-1976 soil water - microwatershed (pawnee) shield count data
1969-1976 soil water - microwatershed (pawnee) summary data
1980 soil water - neutron probe (pawnee) special field data (oswald's data)
1985-1992 soil water - neutron probe (pawnee) OWL field data

Probe 480, ARS

1979 soil water - neutron probe (pawnee) field data (probe 480) - special ARS

Field data

1978-1984 soil water - neutron probe (pawnee) field data (probe 480)

Grasshoppers

1980 soil water - neutron probe (pawnee) field data (probe 480)-grasshoppers (detling)

Field data

1984-1992 soil water - neutron probe (pawnee) SANDY field data
1984-1992 soil water - neutron probe (pawnee) SHALE field data
1986 soil water - neutron probe (pawnee) SILT field data
1984-1992 soil water - neutron probe (pawnee) TOPO field data
1983-1992 soil water - neutron probe (pawnee) ungrazed esa field data

Soil water transects

Field data

1971-1978 soil water - transects (pawnee) field data

Weather

1937-66 grover precipitation data
1937-66 kauffman precipitation data
1940-68 ars rain gauge data (pawnee) -program fms01 tabulates ppt data
1940-70 cper precipitation data
1940-73 cper temperature data table of monthly max and min (english units)
1940-73 cper weather data (english units) missing 1942
1940-73 cper weather data (metric units) missing 1942
1945-67 kauffman temperature data
1946-67 grover temperature data
1948-70 cper temperature data
1969-74 cheyenne weather 16 readings
1969-84 weather data (pawnee central plains
1970-73 cper rain gauge data

Weather, Standard

Field data

1969-84 standard weather (pawnee) field data

Table S2.4 SGS-LTER Related Spatial Data Available Electronically.

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	

Table S2.4.141

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)	

Table S2.4.142

Table S2.5 Data usage reported by number of data downloads for different purposes by SGS and non-SGS students, researchers, educators and other professionals from 2002-2009.

Purpose of Data Downloads	**SGS Requests for Data from 2002-2009**	**SGS**	**non-SGS**
Scientific Research	429	110	319
Graduate Research	79	36	43
Undergraduate Coursework	54	4	50
GK-12	20	3	17
Information System Inquiry	70	7	63
Natural Resource Management and Conservation	14	0	14
Total Data Downloads	666	160	506