TITLE: Assessing impacts of patch-burn grazing management on sustainability of multiple agroecosystem services

A1. INTRODUCTION

Frequently, cattle production comes at the expense of plant and wildlife biodiversity, with cattle management goals at odds with environmental health and conservation (Derner et al. 2009, Toombs and Roberts 2009, Fuhlendorf et al. 2012). In grasslands that can carry fire (mesic grasslands), annual burning and grazing (ABG) is a common management technique (With et al. 2008) to increase forage production for cattle (Allred et al. 2011). However, ABG homogenizes vegetation (Koerner and Collins 2013) removing litter, reducing habitat quality for native flora and fauna (Fuhlendorf et al. 2010). Patch burn grazing (PBG) is a management strategy that promises land owners the ability to prioritize cattle weight gain and promote conservation and sustainability practices simultaneously. PBG employs fire and grazing interactions to create a "shifting mosaic" of forage across a landscape through time (Fuhlendorf and Engle 2004). In an unfenced management unit, fire is used to lure grazing animals to a portion (patch) of the unit that has recently burned (Weir et al. 2013), while unburned patches experience reduced levels of grazing. The patchiness of disturbances across a PBG landscape leads to heterogeneity of vegetation and potentially many other components of the ecosystem. Heterogeneity at large spatial scales, like that created in vegetation by PBG, is predicted to be important for ecosystem health as it can lead to greater diversity, ecosystem connectivity, and stability of ecosystem function and services (*e.g.*, (MacArthur and MacArthur 1961, Loreau et al. 2001, Scasta et al. 2015). Importantly, in addition to its purported benefits for wildlife and natural resources, PBG still provides equivalent cattle production to more traditional management practices, such as ABG. Yet evidence for many of the potential benefits of PBG for bird, small mammal, insect, and plant communities is limited or equivocal, and PBG's belowground effects (*e.g.*, soil health, carbon sequestration) remain completely unexplored. Here, we propose to examine the effects of PBG on the health and sustainability of a grazing ecosystem utilizing long-term PBG experiments in tallgrass prairie.

Long-term goal: Assess the ability of PBG to increase ecosystem health and services at a landscape-level, and thus understand the sustainability of PBG for long-term conservation of natural resources.

Supporting Objectives:

1. Assess the effects of PBG management on ecological properties, processes, and services (including understudied belowground components) at both the landscape and patch scale.
2. Determine whether PBG enhances coupling of various ecosystem components at the landscape scale.
3. Investigate how ecosystem coupling affects ecosystem services in the context of PBG.
4. Examine landscape level ecosystem services generated by long-term PBG at multiple sites throughout eastern Kansas.

Overall, the proposed project will integrate above and belowground measurements across trophic levels to assess the impact of management choices on critical landscape characteristics. These results will be vital for land managers, policy makers, and stakeholders seeking to enhance food production, while simultaneously protecting and conserving environmental health.

Ultimately, conserving environmental health will ensure the long-term sustainability and security of food production in the US.

A2: BACKGROUND

Globally, 50% of the ice-free terrestrial surface is considered rangeland, with livestock providing 25% of protein and 15% of dietary energy for humans around the world (Ellis and Ramankutty 2008). Within the contiguous United States, 40% of the land is used for grazing purposes, two-thirds of which is privately held and managed (Nickerson et al. 2011). Across this vast area of rangeland, cattle production is frequently achieved at the cost of reduced sustainability of natural resources and the wildlife these lands support (Fuhlendorf and Engle 2001, 2004, Churchwell et al. 2008, Derner et al. 2009, Toombs and Roberts 2009, Fuhlendorf et al. 2012). This is particularly true in the tallgrass prairie of the North American Great Plains, which supports an economically important grazing industry.

Standard pasture management in the tallgrass prairie ecoregion involves annual burning (Wilds and Nellis 1988, Valentine 2001, With et al. 2008, Holechek et al. 2010) to enhance forage production and quality (Svejcar 1989, Allred et al. 2011). ABG also tends to decrease spatial heterogeneity by promoting competitively dominant, tall, C_4 grasses (Collins 1987, Koerner and Collins 2013). While spatially homogeneous rangeland may be acceptable for cattle, plant and wildlife diversity are often higher in heterogeneous landscapes (MacArthur and MacArthur 1961, Lack 1969, Ostfeld et al. 1997, Fuhlendorf et al. 2010). Infrequently burned grasslands promote such spatial heterogeneity by increasing patchiness across the landscape (Koerner and Collins 2013), but at the cost of reduced forage quantity. Management practices that combine burned and unburned pastures across the landscape may allow for the maintenance of cattle production, while also protecting the natural resources of tallgrass prairie.

PBG management is a non-equilibrium management technique that touts the ability to simultaneously optimize livestock production *and* wildlife habitat (Fuhlendorf et al. 2006, 2010, Wilgers and Horne 2006, Holcomb et al. 2014, Hovick et al. 2014, Augustine and Derner 2015) by embracing heterogeneity in both space and time. PBG is based on the historical pyric herbivory patterns of bison prior to European settlement of North America, using fire to concentrate grazers and their associated impacts (eating, trampling, defecating) in a portion (patch) of a management unit that has recently burned (Weir et al. 2013). Simultaneously, other patches within the same management unit that have not recently burned experience reduced levels of grazing activity corresponding to time since fire. Cattle spend ~75% of their time in areas that were burned that year (Fuhlendorf and Engle 2004), as they are drawn to the higher quality forage (Vermeire et al. 2004), and hence PBG controls migratory patterns throughout the landscape. PBG has previously been shown to result in animal performance that is equal or superior to that resulting from traditional range management practices (Fuhlendorf and Engle 2004, Limb et al. 2011, Augustine and Derner 2013, Winter et al. 2014).

By concentrating disturbance (fire and grazing) in the landscape, PBG generates patches of habitat that differ substantially in their structure and function. Plant community responses to PBG are well documented and demonstrate that successional processes across patches lead to a shifting mosaic of plant structure (Fuhlendorf and Engle 2004). Through a multi-year burning cycle, a burned (and therefore heavily grazed) patch will see a temporary decrease in grasses and litter, and an increase in both forb abundance and species richness (Koerner et al. 2014); in the following years, the forb dominated areas will be unattractive to grazers, allowing grasses to regain their dominance and promoting litter accumulation. When it comes time to burn again, the grass dominated patch will provide high quality forage and the necessary fuel load to carry fire. Together, patches in different states of recovery from disturbance result in a heterogeneous plant community at the landscape-level (Fuhlendorf and Engle 2004, Sandercock et al. 2015).

Known benefits of landscape heterogeneity include enhanced wildlife habitat (Fuhlendorf et al. 2006, Ricketts and Sandercock 2016), increased biodiversity at multiple trophic levels (Scasta et al. 2015), and maintenance of regionally declining species populations like grassland birds (Churchwell et al. 2008). However, the drivers of these patterns are largely unknown and are likely scale dependent (Collins and Smith 2006). For example, heterogeneity effects on wildlife habitat may be due to increased plant diversity and variability in litter necessary for supporting various species with different habitat preferences (Ricketts and Sandercock 2016). Yet, it could also be due to increased stability of food sources, such as insects (Oliver et al. 2010). Information linking multiple aspects of the ecosystem can help elucidate the beneficial impacts of heterogeneity on ecosystem services and is important for developing and implementing management practices that will reduce the ecological footprint of agricultural systems.

Soil health is a particularly important determinant of the sustainability of agroecosystems, and yet to our knowledge has not been studied in the context of PBG. Soil health, or soil quality, reflects the physical and biotic characteristics of soils and their capacity to sustain ecosystem function (Herrick 2000, Griffiths and Philippot 2013, Stott and Moebius-Clune 2017). Soil health is integral for virtually all ecosystem services, including forage quality and quantity, nutrient cycling, and carbon sequestration (Herrick 2000, Bardgett et al. 2008, Berg and Smalla 2009, Derner et al. 2016) and is posited to be important for ecosystem resilience to variable weather (Mworia et al. 1997, Acosta-Martinez et al. 2014, Derner et al. 2016). In addition to soil physical properties (Stott and Moebius-Clune 2017), soil microbial composition (bacterial, archaeal, and fungal) and function are critical to maintaining soil health (Sinsabaugh 1994). Indeed, microbial function and soil physical properties are tightly linked. Soil physical properties have been shown to control biogeographical patterns of microbial distribution and function (Bardgett et al. 2008, Berg and Smalla 2009, Griffiths and Philippot 2013, Acosta-Martinez et al. 2014). In turn, microbes control nutrient cycling by converting complex substrates into smaller compounds that can then be assimilated by both plants and the microbes themselves (Hobbie 1992, Wardle et al. 2004, Allison 2005, Bardgett et al. 2008). Additionally, several types of microbes, such as N-fixing bacteria and mycorrhizal fungi, form mutualistic interactions with plants that provide plant nutrients in return for carbon. These mutualistic interactions can shape plant community structure and productivity (Grime et al. 1987, Heijden et al. 1998a, 1998b, 2006, Klironomos et al. 2000, Vogelsang et al. 2006). Soil impacts on ecosystem dynamics are often considered a "black box" (Bardgett et al. 2008, Derner et al. 2016). Fortunately, advances in technology are unlocking a new frontier in our understanding of complex edaphic processes and how these processes impact ecosystem services. While continuous grazing may place intense pressure on belowground processes through changes in carbon allocation, plant community composition, and abiotic factors, PBG may alleviate some belowground effects of grazing by introducing periodic rest from grazing pressure and increasing aboveground heterogeneity. However, the benefits to soil biotic characteristics remain understudied.

PBG may also be beneficial for terrestrial carbon (C) sequestration, relative to ABG. First, modeling work has suggested that annual burning may reduce long-term C stores due to continual volatilization of C in aboveground plant tissue (Ojima et al. 1994). Empirical evidence indicates that 19% of grass litter C is incorporated into soil organic matter after 3 years of decomposition (Cotrufo et al. 2015). Additionally, intensive continual grazing can cause soil compaction (Daniel et al. 2002) and reduced root production (Koerner and Collins 2014), both of which may reduce long-term C storage in the soil. Understanding the balance between these two phenomena is critical for providing necessary information for assessing C budgets and making predictions of future biogeochemical cycles (Luo et al. 2015).

Understanding the effects of PBG across a landscape requires an understanding of the linkages among all components of the ecosystem, including those above- and belowground. When applied to ecological systems, network theory allows for the identification of these linkages that underlie complex ecosystem structures (Proulx et al. 2005, Ings et al. 2009). Networks are defined as a set of vertices that connect nodes, and the properties of these series of connections can be studied mathematically (Estrada et al. 2015). While network theory has historically been applied to food webs, mutualisms, and host-parasite interactions, it has recently begun to be used to examine the properties of ecosystems (Ings et al. 2009). Ecosystem networks can incorporate both the number and strength of connections (*i.e.*, interactions) among biotic and abiotic components of an ecosystems (Berlow et al. 2004). These network properties are often related to ecosystem stability through time (Montoya et al. 2006, Thébault and Fontaine 2010, Tang et al. 2014), an important component of ecosystem health. However, it remains unclear how large-scale heterogeneity, such as that introduced by PBG, may influence the network properties of grazing systems both in space and time.

Here we propose to use a two-pronged approach. First, we will study a long-term PBG experiment (currently in its 10^{th} year) located at the Konza Prairie Biological Station, an NSF funded Long Term Ecological Research (LTER) site. Konza Prairie is a mesic tallgrass prairie grassland that would convert to shrubland if not maintained by frequent fire (Briggs et al. 2002), and is therefore particularly well suited for PBG management. At Konza, we propose to intensively sample, for the first time, a variety of biotic and abiotic ecosystem components belowground over multiple years. When combined with multiple co-located aboveground measurements, this will provide a holistic picture of the effects of PBG in this tallgrass prairie system. We will then link these ecosystem components using a network analysis to examine how network properties are affected by PBG and determine whether changes in these properties impact fundamental ecosystem services provided by tallgrass prairie, including forage quality and production, wildlife habitat and diversity, and carbon sequestration. Second, we will contextualize our findings from Konza within the greater tallgrass ecoregion in Kansas by assessing the same fundamental ecosystem services at two additional long-term PBG sites. Together, our proposed research activities will further our understanding of the sustainably of PBG on grasslands and soil health across the tallgrass prairie ecosystem.

B: RATIONALE & SIGNIFICANCE

Rationale: Frequently, cattle production comes at the cost of plant and wildlife biodiversity (Derner et al. 2009, Toombs and Roberts 2009, Fuhlendorf et al. 2012). PBG has the potential to produce multifunctional working lands that allow for equivalent cattle performance to traditional methods while maximizing other ecosystem services. Yet, many purported benefits of PBG for wildlife and ecosystem health, including belowground processes, remain untested. Further, the cascading effects on ecosystem sustainability remain to be investigated.

The long-term PBG experiment at Konza Prairie provides a unique opportunity to explore in depth these benefits, and our proposal is substantially strengthened by leveraging this ongoing infrastructure. First, baseline data in the first ten years of PBG management has been collected continuously on aboveground plant biomass and community composition, grasshopper and bird abundances, and cattle weight gain outcomes. This will allow us to put our proposed intensive belowground sampling into a historical aboveground context. Second, we will capture long-term PBG impacts, which is critical as ecosystem-level responses can take years to develop (Bardgett et al. 2005). Third, the experimental nature of this work facilitates the comparison of traditional and PBG management techniques in a controlled, pairwise nature. Having a control which mimics standard management in tallgrass prairie will allow us to contextualize our results for stakeholders. Lastly, by studying ecosystem services of two other long-term PBG sites, we will gain understanding of how generalizable the benefits of PBG are across the region.

Stakeholder implementation of PBG has the potential to transform the conservation value of semi-arid and mesic rangelands. However, the full potential of PBG cannot be determined until further research explores the knowledge gaps related to its effects belowground and on the connections among the many interacting components of the prairie ecosystem. The proposed work will enhance our understanding of the sustainability and stability of PBG, helping stakeholders to make informed management decisions.

Program area priorities: Our research will maximize the current priorities of Bioenergy, Natural Resources, and the Environment in the priority area of Soil Health by specifically addressing two program goals. First, our research will *assess new management/conservation practices* by experimentally comparing PBG to traditional management. We will assess biodiversity responses to PBG across multiple trophic levels and explicitly study the strengths of the interactions among these levels, both above- and belowground, with a network analysis. This holistic approach will shed light on how PBG can enhance conservation value of rangelands by providing not only provisioning services (cattle production), but also supporting (wildlife habitat for local native species, soil health) and regulating services (nutrient cycling, carbon sequestration). We will explicitly test the hypothesis that PBG maximizes ecosystem health to support natural resources and improve sustainability of this agroecosystem through a cross-site comparison of three long-term PBG experiments in eastern Kansas. Second, our research *will advance scientific understanding of soil physical and biogeochemical processes and interactions* by focusing on soil health, above-belowground connections, interactions across trophic levels, and connectedness of ecosystems. While studying these components in the context of PBG *vs*. traditional ABG management, our findings will also help strengthen our theoretical understanding of the implications of heterogeneity, and the applications of network theory. Overall this research directly relates to the objectives of the Farm Bill and the USDA Strategic Plan (FY 2018-2022 Strategic Goals 5&6) to protect and sustain the country's vital natural resources by conserving working landscapes and promoting biological diversity.

Long-term improvement and sustainability: USDA aims to increase the percentage of land with conservation and management strategies in place to sustain agricultural productivity *and* ecological health. This proposed research aims to understand PBG, a land management technique hypothesized to conserve natural resources on working lands. We will conduct an in-depth study detailing the potential of PBG to improve sustainability and maximize the ecosystem services of the important tallgrass prairie agroecosystem. In addition to disseminating our findings through peer-reviewed publications and extension bulletins, we will also involve the next generation of stakeholders by developing an online Schoolyard LTER unit about PBG administered and maintained by the Konza Prairie KEEP (Haukos Letter of Support). By reaching out to future generations of land managers, the proposed work could inform a management transition that turns working lands into conservation havens, while maintaining functionality.

C: APPROACH

C1: OBJECTIVES

Currently, land management techniques are geared toward creating homogeneous forage and grazing pressure across the landscape (Fuhlendorf and Engle 2001, Holechek et al. 2010), often with negative consequences on ecosystem health and other ecosystem services. PBG touts the ability to simultaneously optimize livestock production as well as other ecosystem services like wildlife habitat. Our project aims to assess the validity of this statement and explore the influence of PBG on ecosystem health and sustainability at three scales, the patch (individual burning units), the landscape (across all burn units), and the region (across sites in Eastern Kansas). We will do this through four supporting objectives that will enhance our understanding of heterogeneity, trophic interactions, and ecosystem services in PBG tallgrass prairie.

Objective 1. Assess the effects of PBG management on ecological properties, processes, and services (including understudied belowground components) at both the landscape and patch scale. Influences of PBG on cattle and a few select groups of native animals have been documented, although minimally in some cases. PBG effect on the multiple ecosystem functions of tallgrass prairies, however, have yet to be explored in detail. We propose to *measure a suite of 33 ecological properties and processes* in ABG and PBG managed landscapes. This in-depth investigation will include for the first time an *assessment of PBG effects on <u>belowground</u> communities and biological processes.* Our proposed measurements include 1) abiotic soil conditions, 2) above- and belowground communities (scaling several trophic levels), 3) above- and belowground biotic responses, and 4) multiple ecosystem services (See Table 1 for details). We will first compare the effects of these two management techniques on each of these response variables. Then, co-located sampling of all variables will enable direct *comparisons of the magnitude and sign (i.e., positive or negative) of linkages across trophic levels*, elucidating mechanisms behind PBG benefits. In addition to studying landscape level effects of PBG, we will also *study successional effects driven by time since burning* by examining how burning creates variability among patches across the landscape and within patches through time for our suite of ecological properties and processes.

Objective 2. Determine whether PBG enhances ecosystem coupling at the landscape scale. Linkages between ecosystem components are critical for the functioning of ecosystems. To understand the effects of PBG on network properties, we will calculate ecosystem coupling – the degree to which abiotic and biotic conditions are correlated with one another – as a measure of connectedness using two approaches. First, employing 17 of our 33 response variables (excluding measures of ecosystem services; see Objective 3), we will quantify the interconnectedness of ecological properties and process across the landscape in an ecosystem coupling network analysis. Creating and quantifying these networks will allow us to compare coupling strength between ABG and PBG. Second, we will study the consistency of ecosystem coupling over the course of three years of data collection. This multi-year approach will provide robustness to our findings, as well as the opportunity to examine variability in ecosystem coupling due to annual precipitation, an important ecosystem driver which is known to be highly variable in grassland systems.

Objective 3. Investigate how ecosystem coupling affects ecosystem services in the context of PBG. Stability of ecosystem services is an important component of ecosystem health and can contribute to the long-term sustainability of working lands. More highly connected ecosystems are predicted to have higher ecosystem stability through space and time. We will *examine the relationship between ecosystem coupling and 6 ecosystem services*: forage production and quality, wildlife habitat structure and provisioning, carbon sequestration, and cattle performance.

Objective 4. Examine landscape level ecosystem services generated by long-term PBG at multiple sites throughout tallgrass prairies. While an in-depth study of a single site is fruitful, expanding our findings to other areas is critical. We will explore the effects of long-term PBG on the same 6 ecosystem services (see Objective 3) at two additional sites across the tallgrass prairie region of Kansas. This cross-site approach will provide robustness to our findings, as well as the opportunity to explore variability in PBG effects on ecosystem services.

Ultimately, our project will enhance understanding of how PBG will affect the sustainability of rangeland ecosystem services outside of cattle production and help facilitate the adoption of novel management practices that promote multifunctional working lands.

C2: METHODS

Stakeholder involvement

We will work with personnel from numerous state and national agencies to determine how to best disseminate study findings to land managers. These agencies include Nature Conservancy, Konza LTER, Konza Prairie Biological Station, Anderson County Prairie Preserve, Kansas Biological Survey, and Tallgrass Prairie National Preserve. Our advisory board is made up of personnel from many of these agencies. Multiple meetings per year will be held with the advisory board, where members will be updated about study findings, and discussions will be conducted to help determine future directions.

Site Descriptions

We address Objectives 1-3 at the Konza Prairie Biological Station (KPBS), located in the Flint Hills ecoregion of northeastern Kansas (Figure 1A). KPBS is a 3,487-ha area of native unplowed tallgrass prairie and has been a Long-Term Ecological Research (LTER) site since 1981. The site is managed as a replicated, watershed-level fire and native grazer (*i.e.*, bison) experiment, established in 1977 and 1987, respectively. Additionally, cattle have occupied an experimental portion of KPBS since 1992. The climate is temperate (mean July temperature = 27°C; MAP = 835 mm/year) (Knapp et al. 1998), and soils are fine textured udic argiustolls underlain by limestone (Melzer et al. 2010). A small number of perennial C_4 grasses including *Andropogon gerardii*, *Schizachyrium scoparium*, and *Sorghastrum nutans* dominate the plant community and account for the majority of herbaceous primary productivity (Knapp et al. 1998), while plant species diversity is generally a function of forb species (Collins and Glenn 1991).

We have selected two secondary sites in eastern Kansas (Figure 1) to address Objective 4. The first is the Tallgrass Prairie National Preserve (TPNP), a 4,409-ha unplowed native tallgrass prairie in the Flint Hills ecoregion of southeastern Kansas due South of KPBS, run by the National Park Service and The Nature Conservancy. The second is the Anderson County Prairie Preserve (ACPP), a 597-ha preserve of unplowed native prairie located due east of TPNP. With deeper soils and slightly higher rainfall, this site boasts slightly higher species diversity than the Flint Hills region.

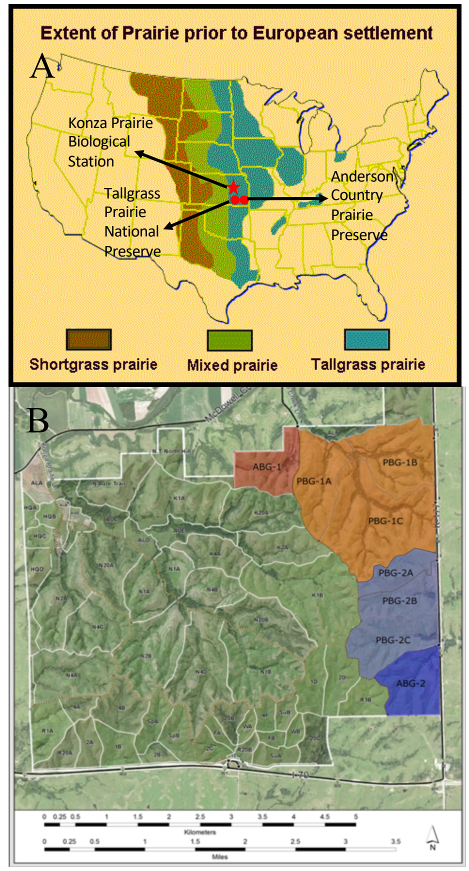

Figure 1. Proposed experimental sites. A) Historical extent of Great Plains prairie ecosystems and location of Konza Prairie Biological Station (KPBS; red star) and the two secondary sites (red circles). B) Map of KPBS. Highlighted are the North (warm colors) and South (cool colors) units where the Patch-Burn Grazing experiment is located. ABG = annual burning and grazing treatment; PBG = patch burn grazing treatment. PBG watersheds labeled A, B, and C are burned in different years.

Experimental Design at Primary Site (KPBS)

Here we propose to work in the PBG experiment located in the cattle grazing portion of KPBS, established in 2010 (Figure 1B). This is a long-term, large-scale (watershed) experiment that addresses the effects of fire-grazing interactions in the context of a PBG management system. There are two replicate management units (Figure 1B: North Unit (orange) and South Unit (light blue), each consisting of three pastures (watersheds). The burning treatments are rotated annually so that each pasture is burned every third year. Thus, only one pasture per unit is burned each year. Cattle can roam the entire unit (*i.e.*, no cross-fencing). Each PBG unit is paired with an ABG unit for comparison with traditional grazing systems (North Unit AGB-1 (red) and South Unit AGB-2 (dark blue)).

All grazing units are stocked with cow/calf pairs from approximately 1 May until 1 Oct at a stocking density equal to 3.2 ha per cow/calf. The South Unit consists of 452 acres and is stocked with 56 cow calf pairs, with 27 pairs on the adjacent control plot. The replicating North Unit is stocked with 103 pairs on 829 acres, with 19 pairs on the adjacent control plot. These stocking rates result in comparable animal densities per land unit area. The Kansas State University Department of Animal Science facilitates and implements the cattle experimental stocking rates and monitors cattle performance, including weight gain and body condition to assess the economic feasibility of using PBG management on a widespread basis (Olsen Letter of Support).

Current data from the PBG experiment at KPBS shows variable effects of PBG on different organismal groups. We investigated the change over time at the landscape scale (n=2, Figure 2 left panels) and successional differences between patches (patch scale) with different burn histories (n=7, Figure 2 right panels) using existing bird, grasshopper, plant species, and plant biomass data (Figure 2). Bird abundance is higher in the PBG treatment compared with ABG, driven by higher bird numbers in areas that were not burned in a given year. In contrast, grasshopper abundances are greater in the ABG treatment compared with PBG over time, regardless of years since burning. For plant species richness, we analyzed rarefied species richness at the landscape level to account for the higher sampling intensity in the PGB treatment. Plant species richness is increasing over time in the PBG treatment, but there is no difference between PBG and ABG. At the patch scale, using average species number per plot, plant species richness did not vary between treatment or years since fire. Lastly, plant biomass, measured using disk pasture meter, was not affected by PBG but did exhibit high variability over the years. At the patch scale, standing biomass accumulates in the absence of fire, but there are no significant treatment differences. The data presented here demonstrate that PBG may influence different trophic levels in unique ways, warranting more comprehensive research. Several of the measurements presented here show interesting trends over time, highlighting the need and opportunity to sample this experiment in its 10th-12th year.

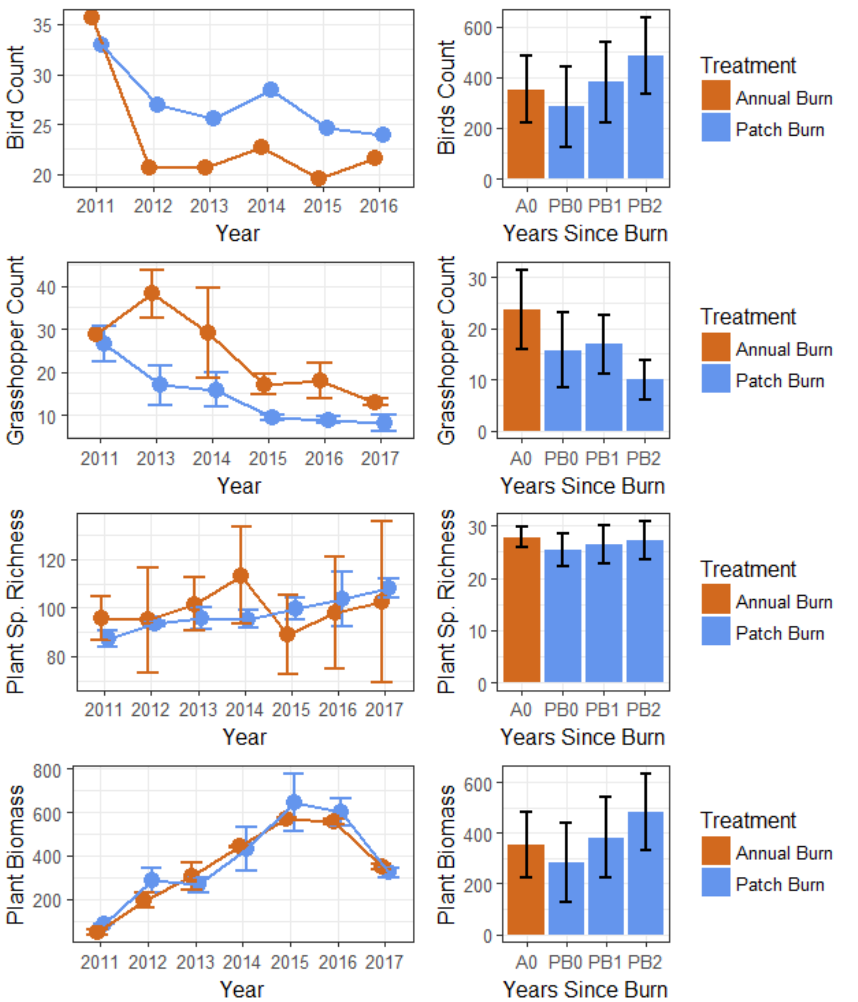

Figure 2. PBG effects summarized from existing data at KPBS. Left panel shows results at the landscape level (n = 2) and displays the change over time. Right panel shows differences among patches (n = 7), where each year of a burn treatment is considered a replicate. Bird and grasshopper count = average number of individuals observed. Plant species richness = rarified number of plant species (landscape scale) or average number of plant species in a plot (patch scale). Plant biomass = estimated g m^{-2} using a disk pasture meter. All methods are described in the "Proposed Activities" section.

Experimental Design at Secondary Sites (TPNP and ACPP)

Each of the secondary sites has a single PBG management unit. At TPNP, PBG began in 2006 in Big Pasture, a 3,820-acre pasture with three patches (1,391, 1,203, 1,223 acre) burned on a rotational basis. Stocker cattle graze Big Pasture from mid-April to mid-July at a stocking rate of approximately 2.8 hectares/cow. Ten long-term vegetation monitoring sites were established in 1997 and have been sampled annually from 2002-2008 and 2010-2014 by the Heartland Inventory and Monitoring Network. Likewise, breeding bird surveys are conducted annually in Big Pasture since 2001. Butterflies and habitat structure sampling has also occurred sporadically by independent researchers. This site has excellent fire history and stocking rate records. The land tenant implements the cattle experimental stocking rates and monitors cattle performance, including weight gain and body condition.

At ACPP, PBG began in 2010 in a 741-acre pasture, with three patches (264, 254, 242 acre) burned on a rotational basis. Cow/calf pairs graze from 1 May until 8 October, with the tenant (Tim Benton, Benton's Hillhouse Angus) maintaining 100-120 pairs yielding a stocking rate of ~2.6 ha/pair. Since 2010, there have been numerous avian, entomologic, herpetologic, and vegetation surveys conducted by independent researchers. This site has complete fire history and stocking rate records, and the tenant implements the cattle experimental stocking rates and monitors cattle performance.

Proposed Activities at Primary Site (Objectives 1-3)

At KPBS, we propose do an in-depth investigation of both the above- and belowground effects of PBG management. This proposal leverages the on-going long-term experiment, for which some data are already annually collected (see Table 1). Long-term plant species composition plots (10 m^2) currently exist in each of the eight watersheds, composing two full sets of PBG treatments and controls (n=2). Each watershed has four transects, each comprised of five species composition plots (20 plots per watershed). During the growing seasons (April-Sept) of 2020-2022, we propose to measure 25 new variables within 2 × 2 m sampling plots (Figure 3), which we will establish 2 m from the species composition plots, such that species composition measurements can be paired with our new measures. Additionally, the 8 variables that have been historically measured within the PBG experiment at Konza will continue to be collected. Below, we describe these 33 total measurements in more detail.

<u>Existing data</u> - As part of the Konza LTER program, a number of measurements are currently collected in PBG that describe plant species composition, aboveground vegetation standing biomass, aboveground net primary productivity (ANPP), habitat structure and quality, cattle performance, grassland bird populations, small mammal populations, and grasshopper community composition and total abundance. Details of each of these data sets can be found in

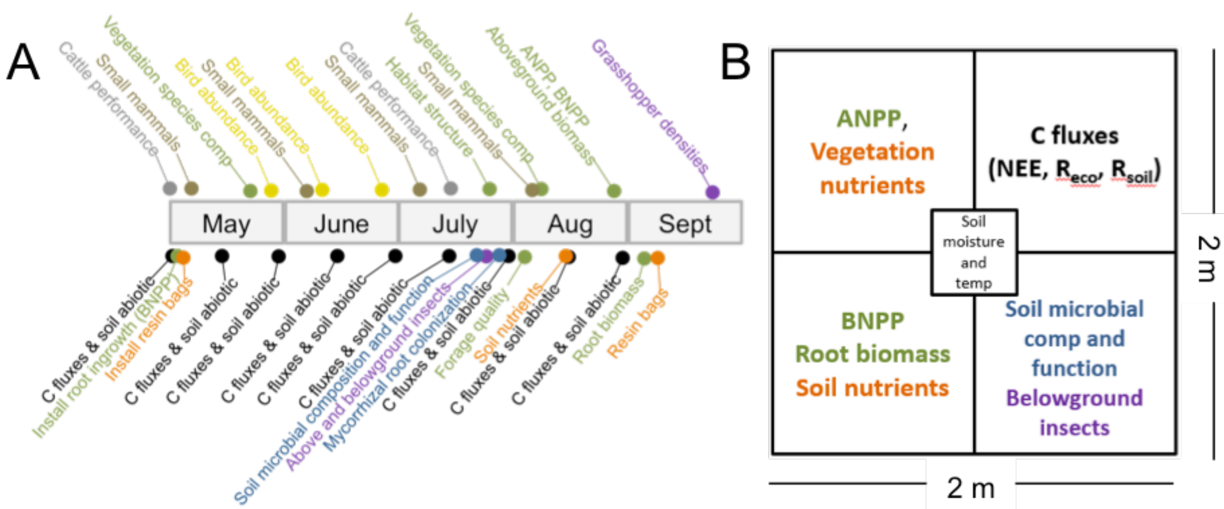

Figure 3. Annual sampling timeline at KPBS (A) and proposed sampling plot layout (B). Measurements indicated below the timeline are new measurements to be collected each year from 2020-2022. The colors in panel A correspond to those in panel B, showing both when (A) and where (B) each measure will be taken. Measurements indicated above the timeline have been collected since 2011 and will continue to through 2022.

the Konza Prairie LTER data catalog.

Above- and Belowground Abiotic Environmental Conditions - Sub-hourly meteorological data, including precipitation, air temperature, relative humidity, and solar radiation, will be obtained from a meteorological station at KPBS that is *ca.* 2.5 miles from the experimental site. Within the center of each sampling plot, soil moisture and temperature will be measured down to 15 cm using a HydroSense II every two weeks from May through August. These measurements will coincide with the timing of soil C flux measurements. Also, soil cores will be taken once per year to measure soil N and C using a LECO Tru-SPEC elemental analyzer. Resin bags will be used to assess integrated soil N and P availability over the growing season.

Aboveground Invertebrate Community Composition and Biomass - Grasshopper abundance has been collected for the first 9 years of the experiment. We propose to assess the entire aboveground invertebrate community and biomass once per growing season at peak invertebrate abundance (mid-July). Aboveground invertebrates will be sampled within a second 2 × 2 m permanent plot (adjacent to the vegetation transect) using a modified leaf blower with a vacuum function. Any Orthoptera (grasshopper/katydid) that hop out of the plot will be visually identified and counted. Sampled aboveground invertebrates will be immediately frozen and stored at -20℃ until sample processing. All aboveground invertebrates will be counted and identified to Family, with Orthoptera being further identified to species and Cicadellidae being further identified to morphospecies, to obtain invertebrate abundance and community composition. All aboveground invertebrates will then be dried at 60℃ for 48 hours and weighed by Family to obtain aboveground invertebrate biomass.

Belowground Invertebrate Community Composition and Biomass - Belowground macroinvertebrates will be sampled using Berlese funnels. Briefly, in mid-July, four 10 cm diameter soil samples taken to a depth of 10 cm will be composited with four 5 g plant litter samples and placed over a mesh screen with an ethanol filled sample collection vial underneath. A 150-watt bulb will be placed above the sample and kept on for 5 days, at which point the sample jars will be capped and stored for invertebrate identification. All belowground invertebrates will be counted, identified to Family, and dried to obtain biomass estimates as described for aboveground invertebrate collection (see above).

Soil Microbial (Bacterial, Archaeal and Fungal) Community Composition - Soil samples will be collected within each plot at peak plant biomass (August) to characterize microbial community composition (Carson and Zeglin 2018). Four 2.5 cm diameter soil cores will be taken to a depth of 15 cm, collected into sterile bags, composited by plot, and transported to the lab on ice. In the lab, each composited sample will be passed through a sterile #30 sieve and homogenized. From the homogenized cores, DNA will be extracted, extracellular (non-living) DNA removed (Carini et al. 2017), an internal standard added (Smets et al. 2016), and frozen for future processing. Fungi and bacteria will be amplified from each DNA extraction using fungal/bacterial-specific primers. Briefly, for fungi the nuclear internal transcribed region 2 (ITS2) will be amplified using a nested PCR design with fungal-specific primers (first run: ITS1F; second run: ITS86F) (U'Ren et al. 2014); for bacteria the V5-V6 region of 16S rRNA gene will be amplified using a nested PCR design and cyanobacteria-excluding primers (first run: 799F and 1492R; second run: 799F and 1115R) (Carrell and Frank 2015). Microbial communities will be sequenced using high-throughput meta-barcoding techniques on a MiSeq Illumina platform with 300bp paired-end reads (Glenn 2011, Orgiazzi et al. 2015). Raw sequences will be demultiplexed and assigned quality reads to operational taxonomic units (OTUs) at 97% similarity (Kembel and Mueller 2014, Kembel et al. 2014). For fungi only, OTUs will be assigned to a functional group using the FUNGuild database (Lankau and Keymer 2016, Nguyen et al. 2016). The FUNGuild database assigns genera to one of several guilds (*e.g.*, ectomycorrhizal, arbuscular mycorrhizal, plant pathogen, endophyte, wood-decay saprotroph) based on a community-annotated database of fungal taxa with known or suspected ecological functions. Such classification will allow us to separately assess diversity relationships within target functional groups, especially AM and non-mycorrhizal fungi (Carson et al. 2019).

<u>Soil Microbial Function</u> - Activity of nine microbial extracellular enzymes will be measured from soils collected for microbial composition (see above). Enzymes involved in processing organic carbon (β-D-cellobiohydrolase, α-glucosidase, β-glucosidase, β-xylosidase, peroxidase, phenol oxidase), nitrogen (N-acetyl-β-glucosaminidase, leucine amino peptidase), and phosphorous (acid phosphatase) will be assayed following standard procedures (Bell et al. 2013). Briefly, soil slurries will be prepared using 1 g fresh soil and pH 5 sodium acetate solution. Substrate and soil slurries will be added to 96-well plates, with 6-8 analytical replicates per sample. Eight replicate wells per plate will be used for negative controls, sample blanks, quench standards, and reference standards. Plates will be incubated at 25°C in the dark for 2-20 hours, with substrate-specific incubation times already determined based on saturation kinetics for local soils (Zeglin et al. 2007, Hsiao et al. 2018). Fluorescence will be measured using a plate reader fluorometer/spectrophotometer with excitation and emission filters set at 360 nm and 450 nm for hydrolytic enzymes, and absorbance filters set at 450 nm for oxidative enzymes.

<u>Mycorrhizal root colonization</u> - Along each transect, 5 soil cores will be taken around the base of the dominant C_4 grassland species (*A. gerardii, S. nutans, S. scoparium*) at peak standing biomass. Roots will be sieved from the soil, cleaned, and stored in 50% ethanol. Roots will be stained with Typan-Blue and scored for root colonization (Phillips and Hayman 1970, McGonigle et al. 1990).

<u>Belowground net primary productivity and root biomass</u> - Belowground net primary productivity (BNPP) will be assessed using 5 cm diameter 30 cm deep root ingrowth cores (Persson 1980). Total root biomass will be measured from soil cores of the same dimensions as root ingrowth cores. Two root ingrowth cores will be deployed within 2 m of each species composition plot in April. Root ingrowth cores will be removed in September. Two soil cores in the same areas will be taken in early August (peak biomass). All root samples will be elutriated to separate roots from soil, sorted to remove SOM and dead root material, dried at 60°C for 48 h, and weighed. Samples will then be burned at 450°C to obtain (and subtract off) ash-free dry mass.

<u>Vegetation stoichiometry and forage quality</u> - Aboveground vegetation within one 20 × 50 cm quadrat will be clipped to ground level within one quadrant of each plot at peak growing season biomass (early August) for stoichiometric measurements. Biomass will be dried, ground, and mixed. Percent N and C per unit dry mass will be determined from a subsample of the mixture using a LECO Tru-SPEC elemental analyzer. Additional forage quality measures will also be

assessed from aboveground vegetation samples: two-stage (microbial and acid) in vitro dry matter digestibility will be conducted (McDougall 1948, Tilley and Terry 1963), and nitrogen values will be multiplied by 6.25 to obtain crude protein (CP); total nonstructural carbohydrates (TNC) will be measured by extracting with 0.2 N H_2SO_4 (Smith 1969) and titrating reducing sugars by the Shaffer-Somogyi technique (Heinze and Murneek 1940); and foliar silica content will be determined using the colorimetric silicomolybdate technique (Allen 1989).

Ecosystem carbon fluxes - Soil flux measurements will allow assessment of PBG impacts on C sequestration throughout the growing season. Measurements of ecosystem respiration (ER) and net ecosystem exchange (NEE) will be taken every two weeks from May through August using a 0.5 × 0.5 × 0.5 m transparent, polycarbonate chamber with an internal fan (Niu et al. 2013) attached to a Li-Cor 6400 Photosynthetic System (Li-Cor, Lincoln, NE) fit over a 0.5 × 0.5 frame permanently inserted into the soil. Ecosystem respiration will be assessed by covering the chamber with an opaque cloth to exclude radiation. Gross primary productivity will be calculated from NEE and ER estimates. Soil respiration will also be measured bi-weekly using a Li-Cor 8100 Soil Gas Flux System fit over PVC collars installed 8 cm deep, with a 2 cm lip. Living vegetation and litter will be removed prior to each sampling. NEE, ER, and soil respiration measurements will all be taken between 11 am and 1 pm on days with full sun.

Proposed Activities at Secondary Sites (Objective 4)

In order to place our in-depth findings at KPBS into a broader context, we selected two secondary sites where we will sample a subset of variables (see Table 1) aimed at assessing ecosystem services provided by PBG. These sites will be sampled in 2020 only, obtaining a snapshot of the ecosystem services provided by PBG. We will sample each of the three burn patches within the PBG unit to assess soil carbon, forage quality and availability, habitat structure, plant biodiversity, habitat provisioning, and cattle performance.

Feasibility - The five co-investigators have complementary research skills in grazing effects on plant community dynamics and forage production (Koerner), functioning and community dynamics of grassland invertebrates (Komatsu), mycorrhizal colonization and nutrient cycling (Avolio), carbon cycling and belowground plant dynamics (Wilcox), and soil microbial communities and function (Zeglin). We also include letters of support from experts on small mammals (Ricketts), grassland birds (Boyle), and cattle production (Olson).

Table 1. Summary of data collection organized by variable type.

Type of Variable	**Response Variables**
Abiotic soil conditions	1. Nitrogen and phosphorus availability (NH4+, NO3-, PO43-) 2. C:N † 3. Soil moisture 4. Soil temperature
Above and belowground communities	1. Plants* (2010-present) † 2. Above* & belowground invertebrates (historically grasshoppers; 2010-present) 3. Soil Fungi 4. Soil Bacteria & Archaea

Biotic processes	1. Aboveground standing biomass* (2010-present) † 2. Belowground standing root biomass 3. Microbial biomass & enzyme activity 4. Mycorrhizal root colonization 5. Above and belowground invertebrate biomass
Ecosystem services	1. Forage quality (leaf C:N, leaf crude protein, leaf silica content, forb:grass ratio) † 2. Forage production (ANPP*; 2010-2013) † 3. Carbon sequestration (NEE, ANPP, BNPP, soil C, soil CO_2 flux, R_{eco}) 4. Habitat structure (vegetation height*, litter*, bareground*; 2010-present) † 5. Cattle performance* (2010-present) † 6. Habitat provisioning (birds*; 2011-present, small mammals*; 2011-2013) †

* data have been collected as part of the on-going PBG experiment at KPBS (dates of collection)
†Variables to be measured at both primary and secondary sites

Expected results and outcomes

Overall, this proposed project will have two broad and impactful outcomes. First, we will provide stakeholders with in-depth information describing the effectiveness of PBG to increase ecosystem health and conservation of natural resources. Second, we will further develop ecological understanding of the importance of ecosystem coupling for stability and provisioning of ecosystem services.

Objective 1: Assess the effects of PBG management. PBG will likely have substantial effects on the variability of ecosystem properties across the landscape. We predict that this increased landscape-level heterogeneity will lead to enhanced biodiversity across all trophic levels and increased heterogeneity of function. We also predict PBG will enhance (*e.g.*, habitat quality) or maintain (*e.g.*, cattle performance) ecosystem services. We expect at least six major publications: 1) Multi-functionality of PBG managed grasslands (synthesis of all variables); 2) Long-term plant dynamics, utilizing previous and proposed data collection; 3) PBG effects on soil health dynamics with a focus on microbial and fungal dynamics; 4) PBG effects on soil health dynamics with a focus on carbon fluxes and sequestration; 5) PBG effects on insect community dynamics; 6) Data paper that includes all current and proposed data for open access by the public

Objective 2: Determine whether PBG enhances ecosystem coupling. We predict that PBG will increase ecosystem coupling. We expect that cattle, much like wildebeest in the Serengeti, will follow plant resource asynchronies across the landscape, creating small-scale 'migrations'. This will enhance spatial nesting and thereby food web stability (McCann et al. 2005, Rooney and McCann 2012). In contrast, we predict that the synchronized resource dynamics of ABG would degenerate this spatial coupling. Further, we predict that the strength of ecosystem coupling will vary temporally in response to annual precipitation. We expect one publication on ecosystem network strength and stability in PBG *vs*. ABG through time.

Objective 3: Investigate how ecosystem coupling affects ecosystem services. The degree of spatial coupling can affect stability of food webs and ecosystem processes (Rooney and McCann 2012). We hypothesize that ecosystem coupling will affect ecosystem services, such that when ecological processes are more closely correlated to one another, this will result in greater ecosystem function and services. We expect at least one publication detailing the relationship between ecosystem coupling and ecosystem services with PBG.

Objective 4: Examine ecosystem services generated by long-term PBG at multiple sites. We predict that PBG will enhance ecosystem services across all sites regardless of site differences via increased heterogeneity across the unit. We expect at least one publication exploring the ecosystem services generated by PBG in the tallgrass prairie region of eastern Kansas.

Evaluation of education activities

The efficacy of education activities associated with this project (see "Communication of results" below), run through the Konza Prairie KEEP program (Haukos Letter of Support), will be assessed using formative evaluation, a method that feeds results back into the program to continually refine the activities (Beswick 1990). Student mastery of skills taught in the KEEP activities will be assessed through student presentations of their work. Additionally, student and teacher questionnaires will identify areas of program improvement for future years.

Analysis assessment and interpretation

The PBG experiment at KPBS currently has two replicates of each management style. There are two ABG control watersheds and six watersheds that are burned once every three years, split into two PBG replicates. Thus, the number of watersheds in each treatment is different (two *vs*. six). We will accommodate this complicated, but necessary, experimental design through careful selection of analytical techniques. Ultimately, we are interested in assessing the effects of PBG at the scale of the landscape, necessitating averaging the three PBG watersheds that constitute a single replicate to the landscape scale. To address our three main objectives, we will run three overarching analyses: 1) test whether PBG affects abiotic soil conditions, above-and belowground communities, biotic processes, and ecosystem services, 2) assess whether PBG affects ecosystem coupling (the degree to which abiotic conditions, biotic communities, and biotic process are correlated with one another), and 3) investigate whether ecosystem coupling affects derived ecosystem services.

<u>Objective 1</u>

To meet our first objective, we will perform three statistical tests. First, to test for the effect of the different management strategies (traditional or PBG, n=2) at the landscape scale we will run separate repeated measures ANOVAs for each response variable (See Table 1 for list of variables). For these analyses we will first average the five plots in a transect, and then the four transects within a watershed, and lastly all watersheds in a replicate (three for PBG, no averaging for ABG), creating a balanced design of two replicates in each treatment. For each response variable, we will collect three years of data (proposed work); however, for those variables that have been collected since the start of the experiment (Table 1 asterisked variables) we will perform additional ANOVAs using all years of data. Second, we will test for differences at the patch (watershed) scale to capture heterogeneity across the landscape and successional patterns for all our response variables. To perform these analyses we will conduct one-way ANOVAs with years since burn (PBG-0, PBG-1, PGG-2 or ABG) as a factor and each year of data as a replicate. Thus, with three years of data there will be an n=6 for each PGB and n=6 for the ABG watersheds. Similarly, when a longer time series exists, we will perform a second analysis that incorporates all years of data. Lastly, for the plant, insect, fungal and bacterial communities, Bray-Curtis dissimilarities will be compared using PERMANOVA to test whether composition differs across (1) different management strategies and (2) years since burning (Anderson 2005). PERMDISP will be used to determine whether community dispersion (a measure of beta diversity) differs among (1) management strategies or (2) years since burning (Anderson 2004).

<u>Objective 2</u>

For our second objective we will investigate ecosystem coupling (Figure 4). Ecosystem coupling can be measured as the overall strength of correlations among communities of organisms and their physical environment (Ochoa-Hueso 2016). Unlike traditional ecological networks (*e.g.*, food webs), ecosystem networks examine the relationships between multi-species communities rather than individual species interactions (Ochoa-Hueso 2016). Ecosystem coupling is indicative of the connectedness of an ecosystem, which can then be related to its functioning and stability through space and time (Morriën et al. 2017).

In order to determine the effects of PBG on ecosystem coupling, we will develop an ecosystem network for each replicate (PGB or ABG managed) for each year of data, resulting in 12 networks (4 landscape level units x 3 years of data). These networks will include the correlational relationships between all collected response variables over the 20 plots in the watershed. Since there are only 20 plots in the traditionally managed replicates we will randomly subset 20 plots in the PBG treatment across all three watersheds. To include community data, the communities of each trophic level (*i.e.*, plants, microbes, and invertebrates) will be composited in PCA space, and PCA axes accounting for 90% of the variation for each level will be included in the network analysis. To calculate ecosystem coupling, first we will run all pairwise correlations between response variables and extract the absolute value of Spearman's rho coefficient for significant correlations only. Next, we will derive ecosystem coupling as the

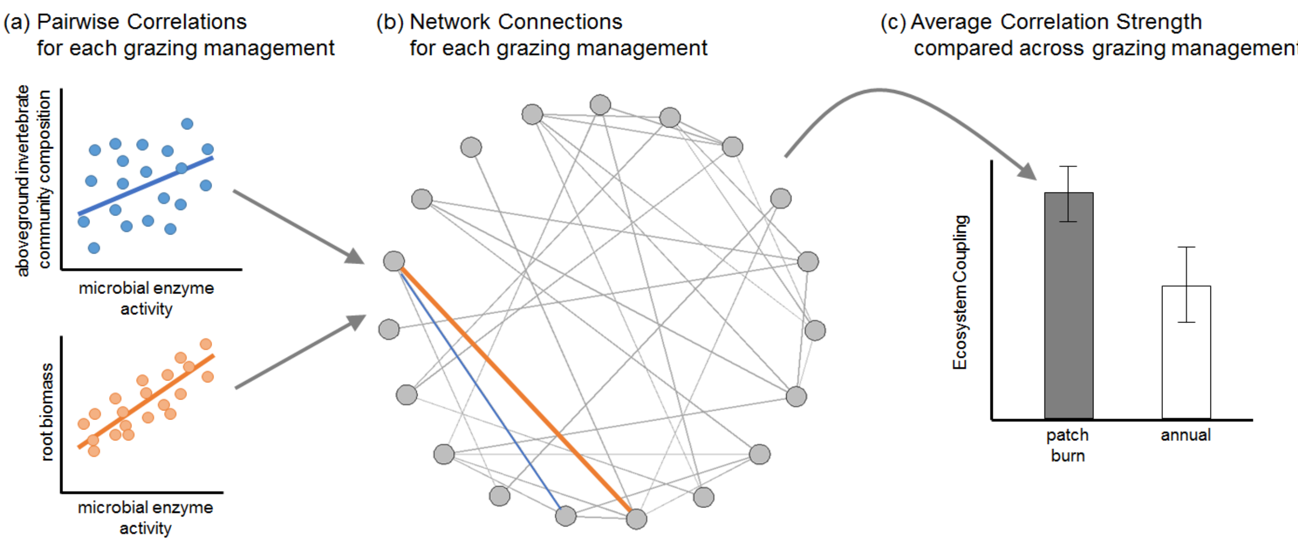

Figure 4. Network analysis pipeline. For each grazing management strategy (PBG and ABG), we will (a) calculate correlation coefficients for all pairwise combinations of variables within each plot, (b) visualize network connections, and (c) take the average correlation coefficient for each network. These average correlation coefficients will be used as a measure of ecosystem coupling, to be compared across grazing management strategies. Non-significant correlations will be considered as zeros for the network visualization and calculation of ecosystem coupling.

average Spearman's rho for all data except ecosystem services (Table 1). Ecosystem networks will be developed by examining rho coefficient across all significant pairwise correlations. Higher rho-values indicate more tightly coupled ecosystems. Once ecosystem coupling metrics have been calculated, we will use repeated-measures ANOVA, with time repeated, to see if the degree of ecosystem coupling differs between the two management techniques. Additionally, we will study whether ecosystem coupling is affected by yearly climatic conditions, such as precipitation and temperature using linear regression.

Objective 3

For Objective 3, we will assess whether the degree of ecosystem coupling is related to derived ecosystem services. To do this we will use linear regression with the degree of ecosystem coupling explaining ecosystem services (See Ecosystem Services row in Table 1). For these regressions we will have 12 data points.

Objective 4

For our final objective, we will assess how PBG influences ecosystem services across sites. We will test for differences at the patch (watershed) scale to capture heterogeneity across the landscape and successional patterns for all our response variables. To do this we will use a two-way ANOVA including site and year since burn. We will run separate models for each response variable (See Table 1 for list of variables).

Communication of results

Overall, we expect this four-year award to train three graduate students, provide research experience for numerous undergraduates, and produce several publications (see "Expected results & outcomes") in rangeland and ecology journals. In addition to presenting at professional meetings, in our fourth and final year of the award, we propose to host organized sessions at both the Ecological Society of America and Society for Range Management annual meetings, focused on the ecosystem services provided by PBG. We will use this opportunity to publicize our and other PBG researchers' findings. These activities will facilitate discussion and exchange of ideas, and we plan to write a synthesis paper with these groups. Furthermore, we will endeavor to convey our findings beyond the scientific community to a wide range of audiences via extension bulletin publications, field tours, and educational materials for middle school and high school students. For example, we will publish our findings in *Science Journal for Kids*, an open-access journal that takes cutting-edged, peer-reviewed research, and adapts it for middle and high school students. As another example, by working at the Konza Prairie, we have access to the Konza Environmental Education Program (KEEP; see letter of support from Jill Haukos). KEEP is an incredibly successful site-based education program with one full time and two part time employees, which brings ~3,000 students to Konza Prairie every year. In collaboration with KEEP, we will develop an online curriculum program aimed at understanding the differences between PBG and more traditional management strategies. By developing a web-based curriculum, we will have the potential to reach thousands of students, not just those who can come to Konza Prairie. Additionally, by taking the units online, we have more flexibility and can incorporate information scaffolding into the curriculum, whereby the same students learn about PBG in different years of school, building on both their knowledge progression about science as well as about PBG. By taking this multifaceted approach to communicating our results, we ensure that we will reach a broad audience.

Pitfalls & limitations

Some key response variables, such as changes to soil C, can take time to develop. While the award period is only four years, we avoid this pitfall by working in the context of ongoing, long-term experimental framework. This increases the probability of detecting long-term effects.

Many grazing and fire studies have a problem of pseudoreplication due to the large scale of rangeland management treatments (*i.e.*, comparing just one pasture of each treatment, with many subsamples within them). By working at an LTER site with existing large-scale infrastructure and experimental manipulations, we can overcome this limitation with two true replicates of both the PBG and ABG management regimes. Thus, our analyses for Objectives 1-3 will be robust to issues of pseudoreplication. We feel that this is a major strength of the proposed work.

Grazing systems are ecologically complex, and differences are often hard to detect. However, at KPBS we are sampling intensively across a broad range of variables. If differences occur at any trophic level, our sampling design enhances our chances of detecting them. Additionally, if a null result is found, and there are no significant differences in soil health, this is still a critical piece of information to disseminate to ranchers.

A limitation of the first three objectives is that they occur only at one grassland site. We will overcome this limitation through a two-pronged approach. First, for Objective 4 we will utilize two additional PBG units in the region that will allow for cross-site comparisons and a broadening of the context of our findings. Second, we will host organized oral sessions at national meetings in the 4th year and will write a synthesis and commentary paper comparing our findings to other projects in PBG systems.

Finally, lack of stakeholder participation in the design of experiment and implementation of findings likely hampers many projects. We have safeguarded our project against this pitfall by teaming up with The Nature Conservancy (Obermyer Letter of Support), to ensure idea sharing and knowledge transfer from the research to the stakeholders and vice-versa.

C3: TIMELINE

The proposed work will occur over four years, with the new data collection at KBPS occurring in Years 1-3, and the new data collection TPNP and ACPP (Objective 4) occurring in Year 1 only. Year 4 will focus on finalizing analyses and preparing manuscripts for submission. In Year 1, we will gather and analyze all available data collected prior to 2020 in the PBG experiments across all three sites. Based on these findings we will develop the first PBG online education unit for the KEEP's Schoolyard LTER program. May-August of the first three years (2020-2022) we will intensively sample the plant, microbial, and insect communities and ecosystem function both above and belowground as well as abiotic characteristics (Figure 3). In Year 4, data analysis, and manuscript preparation will occur, as well as the creation of a second PBG online education unit focused on soil health. Additionally, we will hold organized sessions at the annual meetings of both the Ecological Society of America and the Society for Range Management in Year 4, focused on PBG which will culminate with a synthesis and commentary manuscript. While the proposed work will occur over a 4-year period, we will ensure that the data and findings are available for years to come. During Year 4, we will place all data on the Konza LTER data portal with metadata for continued use. Likewise, the online educational material will be available through KEEP, ensuring accessibility into the future.