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Impacts of holistic planned grazing with bison compared to continuous grazing with cattle in South Dakota shortgrass prairie

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ABSTRACT

We assess holistic planned grazing outcomes in shortgrass prairie of the Northern Great Plains of North America. We compared key ecosystem functions on the ranch managed using adaptive multi-paddocks (AMP) grazing by bison with those on neighboring ranch paddocks managed using set stocked light continuous (LCG) and heavy continuous grazing (HCG) grazed by cattle. Sites on the neighboring ranches in each grazing category were paired for sampling by soil type and landscape position. In all paddocks, management practices had been constant for more than a decade. Positive results with AMP grazing include increased fine litter cover ($P < 0.05$), improved water infiltration ($P < 0.06$), two to three times the available forage biomass ($P < 0.001$), improved plant composition ($P < 0.05$), decrease in invasive plants ($P < 0.05$), and decrease in bare ground ($P < 0.05$). Higher infiltration occurred with AMP on soils having higher permeability but not on soils having a high clay content. Differences were greatest between AMP and HCG management with LCG being intermediate. Counterintuitively, herbaceous biomass in LCG was less than that of the more heavily stocked HCG ($P < 0.05$). This was due to decades of heavy continuous grazing resulting in HCG being dominated by invasive herbaceous plants of no forage value in contrast to LCG paddocks that had a greater proportion of palatable forages. The HCG paddocks were dominated by unpalatable invasive plants that were avoided by cattle. Soil carbon stocks increased under the AMP grazing but not on all soils. Total carbon stocks (TC), summing organic carbon and inorganic carbon, were not different between the AMP and LCG grazing strategies ($P > 0.63$) but both had higher TC values across all soils than HCG ($P < 0.001$). There were no differences in TC among grazing treatments on the different soils ($P > 0.46$) except on the Norrest silty clay loam soil that had the highest permeability. On this soil there were differences between AMP and HCG ($P < 0.0001$) and LCG and HCG ($P < 0.0001$). There were significantly lower TC levels at all soil depths with HCG than with AMP and LCG ($P < 0.05$). Using holistic planned grazing protocols with AMP grazing effectively limited overstocking and overgrazing by adjusting animal numbers to match available forage amounts and grazing for short periods followed by adequate recovery after grazing. This study indicated ecological improvements by AMP grazing on the 777 Bison Ranch compared to HCG pastures is contributing to improvements in this semi-arid short grass ecosystem.

1. Introduction

Healthy functioning grazingland ecosystems are vital for many ecological services of fundamental importance for sustaining humans and lifeforms occurring in these ecosystems. These ecosystem services include soil formation, stable and productive soils, water infiltration, clean water, nutrient cycling, C sequestration, biodiversity, air quality, and wildlife habitat and biological integrity (Daily, 1997; Millennium Ecosystem Assessment (MEA, 2005). Although many of these ecosystems have been converted to crop production, rangeland portions of the global landscape not suitable for producing human-utilizable feedstufs, are the largest portion of the earth's productive terrestrial surface (Millennium Ecosystem Assessment (MEA, 2005; Mottet et al., 2017). These extensive ecosystems can only be used by humans for food and fiber production if domestic or wild grazing herbivores consume and digest plant resources present. Ruminants play a vital role in sustaining grassland ecosystems globally.

Grazing ecosystems on earth coevolved with grazing ruminants

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(Frank et al., 1998) and the co-evolution of grass and grazers over the last 40 million years has contributed to the expansion of carbon-rich soils in semi-arid to semi-humid grassland regions covering approximately 40% of the earth's land area (Retallack, 2013). However, in most of the world's semi-arid and arid grasslands, the replacement of free-ranging wild herbivores with fenced-in livestock has caused degradation of vegetation and soils (Milchunas and Lauenroth, 1993; Teague et al., 2013), resulting in declines in productivity and biodiversity (West, 1993; Knopf, 1994; Frank et al., 1998), a reduction in ecosystem resilience (Peterson et al., 1998), and overall decline in historic ecosystem services generated through the grazer/grassland relationships.

To ensure the sustainability and resilience of grazed ecosystems, they need to be managed using grazing management protocols that avoid overstocking and overgrazing (Teague, 2018). Overstocking is avoided by ensuring that livestock numbers do not exceed the amount of forage available and to retain sufficient herbaceous material to ensure maintenance of essential ecosystem functions. Stocking rate greatly impacts soil function, vegetation composition and production, and animal production. Consequently, it has been extensively investigated and is considered the key management factor needed to maximize ranchers' long-term profits and provision of rangeland goods and ecosystem services (Huffaker and Cooper, 1995; Kobayashi et al., 2007; Ritten et al., 2010). In addition, as rangelands are characterized increasingly by a very variable climate, adapting grazing management to the changing circumstances is fundamentally important to minimizing impacts on the land resource base and economic outcomes (Jakoby et al., 2014; Martin et al., 2014).

Adjusting stock numbers alone is, however, insufficient to prevent overgrazing which is a major factor in rangeland ecosystem degradation (Teague et al., 2004; Müller et al., 2007, 2015; Teague et al., 2013; Barnes et al., 2013; Provenza et al., 2013; Savory and Butterfield, 2016). Livestock in large paddocks repetitively use preferred plants, leading to overgrazing, a major cause of unwanted changes in rangeland ecosystems. To minimize this overgrazing requires timing of grazing, provision of adequate recovery, and distribution of livestock impacts over the entire management unit (Norton, 2003; Norton et al., 2013; Barnes et al., 2008; Teague et al., 2013). Avoidance of overgrazing has been successfully achieved by leading conservation farmers in North America using adaptive multi-paddock (AMP) grazing following holistic planned grazing protocols (Gerrish, 2004; Provenza et al., 2013; Savory and Butterfield, 2016; Teague and Barnes, 2017). Their methods have included using multiple paddocks per herd with short grazing periods, long recovery periods, and adaptively changing recovery periods, residual biomass, animal numbers and other management elements as conditions change. Adaptively stocking in response to changing weather has made range resources less sensitive to overstocking than continuous stocking (Jakoby et al., 2015), and the advantages of adaptive over continuous grazing increase substantially as the number of paddocks per herd increases. This allows more livestock to be carried, while improving resource condition and net economic returns (Teague et al., 2011, 2015). Similarly, Jakoby et al. (2014, 2015) report that grazing with short grazing periods and long rest periods afforded by a large number of paddocks per herd improved carrying capacity and gave superior economic outcomes, lower income variability and greater attainment of a minimum income goal while maintaining resource condition.

In moderately dry and mesic grazing ecosystems these adaptive multi-paddock grazing strategies have been shown to restore soil function and provision of ecosystem services (Gerrish, 2004; Barnes et al., 2013; Provenza et al., 2013; Teague et al., 2013; Teague and Barnes, 2017), but we need to determine how well they work in drier grazed ecosystems. This study was conducted in the dry shortgrass prairie of the Northern Great Plains of North America to evaluate if adaptive multi-paddock grazing management has resulted in improved outcomes on key ecosystem functions in this region. We compared several key ecological functions on the 777 Bison Ranch that has been managed using holistic planned grazing (HPG) decision-making protocols (Savory and Butterfield, 2016) since the mid-1980's with those on neighboring cattle ranches that have been set stocked either heavily (HCG) or lightly (LCG) for decades. The parameters we measured include: soil carbon stocks; soil organic carbon (SOC) accrual rates; water infiltration rates; plant diversity; plant biomass; and forage quality.

2. Methods

2.1. Site description

The 777 Bison Ranch is in the shortgrass prairie ecosystem in Custer County, near Hermosa, SD, (43°41 N 103°12 W). The dry continental climate (Köppen *Dfb*) experiences an average 95 frost-free growing days, winds are predominantly SW at 6 mph (10 km/h), and mean humidity is 42%. Mean annual precipitation is 500 mm, mean annual temperature is 6.8 °C and mean elevation is 1006 m. Vegetation is dry temperate steppe. Plant species taxonomic nomenclature follows Britton and Brown (1973). Soils on the ranches included in the study were predominantly clays or clay loams, which were characterized by having very low permeability (Table 1). The only exception was the Emigrant loam, which had moderate permeability.

2.2. Experimental design

To address landscape ecological impacts and questions posed in the study we used multiple cross-site comparisons among AMP grazing paddocks on the 777 Bison Ranch and matching continuously grazed LCG, HCG paddocks on neighboring cattle ranches as outlined by Hargrove and Pickering (1992) and Teague et al. (2011). The approach provided valid comparisons among sites to assess the relative impacts and benefits of these different grazing management strategies on the bio-physical parameters we studied.

Accessible AMP, LCG and HCG grazed areas were sampled on comparable locations on the 777 Bison Ranch paddocks and adjacent paddocks on LCG and HCG cattle ranches, respectively. The comparisons paired the neighboring paddock pairs with HCG and LCG grazed rangelands to match those biophysical conditions on the 777 Bison Ranch paddocks. These paired grazing management categories were selected from the same bio-physical strata and following the land use history screening, providing comparable bio-physical strata for valid comparisons to identify grazing practice differences. Specifically, only with the same soil types, aspects, and slope positions, and grazing history were selected to ensure that grazing differences were due only to different grazing management. The same investigators and methods conducted all aspects of the study to minimize investigator bias. The paired study sites for the continuous grazing categories needed to have been managed consistently in the same manner for a minimum of ten years to be included in the study.

Table 1
Soil series and hydrological properties of soils (USDA-Natural Resource Conservation Service, 2009) on the 777 Bison Ranch managed using adaptive multi-paddock grazing and neighboring heavy and light continuously grazed ranches, Hermosa, South Dakota.

Soil series	Slope %	Depth cm	Permeability cm $hour^{-1}$	Available Water Capacity cm cm^{-1}
Blackpipe clay loam	0-6	0-13	0.5-1.5	0.40-0.56
		13-38	0.5-1.5	0.28-0.48
Emigrant loam	0-6	0-13	1.5-5.0	0.46-0.51
		13-38	1.5-5.0	0.38-0.43
Kyle clay	0-9	0-13	< 0.15	0.20-0.30
		13-38	< 0.15	0.20-0.30
Norrest silty clay loam	6-15	0-13	1.5-5.1	0.50-0.58
		13-38	0.5-1.5	0.28-0.45

2.3. Grazing management history

The 777 Bison Ranch was originally 4856 ha (12,000 ac) when purchased in 1972 and was continuously grazed with cattle until the early 1980's when grazing shifted to using holistic management. As contiguous land became available it was acquired to make up the current acreage of 12,140 ha (30,000 ac). Newer acquisitions were government owned and private parcels of land that were continuously grazed and in poor condition at purchase. Some previously farmed land was obtained from neighbors who, in the late 1970's, had planted some parcels with crested wheat (*Agropyron cristatum*) and smooth brome *(Bromus inermis)* and some pastures were chiseled to enhance infiltration and stimulate a seed bank response of blue grama and buffalo grass. This grazing and cropping left both soil and vegetation on the ranch in poor condition. LCG and HCG are the most commonly used management practices on ranches in the region with very few managed using AMP techniques.

To restore ecological function, the 777 Bison Ranch has been managed since acquisition in the mid-1980's using AMP grazing management following holistic planned grazing decision-making and planning protocols (Savory and Butterfield, 2016). Overstocking is avoided by assessing available forage in each paddock and adjusting animal numbers to ensure there is enough forage for the animals and to leave sufficient herbaceous material to maintain essential ecosystem functions. Overgrazing is avoided by having short grazing periods followed by adequate recovery after grazing.

The ranch was initially comprised of 10 paddocks, 500–3000 acres in size and management involved moving the bison herd of several thousand animals through these paddocks. Over the years the number of paddocks has been increased to 36, and animals are now moved through paddocks varying in size from 61 to 1619 ha (150–4000 ac), depending on desired residual forage biomass and current season grass growth rate. To achieve these management goals the manager uses separate grazing plans for the growing season (approx. 15 March-15 October) and the non-growing season (approx. 15 October-15 March) following these protocols for each period. In conjunction with these plans an *a priori* drought plan is formulated every year when the ranch creates the growing season plan. The drought plan has a 15 June herd stocking decision deadline if conditions seem to indicate a drought season.

During the growing season the smaller pastures are grazed for 1 to 2 days while the larger ones can be grazed for 1 or 2 weeks. Recovery periods are a minimum of 45 days, averaging around 75 days during the growing season, and a maximum of 120 days in the non-growing season. Each paddock is monitored daily as are the animals, and length of grazing and recovery periods are adjusted throughout the year according to changing growth rates of the forage.

The adjacent HCG and LCG ranches are all managed according to the individual rancher's preferences and experience. Generally, each year the ranchers stock according to past experience and graze the entire growing season without modifying stocking rates unless a drought or some major impediment to the current level of stocking arises (Figs. 1 and 2)

The stocking level recommended by NRCS for cattle in this area is 10.0 AUM 100 ha^{-1} (24–25 acres AUM^{-1}). The 777 Bison Ranch is adaptively stocked at 13.0 AUM 100 ha^{-1} (18/19 acres AUM^{-1}) on average or 30% above the NRCS advised rate. On a 12-month basis, LCG was stocked on average close to the NRCS advised level at 14 AUM 100 ha^{-1} and the HCG was stocked on average at a considerably higher rate of 51 AUM 100 ha^{-1}. Details on grazing for each CG neighbor ranch are included in Table 2, and the percentage of each soil series sampled by grazing category in Table 3.

2.4. Sampling

2.4.1. Landscape vegetation classification and biomass estimation

Vegetation classification and biomass estimation at the landscape level were conducted by aerial imaging and analysis combined with collecting key field data to develop and corroborate statistical models. These models were then used to estimate vegetation composition and biomass for the entire 777 Bison Ranch landscapes and the HCG/LCG ranches sampled in this study (Figs. 3 and 4).

Aerial imagery was collected using Applied Ecological Service's Cessna Turbo 206 with a Leica LCD 30 medium format multispectral imaging camera during the week of June 28, 2016 and generated an on-the-ground resolution of 15-centimeter (6 inch) pixel size. Raw imagery was mosaiced, orthorectified, color normalized, and ranch property boundaries were superimposed on the imagery.

Imagery was evaluated using an assisted classification to identify locations with similar vegetation types and other visible conditions on the land. This image analysis used on-the-ground known locations that were measured for plant species composition and standing crop biomass which coincided spatially with the GPS geo-referenced locations where soil and infiltration measurement sampling also occurred. These known locations were used to create calibration spectral signatures used to model vegetation systems and create vegetation maps. Satellite imagery was then integrated into this analysis to allow more differentiation of the vegetation, by selection of an imagery date when the vegetation phenology supported additional differentiation. The classification workflow included image segmentation and supervised classification by a random forest algorithm. Image segmentation is a process to group pixels with similar spectral characteristics together and delineate each cluster as an object.

For mapping standing crop biomass, clipped forage samples were collected at random locations to represent where random soil samples were collected. The biomass samples were clipped from 1 m^2 quadrats, bagged and returned to AES's laboratory for drying and weighing. Biomass dry weights of plant biomass and the image classification analysis were used to model relationships over the larger landscape. The measured biomass quantities and image characteristics from the known sample points were used to project standing crop biomass across the entire landscape. For each square meter sampled quadrat, it was assumed that the spectral signature was homogeneous, and thereby it was identified as a single land cover type. A 15-cm on-ground pixel size resulted in a minimum object size on the ground of 15 cm × 15 cm, which supported the object definition to be at scale of individual species, especially for clump forming dominant species of prairie grasses and forbs.

To complete image segmentation, AES used a multi-resolution segmentation method, which is a bottom-up, region-merging technique. It begins with individual pixels, then similar pixels are aggregated to the object level. Reference objects, or objects known to be a specific land cover type, are developed from field data. When "parameters" of the random forest algorithm are estimated by using the characteristics of the reference objects, the algorithm is then applied to classify all objects in the ranch. For the final vegetation mapping effort, AES inspected the accuracy by comparing the distribution of each vegetation type on the map to field measurements and observations, to evaluate the degree of accuracy of the classification at the landscape level. This analysis used half of the ground truth data set for testing the predictive accuracy and continued refining the modeling only after species compositions from field and remote sensing achieved required values > 90%.

Biomass was estimated by using Sentinel-2 satellite image, field sampled biomass, and statistical regression modeling. The Sentinel-2 is operated by European Space Agency (https://sentinel.esa.int/web/sentinel/home). It is a land monitoring constellation of two satellites that provide a global coverage of the Earth's land surface every 5 days. The satellite image is characterized by 13 spectral bands at 10–60 m resolution, and a 290-km wide swath. We used a scene of images

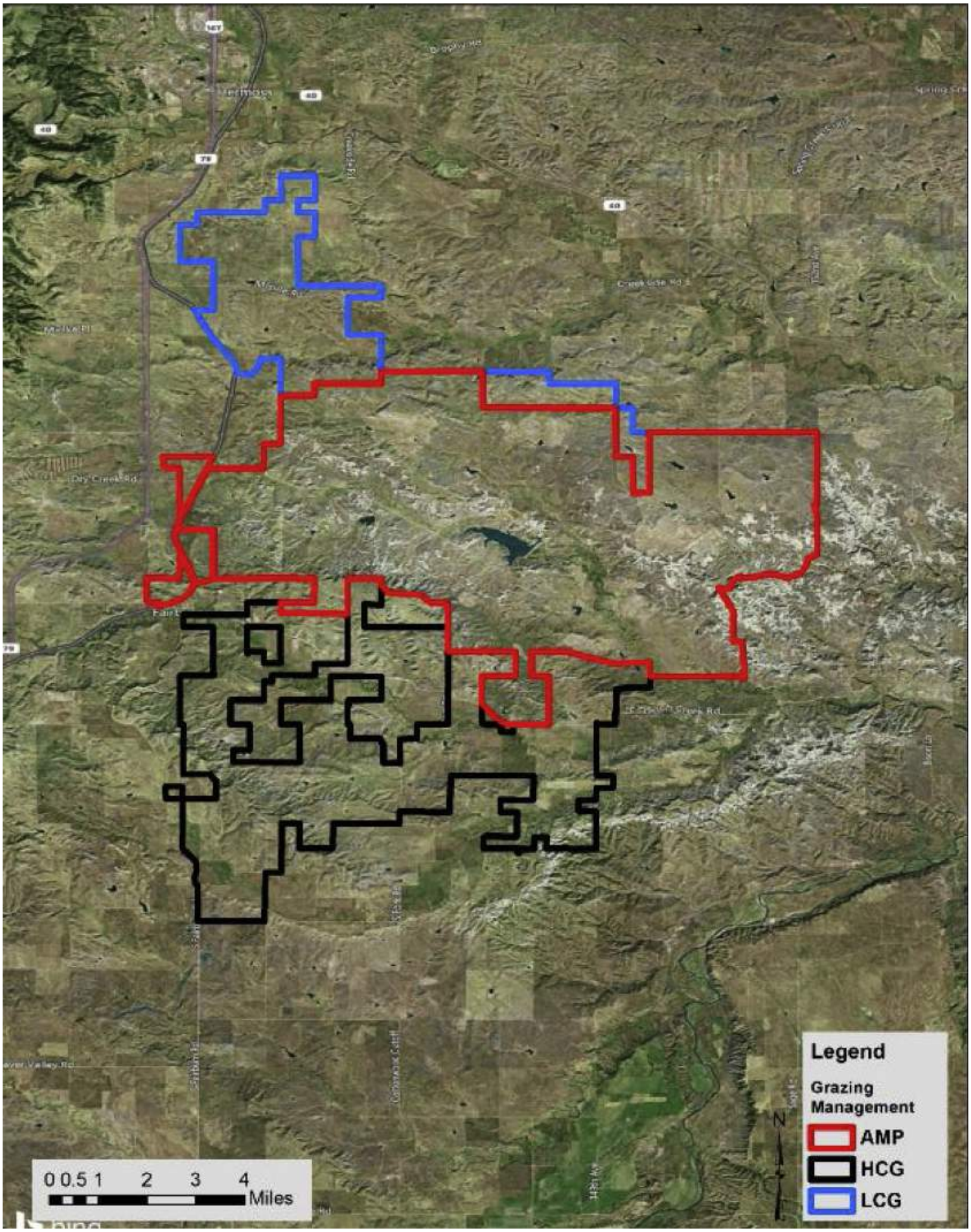

Fig. 1. Location of light (LCG) and heavy (HCG) set stocked continuous grazing ranches and the 777 Bison Ranch that was grazed using adaptive multi-paddock grazing (AMP) in Hermosa, South Dakota, USA.

acquired on June 6, 2016, then processed to correct for distortion and noise in the radiation signal by following standardized remote sensing image processing procedures, such as geometrical and radiometrical correction. The radiation properties of the ground target (e.g. reflectance) derived from the satellite image was then correlated with field biomass measurements with a regression model using the regression procedure PROC REG (SAS Institute, 2016).

2.4.2. *Vegetation composition, structure, and diversity, and ground cover*

Vegetation sampling was conducted along the same transects at the same randomly selected points where the soil carbon measurements occurred. Using GIS, random transect end points were established *a priori* to represent slope positions in the primary soil catenas present on the 777 Bison Ranch and shared with adjoining HCG and LCG ranches. From the initial point on each transect, additional points were established at random distances, using a random numbers table, along comparable approximate slope position zones to represent the catena system present. Soil and vegetation samples were collected from the five (5) to ten (10) point samples along each transect. Biomass samples were collected from one (1) or two (2) points and infiltration samples were collected from three (3) randomly sampled soil/vegetation sample points per transect. For a catena, this resulted in a sample size of 30

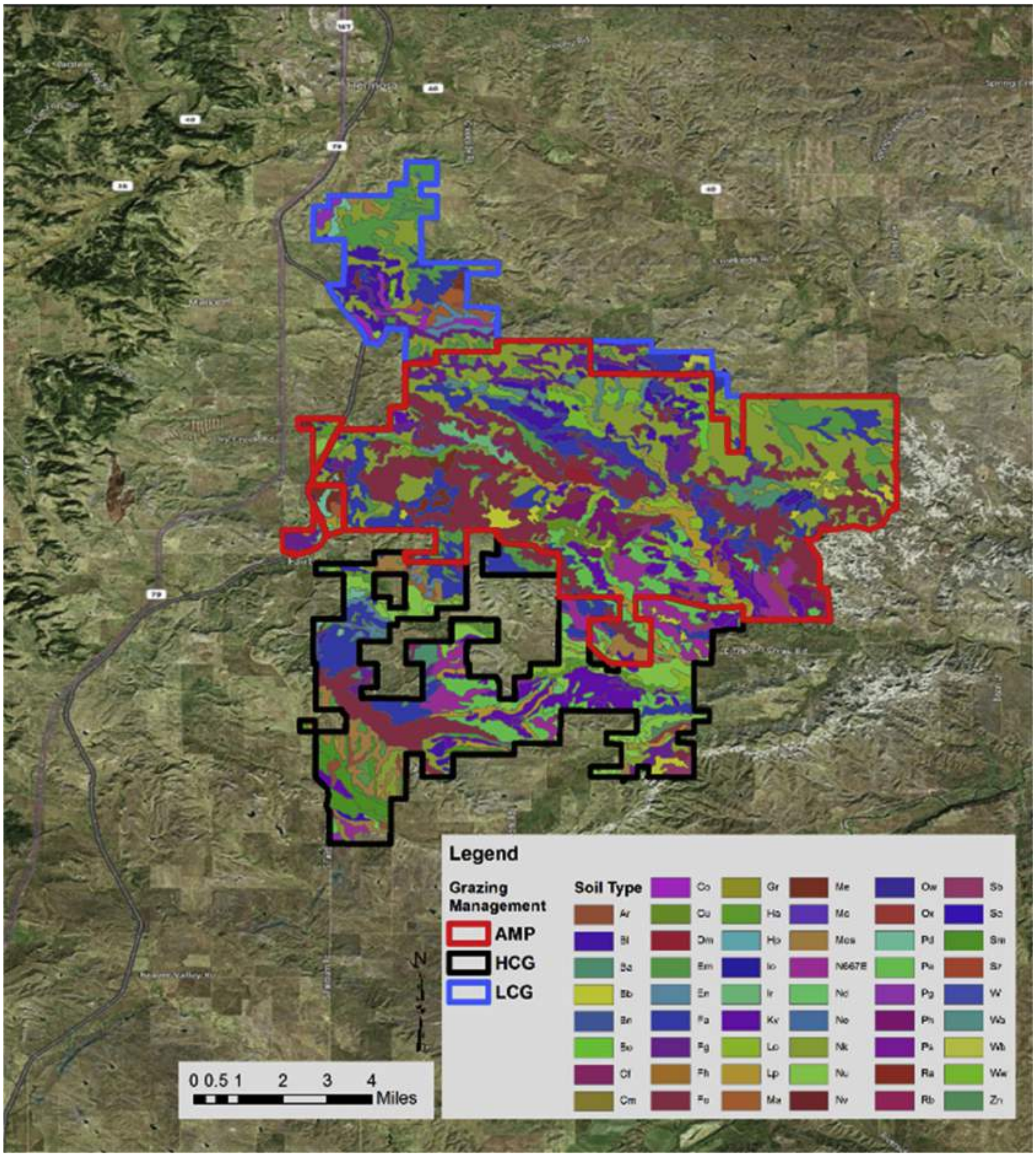

Fig. 2. Soils map of light (LCG) and heavy (HCG) set stocked continuous grazing ranches and the 777 Bison Ranch that was grazed using adaptive multi-paddock (AMP) grazing in Hermosa, South Dakota, USA.

vegetation and soil samples, 3 infiltration and 6 biomass samples. On the 777 Bison Ranch this resulted in 146 × 1 m^2 quadrats being sampled for soils and vegetation along 26 transects. On the HCG ranches, five (5) to ten (10) quadrats along each of the six (6) transects (50 quadrats), and on LCG ranches, five (5) to ten (10) quadrats in each of the five (5) transects (40 quadrats) were sampled. All statistical analysis of AMP and HCG/LCG pairings were run using equal n for the primary catenas shared in the AMP, HCG and LCG sites. Because of the large size of the 777 Bison Ranch, several of the primary catenas were represented by multiple sampling locations and the geographically nearest samples for each sampled strata from the 777 Bison Ranch were paired in statistical analysis with the geographically nearest HCG/LCG data. Also, because several catenas were present in the 777 Bison Ranch that were not available for sampling in HCG/LCG ranches, while equal "n" pairing occurred for the shared catenas, some additional catenas were only sampled to gather regional baseline data and these were not included in this analysis. A previous study that included detailed soil and vegetation sampling using the identical methods on an adjoining

Table 2
Grazing history details for the 777 Bison Ranch grazed using adaptive multi-paddock (AMP) grazing and neighbor ranches using light continuous (LCG) and heavy continuous grazing (HCG), Hermosa, South Dakota.

Grazing category	Where connected to 777 Bison Ranch	Grazing details
LCG	North	Stocked at 14 AUM 100 ha^{-1} (12-month basis) with replacement heifers during May to November.
HCG	South	Stocked at 51 AUM 100 ha^{-1} (12-month basis) with cows and calves during May to October.

Table 3
Soil series and areas of sampled soils on the 777 Bison Ranch using adaptive multi-paddock (AMP) grazing and neighbor ranches using light continuous (LCG) and heavy continuous grazing (HCG), Hermosa, South Dakota study.

Soil series	AMP		HCG		LCG	
	Area(ha)	% of ranch	Area(ha)	% of ranch	Area(ha)	% of ranch
Blackpipe clay loam	368	3.5	39	0.7	289	12.4
Emigrant loam	558	5.3	168	2.9	496	21.3
Kyle clay	365	3.5	657	11.3	8	0.3
Norrest silty clay loam	2415	21.8	164	2.8	562	24.1

ranch informed the design of sampling and sample sizes used in this paper (Apfelbaum et al., 2014).

Plant species presence and percentage coverage by quadrat was estimated by visual estimation to the nearest 5%. Herbaceous species frequency was calculated as the percentage of the total number of quadrats by transect each plant species occurred in, and plant cover was averaged across all quadrats by transect. Average catena plant species richness (the number of different species) was calculated as the number of plant species per quadrat and averaged by transect.

Since abundance and traits of the plant species matter more than taxonomic, functional or phylogenetic diversity of a plant community in explaining its biomass (Wasof et al., 2018), we determined an importance value for all species present, including dominant species for each grazing practice. Plant species average cover was computed using the averaged plant species percent vertically projected living (photosynthetic) tissue measured as species % cover in each sample quadrat, across all quadrats in each transect. Absolute frequency (AF) by transect for each species was computed as the percent of all quadrats in which each species occurred. Relative frequency (RF) and relative cover (RC) expressed each species absolute cover and absolute frequency as a percent of 100%. To compare the importance value for plant species, we summed (RF + RC = IV) relative frequency (RF percentage), and relative cover (RC percentage) to create an Importance Value (IV) for all species within a transect (Apfelbaum and Haney, 1991). Importance Value was computed in the same manner for the additional measured cover categories in each sampled quadrat: exposed rock, bare soil, bryophyte and lichen cover, and cover of coarse (> 5 cm), and fine litter (< 5 cm), which were also summarized as averages by transect.

2.4.3. Vegetation biomass

Along each transect where soil carbon samples were collected, we determined standing crop biomass by clipping the herbaceous plants in one (1) to two (2) randomly placed, one square meter quadrats. Quadrats sampled for biomass were selected using a random number table. This totaled forty-five (45) quadrats in the thirty-seven (37) study transects. All vegetation rooted within the quadrat was clipped at 2.5 cm above the ground surface. The biomass was air and oven dried at 20 °C and re-weighed until constant mass was achieved. A low drying temperature was used to not volatilize plant chemistry which were further analyzed for plant tissue nutrition. Biomass sampling was not controlled for time since last grazing, so the analysis and data provides the standing crop biomass in each pasture at the time of sampling.

Using the harvested field clipped biomass samples from 37 sample transects over the study area, a statistical model was developed that started with the calibration of the estimated biomass from the aerial photography with the field samples (correlation coefficient $r^2 = 0.79$). The resulting model was used to project and map the standing crop biomass for the entire ranch (Fig.4). Predicted biomass from the statistical model and field sampled biomass *f* had an error of 73 g m^2 for values ranging from 1 g m^{-2} to 17,464 g m^{-2} (Fig. 4).

2.4.4. Forage quality analysis

Using forty-three (43) biomass samples, forage quality was analyzed using the dry weight biomass samples and using Near Infrared Reflectance 2 analysis (Cumberland Valley Analytical Services, Maryland[1]) using standard laboratory procedures to prepare and measure each plant tissue specimen.

Analysis included Dry Matter, Moisture, Crude Protein, ADF Protein, NDF Protein, Soluble Protein, ADF, NDF, Lignin, Starch, Sugar, Fat, Ash, Calcium (Ca), Phosphorus (P), Magnesium (Mg), and Potassium (K) with pH by traditional method on an ensiled forage. Calculated values were provided for Available Protein, Adjusted Protein, Degradable Protein, NEL, NEM, NEG (OARDC Summative Energy Equation), and NFC. It also included wet-chemistry minerals - Calcium (Ca), Phosphorus (P), Magnesium (Mg), Potassium (K), Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu).

2.4.5. Soil water infiltration

Soil water infiltration rates were measured using dual-head infiltrometers[2] at the randomly placed vegetation and soil sample locations. The infiltrometers were installed adjacent to the vegetation soil sampling points at an *a priori* determined midpoint and endpoints of each of the transects (n = 3).

The set-up of the units followed the device instructions to reflect the soil catena's texture and the existing moisture conditions in the soil. Depending on these specifics, the tests ran for 90 min to over 3 h, after which data were downloaded for analysis. Water levels were maintained through each test by use of a reservoir tank that allowed the units to draw water on an as needed basis to satisfy the water requirements for each test location.

2.4.6. Soil carbon

The soil sampling followed Verified Carbon Standard (Verified Carbon Standard (VCS, 2011) "The Earth Partners Soil Carbon Quantification Method", a market approved climate mitigation method to measure and report soil carbon stocks. The field sampling plan was designed to follow the VCS physical and abiotic conditions stratification using GIS of the ranch landforms, soils, topography, and hydrologic setting. The strata were then overlain with land use history, interviews based on the knowledge of the 777 Bison Ranch Manager, Moritz Espy. After interviewing with neighboring ranchers, the key dates were corroborated with historic aerial photographs. Soil sampling points were randomly allocated soil throughout each ranch using GIS as the required standard process (Verified Carbon Standard (VCS, 2011).

Sampling represented dominant soil types on the 777 Bison Ranch, paired with the same dominant soil types on HCG and LCG ranch paddocks. Watering point, fences, and other areas where the animal congregate regularly, were avoided. Four primary soil types (USDA NRCS, 2009; Table 1) common to all ranches were studied: 1) Blackpipe clay loam (BIA and BIB); 2) Emigrant loam; 3) Kyle clay; and 4) Norrest silty clay loam.

Soil sample locations represented moisture and topographic gradients for each sampled soil catena. In each sampled pasture, random transect endpoints were marked and random sample points were allocated at random distances along each transect in each catena slope position zones to span the width of the catena. Soil samples were then collected at the random sample points as being representative locations identified by the stratification procedures. Soils were sampled to a 1-meter depth with a Giddings hydraulic soil sampler mounted on an ATV. Core samples were extracted at each sample point in 5-cm diameter plastic sleeves, which were capped at both ends to create a sealed

[1] Cumberland Valley Analytical Services, 4999 Zane A. Miller Drive, Waynesboro, PA 17268.

[2] Manufactured by METER Instruments. Our use of this product does not imply endorsement.

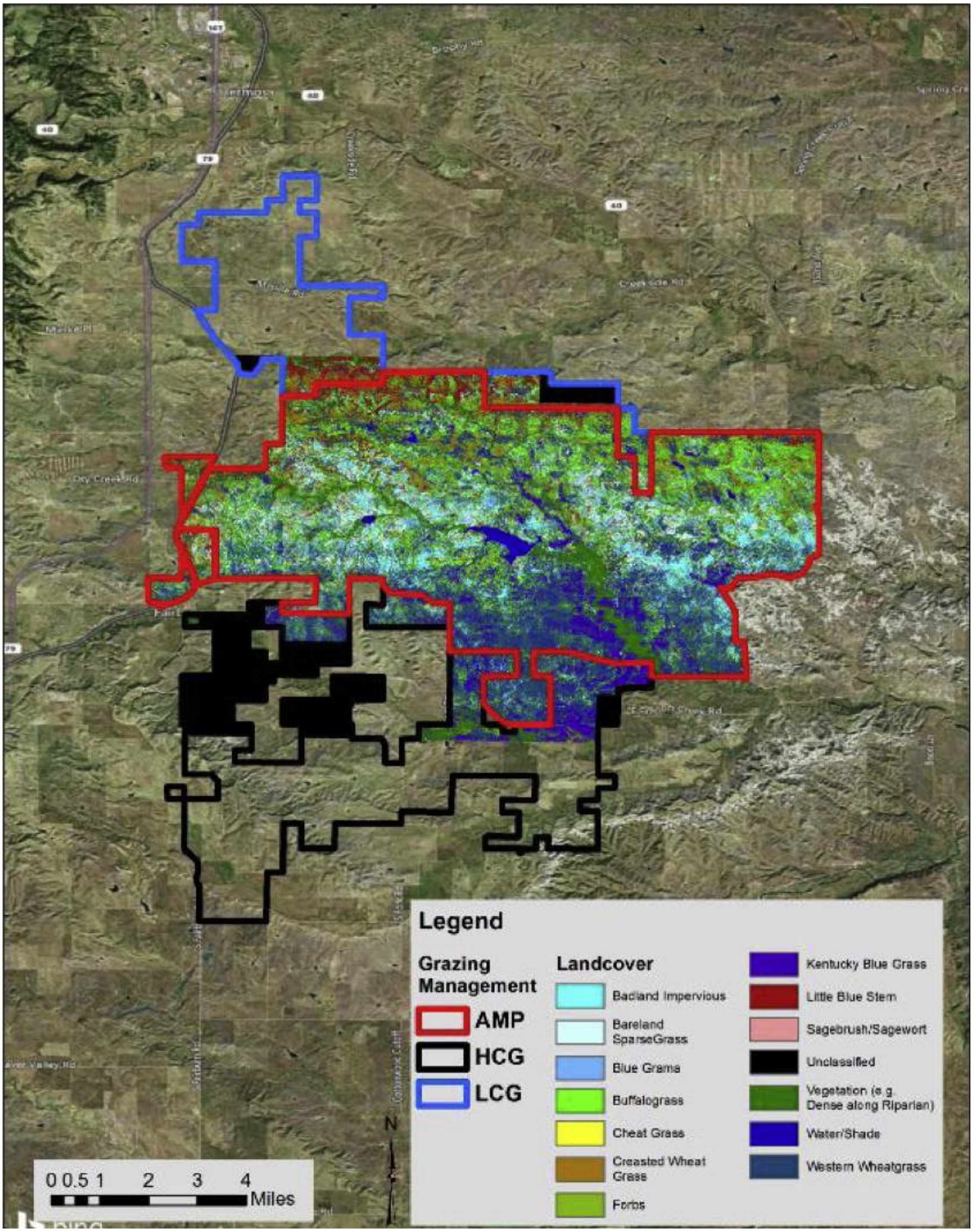

Fig. 3. Aerial image-based vegetation classification of the 777 Bison Ranch, Hermosa, South Dakota, USA.

1-meter length soil sample. Samples were delivered to the University of Missouri Soil Health Assessment Center[3] for all analyses using standard sampling processing (grinding and screening to 80 microns, removal of rock, roots, etc., followed by combustion analysis and the measurement of carbon dioxide. A laboratory approved QA/QC plan was used internally by the lab to evaluate test precision, and the authors submitted ˜5% of the total samples as split samples to the laboratory to independently affirm the precision. Laboratory precision was found to be within their published QA/QC program limits. A total of two-hundred thirty-five (235) core samples were collected.

At the laboratory, the soil cores were divided into samples by genetic strata (e.g. topsoil "A" horizon, subsoil "B" horizon, parent material "C" horizon, etc.). Samples were separated, extracted, homogenized, and screened for twigs and rock, followed by oven drying to constant mass. Subsamples were then extracted and analyzed for total soil carbon, soil organic and soil inorganic carbon levels. An intact section of each core for each stratum was reweighed after drying to calculate soil bulk density. All soil samples and have been archived.

[3] Soil Health Assessment Center, 3600 New Haven Road, University of Missouri, Columbia, MO 65201-9608.

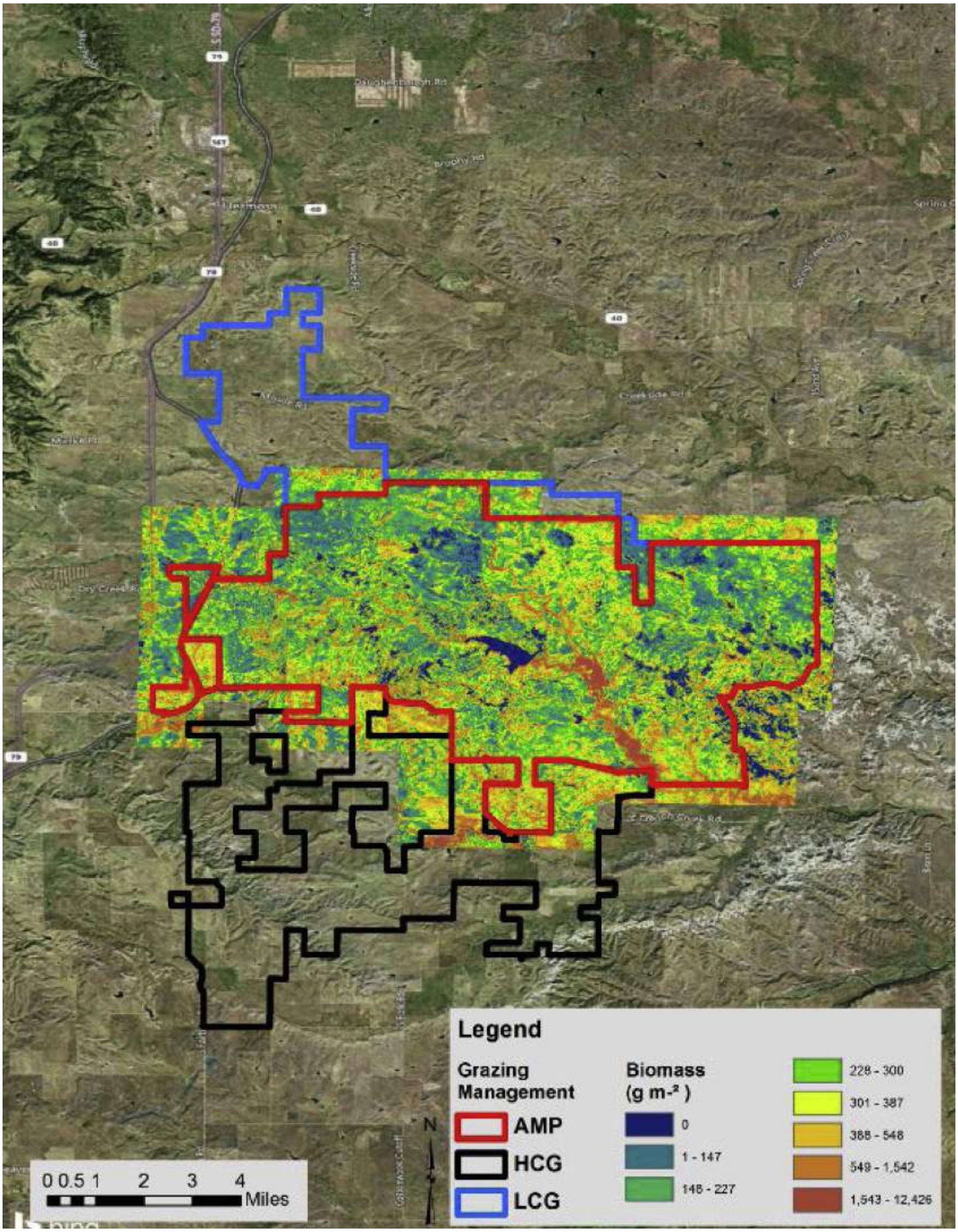

Fig. 4. Projected standing crop biomass map for the entire ranch using field calibrated modeling projections for biomass on the 777 Bison Ranch, Hermosa, South Dakota, USA.

2.4.7. Statistical analyses

Effects of the three grazing treatments AMP, HCG, and LCG on soil carbon, water infiltration and total vegetation cover and the cover and frequency of individual plant species were measured in randomly located transects and meter square quadrats established in catenal positions of upper, middle and lower slope zones on AMP, HCG and LCG managed ranches. Data was averaged by transect for all vegetation, ground cover, soil carbon, and infiltration measurements. For a given paired comparison by soil type, n and error degrees of freedom varied depending on which parameters were being analyzed. The 777 AMP managed buffalo ranch and neighboring HCG and LCG cattle managed ranches were biophysically stratified using soil texture, slope, aspect, depth to bedrock, and management history to randomly allocate transect endpoints in paired conditions strata across the grazing treatments in neighboring ranches.

The data were analyzed with PROC GLM procedure in SAS 9.3, a software package developed by SAS Institute Inc. (http://www.sas.com/) Least square means of the adjusted variable were compared to account for the unbalanced design, and a Tukey post hoc test was used for pair wise comparison of the factors. Prior to analysis, data were

Table 4
Dominant plant species mean absolute cover values in the adaptive multi−-paddock (AMP), light continuous (LCG) and heavy continuous (HCG) grazing ranches. For dominant plant species, means with the same superscript are not significantly different at $P > 0.05$. Only species having 1% cover or more, are included in this table. The full species composition details are available on request.

Species	Mean (n) AMP (n = 146)	HCG (n = 50)	LCG (n = 40)
Dominant species			
Agropyron cristatum	8.56[a]	3.54[a]	0.9[a]
Bouteloua gracilis	20.05[b]	13.50[b]	25.33[a]
Bromus tectorum	4.92[b]	20.52[a]	11.35[b]
Buchloe dactyloides	20.36[b]	11.98[b]	44.18[a]
Conyza canadensis	0.22[a]	3.52[a]	0.40[a]
Nassella viridula	2.99[a]	0.30[b]	0.43[ab]
Pascopyrum smithii	22.70[a]	16.68[a]	2.75[b]
Psoralea tenuiflora	3.11[b]	2.90[b]	6.78[a]
Sphaeralcea coccinea	0.85[a]	1.00[a]	1.2[a]
Taraxacum officinale	1.60[b]	0.4[b]	3.8[a]
Subdominant species			
Aristida purpurea	2.07	0.30	0.75
Artemisia frigida	1.03	0.28	1.73
Bouteloua hirsuta	1.01	0.00	0.00
Bromus inermis	0.53	0.00	2.63
Carex spp.	1.25	0.00	1.30
Convolvulus arvensis	0.14	6.56	0.00
Dactylis glomerata	1.03	0.00	0.00
Medicago sativa	1.63	0.00	0.00
Poa pratensis	2.85	0.00	0.05
Ratibida columnifera	1.04	0.40	0.05

transformed to optimize normality and homogeneity of variance using logarithm function (log10). Values presented are non-transformed, but probabilities associated with differences and standard errors are based on transformed analyses. A significance level of $p \leq 0.05$ was used unless otherwise noted.

3. Results

3.1. Vegetation composition, structure, and diversity

A total of sixty-two herbaceous plant species was measured in the sampled quadrats across all study transects. Of this total, over 76% were native plant species of dry shortgrass plains. The remaining 24% were adventive species, including introduced forage plants such as alfalfa (*Medicago sativa*), and Crested wheat grass (*Agropyron cristatum*) etc., or forbs such as thistles (*Cardus* spp.*, Cirsium* spp.*, etc.*), and sweetclover (*Melilotus* spp.).

The dominance values for the most abundant plant species differed substantially among the three grazing management practices (Table 4). Plant species composition, importance value (IV), litter cover and percentage of bare ground by grazing practice are presented in Table 5. Fine litter ground cover was significantly greater on AMP than LCG grazed lands (91% vs 71%; $P < 0.05$; Table 4) and significantly greater on AMP than HCG areas (91% vs 53%; $P < 0.05$).

Bare soil was also significantly lower with AMP (7%) than LCG (20%; $P < 0.05$; Table 4) and HCG grazed lands (37%; $P < 0.05$). The importance values (IV) of native plant species was the same for AMP and LCG ($P > 0.05$) but AMP and LCG IV values were both higher than HCG (139% and 147, respectively vs 118 for HCG; $P < 0.05$; Table 5).

AMP had significantly lower non-native species IV values than the continuously grazed paddocks (49% for AMP vs 53% for LCG and 82% for HCG; $P < 0.05$; Table 5). The average number of native and non-native plant species per sample quadrat was strongly related to grazing management. The number of non-native species was lowest in AMP compared to HCG and LCG grazed paddocks (2.4 for AMP vs 4.0 for HCG and 3.0 for LCG; Table 5; $P < 0.05$). The average number of native plant species per sample quadrat ranged from 7 to 9 across all grazing treatments and was not significantly different.

On HCG paddocks there was a strong association between the highest levels of cover and importance value of some non-native plants and heavily compacted soils supporting field bindweed (*Convolvulus arvensis*) ($P < 0.05$). In contrast, on AMP paddocks, this and other native plants dominated the plant cover regarding importance value. The legacy presence of historically planted forage grasses (e.g. Crested wheatgrass, Hungarian/smooth brome (*Bromus inermis*), Kentucky bluegrass (*Poa pratensis*) are still measurable in some of the paddocks at the 777 Bison Ranch. Some AMP paddocks that were completely planted to crested wheatgrass have been changing to buffalograss (*Buchloa dactyloides*) and blue grama (*Bouteloua gracilis*) stands, but the legacy of these former planted forage plants was still measurable. The LCG ranch paddocks sampled had intermediate values between those measured for AMP and HCG treatment areas.

3.2. Vegetation biomass

Over all sampled areas AMP grazed paddocks were found to have significantly more biomass than both LCG and HCG paddocks. AMP paddocks had nearly 3 times the standing crop biomass of LCG paddocks (295 vs 102 g m^{-2}; $P < 0.01$) and nearly double that measured in HCG paddocks (295 vs 169 g m^{-2}; $P < 0.001$) (Fig. 5). Based on the variances around these measured mean biomass levels, AMP was also the most highly variable (Fig. 5).

3.3. Forage quality

Analyses of forage quality found no significant differences in any of the forage nutritional samples tested between AMP, LCG and HCG grazed paddocks, although the starch content of the forage biomass overall was higher in the AMP verses HCG and LCG ($P < 0.04$; Table 6). This analysis also found that the average nutritional content levels for the AMP paddocks had higher levels of variance compared to the LCG and HCG. This is probably due to samples being collected in AMP locations without considering when each paddock has been previously grazed so each of the AMP paddocks sampled was in a different stage of recovery after the previous defoliation. Since the HCG and LCG locations are constantly accessed by the animals they change little over time at any location so have more consistent nutrient levels that do not vary considerably. Because of the significantly higher biomass quantities measured in AMP grazed pastures, even if nutrition levels are not

Table 5
Number and overall Importance Value (IV)[*] of different plant categories by transect and by catena of native and non-native plant species, percentage litter cover and bare soil for AMP, LCG and HCG sampled locations. Treatment means (± SD).

Grazing Category	# Native species	# Non-native species	IV for Native Species	IV for Non-native species	% Fine Litter	% Bare Soil
AMP	7.4 ± 4.5	2.4 ± 1.6	138.5 ± 61.1	48.9 + 50.8	90.7 ± 11.2	7.2 ± 9.6
LCG	9.4 ± 4.9	3.0 ± 0.7	147.4 ± 23.0	52.6 ± 23.0	71.4 ± 9.9	19.5 ± 6.5
HCG	8.0 ± 2.1	4.0 ± 1.4	118.2 ± 29.4	81.8 ± 29.4	53.3 ± 35.7	37.2 ± 37.2

* Importance Value = relative frequency plus relative cover (IV = RF + RC) for each species per transect.

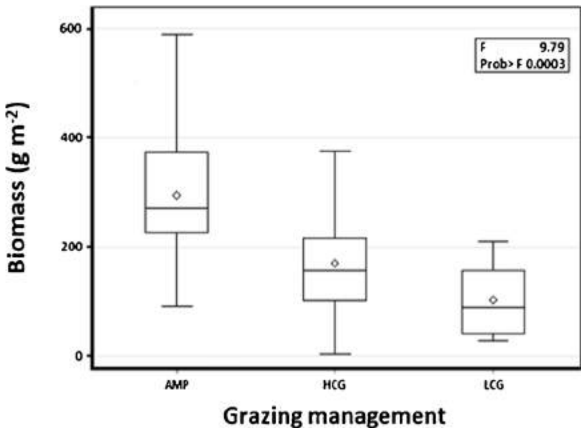

Fig. 5. Mean standing crop biomass for AMP, HCG, LCG grazed ranch study sites. Means (n = 30) are based on 1 m^2 plots in each treatment in Hermosa, South Dakota USA.

Table 6
Nutritional values of forage biomass samples collected on the LCG, HCG, and AMP grazed ranches in Hermosa, South Dakota, USA. Row means denoted with different letters are significantly different ($P < 0.05$); rows without denotation are not significantly different.

Lab Test	Grazing strategies		
	AMP	LCG	HCG
Crude Protein (CP)	9.03	8.86	9.10
Adjusted Protein	7.98	7.90	8.14
Rumen degradable protein (RDP)	6.05	5.95	6.15
RDP Crude protein	66.92	67.09	67.40
Acid detergent fiber (ADF)	51.48	51.79	51.52
ADF_NDF (Neutral Detergent fiber)	82.57	80.63	82.30
Lignin	10.69	10.65	10.77
Lignin NDF	17.26	16.66	17.31
Starch	**4.30** [a]	**3.79** [b]	**4.04** [b]
Starch NFC	29.40	28.16	28.93
Fat Ether Extract (EE)	2.24	2.48	2.62
Relative Feed Value (RFV)	73.30	70.72	72.98
Non-fibrous Carbohydrates (NFC)	15.58	13.88	14.62
Nonstructural Carbohydrates (NSC)	8.08	7.56	7.94
Calcium (Ca)	0.63	0.56	0.60
Phosphorus (P)	0.09	0.09	0.09
Sulfur (S)	0.11	0.11	0.12
Sodium (Na)	0.01	0.01	0.01
Iron (Fe)	506.67	559.49	574.09
Manganese (Mn)	49.70	47.42	49.06
Zinc (Zn)	16.73	16.89	17.06
Copper (Cu)	4.47	4.28	4.29

different per sample, livestock have access to larger quantities of forage and thus potentially more total nutrition.

3.4. Soil water infiltration

There were significant differences in infiltration rates due to grazing management ($P < 0.06$) but not soil type ($P > 0.14$) and there was a significant grazing management and soil type interaction ($P < 0.001$). Across all soil types, AMP grazed pastures had higher numerical but not significantly different infiltration rates (6.32 cm hr^{-1}) than LCG treatment pastures (4.89 cm hr^{-1}; $P = 0.31$), but AMP grazing had significantly higher infiltration rates than HCG (3.8 cm hr^{-1}; $P < 0.05$).

Infiltration rates on the Emigrant loam were higher with AMP (11.23 cm h^{-1}) than HCG (2.51 cm hr^{-1}; $P < 0.01$) and LCG (3.45 cm hr^{-1}; $P < 0.01$) grazing treatment. In the Norrest silty clay loam, infiltration with AMP (4.19 cm h^{-1}) was not significantly higher than HCG (4.05 cm h^{-1}; $P > 0.9$) or LCG (3.51 cm h^{-1}; $P > 0.9$). Similarly, on the Kyle clay loam soils there were not significant differences measured between the AMP (4.2 cm h^{-1}) and HCG paddocks (4.05 cm h^{-1}; $P > 0.9$) or LCG (3.5 cm h^{-1}; $P > 0.2$).

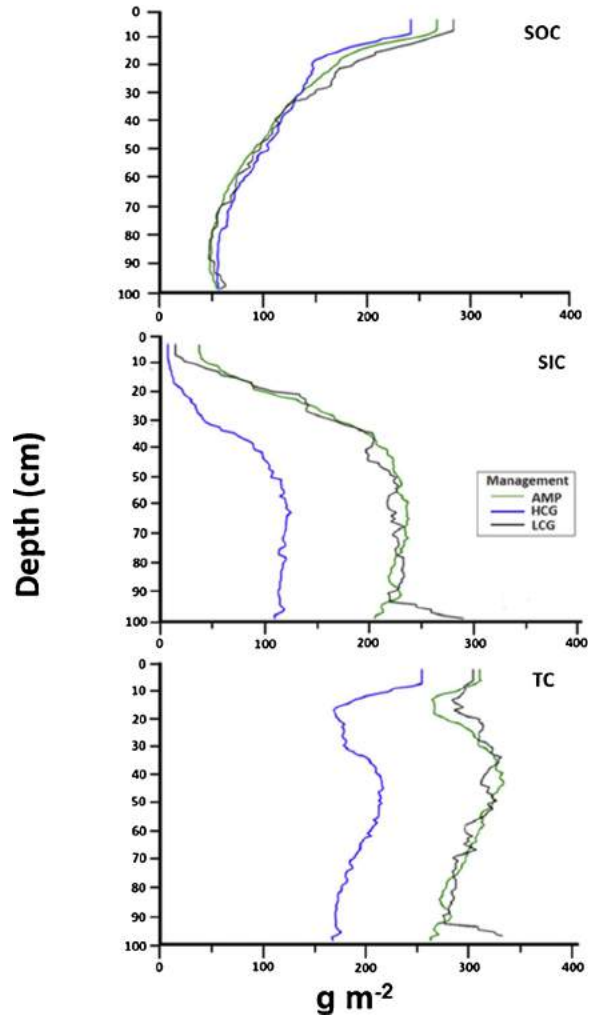

Fig. 6. Mean soil carbon levels with soil depth for the study: a) soil organic carbon (SOC); b) soil inorganic carbon (SIC); and total soil carbon (TC) on the LCG, HCG and AMP grazing ranches, Hermosa, South Dakota USA.

3.5. Soil carbon stocks

3.5.1. Soil organic carbon (SOC) levels across all paired grazing treatment settings of the primary soil types were no different ($P > 0.05$; Fig. 6)

On the Blackpipe clay loam, there was no measured significant difference in SOC levels among AMP, LCG and HCG treatments and average SOC level ranged from 12.5 to 13.0 kg m^{-2} ($P > 0.99$).

Similarly, there were no significant differences among grazing treatments in the Emigrant loam soil; total organic carbon levels ranged from 9.3 to 11.6 kg m^{-2} ($P > 0.08$) and on the Kyle clay soil type where soil organic carbon stocks ranged from 9.4 to 10.1 kg m^{-2} ($P > 0.99$). On the Norrest silty clay loam soil, SOC stocks, were also not significantly different due to grazing treatment with SOC stocks ranging from 9.7 to 12.2 kg m^{-2} ($P > 0.19$).

3.5.2. Soil inorganic carbon (SIC), results were very similar to those for SOC

On the Blackpipe clay loam SIC values ranged from 9.1 to 13.3 kg m^{-2}; with no differences among the grazing strategies ($P > 0.99$; Fig. 6). On the Emigrant loam soils, SIC values ranged from 15.4 to

30.3 kg m^{-2} with no grazing strategy differences ($P > 0.20$), and on the Kyle clay soils SIC values ranged from 4.1 to 9.3 kg m^{-2} and were not different ($P > 0.78$).

On the Norrest silty clay loam there were significant differences in SIC ranged from between AMP and HCG (23 kg m^{-2} v. 6.4 kg m^{-2}; $P < 0.0001$), and LCG and HCG (27 kg m^{-2} vs. 6.4 kg m^{-2}; $P < 0.0001$), but there was no significant difference between AMP and LCG, ($P = 0.96$).

3.5.3. The total carbon stocks (TC), summing SOC and SIC, were not different between the AMP and LCG grazing strategies ($P > 0.63$; Fig. 6) but both had higher TC values across all soils than HCG ($P < 0.001$)

However, there were differences across all grazing strategies among the different soils ($P < 0.0001$) with the Emigrant loam soils having the highest values (34.2 kg m^{-2}), followed by the Norrest silty clay loam (29.9 kg m^{-2}), Blackpipe clay loam (23.8 kg m^{-2}), and Kyle clay soils (16.1 kg m^{-2}), respectively. Only the Kyle clay soil had significantly different values from the other soils ($P < 0.0027$).

There were no differences in TC among grazing treatments on the different soils ($P > 0.46$) except on the Norrest silty clay loam soil. On this soil there were differences between AMP and HCG (34. 2 kg m^{-2} vs. 16.2 kg m^{-2}; $P < 0.0001$) and LCG and HCG (39.4 kg m^{-2} vs. 16.2 kg m^{-2}; $P < 0.0001$).

Regarding changing amounts of SOC with depth there were no differences among the three grazing strategies (Fig. 5; $P > 0.05$) but with SIC there were significantly lower levels with HCG than both AMP and LCG grazing strategies below a depth of 10 cm ($P < 0.05$). This resulted in significantly lower TC levels at all soil depths with HCG than AMP and LCG ($P < 0.05$).

4. Discussion

This study indicates that by using holistic planned grazing protocols with AMP grazing to limit overstocking and overgrazing, the 777 Bison Ranch management has improved outcomes relative to those of neighbors who over decades have used long periods of grazing with cattle usually followed by no growing season recovery. At the 777 Bison Ranch, this has been accomplished by adjusting animal numbers to match available forage amounts and grazing for short periods followed by adequate recovery after grazing. Positive results include increased fine litter cover, herbaceous biomass, plant composition, plant importance value, and decrease in bare ground and improved water infiltration into the soil.

How we manage plants in grazing ecosystems is critical to maintaining or regenerating full soil and ecosystem function. Ecosystem functions provided by soil organisms include: improving soil aggregation; aeration and water-holding capacity; stabilizing soil; improving nutrient acquisition and retention; cycling nutrients to improve nutrient availability; enhancing tolerance to biotic and abiotic stress; and buffering the impact of environmental factors on plants (Altieri, 1999; Green et al., 2008; Van der Heijden et al., 2008; Delgado et al., 2011).

Research conducted on commercial ranches to improve grazing management, such as AMP grazing, has been shown to reverse ecosystem degradation by improving plant management to facilitate improving soil and ecosystem function and economic outcomes (Earl and Jones, 1996; Tainton et al., 1999; Jacobo et al., 2006; Provenza, 2008; Barnes and Hild, 2013; Ferguson et al., 2013; Teague et al., 2011, 2013; Martin et al., 2014; Müller et al., 2014; Díaz Solís et al., 2015; Savory and Butterfield, 2016; Wang et al., 2016; Teague et al., 2011, 2013). The improvements in ecosystem services in our study are, therefore, consistent with published work indicating that management that decreases negative impacts of grazing to improve key soil and ecosystem functions, provides improved outcomes.

The use of AMP grazing resulted in the lowest number of non-native herbaceous species, the highest herbaceous biomass, greatest fine litter cover and lowest levels of bare ground. Differences were greatest between AMP and HCG management, with LCG being intermediate. Greater levels of plant biomass and cover, litter cover and less bare ground are strongly related to enhanced infiltration, buffering of temperatures and decreased soil temperatures as they enhance soil microbial activity, promote soil aggregate stability, sustain plant nutrient status and availability, improve plant growing conditions resulting in the incorporation of more organic matter into the soil (Thurow, 1991; Rietkerk et al., 2000; Bardgett, 2005). To maintain or regenerate lost soil and ecosystem function it is imperative to provide adequate plant and litter cover and decrease bare ground to improve these soil function and soil building processes.

A counter intuitive result was that the herbaceous biomass in LCG was less than that of the more heavily stocked HCG. This was due to the more heavily stocked HCG having been overgrazed continuously for multiple decades. With time this has resulted in domination by invasive plants such as crested wheatgrass (*Agropyron cristatum*), cheat grass (*Bromus tectorum*) and bindweed (*Convolvulus arvensis*). There were 16 species indicating highly disturbed ground in the HCG and to a lesser extent in the LCG treatment. These species have little to no forage value, can form large, monospecific stands that exclude native vegetation and reduce forage diversity and the amount of grazeable forage. They are generally only palatable in spring, after which they are strongly avoided. The more lightly stocked LCG had no *A. cristatum* and considerably less of the other problematic plants. Consequently, a greater portion of LCG pastures provided reasonable amounts of available forage and were thus grazed more resulting in HCG having higher levels of herbaceous biomass, with much of it of no value as forage apart from providing some coverage, to reduce the presence of bare soils.

Regarding forage quality, the high variability of many nutrients in the biomass samples from the AMP paddocks compared to the LCG and HCG pastures is likely a direct result of the management used with AMP grazing. With AMP the herd grazes any paddock for a short period and then is moved to the next paddock to ensure moderate use and post-grazing recovery. The herd is not returned to each grazed paddock before adequate recovery has occurred. Both management actions are used to prevent over grazing. Consequently, AMP grazing causes dynamic, short-term fluctuations in nutritional value of the forage base. Over the season this results in higher levels than the means, but more variability. In contrast, in continuously grazed pasture, fluctuations in the short-term are less variable but deteriorate more quickly at the end of the growing season compared to AMP grazing (Provenza, 2008). This occurs with LCG and HCG as the preferred plants and areas are constantly exposed to defoliation without any planned recovery. Since the changes to plant material takes place much more slowly with AMP grazing, the nutritional profile in the whole paddock changes much more slowly. As there was two to three times the available biomass of forage in AMP paddocks, this suggests that changes in nutrition of the forage may be compensated by the grazers having access to significantly more forage and thus obtaining more net nutrition compared to what might be present for grazers in the reduced forage stocks in HCG and LCG paddocks.

Infiltration rates are probably the most important parameter to decline with poor grazing and to improve with improved management. There were significant differences in infiltration rate due to grazing management but not soil type and there was a significant grazing management and soil type interaction. Across all soil types, AMP grazed pastures had higher infiltration rates than HCG but not LCG. The higher infiltration rates with AMP grazing occurred on the Emigrant loam soil with moderate 0–6% slopes and higher soil permeability values (Table 1). Even though the Norrest silty clay loam had comparable permeability values to the Emigrant loam soil, it occurs on steeper 6–15% slopes and did not experience an increased infiltration rate with AMP grazing. Similarly, both the soils with higher clay content, the Blackpipe silty clay loam and Kyle clay, did not show any improvement in infiltration rate with AMP grazing.

Based on soil organic, inorganic carbon, and total carbon stock levels, as tested at $P < 0.05$ statistical levels, it does not appear that soil carbons stocks have increased under the AMP grazing as it is currently practiced on the 777 Bison Ranch. There was considerable sample to sample variance in carbon levels when compared across all soil types. The most consistent results of higher soil carbon stocks and greater average increases in soil carbon levels were measured in Emigrant loam and Norrest silty clay loam soil types that also had highest intrinsic permeability ratings (USDA-NRCS, 2009) and were the better soils on the landscape.

Those managing the bison grazing on the 777 Bison Ranch have observed that bison behavior with AMP grazing is very different from that of cattle on continuously set stocked ranches. Bison graze while constantly moving, while cattle remain localized for many days as they graze. This indicates there may be fundamental differences in the spatial foraging behavior and needs between these species that may affect the stocking density achievable with bison AMP grazing and the rate of soil carbon stock improvements. Soil carbon stock increases documented under AMP grazing with cattle has produced exceptionally high soil carbon levels. This may, if substantiated, indicate that ranching with bison may not be possible at the very high stocking densities that have been achieved with cattle.

The evolutionary and behavioral adaptation for bison to graze while moving, which now is under confined pasture grazing, impedes achieving higher stocking densities for short periods. Historically, when huge herds passed through the landscape, tens of thousands of animals within a few days would pass over the same landscape (Bergerud, 1988; Frank et al., 1998; Lott, 2003; Carroll, 2016) as observed in extant herds of caribou (*Rangifer tarandus*) in the artic and blue wildebeest (*Connochaetes taurinus*) and associated ungulates in Africa. Thus, the cumulative grazing by large herds historically probably had a more profound effect on soil building than what we now see where a smaller number of animals are moved through a paddock. If bison grazing is to achieve the potential “big herd effect and results” as noted by Retallack (2013), it may be necessary to either graze using continuous movement of a smaller herd moving through the same paddock multiple times in sequence, as with AMP grazing, or moving a larger herd rapidly over the landscape to emulate historical bison grazing impacts.

This is consistent with observations we have made on ranches managed using AMP grazing and published literature. The quickest and greatest improvements to soil and ecosystem services we have encountered have been with very high densities of cattle using many small paddocks to limit grazing periods to a day or less with recovery periods of 80–100 days or more (Teague et al., 2013; Jakoby et al., 2014; Martin et al., 2014; Jakoby et al., 2015; Teague et al., 2015; Wang et al., 2016; Teague and Barnes, 2017; Wang et al., 2018). This has been observed on cattle ranches through North America, notably on ranches of: Kenyon and Towers (Alberta); Dennis and Hjertas (Saskatchewan); Harper (Manitoba); Brown (North Dakota); Judy and Petersen (Missouri); Brann (Kentucky); Keener (Tennessee); Gentry and Lyons (Alabama); Hurst and Williams (Mississippi); and Birdwell-Clark and Dixon (Texas).

5. Conclusions

To ensure long-term sustainability and ecological resilience of agroecosystems, agricultural production should be guided by policies that change degrading management practices to low-input regenerative practices that enhance soil and ecosystem function and resilience to improve long-term sustainability and social resilience. Collectively, conservation agriculture aimed at regenerating soil health and ecosystem function supports ecologically healthy resilient agroecosystems, improves net profitability for ranchers and enhances essential watershed function and ecosystem services humans rely on for their well-being.

The AMP grazing results from this study indicate improved fine litter cover, improved water infiltration, two to three times the available forage biomass, improved plant composition, and decreased invasive plant levels and bare ground, relative to both light and heavy continuous grazing. Regarding infiltration and total soil carbon stocks through the soil profile, AMP was also superior relative to HCG, with LCG providing intermediate results.

These changes indicate a trajectory of improvement in key ecosystem function parameters by using AMP grazing in this semi-arid short grass ecosystem compared to the commonly used continuous grazing. However, there is much room for soil health improvement, simply because of the degraded nature of the ranch at the time of purchase, and limitations of regional soils. Change in rangelands, particularly in low precipitation areas as in South Dakota, usually involve slow progress but the AMP strategies employed in this ecosystem using bison have produced substantive improvements compared to the other grazing management strategies in the area to improve the ecological parameters driving soil health and ecosystem function and resilience.

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