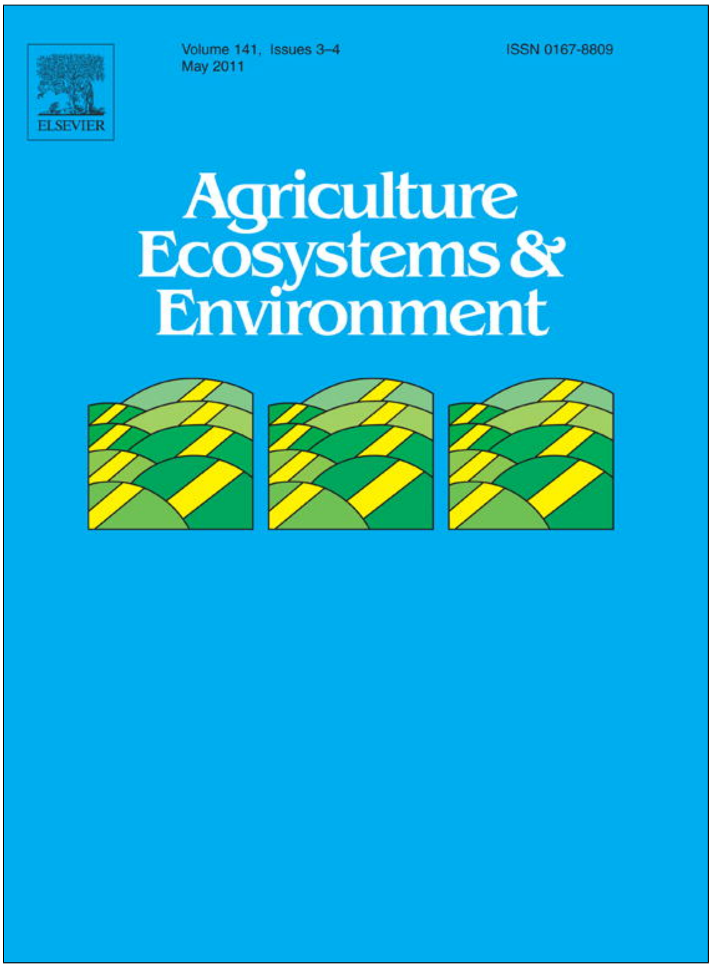

Volume 141, Issues 3–4
May 2011

ISSN 0167-8809

Agriculture Ecosystems & Environment

Agriculture, Ecosystems and Environment 141 (2011) 310–322

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie

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ARTICLE INFO

Article history:
Received 25 August 2010
Received in revised form 11 March 2011
Accepted 16 March 2011
Available online 17 April 2011

Keywords:
Adaptive management
Prescribed grazing
Soil health
Rangeland restoration
Sustainable management

ABSTRACT

To assess whether adaptive management using multi-paddock grazing is superior to continuous grazing regarding conservation and restoration of resources we evaluated the impact of multi-paddock (MP) grazing at a high stocking rate compared to light continuous (LC) and heavy continuous (HC) grazing on neighboring commercial ranches in each of three proximate counties in north Texas tall grass prairie. The same management had been conducted on all ranches for at least the previous 9 years. Impact on soils and vegetation was compared to ungrazed areas (EX) in two of the counties. MP grazing was managed using light to moderate defoliation during the growing season followed by adequate recovery before regrazing after approximately 40 days and 80 days during fast and slow growing conditions, respectively. The vegetation was dominated by high seral grasses with MP grazing and EX, and dominated by short grasses and forbs with HC grazing. LC grazing had a lower proportion of high seral grasses than MP grazing or EX. Bare ground was higher on HC than LC, MP and EX, while soil aggregate stability was higher with MP than HC grazing but not LC grazing and EX. Soil penetration resistance was lowest with MP grazing and EX and highest with HC grazing. Bulk density did not differ among grazing management categories. Infiltration rate did not differ among grazing management categories but sediment loss was higher with HC than the other grazing management categories. Soil organic matter and cation exchange capacity were higher with MP grazing and EX than both LC and HC grazing. The fungal/bacterial ratio was highest with MP grazing indicating superior water-holding capacity and nutrient availability and retention for MP grazing. This study documents the positive results for long-term maintenance of resources and economic viability by ranchers who use adaptive management and MP grazing relative to those who practice continuous season-long stocking.

1. Introduction

Prairie ecosystems prior to European settlement of the Great Plains of North America were characterized by free-ranging herds of large, migratory herbivores which moved constantly in response to changes in the vegetation due to topography, edaphic effects and variable and patchy precipitation to improve their diet quality and grazing efficiency (Frank et al., 1998). They also moved for a variety of other reasons including social factors, fire, predators, and movements by herders and hunters (Bailey and Provenza, 2008). Therefore, although grazing was intense at any particular site, such concentrated grazing seldom occurred at length and defoliated plants were usually afforded time and growing conditions to recover (Frank et al., 1998). This periodic vegetation defoliation and regrowth created by migratory herbivores contributed to ecosystem stability and the availability of high quality diet for these herbivores.

A further factor contributing to stability in these ecosystems is that grazers are important regulators of ecosystem processes in grazing ecosystems (Frank and Groffman, 1998). Ungulates in grazed ecosystems increase forage concentration, grazing efficiency, forage nutrient concentration and above-ground plant production (Frank et al., 1998). They also improve mineral availability by enhancing soil microbial nutrient enrichment and rhizospheric processes that ultimately feedback positively to plant nutrition and photosynthesis (Hamilton and Frank, 2001) in addition to increasing nutrient cycling within patches of their urine and excrement (Holland et al., 1992). Consequently, grazing is an optimization function with low levels of primary production at excessively low or high levels of herbivory and maximum productivity at intermediate levels of herbivory (McNaughton, 1979; Dyer et al., 1993; Turner et al., 1993).

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doi:10.1016/j.agee.2011.03.009

By increasing resource availability locally, herbivores can also diminish the adverse impacts of secondary compounds in plants by providing conditions more conducive to growth rather than to developing chemical defences (Bryant et al., 1983; Coley et al., 1985). Such grazer controls of carbon (C) and nitrogen (N) processes are as important as landscape effects of topography, catenal position and different soils (Frank and Groffman, 1998).

The relatively recent replacement of these free-ranging wild herbivores with livestock that have restricted movements has removed the key stabilizing element of periodic use. In addition, the maintenance of artificially high animal numbers with supplementary feed during less productive periods has led to widespread overgrazing (Oesterheld et al., 1992; Milchunas and Lauenroth, 1993). The result is degraded vegetation and soils, decreased palatable grasses, increased bare ground and erosion, leading to widespread declines in production, vigor and biodiversity of these grasslands (Archer and Smeins, 1991; West, 1993; Knopf, 1994; Frank et al., 1998) and ultimately a reduction in ecosystem resilience (Peterson et al., 1998). These developments have negative consequences for land-surface–atmospheric interactions (Archer et al., 2001).

The most common form of grazing management on rangeland with livestock is continuous year-round stocking. Livestock grazing large paddocks exhibit spatial patterns of repetitive use; heavily using preferred plants, patches and areas while avoiding or lightly using others (Willms et al., 1988; O'Connor, 1992; Ash and Stafford-Smith, 1996; Bailey et al., 1996; Gerrish, 2004; Witten et al., 2005). Therefore, the effective stocking rate on heavily used patches is much higher than that intended for the area as a whole and if threshold amounts of biomass and litter are not maintained on preferred areas, a degradation spiral is initiated and this is accelerated during periods of below average precipitation (O'Connor, 1992; Thurow, 1991; Fuls, 1992; Ash and Stafford-Smith, 1996; Snyman, 1998; Teague et al., 2004). Even under light stocking rates, grasslands can deteriorate with continuous grazing because of constant, high grazing pressure on preferred areas and plants (Merrill, 1954; Thurow et al., 1988; Norton, 1998; Tainton et al., 1999) and this becomes more prevalent as the size of the paddock increases (Teague et al., 2004; Müller et al., 2007; Bailey and Provenza, 2008; Provenza, 2008).

The principal objective of conservation-oriented livestock grazing management is to maintain or improve forage production and forage harvesting efficiency. Maintenance or improvement of forage production is directly related to water infiltration rates and water-holding capacity (Thurow, 1991; Belsky et al., 1993; Snyman, 2003). Therefore, the long-term success of grazing management depends on how well increased livestock harvest efficiency, which reduces herbaceous cover and biomass, is balanced with the need to maintain soil chemical, physical and hydrological properties. Pioneer conservation ranchers and scientists achieved range improvement using growing season rest (Smith, 1895; Sampson, 1913; Rogler, 1951; Scott, 1953; Matthews, 1954; Merrill, 1954; Hormay, 1956; Hormay and Evanko, 1958; Hormay and Talbot, 1961) and subsequent research confirmed the successful improvement of rangeland using growing season rest often in conjunction with multi-paddock grazing (Reardon and Merrill, 1976; Booysen and de Tainton, 1978; Smith and Ownsby, 1978; Daines, 1980; Danckwerts et al., 1993; Taylor et al., 1993; Kirkman and Moore, 1995; Müller et al., 2007).

In the early 1970s a more intensive form of management was developed based on the writings of Voisin (1959) and Acocks (1966) which involved multiple paddocks per herd, high animal densities, very short periods of grazing, long recovery periods and higher stocking rates than were traditionally considered sustainable (Savory and Parsons, 1980; Savory and Butterfield, 1999; Gerrish, 2004). Subsequently, ranchers worldwide have used adaptive management with multi-paddock grazing to refine management protocols and achieve excellent animal productivity and vegetation improvement objectives. Many ranchers who have practiced multi-paddock grazing for decades have reported a high degree of satisfaction with the economic and ecological results and changes in management lifestyle and social environment of their ranch businesses (Goodloe, 1969; Tainton et al., 1977; Cumming, 1989; McCosker, 1994; Dagget, 1995; Earl and Jones, 1996; Stinner et al., 1997; Norton, 1998; Norton, 2003; Berton, 2001; Sayre, 2001; Gordon, 2002; Howell, 2008). Many of these ranchers have received conservation awards from scientific societies and from the ranching and wildlife industries.

In contrast, based on the results of small-scale field research, the efficacy of multi-paddock grazing management for maintaining or improving rangeland condition has been questioned by Briske et al. (2008). However, most of the grazing management research cited by Briske et al. (2008) did not take into account plant and animal processes at appropriate spatial and temporal scales and was not adaptively managed to achieve desirable soil, vegetation and livestock goals, thus resulting in incorrect interpretations for rangeland management on commercial ranches (Norton, 1998; Teague et al., 2009).

Long-term ecosystem health and profitability are the goals of conservation-oriented ranchers. They plan their grazing management within an adaptive, goal-oriented management framework using basic knowledge of plant and animal physiology and ecology. Also, ranchers must manage in environments with all the inherent variability of unique landscapes and the vagaries of the weather and market place. So to achieve desired goals they view grazing schedules and stocking rates as *variables* to be applied in an adaptive management context to meet a variety of management objectives under constantly changing circumstances (Teague et al., 2009). This contrasts with research protocols such as those cited by Briske et al. (2008) that have almost invariably applied grazing variables as fixed "treatments" to avoid confounding "grazing management" with other variables, and reduce variability by using small plots, thus ignoring landscape effects (Teague et al., 2009). Accordingly, there is a need to determine the influence of different grazing management categories at *the ranch-scale* on soil C, ecosystem goods and services and profitability in the southern Great Plains rangelands when they are *managed adaptively* to achieve desirable soil, vegetation, livestock and ecosystem service goals.

This project aimed to assess the effect of multi-paddock grazing when managed adaptively at the ranch scale to achieve desirable vegetation and animal production goals relative to the two most common grazing practices of light and moderate to heavy continuous grazing on the vegetation and soil chemical, physical, microbial and hydrological properties. We hypothesized that, at the ranch management scale, if multi-paddock grazing were managed adaptively to achieve dominance by high seral vegetation and moderate growing season defoliation levels, it would result in superior vegetation composition and standing crop, and superior soil physical, chemical, microbial and hydrological properties compared to season-long continuous grazing.

2. Methods

2.1. Site description

The study was conducted in the Fort Worth Prairie and West Cross Timbers vegetation regions of North Central Texas (98° 08′ N, 33° 16′ W) in Cooke, Parker and Jack counties (Diggs et al., 1999). The climate is continental with an average 220 frost-free growing days. Mean annual precipitation is 820 mm and mean annual temperature is 18.1 °C. Elevation ranges from 300 m to 330 m.

Table 1
Soil and vegetation sampling matrix for three counties in North Central Texas.

Grazing management	Stocking rate AU 100 ha^{-1}	County		
		Cooke	Parker	Jack
Light continuous	14	×	×	×
Heavy continuous	27	×	×	×
Heavy multi-paddock	27	×	×	×
Mowed field	NA	×	–	–
Graze exclosure	NA	×	–	×

The vegetation in the area is rolling tall grass prairie on the uplands with woody vegetation along the larger watercourses. Soils of the prairie areas are predominantly clay-loams derived from limestone (Appendix A, Table 9). The uplands, which make up the major portion of the landscape, are too shallow for agriculture and thus are dominated by the original vegetation and are still used primarily for livestock grazing (Diggs et al., 1999). The uplands are dominated by tall grasses *Schizachyrium scoparius, Andropogon gerardii,* and *Sorghastrum nutans* and midgrasses *Bouteloua curtipendula,* and *Sporobolus compositus* in association with the forbs *Ambrosia psilostachya*, *Aster ericoides* and *Gutierrezia texana.* Where grazing pressure has been heavy the grasses *Nassella leucotricha, Bothriochloa laguroides, Buchloe dactyloides*, *Bouteloua hirsuta* and annual forbs, particularly *Gutierrezia dracunculoides,* are more common (Dyksterhuis, 1946; Dyksterhuis, 1948; Diggs et al., 1999).

2.2. *Experimental design*

While controlled experiments using genuine replication in which all variables except the treatment are held constant usually deliver the most definitive results, this is not practical when addressing landscape ecological impacts and questions (Hargrove and Pickering, 1992). Consequently, in this study we used multiple cross-site comparisons to assess the relative impacts and benefits of different grazing management categories in each of three proximate counties in the same ecoregion and checked for consistency of responses among counties as outlined by Hargrove and Pickering (1992). The vegetation communities used in the study were all native tall grass prairie communities that had never been plowed.

The study was conducted on three neighboring ranches in each of three proximate counties ($n = 9$; Table 1). Ranches had been managed using: (1) light continuous grazing (LC; $n = 3$); (2) heavy continuous grazing (HC; $n = 3$); and (3) planned multi-paddock rotational grazing (MP; $n = 3$) management. The same grazing management had been practiced on all ranches for at least nine years before the study began. The MP ranches included the Richard's Ranch in Jack County, the Pittman Ranch in Cooke County and the Bear Creek Ranch in Parker County. All ranches were from 1200 ha to 4000 ha representing the range in size of ranches for the area.

We also sampled neighboring ungrazed areas within Fort Richardson State Park in Jack County ($n = 1$) infrequently mowed since 1867, and a native prairie field in Cooke County that had never been plowed and for 40+ years mowed annually for hay ($n = 1$; Table 1). Two fenced grazing exclosures (EX; 78.5 m^2 each) that had been in place for 7 years prior to this study were also sampled on the Pittman Ranch in Cooke County.

In each county the same catenal positions and range sites were used for each of the grazing treatments and grazing exclosures being compared. All sites being compared were located on similar landscape positions and aspects. The same investigators and methods were used in all aspects of the study to minimize investigator bias. All ranches sampled in each county were neighboring except for the hay field in Cooke County and the heavy continuous site in Parker County which were 10 km and 18 km from the other ranches sampled, respectively.

2.3. *Grazing management history*

The general management on the ranches using multiple paddocks per herd was to graze a pasture lightly to moderately for 1 or 3 days followed by a recovery period of approximately 30–50 days and 60–90 days during fast and slow growing conditions, respectively (Table 2). This resulted in two light-to-moderate defoliations during the growing season with regrazing before the majority of plants switched from vegetative to reproductive phases. This kept the plants in a leafy, vegetative condition during the growing season to provide a high level of forage quality for the livestock and to ensure the best possible forage regrowth after defoliation. During drought periods animal numbers were adjusted to match forage amounts. In the winter, the goal was to graze and trample most of the standing forage to enhance litter cover and minimize self-shading that would limit plant growth in the following spring.

The continuously grazed ranches in each county were stocked at approximately the same stocking rates from year to year over at least the previous 9 years. They were otherwise selected by the Natural Resource Conservation Service technical staff in each county as being representative of traditional continuous grazing ranches in the region.

2.4. *Sample sites*

Two soils were sampled on each ranch representing upland and footslope catenal positions on the landscapes at each site (Appendix A, Table 9). To ensure the correct soils were selected on each ranch property for valid comparisons, the Natural Resource Conservation Service specialist soil scientist for north Texas[1] chose the sampling sites and conducted the soil sampling. The shallow clay-loam soils on the upland catenal positions in all three counties were of the Aledo series (USDA, 2009). The deeper clay-loam soils on the footslope catenal positions were Sanger, Venus and Thurber series in Cooke, Parker and Jack counties, respectively. Sample sites were all chosen to be 200–400 m from the nearest livestock watering point to eliminate the effect of heavier herbivory in close proximity to water and avoid the decrease in herbivory at distances greater than 1 km from watering points. Livestock gathering points were also avoided for the same reason.

Sampling for soil physical properties was conducted in early summer 2007. Soil microbe sampling was conducted in early June 2008, and sampling for nutrient analyses was conducted in September 2008. Vegetation was sampled in October of 2007 and again in 2009.

The HC site in Parker County was not stocked with grazing animals in 2007 and 2008 and had to be replaced with another site in the same county to complete 2 years of vegetation sampling. The soil physical and microbial sampling was conducted at the new site in April 2009 and June 2010, respectively. We re-sampled the microbial properties at all the Parker County sites in June, 2010 to avoid confounding results between years in this county. The vegetation at the new HC site in Parker County was measured in October 2008 and again in November 2009. Soil organic carbon (SOC) was measured in October 2008.

Rainfall simulator sampling was conducted in fall of 2008, except on the HC site in Parker County, which was sampled in spring of 2009.

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Table 2
Management details for ranches managed using multi-paddock grazing in Cooke, Parker and Jack counties, Texas.

County	Ranch name	Number of camps	Size of camps (ha)	Period of recovery		Strategy to avoid over stocking in periods of low forage supply
				Fast growth	Slow growth	
Cooke	Pittman	41	8	30–45	60–80	Breeding cows <50% of animal biomass and sell off non-breeding stock early
Parker	Bear Creek	28	24	30–45	70–90	Breeding cows <50% of animal biomass and sell off non-breeding stock early
Jack	Richards	10	26	40–50	75–90	Not replace open cows at weaning in fall

Table 3
Dates of vegetation sampling relative to previous grazing period for ranches managed using multi-paddock grazing in Cooke, Parker and Jack counties, Texas.

Ranch name	Year	Sample date	Times grazed before sampling each year	Days since previous graze	
				Upland	Toe slope
Pittman	2007	24 July	3	9	2
	2008	28 July	3	32	30
	2009	27 October	3	67	66
Bear Creek	2007	19 July	3	8	8
	2008	21 July	3	28	28
	2009	20 October	3	12	12
Richards	2007	17 July	3	47	42
	2008	17 July	3	43	38
	2009	18 October	3	52	45

2.5. Soil measurements

At each of the catenal position sites referenced above we measured the following soil parameters: bulk density, penetration resistance, aggregate stability, hydraulic conductivity, and water infiltration to determine the accumulated grazing management effects on the soil. These measurements were done in mid-May to mid-June 2007. The hydraulic conductivity measurements took 10–20 min each and the water infiltration took 40–90 min each. Soil bulk density and moisture were measured at each sampling point using 50-mm diameter × 100-mm long soil sampling tubes and gravimetric analysis. Soil penetration resistance and aggregate stability were measured at 5 cm, 10 cm and 15 cm depths using methods described by Herrick and Jones (2002), and Herrick et al. (2001). Hydraulic conductivity was measured using a disc infiltrometer at suction values of 1 cm and 4 cm tension as described by Zhang (1997) and soil water infiltration using concentric-ring infiltrometers as described by Bouwer (1986). A constant water level was maintained in the outer and inner rings by frequently adding small amounts of water until a constant rate of infiltration was achieved.

Soil sampling for nutrient analyses was down to unweathered parent material on each soil. We sampled at 10 randomly located sub-sample points (cores) in the vicinity of each of the infiltration sampling points. On the shallow Aledo soils in the upland catenal positions this was to a depth of approximately 15 cm. Deeper soils in the footslope catenal positions were sampled at depths of 0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, and 120 cm+. Sub-samples from five randomly located soil cores per location from each of these depths were bulked, homogenized and air-dried. Visible organic matter above mineral earth was carefully removed before taking sample cores. A composite sample for each soil depth was analyzed at a commercial laboratory (Ward Laboratories, Inc., Kearney, NE). Nitrate (NO_3^-) and ammonium (NH_4^+) according to Kenney and Nelson (1982). Total N ($NO_3^- + NH_4^+$) was determined according to McGeehan and Naylor (1988). Soil organic carbon (SOC) was analyzed using the loss on ignition (LOI) described by Combs and Nathan (1998).

Soil microbial composition was sampled by taking ten 5-cm diameter cores to a depth of 5 cm at each soil sampling site in early June when growing conditions were good to excellent and soil microbes would be most abundant (Bardgett, 2005). Samples were located adjacent to the perennial grass tuft nearest to randomly located points at each site. Samples were bulked, put on ice immediately and shipped over-night to the Soil Foodweb laboratory in Corvallis, OR for analysis of active and total bacteria, active and total fungi, endo-mycorrhizal fungi infection, nematodes and protozoa. Active bacteria and fungi were determined using direct microscopy described by Stamatiadis et al. (1990). Total bacteria and fungi were determined by direct enumeration using microscopy as described by Van Veen and Paul (1979). Protozoa were enumerated by the most probable number method as outlined by Stevik et al. (1998), while nematodes were extracted using an enhanced Baermann funnel technique as outlined by Anderson and Coleman (1977). Mycorrhizal colonization was determined using direct microscopy as described by Rajapakse and Miller (1992).

Runoff and sediment loss were estimated using portable rainfall simulators as described by Humphry et al. (2002). Three plots (1.5 m × 2 m) per grazing treatment were mea-

Table 4
Soil physical and hydrological parameter values recorded following heavy continuous, light continuous, heavy multi-paddock grazing and grazing exclosures in Cooke, Parker and Jack counties, Texas.

Parameter	Grazing management			
	Heavy continuous	Light continuous	Multi-paddock	Graze exclosure
Aggregate stability (%)	81_b	90_{ab}	93_a	89_{ab}
Bulk density ($g\,cm^{-3}$)	1.06_a	0.98_a	0.91_a	0.9_a
Hydraulic conductivity ($K \times 10^{-4}$)	44_a	53_a	60_a	66_a
Ring infiltrometer ($cm\,h^{-1}$)	4_a	11_a	7_a	26_a
Penetration resistance (Joules)	246_a	212_b	174_{bc}	160_c
Runoff ($cm\,h^{-1}$)	2.0_a	0.3_b	1.4_a	1.8_a
Sediment loss ($g\,m^{-2}$)	18.0_a	2.0_b	4.0_b	4.0_b
Soil moisture (Volumetric %)	15_b	23_a	25_a	24_a

Within row means followed by the same letter are not significantly different ($p < 0.05$).

Table 5
Soil nutrient parameters following heavy continuous, light continuous, heavy multi-paddock grazing and grazing exclosures in Cooke, Parker and Jack counties, Texas.

Parameter	Grazing management			
	Heavy continuous	Light continuous	Multi-paddock	Graze exclosure
Soil organic matter (%)	2.4^{C}	3.24^{B}	3.61^{A}	3.59^{A}
NO_3 N (mg kg^{-1})	1.82_{b}	1.47_{b}	1.50_{b}	3.58_{a}
Nitrogen (kg ha^{-1})	6.49_{b}	5.28_{b}	5.41_{b}	12.99_{a}
Magnesium (mg kg^{-1})	157_{b}	137_{b}	225_{a}	141_{b}
Potassium (mg kg^{-1})	196_{a}	190_{a}	205_{a}	209_{a}
Manganese (mg kg^{-1})	4.7_{a}	4.9_{a}	5.4_{a}	4.3_{a}
Copper (mg kg^{-1})	0.47_{a}	0.54_{a}	0.56_{a}	0.51_{a}
Phosphorous (mg kg^{-1})	1.6_{a}	1.1_{a}	2.0_{a}	1.6_{a}
Zinc (mg kg^{-1})	0.31_{a}	0.42_{a}	0.43_{a}	0.47_{a}
Iron (mg kg^{-1})	14_{a}	21_{a}	18_{a}	14_{a}
Calcium (mg kg^{-1})	4505_{b}	4395_{b}	4887_{a}	5257_{a}
Sodium (mg kg^{-1})	35_{b}	45_{b}	114_{a}	52_{b}
pH	7.6_{b}	7.7_{b}	7.8_{ab}	7.9_{a}
CEC	24.6^{B}	23.7^{B}	27.4^{A}	27.9^{A}

Means differ if they have a different letter at: upper case superscript $p < 0.05$; lower case subscript $p < 0.10$.

sured at each site. The simulators provided a 70 mm h^{-1} storm event of sufficient duration to give 30 min of continuous runoff.

2.6. Vegetation measurements

Herbaceous vegetation was sampled at each soil sampling site by establishing a random 40-m transect and measuring herbaceous composition at 2-m intervals ($n = 20$) within a 0.05 m^2 quadrat using the dry-weight-rank method of Mannetje and Haydock (1963) as modified by Jones and Hargreaves (1979) and implemented as outlined by Dowhower et al. (2001). The sampling dates conducted in relation to grazing in the multi-paddock sites are presented in Table 3. Sampling was conducted at peak standing crop to estimate the highest biomass values in each situation for that year.

Grass and forb standing crop were determined gravimetrically from the quadrat clippings. Percent bare ground, litter, and herbaceous cover were estimated in each quadrat for a total of 100%. To simplify interpretation, we analyzed herbaceous biomass by functional group using the following seven plant functional groups: annual forbs, perennial forbs, annual C_3 grasses, perennial C_3 grasses, perennial C_4 tall grasses, perennial C_4 midgrasses, and perennial C_4 short grasses. The species making up these functional groups are appended (Appendix A, Table 10). The proportional composition of each functional group was calculated from the biomass to examine proportional species composition resulting from the different grazing management treatments.

2.7. Statistics

The statistical model was 3 counties (blocks) × 2 catenal positions × 4 different grazing management categories: heavy continuous; light continuous; multi-paddock rotation; and ungrazed exclosure using an incomplete randomized blocks design to account for lack of a grazing exclosure in Parker County (Table 1). Data were analyzed using the MIXED MODEL (SAS Institute, 1996) to test for the effects of grazing management and catenal position on soil and vegetation parameters. Least squares means of the adjusted variable were compared to account for the unbalanced design.

Table 6
Soil organic matter (%) following heavy continuous, light continuous, heavy multi-paddock grazing and grazing exclosures in Cooke, Parker and Jack counties, Texas.

Soil depth (cm)	Grazing management			
	Heavy continuous	Light continuous	Multi-paddock	Graze exclosure
0–15	3.76_{b}	5.24_{a}	5.72_{a}	5.62_{a}
15–30	2.45_{b}	3.55_{a}	4.00_{a}	4.01_{a}
30–60	1.49_{a}	2.09_{a}	2.48_{a}	2.63_{a}
60–90	1.78_{a}	1.67_{a}	2.00_{a}	2.34_{a}
Mean	2.49_{c}	3.24_{b}	3.61_{a}	3.59_{a}

Means differ if they have a different letter ($p < 0.05$).

The assessment of grazing management and county differences was based on 6, 7 or 8 error degrees of freedom depending on which parameters were being analyzed (Appendix A, Table 11) from 14 properties (Appendix A, Table 12). Catenal position and its interaction with grazing management were based on 27 property-catenal position combinations. Soil chemistry changes with depth were analyzed using linear estimates unless curvilinear estimates gave a better fit. Year and year effects, soil depths, penetrometer depths, and infiltrometer tensions were all treated as repeated measures regarding grazing management and catenal effects.

Analysis of similarities (ANOSIM; Clarke and Green, 1988) was used to provide an index (R), and probability (p) of plant and soil microbe similarities in multi-dimensional space by comparison of rank similarities generated through permutations of within group to outside group similarity indices. Similarity index analyses included all parameters that were measured to reflect whole community responses to the different county locations and grazing management categories.

Prior to analysis, data were transformed to optimize normality and homogeneity of variance using the Shapiro–Wilk test (Steel and Torrie, 1980). Values presented are non-transformed but probabilities associated with differences and standard errors are based on transformed analyses. Significance is at $p \leq 0.05$ unless otherwise noted.

3. Results

3.1. Soil physical parameters

Aggregate stability was higher with MP than HC grazing but not LC grazing and EX (Table 4). There were no differences in bulk density ($p = 0.60$) due to grazing management category. In contrast, there were large differences in penetration resistance among grazing treatments ($p < 0.001$) with EX having the lowest values, HC grazing the highest and MP and LC grazing being intermediate.

Infiltration rate was similar among the three grazing management categories and EX when measured by infiltrometer (hydraulic conductivity; $p = 0.39$) or ring infiltrometer ($p = 0.13$).

Soil moisture in the surface 300 mm at time of soil physical property measurement was lower with HC grazing than the other

Table 7
Soil microbial biomass and mycorrhizal root colonization recorded following heavy continuous, light continuous, heavy multi-paddock grazing and grazing exclosures in Cooke, Parker and Jack counties, Texas.

Parameter	Grazing management			
	Heavy continuous	Light continuous	Multi-paddock	Graze exclosure
Total bacteria ($g\,m^{-2}$)	82_a	74_a	78_a	98_a
Active bacteria ($g\,m^{-2}$)[a]	5_a	7_a	5_a	4_a
Total fungi ($g\,m^{-2}$)	97_b	98_b	174_a	105_{ab}
Active fungi ($g\,m^{-2}$)	1.1_a	0.8_a	1.0_a	0.7_a
Endo-mycorrhizal fungi (Infection %)	4_b	3_b	6_{ab}	12_a
Ratio of total fungi to total bacteria	1.2_b	1.1_b	3.1_a	0.7_b
Nematodes ($g\,m^{-2}$)	0.25_b	0.40_a	0.25_a	0.27_a
Protozoa ($g\,m^{-2}$)	0.8_a	0.9_a	0.5_a	0.5_a

Within row means followed by the same letter are not significantly different ($p < 0.05$).

[a] To 60 mm depth.

grazing management categories. Runoff measured with the rainfall simulator plots was lower with LC grazing than the other management categories, while sediment loss was much higher with HC grazing.

3.2. Soil chemistry

Table 5 presents the differences in soil chemistry associated with the different grazing management categories. Significant effects were associated with only SOM, N, magnesium (Mg), calcium (Ca), sodium (Na), CEC, pH and base saturation.

Soil organic matter was greater throughout the soil profile with MP grazing and EX than with LC grazing, and HC grazing had the lowest SOM (Table 6). These differences were significant in the upper 300 mm of soil but not at greater depths. Nitrogen was higher in EX while Mg and Na were higher with MP grazing than the other grazing management categories. Cation exchange capacity and Ca were higher with MP grazing and EX than both LC and HC grazing, while pH was higher in EX than both LC and HC grazing.

3.3. Soil microbiota

The microbial communities of MP vs. HC grazing were similar (global $R = 0.15$; $p = 0.267$), as were those of MP vs. LC grazing (global $R = 0.03$; $p = 0.416$), while those of HC vs. LC grazing were dissimilar (global $R = 0.75$; $p = 0.037$). With reference to the ungrazed exclosures, MP vs. EX were similar (global $R = 0.28$; $p = 0.183$), LC vs. EX were dissimilar (global $R = 0.46$; $p = 0.067$) and HC vs. EX were dissimilar (global $R = 0.56$; $p = 0.022$). Accounting for catenal position and grazing differences indicated no difference in microbial assemblage between upland and footslope catenal positions (global $R = -0.068$; $p = 0.745$).

Total and active bacterial biomass was not different among any of the grazing categories and EX (Table 7). Total fungal biomass was highest with MP grazing, lowest with LC and HC grazing, and intermediate with EX. Active fungal biomass was not different among any of the categories. Endo-mycorrhizal fungal root infection (%) was higher with EX than both LC and HC grazing but not MP grazing. The ratio of total fungi to total bacteria was higher with MP grazing than both LC and HC grazing and EX, while nematode and protozoan biomass did not differ among grazing management categories.

3.4. Vegetation

ANOSIM indicated that vegetation differed due to grazing management. MP vs. HC grazing was strongly dissimilar (global $R = 0.95$; $p = 0.003$), MP vs. LC grazing was similar (global $R = 0.18$; $p = 0.170$) and HC vs. LC grazing was dissimilar (global $R = 0.97$; $p = 0.005$). With reference to the ungrazed exclosures, MP vs. EX was similar (global $R = 0.31$; $p = 0.150$), LC vs. EX was similar (global $R = 0.37$; $p = 0.178$) and HC vs. EX was dissimilar (global $R = 0.94$; $p = 0.022$). Accounting for catenal position and grazing differences, ANOSIM indicated no vegetation assemblage difference between upland and footslope catenal positions (global $R = -0.006$; $p = 0.531$).

Table 8
Bare ground (%), biomass composition (%) and standing crop biomass ($kg\,ha^{-1}$) per herbaceous functional group for heavy continuous, light continuous heavy multi-paddock grazing and grazing exclosures in Cooke, Parker and Jack counties, Texas.

Parameter	Grazing management			
	Heavy continuous	Light continuous	Multi-paddock	Graze exclosure
	%			
Tall grass	7^D	20^C	45^B	69^A
Midgrass	32^{AB}	42^A	34^{AB}	20^B
Short grass	7_a	1_b	0_b	0_b
Perennial C_3 grass	15_a	7_b	2_{bc}	0_c
Perennial forbs	23_a	23_a	14_{ab}	8_b
Annual C_3 grass	3	3	1	3
Annual forbs	13_a	3_b	3_b	2_b
Bare ground	30_a	4_b	1_b	3_b
	$kg\,ha^{-1}$			
Tall grass	184_c	870_b	2276_a	3374_a
Midgrass	684_b	1698_a	1450_{ab}	917_{ab}
Short grass	149_a	28_b	10_b	13_b
Perennial C_3 grass	467_a	273_{ab}	104_c	106_c
Perennial forbs	503_b	875_a	625_{ab}	367_b
Annual C_3 grass	116_a	114_a	48_a	187_a
Annual forbs	371_a	93_a	108_a	125_a
Total	2696_c	3960_b	4680_a	5149_a

Means differ if they have a different letter at: lower case subscript for $p < 0.05$; and uppercase superscript for $p < 0.10$.

Table 9
Summary of soil characteristics from USDA NRCS (USDA, 2009) for catenal positions sampled in Cooke, Parker and Jack Counties, Texas.

Parameter	Soil series				
	Aledo	Anocon	Sanger	Thurber	Venus
Catenal position	Upland	Upland	Footslope	Footslope	Footslope
Drainage	Well	Well	Well	Moderately well	Well
Solum depth	0.15–0.40 m	2–3 m	1.2–2 m	2–3 m	1.2–2 m
Permeability	Moderate	Moderate	Very slow	Very slow	Moderate
Runoff	Medium-rapid	Medium	Slow-medium	Slow-medium	Slow-medium
Hydrology	Run-off	Run-off	Run-on	Run-on	Run-on
Slope (%)	1–8	1–8	1–5	0–3	1–8
Ecological site	Clay-loam	Loamy prairie	Clay	Clay-loam	Loam
FAO soil order	Lithosol	Chernozem	Vertisol	Luvisol	Chernozem
Site I.D.	R085XY185TX	R080BY152TX	R085XY177TX	R080BY147TX	R085XY179TX
Taxonomic Class	Loamy-skeletal, carbonatic, thermic Lithic Calciustolls	Fine, mixed, active, thermic Udic Argiustolls	Fine, smectitic, thermic Udic Haplusterts	Fine, smectitic, thermic Typic Haplustalfs	Fine-loamy, mixed, superactive, thermic Udic Calciustolls

The amount of bare ground was similar among counties ($p > 0.05$) but it was considerably higher with HC than LC grazing, MP grazing and EX which did not differ (Table 8).

The differences in biomass for each plant functional group resulted in different functional group compositions for each grazing management category (Table 8). Under HC grazing, the community had high percentages of midgrass, perennial C_3 grass, perennial forbs and annual forbs, and a very low percentage of C_4 tall grass. LC grazing resulted in high percentages of midgrass, perennial forbs, and moderate percentages of tall grass annual grass and annual forbs. With MP grazing, tall grass percentage was very high, the percentages of midgrass and perennial forbs were moderate, and the percentages of short grass, cool season grass, and annual forbs were very low. Grazing exclosure resulted in near total dominance by tall grass, a low percentage of midgrass, and relatively low percentages of all the other functional groups.

There were large differences in standing crop biomass and proportional composition of the different functional groups among the different grazing management categories and EX. The exclosures and MP grazing had the highest biomass followed by LC grazing and HC grazing that had the lowest (Table 8) this despite the fact that the MP treatments in each county had been grazed 3 times each year before we measured biomass standing crop (Table 3). The biomass of tall grasses was higher in EX and MP grazing and lowest with HC grazing. Midgrasses were higher with LC than HC grazing but not MP grazing and EX. Short grasses had considerably higher biomass with HC than LC and MP grazing, and EX. Perennial forbs had lower biomass with HC grazing and EX, while annual C_3 grasses and annual forbs did not differ among the different management categories.

4. Discussion

4.1. Vegetation

The results we measured, representing the combined positive effects of multi-paddock (MP) management, indicate the multiple advantages of this management option. MP grazing resulted in a higher proportion of desirable tall grasses, a lower proportion of less desirable short grasses, annual C_3 grasses and forbs, and higher standing crop than the more lightly stocked continuous (LC) grazing and the similarly stocked HC. Herbaceous biomass of MP treatment was the highest despite the fact that MP grazing treatments in all counties had been grazed three times prior to measurement at intervals of 2– 67 days after grazing (mean = 31 days). This speaks to the merits of MP grazing as it was conducted in this study.

With LC grazing, the preferred plants and areas are not allowed recovery under continuous grazing, while with correctly managed MP grazing, overgrazing is prevented and adequate recovery after defoliation is allowed. Under MP grazing, by ensuring light to moderate use in the growing season with adequate recovery the preferred forages are not over-utilized and are able to capitalize on

Table 10
Species dominating herbaceous functional groups in Cooke, Parker and Jack Counties, Texas. Species in each functional group are listed in order of abundance. Figures in parentheses indicate the number of species in that functional group encountered. Only species averaging >10 kg ha^{-1} are listed.

Warm season C_4 tall grass (6)
Schizachyrium scoparium
Sorghastrum nutans
Andropogon gerardii
Panicum virgatum
Sorgum halepense

Warm season C_4 midgrass (21)
Sporobolus compositus
Bouteloua curtipendula
Paspalum urvillei
Bothriochloa laguroides
Paspalum distichum
Bracharia ciliatissima
Eriochloa sericea
Aristida longiseta
Coelorachis cylindrica
Panicum obtusum
Panicum capillare

Warm season C_4 shortgrass (8)
Bouteloua hirsuta
Buchloe dactyloides
Panicum hallii

Perennial cool season C_3 midgrass (3)
Nassella leucotricha
Elymus canadensis
Sedges
Cyperus spp.
Eleocharis spp.

Annual cool season C_3 grass (3)
Bromus japonicus
Bromus unioloides

Perennial warm season forbs (59)
Ambrosia psilostachya
Aster ericoides
Artimisia ludoviciana
Rosa foliosa
Symphoricarpos orbiculatus
Solanum dimidiatum
Desmanthus illinoensis
Ruellia humilis
Vernonia marginata
Tragia ramose
Menodora heterophylla

Annual forbs (44)
Gutierrezia texana
Monarda ciriodora
Centaurea americana
Helianthus annuus
Coreopsis tinctoria
Gaillardia pulchella
Xantium strumarium
Gaillardia suavis
Croton monanthogynus

good growing conditions. These positive results were achieved by varying the periods of grazing and recovery according to prevailing conditions. In addition, the grazing is spread over the whole landscape with MP grazing while only a portion of the landscape is grazed with LC grazing and is subject to greater grazing pressure than intended for the area as a whole resulting in deterioration of the overgrazed areas. Heavy continuous grazing (HC) allows the overgrazing evident in small portions of the landscape with LC grazing to be more widespread over the landscape. Thus, in this study, HC grazing resulted in the lowest proportion of desirable grasses and forbs and highest proportion of less desirable short grasses, cool C_3 grasses, and annual forbs, lowest standing crop, and greatest percentage of bare ground compared to the other grazing management categories.

In contrast to the management of MP treatments in this study, research protocols in most previous studies, such as those cited by Briske et al. (2008), have almost invariably applied grazing variables as fixed "treatments" to avoid confounding "grazing management" with other variables. Stocking rates, grazing schedules and resting schedules are examples of "treatments" that have been kept constant without adjustments during periods of low forage production. Consequently, MP grazing management in experiments has seldom been applied in response to changing circumstances or to explicitly achieve desirable ecosystem and economic goals (Teague et al., 2009). Compounding the problem, researchers have chosen to use small treatment areas as a means to reduce variability. Vegetation heterogeneity and associated livestock selective grazing impacts increase with scale, so using small treatment areas to conduct research on underestimates and misrepresents the impact of continuous stocking on the vegetation and soils in these experiments compared to the impact of using such grazing management on commercial ranches.

Overgrazing occurs when individual plants are subjected to multiple, severe defoliations without sufficient physiological recovery time between such events (Roshier and Nicol, 1998). This invariably leads to a decline in the plant's productivity, root biomass and vigor (Briske, 1991), particularly in species that are less tolerant of high levels of herbivory (Ingham and Detling, 1984). This in turn results in less recruitment and survival of preferred plants due to competition from non-selected plants (Briske, 1991).

Due to the dependence of livestock on water, grazing impacts are, in general, negatively correlated with distance from water. However, this water effect on grazing patterns is compounded by vegetative, topographic and edaphic variation within the herbivore's maximum walking range. In combination, these factors can increase the heterogeneity of herbivore impacts on rangelands (Stuth, 1991; Illius and O'Connor, 1999; Bailey and Provenza, 2008). Specifically, area- and patch-selective grazing leads to much higher effective grazing pressure on preferred patches and plants than that which is sustainable for the area as a whole. This usually causes resource deterioration in preferred areas of the landscape even at low stocking rates. If excessive herbivory regularly removes threshold amounts of biomass and litter, a degradation spiral is initiated especially in heavily used patches. This progressive deterioration is characterized by replacement of taller perennial grasses by shorter perennial grasses, then annual grasses and forbs, and finally bare ground (Thurow, 1991; Fuls, 1992; O'Connor, 1992; Ash and Stafford-Smith, 1996; Teague et al., 2004). Droughts, which are a common feature on rangeland ecosystems, exacerbate these effects of chronic defoliation (McIvor, 2007).

Both the scale and spatial arrangement of vegetative patchiness are major determinants of site selection by contained grazing livestock (WallisDeVries et al., 1999). Such site selectivity is affected most by vegetative heterogeneity at the landscape-level and to a lesser degree by plant heterogeneity at the feeding station scale (WallisDeVries and Schippers, 1994; Barnes, 2002; Barnes et al., 2008). In addition, herbivory patterns in contained grazing situations are influenced by topographic variation, the distribution of water, mineral licks and cover, and both intra- and inter-specific social interactions (Coughenour, 1991; Bailey and Provenza, 2008). These factors combine to increase vegetative heterogeneity and the impact of selective grazing as paddock size increases.

For these reasons, LC grazing at the scale of commercial ranches only decreases the number of preferred areas and palatable plants that are overgrazed in comparison with HC grazing. The use of multiple paddocks per herd on commercial ranches gives managers the opportunity to decrease the area on offer to livestock at any one time, thus decreasing heterogeneity of vegetation on offer and the degree of selection by livestock. This spreads grazing over the entire landscape in the numerous smaller paddocks, rather than allowing a concentration of grazing pressure on preferred areas in the landscape. It also provides the manager with the option of regulating the grazing pressure on preferred areas and plants by adjusting when to move animals to a new paddock, and provides the means to allow grazed plants to recover before they are grazed again (Norton, 1998; Teague et al., 2009).

The original vegetation determined from relicts was dominated by *S. scoparium* with *A. gerardii* and *S. nutans* (Dyksterhuis, 1946; Dyksterhuis, 1948) but these preferred forages decrease and disappear under heavy grazing or if plants are not allowed adequate recovery after defoliation (Vinton and Hartnett, 1992; Vinton et al., 1993). Excessive grazing pressure and overoptimistic stocking rates over an extended period of time result in the vegetation changing to primarily annual forbs, and mid- and shortgrasses such as *N. leucotricha*, *B. dactyloides*, *Aristida* spp. and *B. hirsuta* (Dyksterhuis, 1946; Dyksterhuis, 1948).

Tall grasses deteriorate in the absence of disturbance in the form of fire, mowing or infrequent grazing while they thrive and remain competitive under infrequent and light to moderate defoliation (Old, 1969; Knapp, 1985; Hulbert, 1988). In undefoliated or lightly defoliated tall grass prairie, light is the primary limiting factor. Under these conditions water and N can be accumulated as plant growth is strongly reduced (Seastedt, 1995). When the top-hamper of undefoliated or lightly defoliated plants is removed, plant reserves, N and water are relatively high resulting in a high but temporary growth increase that results in N and water becoming the limiting factors (Seastedt and Knapp, 1993; Blair, 1997). This can result in compensatory growth under a light to moderate defoliation regime in tall grass and mixed grass grazing ecosystems as there is a bi-phasic response to herbivory in nutrient rich areas resulting in high growth rates at intermediate levels of foliar biomass and low growth rates at both low and high foliar biomass (Booysen and de Tainton, 1978; Dyer et al., 1993; Turner et al., 1993). Consequently, there is a negative growth response under repeated heavy defoliation in tall and midgrasses (Ingham and Detling, 1984; Holland and Detling, 1990; Seastedt, 1995) and a positive response to herbivory is contingent on suitable fertility levels and climatic conditions (McNaughton, 1979; Wallace et al., 1984; Coughenour et al., 1985; Louda et al., 1990; Dyer et al., 1993). Thus, any positive feedbacks on the ecosystem from grazers are contingent on suitable climatic conditions, and are weakly expressed or prevented during low-rainfall periods and years.

As indicated by these results, adaptively managed MP grazing can take advantage of positive responses and minimize negative responses to livestock grazing outlined above to achieve desired results if knowledge of these biological responses is incorporated into timely management decisions. This was achieved in this study by managing MP grazing to achieve light to moderate growing season defoliation with adequate recovery, and regrazing before the forage plants developed from the vegetative to the reproductive phase. This was managed adaptively in response to prevailing conditions rather than using fixed grazing and recovery schedules.

4.2. Soil parameters

In rangeland ecosystems, maintaining normal soil function and ecosystem health is only possible if adequate plant and litter cover is present to provide protection from soil loss and to allow soil microorganisms to perform optimally (Thurow, 1991; Rietkerk et al., 2000; Bardgett, 2005). Plant and litter cover enhance infiltration, buffer temperatures and decreases evaporation so that soil moisture is retained for longer after each precipitation event. This enhances soil microbial activity, which promotes soil aggregate stability, sustains plant nutrient status and availability, improves plant growing conditions and results in the incorporation of more organic matter into the soil.

These soil-building processes are inhibited by excessive herbivory, excessive trampling, extended drought, and fire (Thurow, 1991; Wright and Bailey, 1982). Soil degradation associated with these factors is indicated by an increase in soil compaction and bulk density, which elevates penetration resistance and reduces aggregate stability (Herrick et al., 1999; Herrick and Jones, 2002). The amount of bare ground is a good indicator for soil function and erosion risk (Thurow, 1991). Bare ground is not protected from the sun and gets much hotter than covered soil, causing a decrease in microbial activity, accelerated loss of organic matter, and the erosion risk increases if there is insufficient cover to dissipate the energy of raindrops before they strike the soil (Blackburn, 1975; Blackburn et al., 1986). Elevated soil temperature and soil loss have a direct negative effect on infiltration rates, soil evaporation, nutrient retention and biological functions that contribute to ecosystem function (Neary et al., 1999; Wright and Bailey, 1982).

To be sustainable in the long-term, grazing management should at least maintain soil function and the soil building process, and preferably enhance them. The various grazing management categories we studied resulted in very different impacts on these soil function parameters. Heavy continuous grazing was associated with a number of negative impacts, including greater bare ground, lower aggregate stability, greater penetration resistance and greater sediment loss relative to MP and LC grazing and EX.

Previous research has indicated that type and amount of vegetation cover greatly influences soil physical parameters and hydrological properties (Blackburn, 1975; Thurow et al., 1986, 1987; Pluhar et al., 1987). Benefits are least likely under bare ground, followed in ascending order by short grasses, bunch grasses and woody plant canopies (Thurow, 1991). Bunchgrasses and shrubs tend to produce greater amounts of foliage and root biomass than annuals and short grasses, and the fallen foliage accumulates above-ground as litter and dead root biomass builds up below-ground. This leads to greater amounts of above- and below-ground organic matter biomass and increased diversity of soil microbes below-ground (Milne and Haynes, 2004). Above-ground litter and plant cover creates a more consistent temperature and moisture microenvironment, which in turn favors microorganism activity (Devi and Yavada, 2006). These factors enhance formation of stable soil aggregates that aid water infiltration and improve soil fertility (Herrick et al., 1999).

The manner in which the MP grazing was managed in all three counties contributed greatly to these results. By defoliating moderately for short periods during the growing season and leaving relatively high biomass levels when exiting paddocks, combined with allowing sufficient time for recovery before grazing again, herbaceous biomass was always relatively high, the plants recovered quickly and provided excellent cover at all times. This allowed the most productive, high seral bunch grasses to dominate vegetation while maintaining a high rate of nutrient cycling. Although the higher density of animals has resulted in elevated soil compaction in other studies, this was not the case in this study. With adequate cover and maintenance of aggregate stability, soils recover rapidly from such compaction as evidenced by the favorable soil physical parameters under MP grazing relative to LC grazing and EX. Previous research has indicated that MP grazing implemented in this manner results in less bare ground, lower soil temperatures and higher soil C than continuous grazing at the same stocking rate (Teague et al., 2010). Similarly, in agreement with our results here, Thurow (1991) demonstrated that at higher stocking rates, MP grazing on semi-arid rangeland resulted in less impact on soil physical properties and infiltration than continuous grazing *at the same high stocking rate*.

In our study, in common with that of Beukes and Cowling (2003) and Teague et al. (2004,2010), the MP grazing was managed to achieve the best animal and vegetation responses by managers aiming to conserve resources. There is little resemblance between this management and artificial studies, such as reported by Warren et al. (1986) and Savadogo et al. (2007), which were conducted on small plots in a manner that would result in very poor animal performance and considerable damage to the vegetation and soil in a production ranch setting. Such small-plot, artificial studies do not impact the land the way livestock do when managed by conservation-oriented ranchers and consequently have little relevance for ranchers managing to maintain resource and economic viability whatever their scientific design merits might be.

Soil organic carbon, which constitutes approximately 60% of SOM, has beneficial effects on the chemical, physical and biological functions of soil quality (Bardgett, 2005). It increases the CEC and water-holding capacity, and contributes to soil structural stability. Organic matter increases adsorption of nutrients, cations and trace elements that are of importance to plant growth, prevents nutrient leaching and is integral to the organic acids that make minerals available to plants. It also buffers soil from strong changes in soil pH. Consequently, it is widely accepted that the C content of soil is a major factor in overall soil health, plant production, the health of water catchments as well as being a sink for atmospheric C to offset climate change (Charman and Murphy, 2000; Lal, 2008).

The manner in which land is used and managed affects the soil's ability to sequester and retain organic C. Practices that increase plant productivity and C inputs to the soil and those that decrease soil exposure to erosion and exposure to sunlight, which increase the rate of C loss, allow higher levels of C to accumulate in the soil (Parton et al., 1987). We measured the highest levels of soil C, highest herbaceous biomass and lowest levels of bare ground with MP grazing and EX. Similarly, LC grazing had higher herbaceous biomass and lower bare ground than HC grazing, which had the lowest soil C. Therefore, soil water-holding capacity would be much higher with MP and EX than LC, and lowest with HC based on the work of Allen (2007) and Leake et al. (2004). This is of paramount importance to maintenance of ecosystem productivity and function. Our results are consistent with numerous studies that show that soil C availability is regulated by plant production and the amount of plant and litter cover providing physical protection of the soil (Conant et al., 2001; Jones and Donnelly, 2004).

The highest levels of N were found in EX while the three grazing treatments had similar levels. High N levels are commonly measured in undefoliated or lightly defoliated tall grass since, under these conditions, light is the primary limiting factor decreasing plant growth which allows both water and N to be accumulated (Seastedt, 1995). When light is removed as a limiting factor by removing the top hamper, N becomes the limiting factor resulting in high temporary growth increase (Seastedt and Knapp, 1993; Blair, 1997). Care must be taken with these results as they were only sampled at one time and N varies at any location during the year due to many factors.

Cation exchange capacity was higher with MP grazing and EX than with both LC and HC grazing. This is consistent with the differences in soil C we measured as organic C is able to retain nutrients and water. The high pH level of EX is presumably also related to the ability of soil C to buffer the soil from changes in soil pH as outlined above.

The other differences we measured among the grazing management categories were higher levels of Mg and Na with MP grazing. The rate of nutrient cycling would have been higher with MP grazing than LC and EX, which possibly accounted for it being higher than these two management categories. It is possible that MP grazing had higher levels of these nutrients than HC grazing because MP grazing resulted in dominance by tall grasses which have much deeper root systems than the midgrass plants that dominated with HC grazing so a greater volume of soil would have been accessed under MP grazing. However, it is not clear why these differences should have occurred with Mg and Na alone.

Species changes in a plant community can cause changes in the composition and function of soil biota, providing feedback that can be positive or negative (Coleman and Crossley, 1996). Such interactions between plants and soil biota provide major structuring forces in plant communities and are important drivers of ecosystem function, composition and productivity (Bardgett, 2005). These interactions include: (1) microbial breakdown of organic matter making nutrients available for plants; (2) plant root exudates providing nutrition for microbes; (3) fungal associations with plant roots enhancing nutrient availability for plants; and (4) soil microbe alteration of the physical structure of the soil affecting habitat for other soil fauna and microbes and influencing the movement of water and nutrients through the soil.

Decomposition of organic matter, which provides nutrients for plants, is performed primarily by bacteria and fungi. Fungi are more efficient at assimilating and storing nutrients, including C, than bacteria (Bardgett and McAlister, 1999; De Vries et al., 2006). A higher fungal population increases the soil's ability to hold C and other nutrients creating a more persistent microbial food source and nutrient pool. Fungi are also better able to buffer against low pH. Consequently, the fungal/bacterial ratio is a good indicator of environmental change and health in the soil and increases in fungal/bacterial ratios indicate improvement in soil heath and C sequestration (Beare et al., 1992; Yeates et al., 1997; Bailey et al., 2002; De Vries et al., 2006). We measured the highest fungal/bacterial ratio with MP grazing. The tall grass species in the Great Plains of North America are known to be obligate mycotrophs (Hartnett and Wilson, 1999) and our results on fungal abundance probably reflect the relative abundance of tall grass species modified by soil N levels among these grazing management categories.

Similarity indices indicated that the composition of soil microbes with MP grazing was similar to that of EX and LC grazing but dissimilar from HC grazing. It is possible that MP grazing and EX were similar as they were both dominated by tall grasses, while MP and LC were similar because they both had a substantial presence of midgrasses. LC and HC grazing were dissimilar from each other and EX. We postulate that this is a result of HC having a greater proportion of cool season grass and annual forbs than the other grazing management categories and EX. Similarly, Patra et al. (2005) determined that intensive grazing resulted in changes in the composition and structure of these plant communities relative to light grazing that changed the activity and composition of the soil microbial communities.

5. Conclusions

In rangeland ecosystems, maintaining normal soil and ecosystem function over the landscape and watershed is possible only if there is adequate plant cover and species composition to provide protection from soil loss and maintenance of conditions for soil microorganisms to prosper and maintain ecosystem functions that provide ecosystem goods and services. In our study we examined the accumulated impacts of 9 years of different grazing management categories on vegetation and soil parameters at a commercial ranch scale. We have checked for veracity and reproducibility in response to these different management categories by checking for consistency of response in each of three proximate counties. While this approach allows less management control than a controlled small-plot experiment, we were better able to study the impact of these grazing management strategies at the scale of commercial ranches. In addition, the ranchers using MP grazing in this study used adaptive management to maintain or restore the ecosystem health and resilience while achieving desired vegetation, livestock and economic goals. This represents the adaptive management approach that ranchers need to follow to maintain resource and economic viability in the long-term in rangeland ecosystems.

This study could not refute the hypothesis that by managing multi-paddock grazing adaptively to achieve dominance of rangeland by high seral grasses would result in superior conservation and restoration of resources, and provision of ecosystem goods and services compared to season-long continuous grazing. Our study contradicts a recent review of rangeland grazing studies (Briske et al., 2008) which suggested MP grazing does not improve vegetation or animal production relative to continuous grazing. The discrepancy is because we measured the impacts on vegetation and soils achieved by ranchers managing at the ranch scale and adapting management in response to changing circumstances in order to achieve desirable outcomes. Similarly, Jacobo et al. (2006) and Earl and Jones (1996) studied adjacent producer-managed ranches to compare continuous and multi-paddock grazing at the ranch scale. The ranches in both these studies were adaptively managed for the best possible outcomes within the constraints of each system. In contrast, studies cited by Briske et al. (2008) investigated MP grazing in relatively small experimental areas and did not manage adaptively the way a successful, conservation-oriented commercial rancher would (Teague et al., 2009).

On the evidence we present here we propose the following hypothesis as an alternative to that of Briske et al. (2008). At the ranch scale, when multi-paddock grazing is managed to give the best vegetation and animal performance it is superior to continuous grazing regarding conservation and restoration of resources, provision of ecosystem goods and services, and ranch profitability.

Acknowledgements

Funding was provided by the Dixon Water Foundation and Texas AgriLife Research under project H8179. We are indebted for invaluable help with statistical design and analyses to Drs Joaquin Sanabria, Sara Duke, Fred Smeins and Bill Pinchak. We acknowledge the invaluable help of Nathan Haile and Jessica Jobe, soil scientists with the Natural Resources Conservation Service, Weatherford, TX, USA, for locating the correct soils to sample and collecting soil cores for analysis. We thank Tony Dean, Matt Gregory, Robbie Tuggle, Jerry Baggs, Danny Parker, and Wayne Becker for assistance in locating and organizing landowner collaborators and Kathryn Bachman for field sampling assistance. We also thank the following landowners and managers who allowed us to sample on land they owned or managed: Clint Josey, Robert Potts, John Hackley, Brent Hackley, Jerry Craft, Royce Turner, Jim House, Robert Frei, Claude Walter, Ken Mitchell, Billy Felderhoff, David Davis and Larry Fuller.

Appendix A.

See Tables 9–12.

Table 11
Statistical model for analysis of different parameters.

Parameter	Numerator df	Denominator df
Herbaceous composition and biomass		
Graze	3	8
Soil	1	11
County	2	11
Soil × county	2	11
Year	1	12
Graze × year	3	12
Soil × year	1	12
County × year	2	12
Runoff and sediment		
Graze	3	6
County		8
Soil		8
Infiltration, aggregate stability, chemical parameters		
Graze	3	7
County	2	8
Soil	1	8
Soil × county	2	8
Patch	1	15
Graze × patch	3	15
County × patch	2	15
Soil × patch	1	15
Soil hydraulic conductivity and penetration		
Graze	3	7
County	2	8
Soil	1	8
Soil × county	2	8
Patch	1	15
Graze × patch	3	15
County × patch	2	15
Soil × patch	1	15
Water tension[a]	1	38
Graze × water tension		
County × water tension		
Soil × water tension	3	7
Patch × water tension	2	8
Soil microbe composition		
Graze	3	7
County	2	8
Soil	1	8
County × soil	2	8

[a] Hydraulic conductivity, water tension.

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Table 12
Summary of different ranches used for sampling in the two catenal positions and four grazing management categories in Cooke, Parker and Jack Counties, Texas.

County	Catenal position	Soil series	Grazing management				Total sites
			Heavy Continuous	Light continuous	Multi-paddock	Graze exclosure	
Cooke	Upland	Aledo	Mitchell	Walters	Pittman	Pittman[a]	4
						Knauf[b]	1
	Footslope	Sanger	Mitchell	Walters	Pittman	Pittman[a]	4
						Knauf[b]	1
Parker	Upland	Aledo	Fuller	Smelly	Bear Creek		3
				Nazarian			1
	Footslope	Venus	Fuller	Smelly	Bear Creek		3
		Venus		Nazarian			1
Jack	Upland	Anocon	Turner	Craft	Richards (2)	Ft. Richardson[a]	5
	Footslope	Thurber	Turner	House	Richards		3
Total							27

[a] Grazing exclosure.

[b] Hay meadow.

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