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Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing

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ABSTRACT

This paper examines if post-fire deferment and periodic rests provided by rotational grazing allowed for more rapid recovery of soil cover, soil chemical and physical parameters, and vegetation composition after summer patch burning than continuous grazing. We evaluated the recovery of native rangeland vegetation and soils subjected to summer patch burns in continuously and rotationally grazed pastures in 2002, 2003 and 2004. Each year, 12% of each treatment replicate was burned as a single patch in a different, non-adjacent area under continuous grazing, and as a single paddock of a rotationally grazed 8-pasture-1-herd system. Recovery of vegetation and soils on burned patches were measured annually until the summer of 2006 and compared to those in immediately adjacent unburned areas in both grazing treatments. Herbaceous cover and biomass took 2 years to recover to control levels on soils with greater mesquite cover and more C_3 grasses, and 3 years on soils with more C_4 grasses. The rotational grazing treatment had less bare ground and lower soil temperatures on both unburned and burned areas than the continuously grazed treatment, which has significant implications for infiltration rates, runoff and erosion in favor of the rotational management. Soil C and C to N ratios were also higher with rotational grazing. Soil physical parameters were not affected by either the burn or grazing treatments but the presence of trees reduced soil temperature, improved soil physical parameters and infiltration rate relative to open grassland.

1. Introduction

Prior to European settlement of the Great Plains of North America, free ranging herds of large, migratory herbivores occupied prairie grazing ecosystems. These large herds moved at will to improve their diet quality and grazing efficiency in an ecosystem that was characterized by abiotic gradients and perturbations such as fire that resulted in high spatio-temporal heterogeneity of forages conditions (Frank et al., 1998). The cyclic vegetation defoliation and regrowth created periodic herbivory and migration that contributed to ecosystem sustainability and the availability of high quality diet for these herbivores. European settlement interrupted these cyclical patterns through the reduction of naturally occurring fires (Brown and Archer, 1989; Archer, 1990; Archer et al., 1995), more sedentary and concentrated use of the vegetation by herbivores (Frank et al., 1998), and the maintenance of artificially high animal numbers with supplementary feed during less productive periods (Oesterheld et al., 1992; Milchunas and Lauenroth, 1993). This over utilized palatable forages, leading to less herbaceous diversity and production, more bare ground and erosion, and greater density of unwanted plant species (Archer et al., 1995; Grover and Musick, 1990; Archer and Smeins, 1991).

Patch burning has been suggested as a means of restoring and maintaining ecosystem function in rangeland ecosystems by re-establishing the movement and grazing habits of large herbivores such as bison that existed prior to settlement of North America by Europeans (Collins and Gibson, 1990; Collins et al., 1998; Frost, 1998; Fuhlendorf and Engle, 2001, 2004; Vermeire et al., 2004). The general hypothesis is that the annual application of natural disturbances, such as patch fires on different areas each year, would cause large herbivores to concentrate on the most recently burned patches shortly after the disturbance. In subsequent years the grazers would shift grazing pressure to the more recently burned patches, creating a phased distribution or spatio-temporal pulses of vegetation growth, nutrient recycling and increased plant biodiversity, contributing to structural diversity across the landscape to ultimately maintain a high level of ecosystem

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function and stability at the landscape scale. Anthropogenic application of such patch disturbances may thus provide a means for restoring degraded rangelands and increasing the sustainable use of this resource.

Since fire and grazing regimes can be manipulated directly, they are potentially important management tools to maintain ecosystem function and the provision of ecosystem services (Frost et al., 1986; Biondini et al., 1989; Petraitis et al., 1989; Liedloff et al., 2001). Fire and grazing interact both in time and space and their co-occurrence can have a synergistic positive effect on plant communities (Frost et al., 1986; Coughenour, 1991), and both can cause resource degradation on rangelands where livestock are sedentary (Frank et al., 1998; Milchunas and Lauenroth, 1993; Wright, 1974a; Snyman, 2003).

Biologically, fire can cause ecosystem degradation since it removes herbaceous vegetation that protects the soil from exposure to the sun, raindrop action and overland flow (Liedloff et al., 2001; Wright, 1974a; Thurow, 1991; Rietkerk et al., 2000; Savadogo et al., 2007). Without post-fire deferment of grazing by livestock, excessive herbivory on burned areas exacerbates this damage (Wright, 1974b). As a key component of overall ecosystem sustainability occurs below ground, recovery after fire is tied to the soil's physical, chemical, and biological functions and processes (Neary et al., 1999). This can alter above- and below ground species composition, generate volatilization of nutrients, produce rapid or decreased mineralization rates, alter C to N ratios, and result in subsequent nutrient losses through accelerated erosion, leaching or denitrification (Wright, 1974a; Snyman and du Preez, 2005). Vegetation recovery from fire is most strongly influenced by soil moisture (Frost et al., 1986; Wright, 1974a). With average or greater precipitation, recovery can occur within a year, but under drought conditions recovery can take 3–5 years or longer (Teague et al., 2008).

Grazing by livestock can decrease the rate of recovery as animals tend to concentrate on recently burnt areas. These preferred patches are often overgrazed even if the grazing management unit is not overstocked (Fuls, 1992; O'Connor, 1992; Bailey et al., 1996; Morris, 2002; Teague et al., 2004; Archibald et al., 2005). Rotational grazing management has the potential to minimize the effects of overgrazing of burnt patches and patch overgrazing by providing periodic rests from defoliation and regulating the severity of defoliation between grazing periods. Compared to continuous grazing, rotational grazing has also been shown to result in less bare ground and greater herbaceous ground cover and to reduce the expansion of bare ground during extended droughts (Teague et al., 2004).

Resource managers in the southern Great Plains have become increasingly interested in applying prescribed fire during the summer because burning at this time of year is more effective in controlling unwanted woody and succulent species than are winter fires (Ansley and Jacoby, 1998; Ansley and Castellano, 2007a). However, summer patch burning cannot be widely advocated until the environmental thresholds for safe burns, as well as the ecological and hydrological impacts of such burns, have been adequately quantified (Daubenmire, 1968; Daowei and Ripley, 1997; Ansley et al., 2006a). We need to know if deferment using rotational grazing reduces negative impacts associated with summer burning and allows for more rapid recovery of herbaceous biomass and cover.

Our study examines the recovery of native rangeland patches burnt in summer under rotational and continuous grazing. We hypothesize that, in comparison with continuous grazing, the post-fire deferment and periodic rests provided by rotational grazing will result in less bare ground, lower soil temperatures, improved soil physical properties, higher levels of soil carbon and nitrogen, more rapid recovery of vegetation biomass, and improved herbaceous species composition.

2. Methods

2.1. Site description

The investigation was conducted in the Rolling Plains ecoregion of north-central Texas (Gould, 1975) on the Waggoner Ranch (33°50′N, 99°5′W) near Vernon. Elevation ranges from 335 to 396 m above sea level. The climate is continental with an average 220 frost-free, growing days and a mean annual temperature of 17 °C. Mean annual precipitation is 648 mm and bimodal with peaks in May (95 mm) and September (76 mm).

Vegetation consists of honey mesquite (*Prosopis glandulosa* Torr.) savanna with a shrub lotebush (*Ziziphus obtusifolia* (L.) H. Karst), and succulents tasajillo (*Opuntia leptocaulis* DC.), and prickly pear cactus (*Opuntia phaecantha* Engelm.) of infrequent occurrence. The herbaceous understory is dominated by silver bluestem (*Bothriochloa laguroides* (DC.) Herter. subsp. torreyana (Steud.), meadow dropseed (*Sporobolus compositus* Torr.), Texas wintergrass (*Nassella leucotricha* Trin. & Rupr.), sideoats grama (*Bouteloua curtipendula* Torr.), buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.), and the annual Japanese brome grass (*Bromus japonicus* Thunb. Ex Murray). The most common forbs are western ragweed (*Ambrosia psilostachya* DC.), heath aster (*Aster ericoides* L.), and annual broomweed (*Gutierrezia texana* (DC.) Torr. & A. Gray). Nomenclature follows Diggs et al. (1999).

Sampling sites were located on the 2 dominant soil types, Tilvern and Wichita series clay-loam soils (Table 1). The Tilvern soils had greater mesquite cover (44% vs. 20%) and C_3 grasses (60%), while the Wichita soils had more C_4 grasses (64%).

2.2. Experimental treatments

The study had two replicates of summer patch burning within two grazing treatments: continuous grazing and rotational grazing with an 8-paddock, 1-herd configuration. The continuously grazed replicates were 326 and 496 ha in size, respectively. The rotationally grazed treatment replicates were 1888 and 2161 ha in size, giving mean individual subdivision paddock sizes of 236 and 270 ha, respectively. Each replicate was stocked with commercial beef cattle bred to calve in January through March. A light to moderate stocking rate (14 ha AUY^{-1}) was applied to all replicates. In the rotational grazing treatment, cattle were moved when preferred plants were moderately defoliated, resulting in periods of absence following grazing of approximately 45 and 90 days during fast and slow forage growth periods, respectively. The movement of livestock in each of the rotational grazing replicates was conducted to achieve the goals of obtaining the highest animal performance and most favorable impact on the vegetation

Table 1
Summary of soil characteristics from USDA (2009) and FAO (2006) for soils sampled on the Waggoner Experimental Ranch in Wilbarger County, Texas.

Parameter	Tilvern clay loam	Wichita clay loam
Catenal Position	Upland	Footslope
Drainage	Well	Well
Solum depth	100–150 cm	150–200 cm
Permeability	Very slow	Slow
Runoff	Very high	High
Hydrology	Runoff	Run-on
Slope (%)	1–3	1–3
Color	Dark brown	Reddish brown
Ecological site	Clay prairie	Clay loam
Site I.D.	078 BY090 TX	078CY096 TX
Taxonomic Class	Fine, mixed, active, thermic Vertic Haplustepts	Fine, mixed, superactive, thermic Typic Paleustalfs
FAO soil order	Regosol	Kastanozem

possible. This was achieved by grazing lightly to moderately for short periods in the growing season to ensure high animal performance and leaving the forage in a condition so that it could recover quickly. At the moderate stocking rates applied and by grazing so that no more than half the preferred forage was consumed before moving in the rotation treatments, the herbaceous biomass level even after grazing was not low. This means that livestock movements in each replicate were completely out of synchrony with each other so that the desired and logical goal stated above could best be achieved for each.

Other animal management practices were the same across the treatments. All grazing was within 1.2 km of a water source, and vegetation and soil sampling was conducted no closer than 300 m from any water or gathering point. With both grazing treatments mineral and protein supplements were strategically located to disperse grazing pressure as much as possible through each grazing unit.

In each of the 3 years from 2002 to 2004 summer fires (August–September) were applied to different, non-adjacent patches, each about 12% of the land area, in each continuously grazed replicate. In the rotational grazed treatment, one entire paddock, the equivalent of 12% of the area of the system, was summer burned in the same years.

2.3. Assessing soil and vegetation impact and recovery

To determine the impact of the summer patch burns, we measured plant cover and bare ground, and proportional herbaceous species composition of unburned control (UC) areas relative to that of paired burn treatment (BT) areas from August 2002 until the summer of 2006. Immediately adjacent to the burned patches in both grazing treatments, unburned areas of the same soil in the same grazing unit (pasture) were measured as paired controls. Degradation was judged to have taken place if one or more of the following changes took place on burned areas relative to the paired unburned control areas after Archer and Smeins (1991) and Thurow (1991):

1. Increase in bare ground, soil temperature, bulk density, penetration resistance, C_4 shortgrasses, C_3 midgrasses, annual grasses, perennial forbs, and annual forbs.
2. Decrease in infiltration rate, aggregate stability, soil carbon, herbaceous cover and the proportion of C_4 midgrasses.

Recovery of summer patch burns was deemed to have taken place when the return of these criteria to control levels of the paired unburned control plots had taken place.

2.4. Vegetation measurements

Paired unburned (UC) and burned (BT) plots in each grazing treatment were sampled by establishing a randomly located 400 m transect line and measuring herbaceous composition within a 0.05 m^2 quadrat placed at 20 m intervals along the transect. We used the dry-weight-rank method of 't Mannetje and Haydock (1963) as modified by Jones and Hargreaves (1979) and implemented as outlined by Dowhower et al. (2001). Vegetation was sampled in March, July and November each year.

Grass and forb standing crop were determined gravimetrically from the quadrat clippings. The proportions of 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 6 groups: annual forb, perennial forb, annual C_3 grass, perennial C_3 midgrass, perennial C_4 shortgrass, and perennial C_4 midgrass.

2.5. Soil measurements

To determine treatment effects on soils, key soil parameters were measured after the 2003 and 2004 burns and for 2 years after the final fire treatments were applied. These measures included bulk density, penetration resistance, soil infiltration, and aggregate stability. Each parameter was measured at each burned and paired unburned site in each grazing treatment. As mesquite canopies were significant on both the soils that were sampled we stratified sampling within each site (BT and UC) at 5 points within mesquite sub-canopies and 5 points in adjacent open grassland between trees (2 per sample point, $n = 20$ for burn and $n = 20$ for unburned paired sites).

In this large scale experiment distances between sample points for different treatment replicates were as large as 4 km. This meant that to make valid and comparable measures between replicates, years and treatments we had to choose soil moisture conditions that were as constant as possible for the duration of each sampling period. As it took a full week to measure all areas we chose periods that would be relatively dry with no expected precipitation and similar temperatures and wind for each sampling period. This was more important than measuring at a constant time before or after the livestock had grazed the particular replicate, since this would have meant taking measures at different soil moisture and weather conditions between each replicate. Prevailing weather conditions each year meant we sampled all soil parameters in early December in 2003, late April in 2004, mid June in 2005 and mid May in 2006.

Soil water infiltration was measured at each of the above sampling points using concentric-ring infiltrometers. To reduce variability we pre-wet each infiltration ring set the night before measuring infiltration. 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 as described by Bouwer (1986).

Soil bulk density and soil moisture were measured at each sampling point using 50 mm diameter × 100 mm long soil sampling tubes and gravimetric analysis. At each sample point we measured penetration resistance with an impact penetrometer as described by Herrick and Jones (2002), and soil aggregate stability as described by Herrick et al. (2001).

Soil samples for nutrient analyses were taken at 0–5 cm at 10 randomly located points in the vicinity of the infiltration sampling points. Samples from each location were bulked, homogenized and air-dried. A composite sample was sent off for laboratory analysis at Ward Laboratories, Inc., Kearney, NE. Nitrate nitrogen (NO_3^-) and ammonium (NH_4^+) were measured in April, June and October each year and determined according to Kenney and Nelson (1982). Total N was determined according to McGeehan and Naylor (1988). Soil organic C (SOC) was measured in October each year and analyzed using the method of Combs and Nathan (1998).

Soil temperature was recorded at 10 mm depth in open grassland and under mesquite tree canopies in the paired unburned control areas and in each of the year-of-burn areas for the 2003 and 2004 burns. HOBO® Pendant™ automatic data loggers[1] were installed and active from April 2005 to October 2006 and recorded at hourly intervals. Each replicate grazing unit had 2 temperature loggers for the 2 burns and unburned control for the open grassland and mesquite tree canopies totaling 48 loggers. For minimum and maximum temperature analysis the day began at 10 am to reduce the occurrence of a single weather event affecting consecutive days.

2.6. Statistical analysis

Statistical analyses compared the burn treatment (BT) to the unburned control (UC) in each of the 3 post-fire sample years using

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[1] Use of trademark does not imply endorsement.

the MIXED procedure with the paired UC area as a covariable to account for antecedent conditions (SAS, 1990) Individual transects within a pasture burned/unburned pair were treated as repeated measures. Least squares means of the adjusted variable were compared. 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. Precipitation

There was considerable variation in seasonality of precipitation among years even when annual precipitation was similar (Fig. 1). The year prior to this experiment, 2001, was drier than average in summer and fall but 2002, the year we began the experiment, was wetter than average. Precipitation in 2003 was lower in spring but close to average in summer while 2004 experienced higher than average precipitation. In 2005 and 2006 spring and summer precipitation was lower than average.

3.2. Bare ground

Prior to the patch burn treatments, the percent bare ground on both the Tilvern (Fig. 2) and Wichita soils (Fig. 3) did not differ significantly between the continuous and the rotation pastures. On the unburned areas on the Tilvern soils there was no difference in percent bare ground in 2002–2005 averaging 11% on continuous vs. 9% on the rotational grazing ($p > 0.10$) but in 2006 that in the rotations (12%) was significantly lower than in the continuous grazing treatments (27%; Fig. 2). In contrast, on the Wichita soils there were no significant differences in bare ground on unburned areas at ±12% between the rotationally and continuously grazed treatments in all years (Fig. 3).

Following burning the percent of bare ground increased 4–5-fold the year after burning in both rotationally and continuously grazed treatments (Figs. 2 and 3). However, bare ground levels on burned areas on the Tilvern soils returned to those of unburned areas the second and third year after burning in 2002 and 2004, and third year after burning with the 2003 burn.

In contrast, on the Wichita soils, reduction of bare ground to control levels took a year longer for the 2003 burned areas to recover by 2006 when measurements were discontinued (Fig. 3). At the final evaluation the 2004 burns had not recovered percent bare ground to unburned control levels.

Following the 2002 burns bare ground percent in the rotation and continuous grazed treatments remained similar through 2006 on the Tilvern soil (Fig. 2) and in 2006 bare ground of the rotationally grazed 2002 burned portions exceeded the rotationally grazed unburned portions.

For the areas burned in 2003 and 2004, percent bare ground on the Tilvern soils was higher on the continuously grazed than the rotationally grazed treatments in 2004 and 2005 (Fig. 2). In contrast, there were no differences in percent bare ground between grazing treatments on the Wichita soils through 2006 (Fig. 3).

3.3. Soil temperature

Over the 6–26-month period after the 2003 and 2004 fires, the mean maximum daily soil temperatures at 10 mm depth in unburned areas did not differ from those in burned areas ($p = 0.186$; Table 2). However, mean separations indicate that the 2004 burns had marginally greater soil temperatures than the unburned areas (2.5 ± 1.3 °C). Soil temperatures of open grasslands were greater than under tree canopies (32.2 ± 0.8 °C vs. 28.8 ± 0.8 °C) and between continuous and rotational grazing in open unburned and burned grassland. There was an interaction between vegetation

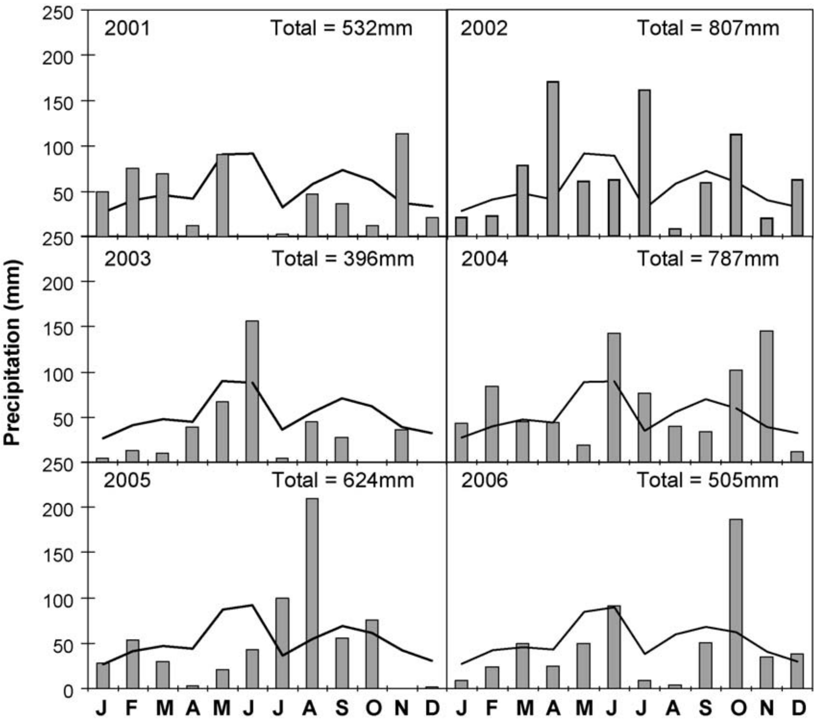

Fig. 1. Monthly precipitation (▨) relative to long-term mean monthly precipitation (▬) (590 mm; $n = 30$ years) at the Lake Kemp weather station on the Waggoner Ranch from 2002 to 2006.

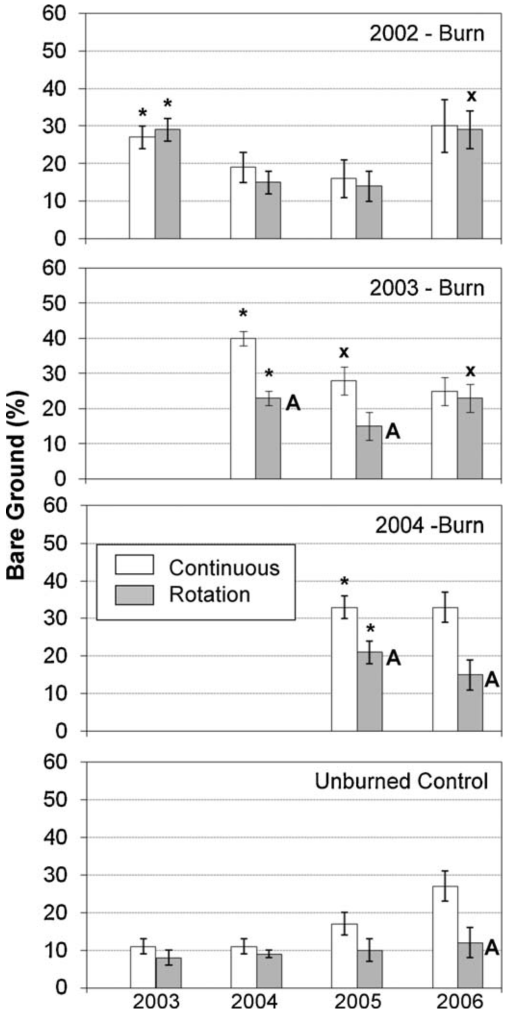

Fig. 2. Bare ground (±SE) on the Tilvern clay-loam soils following summer patch burning under continuous grazing and rotational grazing compared to unburned plots by year of burn measured in the year of burn in each case. Means differ significantly from unburned control plots for each burn year at * = $p \leq 0.05$; × = $p \leq 0.10$. Means differ significantly within a burn year for continuous vs. rotational grazing at A = $p \leq 0.05$; a = $p \leq 0.10$.

category and grazing management ($p = 0.056$) as open grassland under continuous grazing had higher soil temperatures compared to rotational grazing while temperatures beneath mesquite canopies were similar between grazing regimens. On unburned grasslands continuous grazing had higher soil temperatures than rotational grazing.

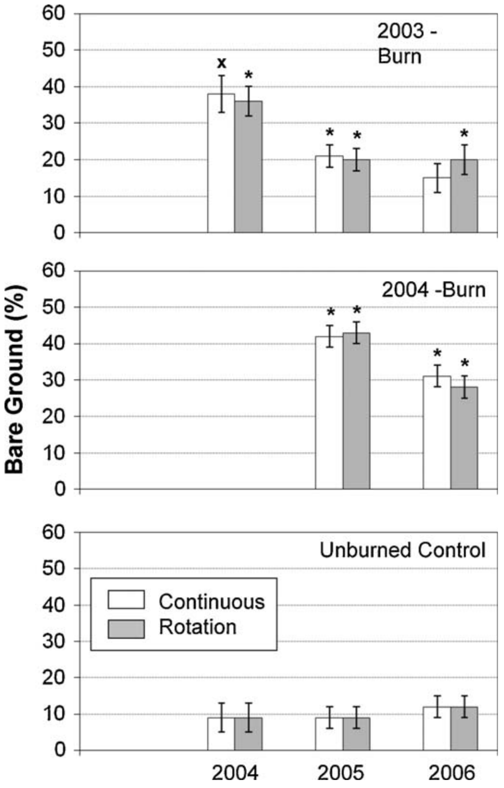

Fig. 3. Bare ground (±SE) on Wichita clay-loam soils following summer patch burning under continuous grazing and rotational grazing compared to unburned plots by year of burn measured in the year of burn in each case. Means differ significantly from unburned control plots for each burn year at * = $p \leq 0.05$; × = $p \leq 0.10$. Means differ significantly within a burn year for continuous vs. rotational grazing at A = $p \leq 0.05$; a = $p \leq 0.10$.

3.4. Soil physical parameters

There were no differences in bulk density between the no-burn controls and either burn or grazing treatments, but the bulk density under mesquite trees was lower than in open grassland (Table 3). Similarly, penetration resistance was lower under tree canopies than in open grassland but did not differ between any of the treatment categories ($p > 0.10$). In contrast, aggregate stability did not differ between open grassland and tree canopies or between any of the grazing or fire treatment categories.

Infiltration rates were consistently higher under mesquite canopies than in the open grassland but did not differ between burning and not burning or between rotational and continuous grazing (Table 3). One factor that has a strong influence on infiltration rate is soil moisture (Bouwer, 1986), but soil moisture

Table 2
Soil temperature (°C; mean ± SE) at 10 mm depth in no-burn control areas and following summer burning with continuous or rotational grazing under mesquite tree canopies or in open grassland between trees.

Treatment	Grass			Tree		
	Continuous		Rotation	Continuous		Rotation
No burn	35.4 ± 1.9		28.5 ± 1.8*	25.2 ± 1.8		24.7 ± 1.8
Burn 2003	33.8 ± 1.8		30.8 ± 1.8	27.2 ± 1.8		27.8 ± 1.8
Burn 2004	34.2 ± 1.8		30.8 ± 1.8	29.3 ± 1.8		30.3 ± 1.8
Cont. vs. Rot.	34.4 ± 1.1		30.0 ± 1.1*	27.2 ± 1.1		27.6 ± 1.1
Cont. vs. Rot.		30.8 ± 0.8			28.8 ± 0.8^{+}	
Grass vs. Tree		32.2 ± 0.8			28.8 ± 0.8**	

** $p < 0.01$ within each treatment category.
* $p < 0.05$ within each treatment category.
$^{+}$ $p < 0.10$ within each treatment category.

Table 3
Soil bulk density, aggregate stability, penetration resistance and infiltration rate (mean ± SE) following summer burning with continuous or rotational grazing under mesquite tree canopies or in open grassland between trees.

Soil parameter (units)	No-burn control	Burn treatment		Vegetation		Graze treatment	
		2003	2004	Grass	Tree	Continuous	Rotation
Bulk density ($g\,cm^{-3}$)	1.16 ± 0.02	1.14 ± 0.02	1.14 ± 0.02	1.17 ± 0.01	1.11 ± 0.01**	1.14 ± 0.02	1.14 ± 0.02
Aggregate stability (%)	85.5 ± 1.2	83.8 ± 1.3	83.3 ± 1.3	84.5 ± 1.1	83.9 ± 1.1	83.4 ± 1.1	85.0 ± 1.1
Penetration resistance (J)	29.6 ± 1.4	28.9 ± 1.6	31.6 ± 1.6	32.3 ± 1.2	27.7 ± 1.2*	30.7 ± 1.2	29.4 ± 1.2
Infiltration ($cm\,h^{-1}$)	5.2 ± 0.9	5.5 ± 1.0	4.6 ± 1.0	3.3 ± 0.8	6.9 ± 0.8*	4.4 ± 0.8	5.9 ± 0.8

** $p < 0.01$ within each treatment category.
* $p < 0.05$ within each treatment category.

Table 4
Soil moisture (0–10 cm; mean ± SE) determined at each infiltration sampling date following summer burning with continuous or rotational grazing under mesquite tree canopies or in open grassland between trees.

Year	Vegetation		Graze treatment	
	Grass	Tree	Continuous	Rotation
2003	9.9 ± 1.74	8.9 ± 1.74	9.7 ± 1.77	9.1 ± 1.77
2004	8.9 ± 1.74	9.0 ± 1.74	6.7 ± 1.77	11.2 ± 1.77*
2005	9.9 ± 1.74	9.2 ± 1.74	8.1 ± 1.77	11.0 ± 1.77
2006	10.0 ± 1.74	9.3 ± 1.74	8.2 ± 1.77	11.1 ± 1.77

* $p < 0.05$ within each treatment category.

levels at the time that infiltration sampling was conducted reveals very small differences in this parameter (Table 4).

3.5. Soil organic matter

Total soil N was not different between the unburned controls and both the 2003 and the 2004 burns or between unburned rotationally and unburned continuously grazed pastures (Table 5). However, total soil N was higher under trees than in open grassland.

Similarly, soil organic C was not different between the unburned and burned patches in 2003 and 2004 (Table 5). However, it was higher under trees than in open grassland and it was higher in unburned rotationally grazed than unburned continuously grazed pastures.

The C to N ratio did not differ between unburned and burned patches in 2003 and 2004 (Table 5) but it was lower under trees than in open grassland even though total N was higher under trees (see above). C to N ratio was higher in unburned rotationally grazed than unburned continuously grazed pastures due to the higher organic C levels in the rotationally grazed treatment.

3.6. Herbaceous biomass and composition

There were large differences in standing crop biomass between years due to climatic variability but there were few differences in herbaceous biomass that could be ascribed to either burning or grazing management treatments.

Recovery of herbaceous biomass relative to unburned controls on Tilvern soils occurred in the 2nd year after the 2002 burns and 1 year after burning in the 2003 and 2004 burns (Fig. 4). In contrast, recovery took at least 3 years after burning on Wichita soils ($p > 0.10$; Fig. 5). There were no changes in the relative abundances of C_4 and C_3 midgrasses and shortgrasses ($p > 0.10$) in response to either burning or grazing treatments. However, annual grasses had lower biomass on Wichita soils after the 2003 and 2004 burns in both continuously grazed and rotationally grazed treatments ($p < 0.075$).

There were no differences in forb biomass between burned and non-burned patches ($p > 0.05$; data not presented) except for the 2004 burns on Tilvern soils and Wichita soils where forb biomass was higher in the burned than non-burned patches for 1 year after burning.

There were no differences in rate of recovery after burning between continuously grazed and rotationally grazed pastures ($p > 0.10$).

4. Discussion

4.1. Bare ground

In the unburned controls percent bare ground was steady at 10–12% except on the Tilvern soils that were continuously grazed where it increased to 27% in 2006. We believe this was due to the drier than average summers of 2005 and 2006. The Tilvern soils under continuous grazing were more affected since these soils are more xeric being associated with runoff rather than run-on sites and shallower solum depth compared to Wichita soils (Table 1). Rotational grazing has been shown in previous research at this site to result less bare ground and more litter cover than continuous grazing even under prolonged drought (Teague and Dowhower, 2003; Teague et al., 2004).

Burning in summer caused an increase in bare ground through a reduction in plant and litter cover. The precipitation received during the experimental period was less than average in only 2003 and 2006, so recovery of phytomass and cover following burn treatments should have been relatively rapid. Nevertheless, the amount of bare ground following these burn treatments took 2 years to return to control levels on the Tilvern soils and at least 3 years on the Wichita soils. One of the main concerns regarding summer burning is that it increases the exposure of soil to direct sunlight, raindrop action and overland flow due to the removal of

Table 5
Soil nitrogen, organic carbon and C to N ratio (mean ± SE) in the top 10 cm of soil following summer burning with continuous or rotational grazing under mesquite tree canopies or in open grassland between trees.

Soil parameter (units)	No-burn control	Burn treatment		Vegetation		Graze treatment	
		2003	2004	Grass	Tree	Continuous	Rotation
Total N (ppm)	2159 ± 100	2180 ± 106	2069 ± 106	1979 ± 95	2294 ± 95**	2059 ± 84	2213 ± 85
Organic carbon (%)	3.6 ± 0.1	3.6 ± 0.2	3.5 ± 0.2	3.5 ± 0.1	4.1 ± 0.1**	3.3 ± 0.1	3.8 ± 0.1*
C:N	9.4 ± 0.1	9.3 ± 0.1	9.4 ± 0.1	9.5 ± 0.1	9.2 ± 0.1^{+}	9.1 ± 0.1	9.6 ± 0.1**

** $p < 0.01$ within each treatment category.
* $p < 0.05$ within each treatment category.
$^{+}$ $p < 0.10$ within each treatment category.

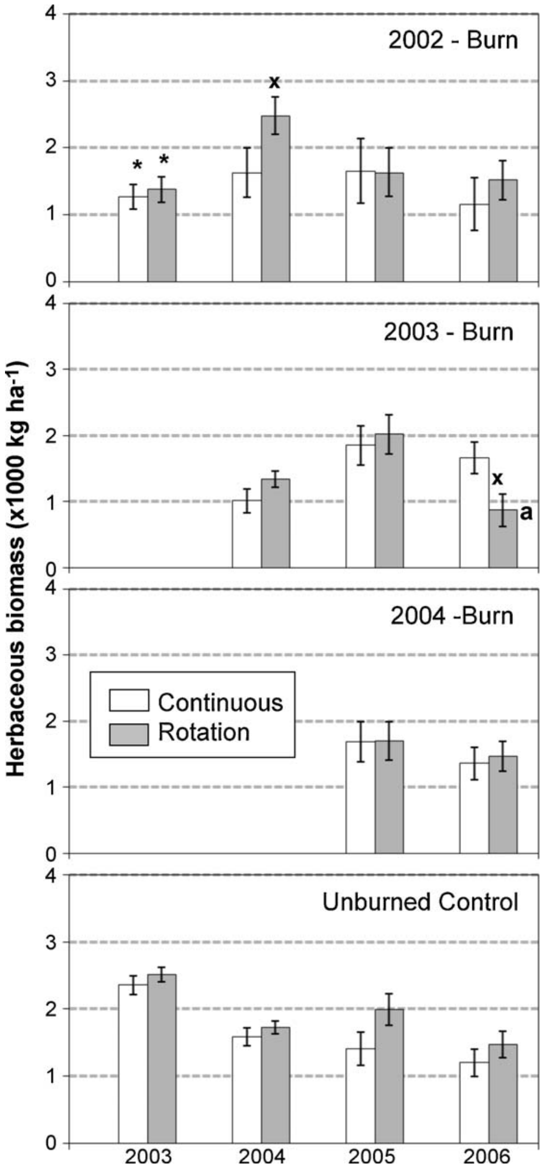

Fig. 4. Total herbaceous biomass (±SE) on Tilvern clay-loam soils following summer patch burning under continuous grazing and rotational grazing compared to unburned plots by year of burn measured in the year of burn in each case. Means differ significantly from unburned control plots for each burn year at $* = p \leq 0.05$; $\times = p \leq 0.10$. Means differ significantly within a burn year for continuous vs. rotational grazing at $A = p \leq 0.05$; $a = p \leq 0.10$.

herbaceous plant cover during the hottest and driest time of the year (Wright, 1974a; Thurow, 1991). This increase in exposure has been shown to increase soil loss and evaporation, and reduce water infiltration and the microbial processes and populations essential to maintaining soil biological functions upon which the health and productivity of plants populations depend (Snyman, 2003; Neary et al., 1999).

As hypothesized, rotational grazing resulted in less bare ground than continuous grazing on Tilvern soils. However, this was not the case on Wichita soils. Periods of deferment after burning reduced levels of herbivory, so, relative to continuous grazing, rotational grazing allows for quicker herbaceous recovery in the burn treatments that are otherwise preferentially grazed as was previously reported in this environment (Teague and Dowhower, 2003; Teague et al., 2004). Tilvern soils support more mesquite trees and C_3 grasses than do Wichita soils. We speculate that the Tilvern soils benefited from grazing deferment under rotational grazing because of the higher proportion of C_3 grasses on this soil. There was less bare ground with rotational grazing on the Tilvern soil than with continuous grazing treatments on this soil and both grazing treatments on the Wichita soils. We received adequate cool season precipitation to support C_3 plant growth during the experimental period, resulting in a quicker decrease in bare ground on the Tilvern soil rotations. The greater proportion of C_3 grasses would have more quickly reduced bare ground under periodic deferment because of the favorable cool season growing conditions.

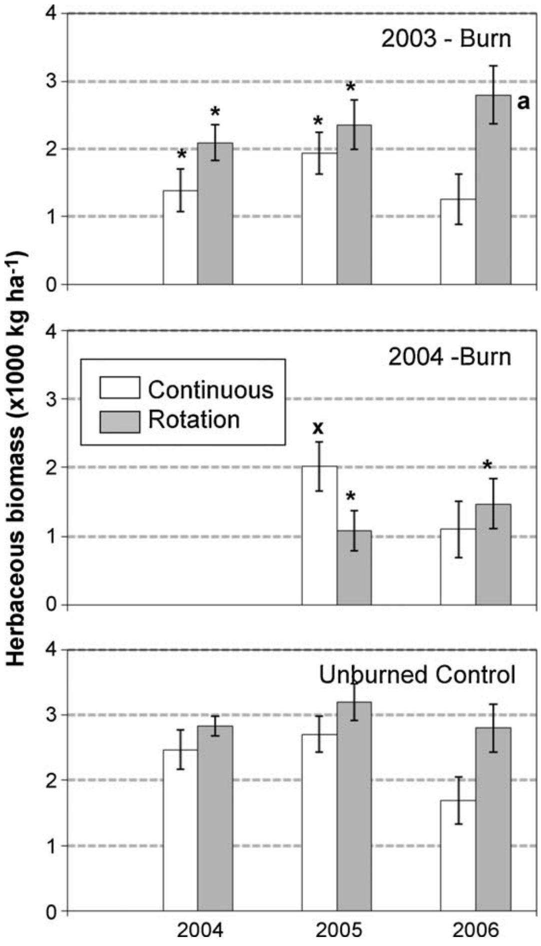

Fig. 5. Total herbaceous biomass (±SE) on Wichita clay-loam soils following summer patch burning under continuous grazing and rotational grazing compared to unburned plots by year of burn measured in the year of burn in each case. Means differ significantly from unburned control plots for each burn year at $* = p \leq 0.05$; $\times = p \leq 0.10$. Means differ significantly within a burn year for continuous vs. rotational grazing at $A = p \leq 0.05$; $a = p \leq 0.10$.

4.2. Soil temperature

Soil temperature was influenced by tree cover and grazing treatment. Surprisingly, soil temperatures over the experimental period did not differ between the burnt and non-burnt areas for an extended period of time. This is probably due to the average to above-average amounts of rainfall experienced and moderate stocking, both of which would have quickly restored vegetative cover on the burnt areas. Tree cover had the greatest effect in reducing soil temperature, resulting in temperatures under trees being lower than in open grassland in the areas that were not burned. The reduced tree canopies in the burn treatment areas provide less cover and reduced temperature differences between open grassland and tree canopies.

Soil temperatures were also higher under continuous than under rotational grazing management. This was closely related to higher amounts of bare ground associated with continuous grazing noted above and reported in previous studies in this environment (Teague and Dowhower, 2003; Teague et al., 2004). Higher levels of bare ground and lower vegetation cover allow more exposure to the sun resulting in elevated temperatures. The soil temperature differences due to grazing treatment were particularly evident in the no-burn areas where temperatures were higher with continuous than rotational grazing in both open grassland and under tree canopies. In the burn treatment areas this was the case only in open grassland presumably because tree canopy cover had been reduced by burning.

Elevated soil temperatures have a direct negative effect on soil evaporation, nutrient retention and biological functions and processes all of which are closely tied to proper ecosystem function (Neary et al., 1999; Wright and Bailey, 1982). Maintaining normal soil function in rangeland ecosystems is possible only if adequate plant cover is maintained to protect soil from eroding and direct sunlight and to create conditions suitable for soil microorganisms to support ecosystem functions (Thurow, 1991; Rietkerk et al., 2000; Bardgett, 2005). Consequently, in semi-arid rangelands sustainable use of herbaceous plant is closely allied to maintaining adequate soil cover and preventing increases in soil temperature.

4.3. Soil physical parameters

In rangeland ecosystems healthy soil needs a cover of live plants and plant litter that buffers temperatures, enhances infiltration and decreases evaporation so the soil moisture is retained for longer after each precipitation event. This enhances soil microbial activity which leads to the incorporation of more organic matter into the soil, thereby supporting soil aggregate stability, sustaining plant nutrient status and availability, and improves plant growing conditions (Thurow, 1991; Rietkerk et al., 2000; Bardgett, 2005). Losses of plant and litter cover by extended drought, fire or excessive herbivory and excessive trampling pressure inhibit these soil building processes. Parameters that are associated with such soil degradation are an increase in bulk density, soil compaction which elevates penetration resistance and reduced aggregate stability (Herrick et al., 2001; Herrick and Jones, 2002). These changes result in lower rates of water infiltration into the soil with resulting reduction in ecosystem function.

Bulk density, penetration resistance and aggregate stability were not affected by the burn treatment or the different grazing treatments but mesquite tree cover had a positive effect on both bulk density and penetration resistance. This is closely related to the elevated soil organic matter levels associated with woody plant canopies in this study.

Aggregate stability was not affected in our study by either tree canopies or the grazing and burning treatments or when burns were conducted under extreme drought conditions (Teague et al., 2008). It appears that when these ecosystems are still dominated by naturally occurring herbaceous species and have not been cultivated, soil aggregate structure is fairly resistant to change. Adequate vegetation cover intercepts rainfall dissipating the kinetic energy of raindrops before they strike the soil, thus protecting soil aggregate structure (Thurow, 1991) and the additions of organic matter to the soil from the vegetation maintains or enhances aggregate stability of the soils (Bardgett, 2005).

Infiltration rates in this study were higher under tree canopies but did not differ between the burning or grazing treatments. This reflected the lower bulk density, penetration resistance and elevated soil organic matter under tree canopies. Previous research has indicated that type of vegetation cover greatly influences infiltration rate, which is greatest under woody plant canopies followed in descending order by bunch grasses, shortgrasses, and bare ground (Blackburn, 1975; Thurow et al., 1986, 1987; Pluhar et al., 1987). Thurow (1991) indicates that under continuous grazing an increase in stocking rate decreased infiltration. However, the same study indicated that infiltration was higher in a rotational grazing system than in a continuously grazed treatment *at the same heavy stocking rate*. Pluhar et al. (1987) found no differences in infiltration and sediment yield among a heavily stocked rotationally grazed treatment, a deferred rotation treatment and a continuously grazed treatment, both moderately stocked. Our results are broadly consistent with these previous studies. We used moderate stocking rates and experienced average or above average precipitation, both of which resulted in moderate levels of herbaceous cover. This may be the reason why we did not find any difference in infiltration between continuous and rotational grazing treatments.

However, the infiltration results in our study underestimate the importance of the differences we found between grazing treatments. Concentric-ring infiltrometers are useful for measuring the infiltration rate characteristics for soil in general. However, rainfall simulators give superior assessments of infiltration rates because they simulate the disaggregating impacts of raindrops on bare soil, which are very important in causing the soil surface to seal and leading to acceleration of runoff and erosion, and the interception of rainfall by the vegetation (Thurow et al., 1986, 1987).

Work conducted on Texas rangeland using rainfall simulators has indicated that type of vegetation cover greatly influences infiltration rate. Bare ground has considerably lower infiltration and higher runoff and erosion than under woody plant canopies and perennial grasses (Blackburn, 1975; Blackburn et al., 1986; Thurow et al., 1986, 1987). Focusing on bare ground as we have done in our study is a well documented way to assess erosion hazard (Blackburn, 1975; Blackburn et al., 1986) because erosion hazard increases if there is insufficient cover to dissipate the energy of raindrops before they strike the soil. The rainfall simulator results from other studies indicate that the higher levels of bare ground with continuous grazing compared to rotational grazing in our study would result in higher levels of runoff and soil erosion. Clearly the rotational grazing treatments result in better hydrological conditions than does continuous grazing on at least on the more xeric Tilvern soils. Under more droughty conditions than were experienced in this study it is possible the more mesic Wichita soils would also benefit from rotational grazing as reported by Teague et al. (2004).

Since we used moderate stocking levels and managed the rotations to maintain relatively high phytomass levels when exiting the paddocks, we would have minimized any negative effects of grazing on infiltration and related hydrological properties as discussed by Thurow (1991). This is in stark contrast to other research on the effects of rotational grazing on soil hydrological characteristics such as that of Warren et al. (1986) and Savadogo et al. (2007). By managing our rotational grazing with light to moderate stocking levels, grazing for short periods so that no more than half the preferred forage was consumed before moving paddocks, the herbaceous biomass level even after grazing was not low. In addition, in the rotations, the higher animal density for a short period increases both the amount of litter on the ground and perennial herbaceous basal area compared to continuous grazing at the same stocking rate using the same grazing management of rotations we used in this study (Teague et al., 2004).

The grazing management in our study was aimed at achieving the best animal and vegetation responses, the way a competent conservation rancher would. This management bears no resemblance to the highly artificial studies such as that of Warren et al. (1986) which was conducted on 10 m × 10 m plots and conducted in a manner that could be guaranteed to cause maximum damage to the vegetation and soil, and result in very poor animal performance in a ranch setting. Such small-plot studies might be academically interesting but have no relevance for ranchers managing commercial operations to maintain resource and economic viability in the long-term.

4.4. Soil carbon and nitrogen

As has been reported elsewhere, both soil C and N have been found to be higher under mesquite canopies than in open grassland (Barth and Klemmedson, 1978, 1982; Virginia et al., 1992; Dahlgren et al., 1997). This was not influenced by burning. The lack of response to the burning treatments is consistent with other rangeland burning investigations (Savadogo et al., 2007) and may be related to the fact that we sampled to a depth of 5 cm. Mills and Fey (2004) recorded differences between burnt and unburnt samples when sampling the 0–1 cm layer but these differences were not apparent in 0–10 cm samples suggesting that burn effects on soil carbon and nitrogen would be found only in the top 1 cm of soil. Ansley et al. (2006b) also found that summer fires on soils similar to the current study increased soil total C and total soil N in 0–10 cm soil depth for 1–2 years post-fire. However, there was no grazing in the Ansley et al. (2006a,b) study and this may have affected rates of grass recovery and contribution to soil C via very fine roots and plant shading of the soil surface.

Both soil C and C to N ratio were higher in unburned soils in the rotational than continuous grazing treatments. This difference may be due to the differences in bare ground we recorded between these treatments. This resulted in higher soil temperatures in the continuously grazed treatment as noted above and elevated soil temperatures are a contributing factor to lower soil C levels (Parton et al., 1987).

4.5. Herbaceous biomass and composition

The rate of recovery of phytomass to control levels after burning did not differ between rotational and continuous grazing treatments. However it was more rapid on the Tilvern (2 years) than the Wichita soils (3 years). These responses may be due to the difference in grass composition on the two soil types. Ansley et al. (2006a,b) and Ansley and Castellano (2007b) found that recovery from summer fire was more rapid for C_3 midgrass Texas wintergrass (1–2 years) than for C_4 sideoats grama (3 years) and is probably related to the favorable cool season moisture experienced over the experimental period. The Tilvern soil type had more C_3 grasses, while the Wichita soil type had more C_4 grasses.

There were no changes in grass species composition due to either burning or grazing management treatments except for annual grasses which had lower biomass on Wichita soils after the 2003 and 2004 burns. This is not surprising because at moderate stocking rates, species composition generally does not change in response to such treatments alone, particularly in the short term (Milchunas and Lauenroth, 1993). Moreover, the rainfall was lower than average only in 2003 and 2006 and recovery after fire has been shown to occur within a year following average rainfall in this environment, even with single summer patch burns and no pre- or post-fire deferment (Teague et al., 2008).

Although there were no differences in forb biomass due to burning with the 2002 and 2003 burns, forb biomass was higher on both soils for 1 year after the 2004 burns. This was consistent between both rotational and continuous grazing treatments. In this study, rainfall in the fall after burning was adequate to good in all years, so the grasses had good soil moisture for quick recovery and were not outcompeted by forbs, which can happen under drought conditions. Wright (1974a) reported that as long as soil moisture is adequate, bunch grasses thrive after fire. In contrast, summer patch burning in this ecosystem during drought years resulted in an increase in forbs for 3–5 years after the original burns (Teague et al., 2008).

5. Conclusions

While research findings often suggest multi-paddock grazing management is not superior to continuous grazing (Briske et al., 2008) researchers have generally not managed experiments relevant to achieving desirable management goals on commercial ranches (Teague et al., 2009). Most conservation oriented ranchers manage strategically to achieve the best possible profitability and ecosystem health, and the benefits of multi-paddock rotational grazing on commercial livestock enterprises have been evident for many years in many countries (Norton, 1998; Teague et al., 2009). As indicated by Provenza (1991), to be relevant to managers, reductionist studies of processes must, at the very least, be rooted in potential for application to managing landscapes within a systems framework or they will be irrelevant and possibly misleading. By managing our study with goals to which responsible conservation ranchers can relate the results are relevant and meaningful.

In rangeland ecosystems, maintaining normal soil function is possible only if adequate plant cover is available to provide protection from soil loss and maintenance of conditions that allow the soil microorganisms to perform and maintain ecosystem functions. Grazing and fire can both cause a reduction in infiltration and increase runoff and erosion in rangeland ecosystems. In our study we examine how rapidly key soil and plant parameters recover following burning with rotational grazing or following burning different patches in successive years with continuous grazing. With patch burning and continuous grazing the assumption is that the newly burned patch each year will attract heavier utilization and relieve earlier burned patches to allow more rapid recovery.

Fire decreases the vegetation cover leading to increased ground temperature as well as a disturbance of hydrological cycle and soil compaction, and release of nutrients at the soil surface that leads to nutrient losses via runoff, volatilization and leaching. Livestock grazing reduces grass biomass and often creates patchy vegetation alternated by bare soil. The rotation grazing treatment in this study had less bare ground on both unburned and burned areas than the continuously grazed treatment on the Tilvern soil. As a consequence, soil temperatures were lower and soil C and C to N ratio were higher with rotational grazing. The lower incidence of bare ground and lower soil temperatures with rotational grazing were evident on unburned areas, presumably because of the manner in which we managed the rotational grazing. The lower incidence of bare ground we measured with rotational grazing indicates the potential of rotational grazing to improve soil hydrological characteristics using evidence from rainfall simulation studies and other, similarly managed, rotational grazing studies.

Adequate rainfall for rapid post-fire recovery was experienced in this study but, under drought conditions, responses may be different. Other studies have indicated that areas burned in any year do not recover until after a season of favorable precipitation. When drought conditions precede and follow burning, there can be an increase in bare ground and the proportion of annual forbs and annual grasses at the expense of perennial grasses, with recovery taking 3–5 years (Teague et al., 2008; Wright and Bailey, 1982). The response to rotational compared to continuous grazing may be different under drier conditions. Bare ground was less under rotational grazing on the xeric soils but not the more mesic soils. If conditions were drier, the more mesic soils may also have benefitted from rotational grazing.

The positive effects of mesquite trees on soil hydrological characteristics emphasize the factors influencing soil hydrological characteristics. Shading provided by trees reduces soil temperature which decreases soil carbon loss and tree leaf litter breaks down more slowly than grass phytomass resulting in higher levels of soil carbon. This emphasizes the factors that are important for managers to aim at if they wish to maintain or improve ecosystem function, namely the importance of vegetation and litter cover.

Care needs to be taken in interpreting the results of short-term studies such as this. There are no long-term experiments in this ecoregion to indicate whether burning at frequencies of 6–7 years required to effectively reduce woody plants and cacti would maintain the health of this ecosystem in the long-term. Before summer burning can be advocated, it will be necessary to determine whether burning with rotational grazing or patch burning in successive years with continuous grazing will be sustainable in the long-term, or if post-burn deferment is needed until burned areas have recovered plant and litter cover. Research needs to determine what post-fire grazing management will be necessary to ensure burned areas have recovered plant and litter cover in below average precipitation periods. If fire is used in these communities to regularly reduce mesquite and cacti, managers need to pay careful attention to stocking levels and monitor key parameters to ensure full recovery after burning before applying further burns to the same area.

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