Management-Intensive Rotational Grazing Enhances Forage Production and Quality of Subhumid Cool-Season Pastures

Lawrence G. Oates,* Daniel J. Undersander, Claudio Gratton, Michael M. Bell, and Randall D. Jackson

ABSTRACT

Management-intensive rotational grazing is used by many farmers seeking to balance profitability, environmental stewardship, and quality of life. Productivity of pastures in much of the upper Midwest is limited to April through October, so promoting high quality forage production during the grazing season and for winter storage is critical to dairy and beef farm profitability. We conducted an experiment on pastures dominated by Kentucky bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), meadow fescue [*Schedonorus pratensis* (Huds.) P. Beauv.], perennial ryegrass (*Lolium perenne* L.), and white clover (*Trifolium repens* L.) to compare forage production, forage quality, and root production under management-intensive rotational grazing, continuous grazing, haymaking, and land with no agronomic management. Rotational paddocks were grazed by cow-calf pairs monthly for ~2 d and then allowed to rest for ~28 d. Plots designated for haymaking were harvested two times per growing season. Potential utilizable forage, quantified by incorporating the estimates of refused and nonutilized biomass, and relative forage quality were significantly greater under management-intensive rotational grazing when compared to the other treatments. Root production in the surface 15 cm was significantly lower under both grazing treatments compared to the undefoliated control site. The perception of improved production has been used to advocate for rotationally grazed over continuously grazed systems in subhumid pasture, but experimental results have been equivocal. Our results point to managed grazing as a viable alternative to continuous grazing and haymaking in terms of both forage production and quality but not root production.

L. G. Oates, Nelson Institute for Environmental Studies, Univ. of Wisconsin–Madison, 550 N. Park St., Madison, WI 53706; D. J. Undersander, Dep. of Agronomy, Univ. of Wisconsin–Madison, 1575 Linden Dr., Madison, WI 53706; C. Gratton, M.M. Bell, and R.D. Jackson, Agroecology Cluster, Univ. of Wisconsin–Madison, 139A King Hall, 1525 Observatory Dr., Madison, WI 53706. Received 19 Apr. 2010. *Corresponding author (oates@wisc.edu).

Abbreviations: A.U., animal units; BNPP, belowground net primary production; CONT, continuous grazing; HARV, hay harvesting; LAI, leaf area index; MIRG, management-intensive rotational grazing; NIRS, near-infrared reflectance spectroscopy; NONE, no agronomic management; PAR, photosynthetically active radiation; PUF, potential utilizable forage; RFQ, relative forage quality.

Nonequilibrium models of vegetation change are frequently promoted for arid and semiarid grasslands because equilibrium models inadequately describe plant community dynamics (Bestelmeyer et al., 2003; Jackson and Bartolome, 2002; Westoby et al., 1989). Nonequilibrium models are more appropriate for systems where plant–herbivore interactions are loosely coupled or decoupled and abiotic limitations are of overriding importance at spatial and temporal scales relevant to management (Jackson and Allen-Diaz, 2006; Wiens, 1984). A recent review focused on rangelands showed that grazing systems focusing on manipulating the timing and distribution of livestock were less important than controlling grazing intensity for affecting desirable community trends and forage production (Briske et al., 2008). These authors argue that irrespective of the grazing system being used stocking rate exerts the main management influence on forage production and availability when abiotic factors such as weather are the main drivers of plant composition and productivity. However, in

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subhumid grasslands of the upper Midwest, Woodis and Jackson (2008a) showed that plant community dynamics behave in an equilibrium way and management of livestock distribution and timing of grazing events were the primary influence on plant community dynamics. In this context, enhanced forage production and quality may be achieved by delaying plant maturation, reducing shading of young leaves, excluding unpalatable species, and altering nutrient cycling through management (Bardgett and Wardle, 2003; Schuman et al., 1999). In subhumid grasslands, where weather is more predictable than in arid and semiarid regions, limited research, observation, and anecdote have indicated that rotational grazing enhances productivity compared to extensive, continuous grazing (Fales et al., 1995; Paine et al., 1999).

While aboveground production may be manipulated by grazing management, the effects of grazing on root systems are equivocal (Milchunas and Lauenroth, 1993). Grasses respond to defoliation by increasing C allocation to new leaves while decreasing allocation to roots (Detling et al., 1979). Repeated frequent simulated grazing resulted in decreased root biomass and root N reserves, and C allocation to leaves was enhanced at the expense of root biomass (Schuman et al., 1999; Turner et al., 1993). But root production may be less affected with adequate rest periods between defoliation events (Holland and Detling, 1990).

Management-intensive rotational grazing has been adopted by a large number of dairy and beef farmers in Wisconsin and the upper Midwest and Northeast. Where grazing was once considered the antithesis of technological innovation, it is now an established practice (Hassanein and Kloppenburg, 1995; Taylor and Foltz, 2006). This management strategy entails livestock grazing in relatively small paddocks at high densities but for short durations. In a management-intensive rotational grazing system, large pastures are divided into smaller paddocks, and once a sward height objective is reached in the paddock being grazed, the herd is moved to the next paddock. Management-intensive rotational grazing has been publicized as beneficial to both farmers and livestock for social, economic, and production (both quantity and quality) benefits (Paine et al., 2000). And, while this type of grazing operation typically results in lower livestock production and output when compared to confinement systems, it requires lower capital inputs, thereby decreasing the economic risk and increasing the flexibility and profit of the individual dairy farmer (Frank et al., 1995). Despite the potential advantages of management-intensive rotational grazing, Paine et al. (1999) reported that ~690,000 pasture hectares in Wisconsin were in unmanaged continuous grazing at that time.

While the perception of improved production has been commonly used to advocate for rotationally grazed systems in subhumid pasture, experimental results indicate inconsistent results over continuously grazed systems (Holechek et al., 2000; Briske et al., 2008). We compared the effects of rotational and continuous grazing at similar stocking rates on forage yield, forage quality, and root production. We also compared the grazed systems to haying and an unmanaged control treatment.

MATERIALS AND METHODS

Study Site – Experimental Design

This study was conducted at the Franbrook Farm, a research property in south central Wisconsin (42°44'16.65" N, 89°45'13.27" W). Elevation range at the farm is 265 to 320 m above sea level. The climate is continental with warm summers and cold winters. Average temperatures range from ~ −7°C in January to 22°C in July. For our study period, 2006 and 2007, mean temperature range was 0 to 22 and −5 to 21°C, respectively. Mean annual precipitation is ~900 mm, of which ~100 mm is from snow. Approximately two-thirds of the annual precipitation falls during the growing season, April through October (Fig. 1). Yearly precipitation totals for 2006 and 2007 were 691 and 583 mm, respectively. The research area is ~26 ha of valley bottom pasture dominated by cool-season grasses such as Kentucky bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), meadow fescue [*Schedonorus pratensis* (Huds.) P. Beauv.], perennial ryegrass (*Lolium perenne* L.), and white clover (*Trifolium repense* L.). Soils in this area are ~90 cm deep and are classified as Otter silt loam (Cumulic Endoaquolls), Arenzville silt loam (Typic Udifluvents), and Huntsville silt loam (Cumulic Hapludolls) (USDA-NRCS Soil Survey Staff, 2008). In the surface 15-cm of soil, bulk density, pH, organic C, and total N were 1.15 g cm^{-3}, 6.8 (1:1), 4.2%, and 0.31%, respectively.

In April 2005, we established a randomized complete block field experiment with four treatments within three blocks. The four treatment levels mimicked management-intensive rotational grazing (MIRG), continuous grazing (CONT), hay harvesting (HARV), and no agronomic management (NONE). Beginning May 2005, MIRG paddocks (0.6 ha) were grazed monthly (six grazing cycles to ~ 15 cm residual stubble height) by separate 25 cow-calf pair herds (1 pair = 1.3 animal units [A.U.]) at high animal stocking rates (i.e., instantaneous stocking rate of 54 A.U. ha^{-1}) for a brief duration of ~2 d (i.e., a stocking rate of 108 A.U. d mo^{-1}) and then allowed to rest for ~28 d (Paine et al., 1999). Continuous pastures (8.1 ha) had lower instantaneous stocking rates (i.e., 4 A.U. ha^{-1}), but pastures were rested only during the 2 d that the herd was confined to the MIRG paddocks, resulting in a comparable stocking rate to MIRG (i.e., a stocking rate of 112 A.U. d mo^{-1}). Plant biomass was mechanically harvested to ~ 6 cm residual stubble height and removed from the HARV plots (0.3 ha) to mimic the making of hay typical to confinement operations. The first harvest took place at boot stage in May 2006 and 2007. A second cutting took place when plant biomass was ~30 to 35 cm high. Finally, we set aside 0.3 ha plots for no agronomic management (NONE) to mimic a conservation reserve program site. To represent standard management practice, granular ammonium phosphate (11–44–0) fertilizer was applied at the University of Wisconsin Extension recommended rate (57 kg N ha^{-1}) to all treatment areas except NONE in early June in 2005, 2006, and 2007.

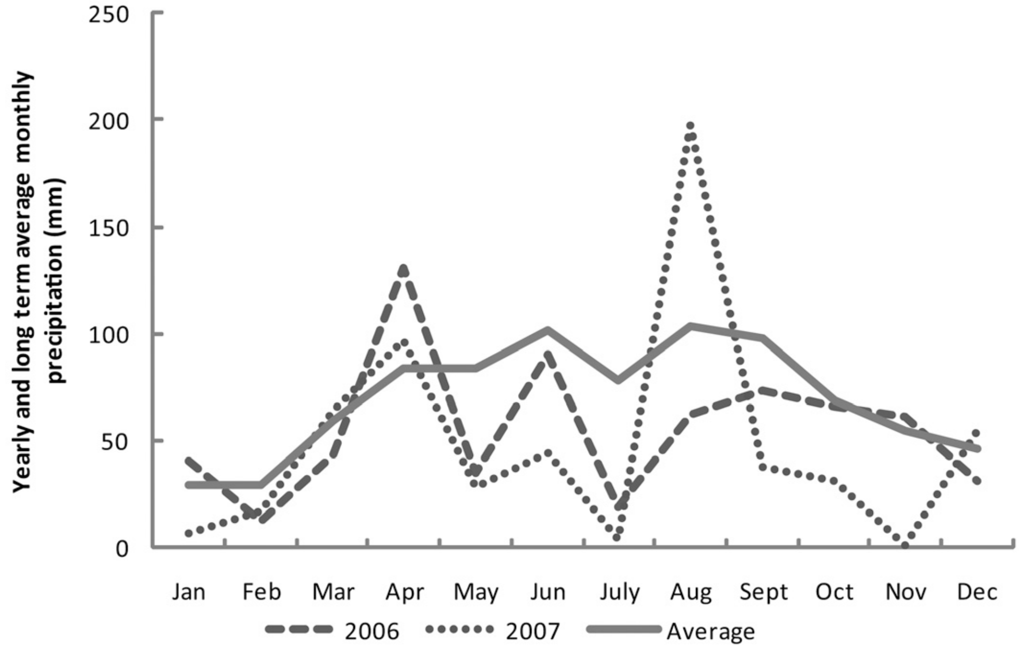

Figure 1. Average monthly precipitation for 2006 and 2007 and long-term average precipitation.

Vegetation Sampling

Starting in May 2006 and continuing through October 2007, aboveground net primary production (ANPP) was estimated monthly for both MIRG and CONT. In the HARV plots, biomass production was estimated for three growth periods: April through May, June to mid-July in 2006 and June through July in 2007, and from the end of the second growth period through October. Biomass in the NONE treatment was estimated for three growing periods: April through June, July and August, and September and October. Biomass was estimated using leaf area index (LAI), which is defined as the amount of leaf area in a canopy per unit ground area. In 2005, at multiple time points throughout the season, LAI was calculated as a function of intercepted photosynthetically active radiation (PAR). Intercepted PAR was determined by measuring incoming PAR above and below the leaf canopy in randomly placed 0.1-m^2 quadrats with an AccuPAR LP-80 Ceptometer (Decagon Devices, Inc., Pullman, WA [see Campbell and Norman, 1989]). Biomass was harvested from these quadrats, dried at 60°C for 48 h, and weighed. An allometric equation was developed from the relationship between LAI measured and biomass ($r^2 = 0.72$). Production in MIRG paddocks was calculated as the difference between pregrazing event measurements and postgrazing measurements of the previous grazing event. For CONT pasture, grazing exclusion cages were randomly located and moved each month. Biomass was estimated inside and outside the cage, and monthly production was calculated as the difference in biomass estimated from inside the cage minus biomass estimated outside the cage.

At the beginning of the season in all treatments, and during the season and at the end of the season in NONE, live and dead fractions were calculated using a line-point transect. Five 10-m transects were randomly located in each treatment, and point determinations of live or dead were made at each decimeter resulting in 100 point determinations in each treatment at each sampling date. Biomass estimates were adjusted by multiplying total biomass by percentage of live biomass to reflect incremental growth of live biomass for the given growth period. To quantify potential forage for utilization by livestock in the grazing treatments, five randomly placed 1-m × 20-m band transects were sampled for each season (spring, summer, and fall) to determine refused and nonutilized forage. Production in our study is defined as potential utilizable forage (PUF) and was quantified by incorporating the estimates of refused and nonutilized biomass into our estimates of total production. Potential utilizable forage was then binned into three seasons: spring (April, May, June), summer (July and August), and fall (September and October).

Belowground net primary production (BNPP) was estimated in 2006 and 2007 from root in-growth cores (Fahey et al., 1999). Five 5-cm diameter × 15-cm deep mesh cores containing a neutral soil medium (75% field soil and 25% sand) were installed within each treatment at the beginning of the growing season (April). The cores were harvested at the end of the season (October), and the roots were washed free of soil over a 1-mm sieve, dried at 60°C for 48 h, and weighed.

To estimate forage quality, grab samples of biomass were harvested monthly from April through October in 2006 and 2007. To compare forage *on offer*, or forage that grazing animals would be exposed to at the time they were turned into the pasture, samples were taken at any given time for CONT (monthly at the same time as biomass estimates) and immediately before animals were turned into the paddock for MIRG (sampling in the MIRG paddocks was done at the same time as pregrazing biomass estimates were made). Five random samples of standing biomass were harvested from within each replicate of each treatment, composited, and then dried at 65°C for 48 h. Samples were ground through a 1-mm screen in a Model 4 Wiley mill (Thomas Scientific, Swedesboro, NJ) and analyzed for forage quality attributes at the University of Wisconsin Forage Lab (Madison, WI) by near-infrared reflectance spectroscopy (NIRS) using a Foss NIR Model 6500 (Foss NIRSystems Inc., Laurel, MD). Forage analytes were determined using the NIRS Forage and Feed Testing Consortium grass equation (http://nirsconsortium.org/Documents/eqa.pkgs.Feb10.for%20web.pdf [verified 6 Dec. 2010]). Samples were checked to ensure the data was not spectrally different from those samples included in consortium equation database. The r^2 values for equation calibration were 0.93, 0.99, 0.97, and 0.87 for dry matter (DM), crude protein (CP), neutral detergent fiber (NDF), and neutral detergent fiber digestibility (NDFD), respectively. We report forage quality as relative forage quality (RFQ), which is a single numeric index that reflects the sum of forage quality attributes measured in a forage sample. Relative forage quality is calculated from predicted values of voluntary forage intake and the estimated available energy derived from that forage. In this way, it is similar to the more common relative feed value (RFV) that was developed to market forages and to be used as a forage education tool (Rohweder et al., 1978). But, because RFQ is applicable over a greater range of forage types and improves estimation of dry matter intake of high-quality grasses, it is the preferable index to use for cool season grasses (Moore and Undersander, 2002).

Soil cores to 15-cm depth were used to estimate N availability. Duplicate 10-g subsamples were weighed out, with one subsample for immediate inorganic N extraction in 2 mol L^{-1} KCl and one that was aerobically incubated for a period of 7 d and then extracted to measure net N mineralization following Robertson et al. (1999). Extracts were frozen before colorimetric NH_4^+ (method #12-107-06-2-A) and NO_3^- (method #12-107-04-1-B) determination on a Lachat QuikChem flow injection analyzer (Lachat Instruments, Milwaukee, WI).

Vegetative cover was estimated in late July (2005 through 2007) and late September (2006 and 2007). Five 10-m transects were randomly located within each treatment plot. At 50-cm intervals along each transect a sharpened point was lowered from above the vegetation and the first plant species intercepting the point was recorded (Heady et al., 1959). Absolute cover was calculated by dividing species intercepts by total intercepts. The cover estimates by species were categorized into the following functional groups: C_3 cool-season grasses, perennial legumes, and nonleguminous forbs.

Sward variability was estimated in July and September of 2006 and 2007 using the same five transects used for vegetative cover. At 50-cm intervals plant biomass was measured for height and recorded. Coefficient of variation was calculated at the plot level and then averaged across blocks.

Statistical Analysis

Averages calculated from subsamples within each experimental unit (paddock) were used in ANOVA linear mixed-effects (LME) modeling using the maximum likelihood algorithm. All modeling was done using S-Plus 7.0 (Insightful Corp., Seattle, WA; 2005). Saturated models were constructed to analyze response variables as a function of management treatments, once we accounted for the random effect of block. To test the significance of the fixed effect, we dropped the treatment term and compared a model with only the intercept term to the model including the treatment term using likelihood ratios (Crawley, 2002). If models were significantly different ($p < 0.05$), the model with the lower Akaike's information criterion (AIC) was retained. If not, we selected the simpler model. If treatment was significant, treatment levels were sequentially collapsed and subsequent models were compared with likelihood ratio tests using the same approach of model selection. Separate model selection procedures were run for each year (2006 and 2007) to test for treatment effects on PUF, BNPP, and RFQ. To test for treatments effects on PUF and RFQ by season, separate models were run for each season within year, spring (April through June), summer (July and August), and fall (September and October).

RESULTS

Potential Utilizable Forage

None of the treatment levels could be combined for 2006 without a significant increase in residual deviance indicating that all treatments were significantly different from each other ($p < 0.001$). In 2007, all treatment levels were significantly different except CONT and HARV ($p < 0.001$). Total PUF was greatest in MIRG for both years, while the NONE treatment had the lowest total production (Fig. 2).

Potentially utilizable forage in spring 2006 was greatest in MIRG followed by CONT, while in 2007 it was greatest in MIRG followed by CONT and HARV. A comparison of 2006 to 2007 shows a small but insignificant increase in MIRG (10%) and HARV (11%) PUF, while CONT (12%) and NONE (15%) showed small but insignificant decreases. In summer 2006 MIRG PUF was greater than all treatments, but this pattern was slightly altered in 2007 (Fig. 2).

Fall PUF was greater under MIRG and CONT in 2006 and under MIRG in 2007 (Fig. 2). Relatively low variability in PUF under MIRG across the summer and fall seasons in 2007 was noted.

Forage Quality On Offer

Spring RFQ values in both years were not different except under the NONE treatment (Fig. 3). For summer 2006, MIRG and HARV treatments were greater than CONT and NONE. For summer 2007, RFQ was highest in the MIRG treatment followed by HARV, CONT, and NONE, respectively (Fig. 3). Fall RFQ was greater under MIRG in both years, and the pattern of fall RFQ among treatments was consistent for both years (Fig. 3).

Belowground Net Primary Production

In 2006 and 2007, there was a significant treatment effect on BNPP ($p < 0.05$). In 2006, MIRG and CONT were not different and neither were HARV and NONE, but these latter treatments were greater than the two grazing treatments (Fig. 4). This pattern was repeated in 2007 for the grazing treatments, but unlike 2006 the HARV treatment was significantly less productive than NONE.

Vegetation Cover and Sward Height Variability

Estimates of cover by functional group showed no significant directional trends between years for all treatments with the exception of an increase in grass cover in the HARV treatment ($p = 0.04$). At the species level, the CONT treatment contained greater Kentucky bluegrass cover ($p = 0.02$) but less orchard grass cover ($p < 0.001$). Also, the proportion of bare ground was greater in the CONT treatment ($p = 0.002$; Table 1).

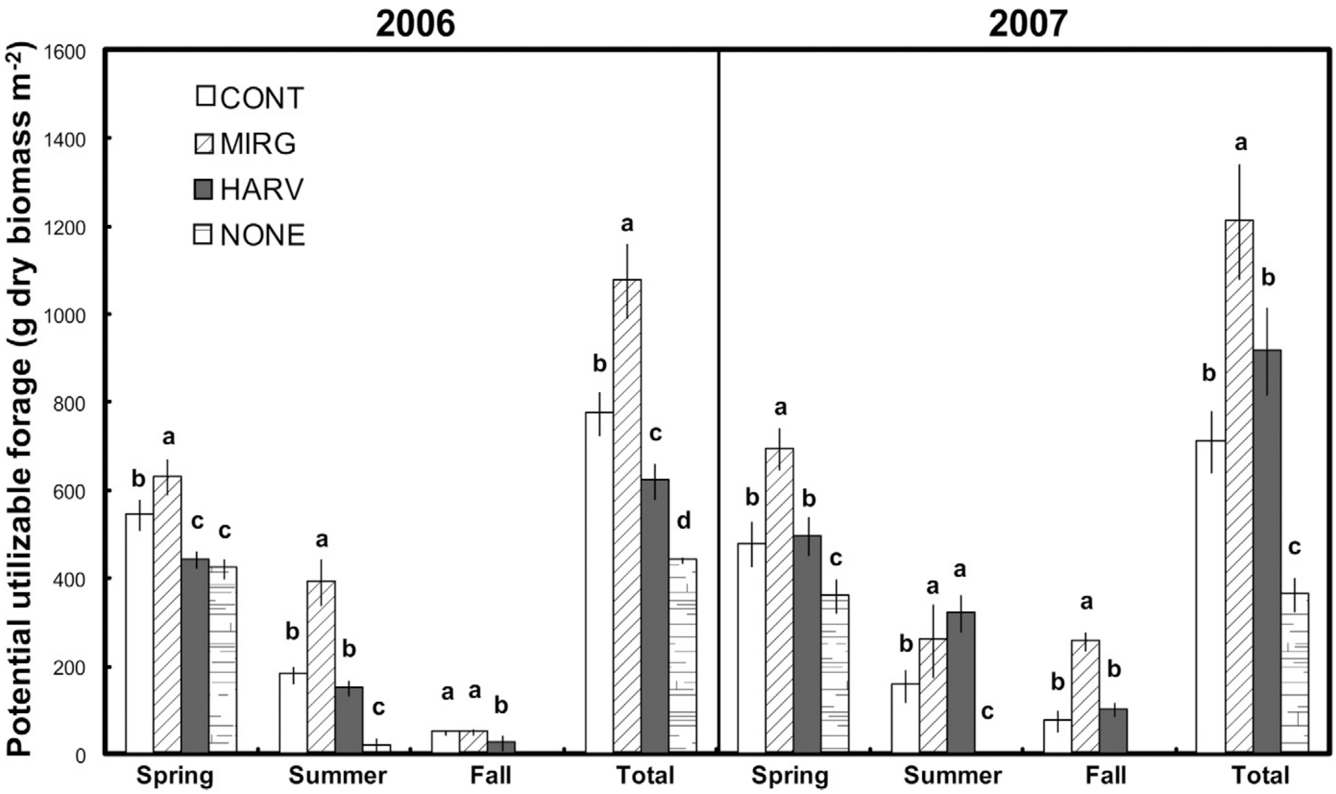

Figure 2. Potential utilizable forage for 2006 and 2007. Error bars show ± SE, $n = 3$. Means of PUF shown with different letters were determined to be significantly different using ANOVA linear mixed-effects model selection, $p < 0.05$. CONT, continuous grazing; MIRG, management-intensive rotational grazing; HARV, hay harvesting; NONE, no agronomic management.

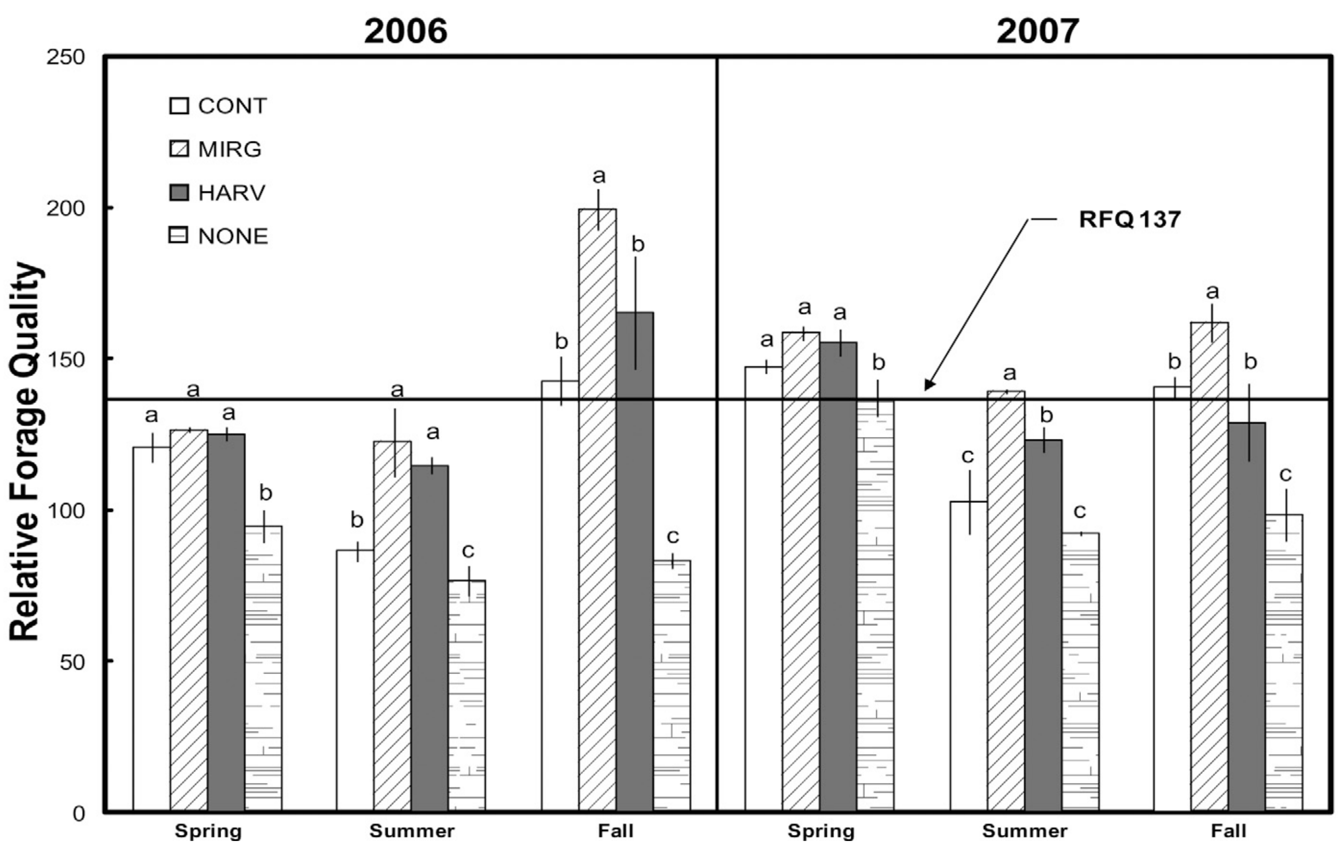

Figure 3. Relative forage quality (RFQ) for 2006 and 2007. An RFQ estimate of 137 is the level at which forage is deemed medium quality. At this level growing cattle would gain 0.6 kg d^{-1}, and lactating cows would produce 10 kg milk d^{-1}. Error bars show ± SE, $n = 3$. Means of RFQ shown with different letters were determined to be significantly different using ANOVA linear mixed-effects model selection, $p < 0.05$. CONT, continuous grazing; MIRG, management-intensive rotational grazing; HARV, hay harvesting; NONE, no agronomic management.

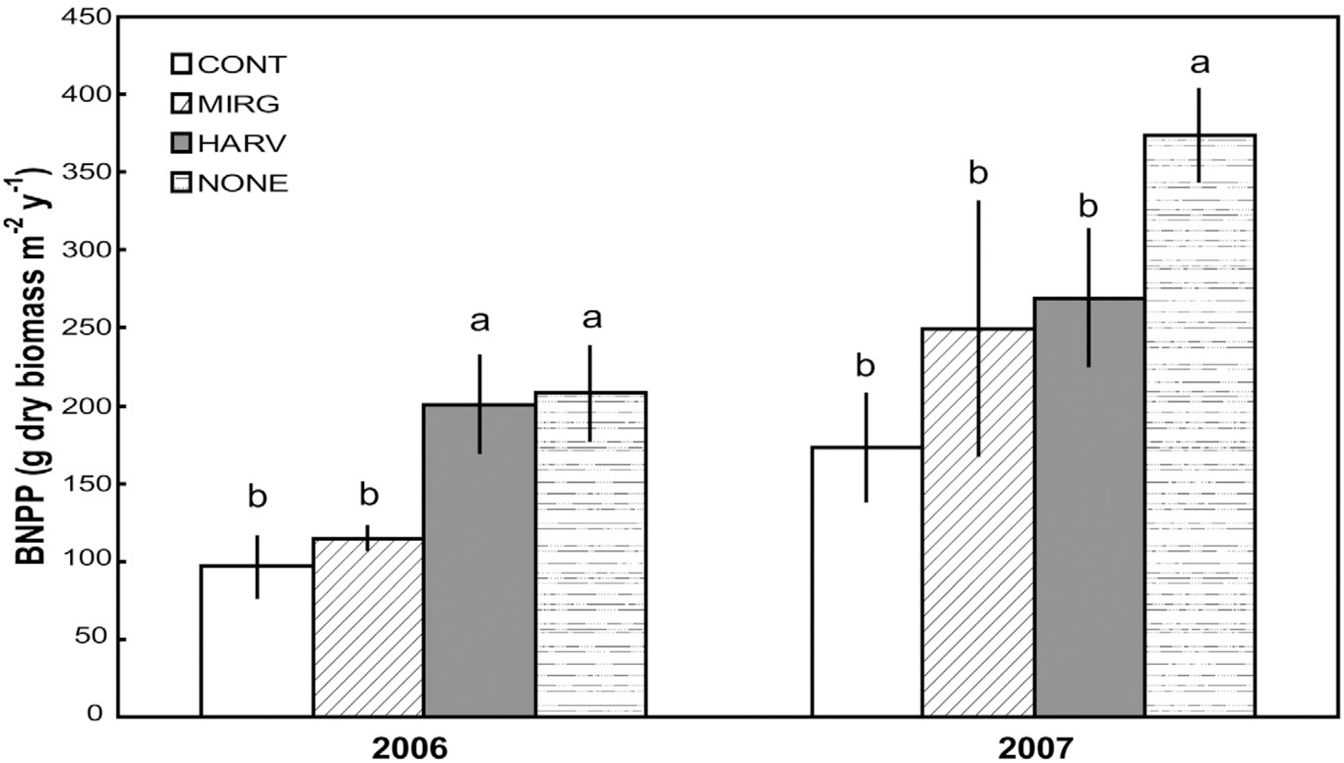

Figure 4. Belowground net primary production (BNPP) for 2006 and 2007. Error bars show ± SE, n = 3. Means of BNPP shown with different letters above error bars were determined to be significantly different using ANOVA linear mixed-effects model selection, $p < 0.05$. CONT, continuous grazing; MIRG, management-intensive rotational grazing; HARV, hay harvesting; NONE, no agronomic management.

Treatment had a significant effect on sward height variability on all measurement dates ($p < 0.05$). Variability was greater in CONT than HARV on all dates in 2006 and 2007 and greater than MIRG with the exception of July 2006. In July 2006 and September 2007 MIRG had greater sward height variability than HARV, but they were not different on the other measurement dates (Fig. 5).

Net Nitrogen Mineralization

Across the 2006 and 2007 growing seasons, net N mineralization was significantly affected by treatment (p = 0.02), while there was no significant treatment by year interaction (p = 0.27). Nitrogen availability was greater, and variability lower, in the grazed treatments when compared to the ungrazed treatments. Rates of net N mineralization were CONT: 0.31 ± 0.04, MIRG: 0.22 ± 0.02, HARV: 0.08 ± 0.07, and NONE: −0.04 ± 0.15 μg N g^{-1} dry soil d^{-1} (mean ± SE).

DISCUSSION

Our finding that PUF over the entire growing season was enhanced by MIRG supports the hypothesis that cool-season pastures are sensitive to the timing and frequency of grazing. This is an indication that the relationship between plant production and foliar removal is affected by the distribution of grazing pressure in space and time for a given stocking rate and is beneficial as a production strategy over stocking rate alone in this subhumid setting. Our results compare favorably with a mensurative study in Wisconsin by Paine et al. (1999) who reported increased forage production in MIRG compared to continuous grazing.

Management-intensive rotational grazing had seasonal benefits as well indicating that rotational grazing enhanced PUF and RFQ during the summer months relative to continuous grazing. Most of the total seasonal growth of cool-season grasses occurs in the spring—as much as 60% of growth is attained by July (Riesterer et al., 2000)—so the ability to manage for adequate forage production and quality through the summer is a key challenge (Paine et al., 1999). Cool-season grasses require as much as 2.5 times longer for regrowth in summer as they do in spring, a condition commonly referred to as the *summer slump* (Balasko and Nelson, 2003; Brink et al., 2007; Paine et al., 1996; Smart et al., 1995). Others have reported production peaks early in the growing season with a decline in production as the growing season progresses (Paine et al., 1999; Phillip et al., 2001; Popp et al., 1997). Our results were similar with the notable exception of more summer production under MIRG indicating a positive production benefit to rotational graziers. Moreover, this result occurred during two below-average rainfall years.

We observed no difference in PUF between defoliation treatments in fall of 2006, and production declined relative to both spring and summer. In 2007 there was a significant fall production advantage under MIRG. This was surprising given the droughty conditions of summer and that there were no differences in soil moisture status between treatments (data

Table 1. Mean (SE) percent cover of dominant taxa across last two experimental years (2006–2007).

Functional group	Common name	Scientific name	Treatment†							
			CONT		MIRG		HARV		NONE	
Annual grass	Hairy crabgrass	*Digitaria sanguinalis* (L.) Scop.	0.2	(0.2)						
Cool season (C_3 grass)	Kentucky bluegrass	*Poa pratensis* L.	61.6^{a}	(10.6)	37.0^{b}	(9.0)	43.5^{b}	(4.5)	49.9^{a}	(4.2)
	Meadow fescue	*Schedonorus pratensis* (Huds.) P. Beauv.	2.5	(3.0)	5.0	(4.9)	1.9	(2.1)	4.1	(5.0)
	Orchardgrass	*Dactylis glomerata* L.	4.2^{a}	(2.4)	24.9^{b}	(6.2)	30.9^{b}	(6.9)	14.4^{b}	(8.1)
	Perennial rye	*Lolium perenne* L.	2.3	(2.0)	4.2	(2.8)	2.1	(2.7)	0.2	(0.2)
	Quackgrass	*Elymus repens* (L.) Gould	0.1	(0.1)	0.1	(0.1)	1.5	(2.1)	3.0	(3.2)
	Redtop	*Agrostis gigantea* Roth			0.3	(0.3)			0.5	(0.6)
	Reed canarygrass	*Phalaris arundinacea* L.			0.2	(0.2)	0.2	(0.2)	0.7	(0.7)
	Smooth brome	*Bromus inermis* Leyss.	0.3	(0.2)	2.4	(2.1)	0.6	(0.5)	2.8	(1.5)
	Tall fescue	*Schedonorus arundinaceus* (Schreb.) Dumort = *Lolium arundinaceum* (Schreb.) Darbysh.	0.3	(0.4)	0.9	(1.3)	0.9	(1.0)	2.5	(2.5)
	Timothy	*Phleum pretense* L.	1.5	(1.6)	1.0	(1.3)	2.5	(2.5)	1.9	(2.4)
Perennial legumes	Bird's foot trefoil	*Lotus corniculatus* L.	0.6^{a}	(0.7)	0.5^{a}	(0.5)	7.5^{b}	(4.8)	13.7^{b}	(7.5)
	Black medic	*Medicago lupulina* L.	0.8	(0.9)			0.2	(0.4)		
	Red clover	*Trifolium pretense* L.	0.7	(0.8)	1.4	(0.6)	0.1	(0.1)	0.1	(0.1)
	White clover	*Trifolium repens* L.	9.1^{a}	(4.6)	15.6^{a}	(8.1)	0.9^{b}	(1.2)		
Forbs	Bull thistle	*Cirsium vulgare* (Savi) Ten.	0.3	(0.3)	0.1	(0.1)	0.1	(0.1)	0.6	(0.8)
	Canada goldenrod	*Solidago canadensis* L.							0.2	(0.2)
	Canada thistle	*Cirsium arvense* (L.) Scop.					0.3	(0.5)	0.3	(0.3)
	Carolina horsenettle	*Solanum carolinense* L.					0.4	(0.4)	0.4	(0.4)
	Dandelion	*Taraxacum officinale* F. H. Wigg. aggr.	7.2^{a}	(4.7)	3.6^{b}	(1.9)	4.4^{b}	(2.5)	0.8^{b}	(0.8)
	Giantchickweed	*Myosoton aquaticum* (L.) Moench	0.3	(0.3)			1.0	(1.0)	0.2	(0.2)
	Rough fleabane	*Erigeron strigosus* Muhl. ex Willd.	0.1	(0.1)						
	Smartweed	*Polygonum* spp.	0.7	(0.6)						
	Spiny plumeless thistle	*Carduus acanthoides* L.	0.2	(0.2)			0.2	(0.1)	0.7	(0.4)
	Wild parsnip	*Pastinaca sativa* L.	0.1	(0.1)					0.3	(0.5)
Sedge	Sedge	*Carex* spp.	0.2	(0.2)	0.2	(0.2)			2.2	(2.0)
Other			3.1		2.3		0.5		0.3	
Bare ground	Bare		3.6^{a}	(2.2)	0.3^{b}	(0.3)	0.3^{b}	(0.5)	0.2^{b}	(0.2)

†CONT, continuous grazing; MIRG, management-intensive rotational grazing; HARV, hay harvesting; NONE, no agronomic management. Significant differences are shown by different superscript letters.

not shown). A possible explanation is that MIRG maintained the vegetation in the regrowth phase giving the plant community an advantage when conditions subsequently became favorable for growth. Strategically managing the timing, duration, and intensity of grazing may allow graziers to capitalize on the seasonal growth patterns of cool-season grasses.

As grazing farmers seek to balance profitability despite lower farm output compared to confinement operations, forage quality becomes increasingly important for livestock performance and for lowering feed costs by reducing the need for supplements (Parker et al., 1992). Forage utilization and livestock performance are known to increase as forage quality increases. An RFQ estimate of 137 is the level at which forage is deemed to be of moderate quality—a level where growing cattle would gain 0.6 kg d^{-1} and lactating cows would produce 10 kg milk d^{-1} (Moore and Undersander, 2002). Management-intensive rotational grazing was the only treatment that consistently met this RFQ value, with the exception of spring and summer 2006.

Even in years when precipitation was less than normal, MIRG produced forage that was of consistent quality for livestock performance and profitability. Relative forage quality estimates did not differ between treatments in spring with the exception of NONE; this was not surprising given that spring growth in all treatments results in new foliar tissue of high nutrient concentrations, while defoliation maintained plant development in the juvenile stage. In contrast, summer and fall RFQ estimates were highest under MIRG, which is an important finding for graziers because during the less productive summer months MIRG treatments not only offer a greater quantity of forage but also forage that is of higher quality.

It has been suggested that optimization of forage production and quality is a function of defoliation timing relative to growth state of the vegetation (Turner et al., 1993), exclusion of less palatable species (Bardgett et al., 1998; Menke and Bradford, 1992), and increased nutrient cycling (Conant et al., 2003; Frank and Groffman, 1998; Le Roux et al., 2003). Our positive MIRG results were most likely influenced by (i) maintenance of the plant community in a homogeneous juvenile vegetative state—variability in sward height was almost double in CONT plots, (ii) retention of taller bunch grasses such as orchard grass, and (iii) increased rates of net N mineralization.

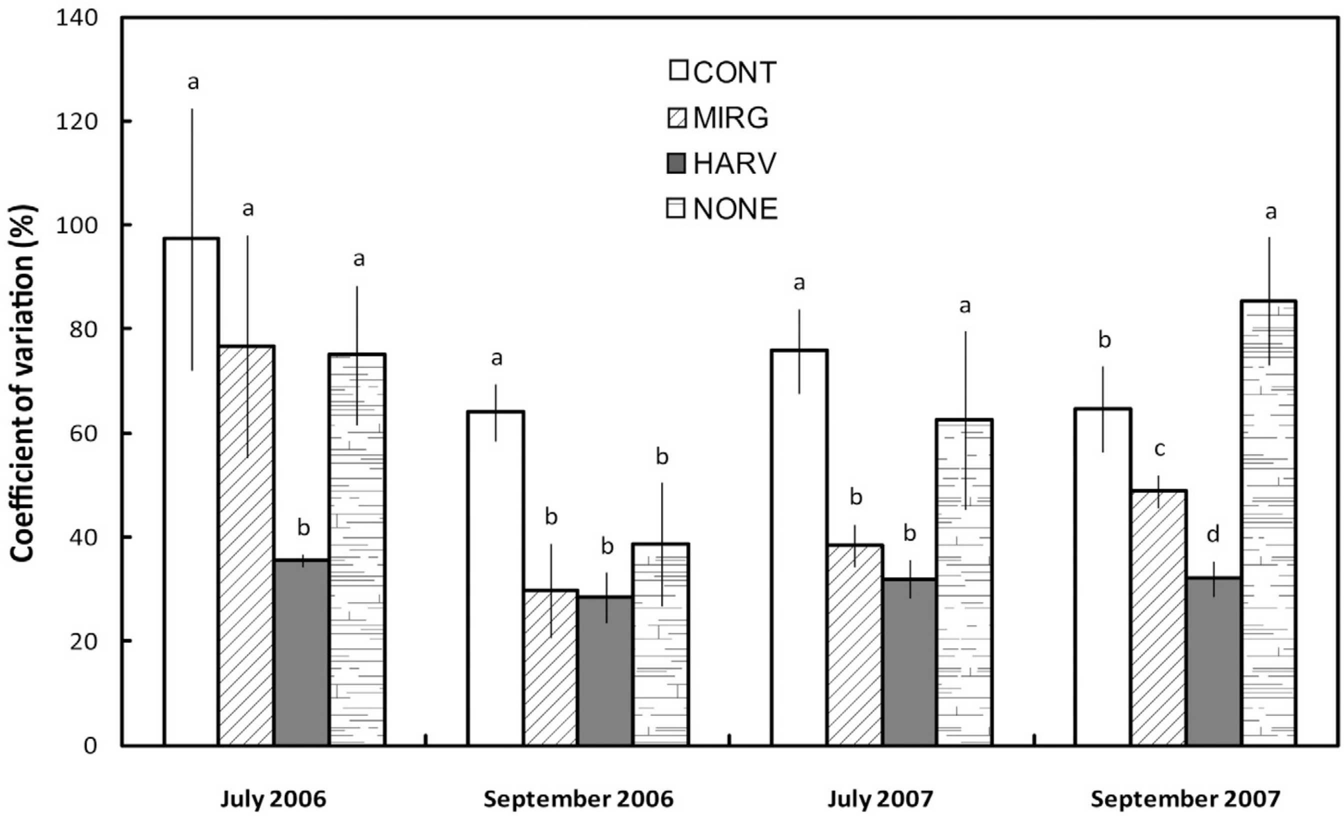

Figure 5. Coefficient of variation in sward height for pasture grazed continuously (CONT) and monthly to ~15 cm (MIRG), harvested twice during the growing season to ~6 cm (HARV), and with no agronomic management (NONE) for two sample dates (July and September) in 2006 and 2007. Error bars show ± SE, $n = 3$. Means shown with different letters above error bars were determined to be significantly different using ANOVA linear mixed-effects model selection, $p < 0.05$. CONT, continuous grazing; MIRG, management-intensive rotational grazing; HARV, hay harvesting; NONE, no agronomic management.

Our root production results compare favorably with the results of Woodis and Jackson (2008b) who found roots of smooth brome (*Bromus inermis* Leyss.), a major component of many cool-season pastures, were affected negatively by both intensity and frequency of clipping relative to an unclipped control. Grazing lands in the temperate latitudes are thought to contain a significant portion of the terrestrial C sink, and understanding root contribution to this pool is important as it represents a major organic C input in grasslands (Reeder et al., 2001). A reduction in root production under grazing lands may limit C sequestration opportunities.

In their review of experiments comparing rotational grazing strategies with continuous grazing, Briske et al. (2008) reported that rotational grazing systems can be a viable management option in arid and semiarid grazing land, but that stocking rate was the most important management tool irrespective of grazing strategy. This view is well established for arid and semiarid rangelands (Barnes et al., 2008). For subhumid systems, what has not been well established is whether stocking rate alone or controlling the distribution of grazing pressure in space and time is beneficial for forage production and quality. In fact, the evidence is equivocal, with some researchers reporting little or no benefit from rotational systems when compared to continuous grazing (Bransby, 1991; Dale et al., 2008; Popp et al., 1997), while others have found production benefits in livestock weight gain and parasite reduction (Papadopoulos et al., 1993), increased pasture productivity (Paine et al., 1999; Fales et al., 1995), and land use efficiency (Phillip et al., 2001).

In our subhumid grassland, herbivore–plant interactions appeared to be tightly coupled and to be the main drivers of productivity (sensu Jackson and Allen-Diaz, 2006). Management of the spatial distribution of livestock and timing of defoliations positively impacted biomass production, increasing forage production and quality in both years while having a negative impact on fine root production. These results support the hypothesis that our pasture behaved as an equilibrium ecosystem. It then follows that in pasture systems with equilibrium dynamics, carefully managing grazing pressure may be beneficial as a production strategy over stocking rate alone.

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