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IMPACT OF GRAZING MANAGEMENT ON THE CARBON AND NITROGEN BALANCE OF A MIXED-GRASS RANGELAND

G. E. Schuman,[1,3] J. D. Reeder,[2] J. T. Manley,[1] R. H. Hart,[1] and W. A. Manley[1]

[1]*USDA-ARS, High Plains Grasslands Research Station, 8408 Hildreth Road, Cheyenne, Wyoming 82009-8899 USA*
[2]*USDA-ARS, Crops Research Laboratory, 1701 Center Avenue, Fort Collins, Colorado 80526 USA*

Abstract. Rangeland grazing management strategies have been developed in an effort to sustain efficient use of forage resources by livestock. However, the effects of grazing on the redistribution and cycling of carbon (C) and nitrogen (N) within the plant–soil system are not well understood. We examined the plant–soil C and N balances of a mixed-grass rangeland under three livestock stocking rates using an area that had not been grazed by domestic livestock for more than 40 years. We established nongrazed exclosures and pastures subjected to continuous season-long grazing at either a light stocking rate (20 steer-days/ha) or a heavy stocking rate (59 steer-days/ha, ~50% utilization of annual production). Twelve years of grazing under these stocking rates did not change the total masses of C and N in the plant–soil (0–60 cm) system but did change the distribution of C and N among the system components, primarily via a significant increase in the masses of C and N in the root zone (0–30 cm) of the soil profile. The mass of soil C (0–60 cm) under heavy grazing was comparable to that of the light grazing treatment. Grazing at the heavy stocking rate resulted in a decrease in peak standing crop (PSC) of aboveground live phytomass, an increase in blue grama (*Bouteloua gracilis* [H.B.K.] Lag. Ex Steud.), and a decrease in western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Love) compared to the light grazing treatment. The dominant species under light grazing was western wheatgrass, whereas in the nongrazed exclosures, forbs were dominant and appeared to have increased at the expense of western wheatgrass. The observed increase of soil C and N in the surface soil where roots dominate indicates a greater opportunity for nutrient availability and cycling, and hence enhanced grazing quality.

Key words: C and N balance; carbon; mixed-grass prairie; nitrogen; rangelands.

Introduction

Rangeland grazing management strategies have been developed in an effort to sustain efficient use of the forage resource by livestock. However, these management practices affect many ecosystem components besides livestock and forage production. Grazing can also influence plant community structure, soil chemical and physical properties, and the distribution and cycling of nutrients within the plant–soil system. This paper examines the effects of grazing on C and N distribution within a semiarid, mixed-grass plant–soil system.

Historically, most grazing studies have focused on the effects of management practices on forage production and animal response, although a few researchers have evaluated the effects of grazing on soil C and N (Smoliak et al. 1972, Bauer et al. 1987, Frank et al. 1995). Grazing of the northern mixed prairie reduces canopy biomass by depressing the vigor of cool-season grasses and causing the replacement of mid-grasses by warm-season short grasses (Coupland et al. 1960, Dormaar and Willms 1990). The degree to which this shift in species composition occurs depends on the density and duration of stocking (Coupland 1992). Grazing also partially controls the quantity and chemical composition of soil organic matter and the distribution of C and N in the soil profile (Rosswall 1976, Smoliak et al. 1972, Dormaar and Willms 1990, Dormaar et al. 1990, Frank et al. 1995), thus influencing the largest reservoir of N and C in the perennial grass plant–soil system. Since plant-available N is usually the limiting nutrient to grass production in the semiarid Great Plains (Power 1977), the quantity and chemical composition of soil organic matter is of critical importance to N and C cycling and primary productivity (Power 1994), and thus to overall ecosystem function. Aboveground plant productivity and composition also influence C and N inputs. Grazing has been shown to influence litter accumulation and depletion (Christie 1979, Hart et al. 1988, Naeth et al. 1991), its rate of decomposition (Shariff et al. 1994), and its subsequent effects on herbage production (Willms et al. 1993).

Milchunas and Lauenroth (1993) reviewed a worldwide 236-site data set and found no clear relationship between species composition, root biomass, soil organic C, or soil N of grazed vs. ungrazed grasslands. These cited studies clearly indicate the variance of findings on the effects of grazing on soil organic C and N. We believe that much of the variance noted in earlier

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[3] E-mail: gschuman@lamar.colostate.edu

research results from soil variations within the studies, differences in the depth of the soil profile being evaluated, and a lack of thorough evaluation of the C and N distribution within the system. For example, a significant number of past studies only evaluated the surface 5–10 cm of the soil profile. We feel that careful evaluation of the effects of grazing on ecosystem C and N balance can be a useful indicator of the effects of grazing management on rangeland health (National Research Council 1994). Therefore, the objective of this research was to quantify the effects of 12 yr of livestock grazing at three stocking rates on plant biomass, plant community composition, and the C and N balance of a mixed-grass prairie.

Methods

Study sites

The research was conducted at the High Plains Grasslands Research Station near Cheyenne, Wyoming, on a native mixed-grass rangeland with rolling topography and elevations ranging from 1910 to 1950 m. The climate is semiarid, with an annual frost-free period of 127 d, and average annual precipitation (1971–1994) of 384 mm, of which 70% occurs from 1 April through 30 September (National Oceanic and Atmospheric Administration 1994). Dominant soil series are Ascalon and Altvan sandy loams (mixed, mesic, Aridic Argiustoll; Stevenson et al. 1984).

Vegetation is predominantly grasses (55% cool-season species and 23% warm-season species), forbs, sedges, and half-shrubs. Dominant cool-season species are western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Love) and needleandthread (*Stipa comata* Trin & Rupr.), and the dominant warm-season species is blue grama (*Bouteloua gracilis* (H.B.K) Lag. Ex Steud.). Legumes comprised <2% of the plant community of this mixed-grass ecosystem. Prior to establishment of the grazing management and stocking rate phase of this research, the area had not been grazed by domestic livestock for >40 yr.

Treatment pastures were established in 1982 in a randomized block design with two replicate blocks (pastures) for each of seven grazing strategy–stocking rate treatment combinations. Three of the treatments were evaluated in this study: (1) EX, nongrazed exclosures, (2) CL, pastures with continuous season-long grazing at a light stocking rate of 0.16 to 0.23 steers/ha (mean of 20 steer-days/ha), and (3) CH, pastures with continuous season-long grazing at a heavy stocking rate of 0.56 steers/ha (mean of 59 steer-days/ha). The light stocking rate was ~35% below the stocking rate recommended by the Natural Resources Conservation Service (NRCS, formerly the Soil Conservation Service) for the condition of the site, whereas the heavy stocking rate, which utilized slightly <50% of annual production, was ~33% higher than the NRCS recommended rate (Hart et al. 1988). Further details of the grazing treatments and pasture design are given in Hart et al. (1988) and Manley et al. (1995).

Field sampling

In 1982, prior to initiation of grazing treatments, a 50-m permanent transect was established in each replicate pasture on near-level sites on the Ascalon soil series. The A horizon and solum (A + B horizons) of the Ascalon soil have mean (±1 SD) depths of 15 ± 2 cm and 100 ± 7 cm, respectively. The soil ranges from 6.4 to 7.3 pH. In July 1993, soil and plant samples were collected to measure the C and N content in the various components of the plant–soil system. Five sample locations were established at 10-m intervals along the 50-m transect in each pasture. Soil samples (4.6 cm diameter) were collected to 90-cm depth with a hydraulic soil sampling machine. All plant litter was removed from the soil surface before the samples were taken. Soil samples were segregated into 0–3.8, 3.8–7.6, 7.6–15, 15–30, 30–45, 45–60, and 60–90 cm increments. The first three segments, 0–15 cm, encompass the soil A horizon; the 15–90 cm segments represent the various components of the soil B horizon. Because the soil profile was extremely dry below 60 cm, we were unable to collect a complete set of soil samples at the 60–90 cm depth; therefore, soil C and N and root biomass were only assessed to the 60-cm depth. Two cores were taken at each sample site and composited by depth increment to provide adequate sample for analyses. Samples were placed in sealed plastic bags and transported to the laboratory in coolers. Separate soil cores were collected at the second and fourth sampling sites along each transect to assess bulk density as described by Blake and Hartge (1986). The bulk density data were used to convert soil C and N concentrations (in milligrams per kilogram) to C and N mass (in kilograms per hectare) in the soil. These soils contain <1% fine gravels that are generally found in the C horizon; therefore, no adjustment of the bulk density was necessary.

Five additional cores were collected at 10-m intervals along each transect to assess root biomass and root C and N. The surface 30 cm were sampled with a 9.9 cm diameter core, and the 30–60 cm depth was sampled with a 4.6 cm diameter core. Soil cores were separated into 0–15, 15–30, and 30–60 cm increments. The smaller diameter core was required to obtain the lower depth samples because of low soil moisture levels. Root core increments were placed in sealed plastic bags and stored at 5°C until roots could be washed from the soil.

Surface litter and standing dead plant biomass were estimated along each transect with five 0.18-m^2 quadrats, spaced at 10-m intervals. Estimates of annual aboveground biomass production were obtained at peak standing crop from three 1.5 × 1.5 m temporary exclosures randomly located throughout each treatment pasture; two 0.18-m^2 quadrats were sampled within each of the temporary exclosures. In the nongrazed

TABLE 1. Comparison of total biomass of vegetation components as affected by stocking rate (NS = not statistically significant).

System components	Exclosure (kg/ha)	Continuous light grazing (kg/ha)	Continuous heavy grazing (kg/ha)	Least significant differences	
				P = 0.10	P = 0.05
Above ground					
Live biomass	1 330	1 224	816	270	325
Standing dead	472	492	0	155	187
Litter	2 872	1 647	1 271	1018	1227
Total above ground dead	3 344	2 139	1 271	1054	1270
Total above ground biomass	4 674	3 363	2 087	1176	1418
Roots					
0–15 cm	31 474	21 695	27 319	6500	NS
15–30cm	5 516	6 971	5 289	NS	NS
30–60cm	1 618	1 779	1 162	NS	NS
Total roots:	38 608	30 445	33 770	NS	NS
Root : shoot ratio	28.4	26.9	41.6	10.4	12.5
Total plant biomass	43 282	33 808	35 857	NS	NS

permanent exclosures (EX), five 0.18-m^2 quadrats were sampled at 10-m intervals along the 50-m transect for all aboveground plant components.

Laboratory analysis

Soil samples intended for C and N analysis were passed through a 2-mm screen to remove plant crowns and visible roots and root fragments. Each sample was mixed and a 10-g field-moist subsample removed for NH_4^+ and NO_3^- extraction; the remaining soil was air-dried and stored at 4°C until analyses for total C and N were completed. Root separation from root cores was accomplished by hand with the washing method described by Laurenroth and Whitman (1971). Vegetation components were dried at 60°C, weighed, and the final biomass estimates converted to a kilogram per hectare basis using the area of the sample quadrat, or in the case of the roots, the surface area of the root core. Ash content of all components of the vegetation was used to calculate/adjust the C and N masses.

Plant samples were analyzed for organic C and N with a Carlo-Erba automated combustion analyzer. Organic N concentrations of soil samples were determined with a modified micro-Kjeldahl procedure (Schuman et al. 1973). Soil organic C was determined with the Walkley-Black dichromate oxidation procedure (Nelson and Sommers 1982). Soil NH_4^+ and NO_3^- were extracted from field moist soils with 1 mol/L KCl at a 1:10 soil : solution ratio; extracts were filtered and analyzed with a Technicon autoanalyzer (Environmental Protection Agency 1983).

Statistical analysis

Analysis of variance was used to test stocking rate effects on soil and plant component C and N masses and on plant component biomass data using a randomized complete block design with two blocks. Individual system components (litter, standing dead, live biomass, root by depth, and soil by depth) were each tested with a separate analysis of variance with replicate pastures treated as blocks. Least-significant-differences (LSD) procedures were used for treatment mean separation (Steel and Torrie 1980). All statistical evaluations and discussion are based upon $P \leq 0.10$. While we believe that the 10% probability level is very appropriate to test and evaluate the effects of management alternatives on grassland C and N balance, we present LSD values for both the 5 and 10% probability levels in each table. Only 20% of the statistical test accomplished did not meet the 5% probability.

RESULTS

Vegetation components

Twelve years of grazing at the heavy stocking rate resulted in decreased peak standing crop (PSC) of aboveground live phytomass (Table 1), as well as shifts in the plant composition of the PSC (Table 2). Western wheatgrass declined from 45 to 21% of PSC (mass

TABLE 2. Proportional botanical composition of peak standing crop biomass as affected by stocking rate (NS = not significant).

Taxon	Exclosure	Continuous light grazing	Continuous heavy grazing	Least significant differences	
				P = 0.10	P = 0.05
Blue grama	0.165	0.170	0.272	0.092	NS
Western wheatgrass	0.290	0.448	0.214	0.124	0.149
Needleandthread	0.129	0.068	0.111	NS	NS
Other grasses	0.026	0.046	0.116	0.046	0.068
Sedges	0.060	0.105	0.071	NS	NS
Forbs	0.330	0.163	0.216	0.124	NS

TABLE 3. Mass of C from vegetation components and soil (0–60 cm profile) as affected by stocking rate (NS = not statistically significant).

System components	Exclosure (kg/ha)	Continuous light grazing (kg/ha)	Continuous heavy grazing (kg/ha)	Least significant differences	
				$P = 0.10$	$P = 0.05$
Above ground					
Live biomass	587	535	355	119	143
Standing dead	206	209	0	65	79
Litter	809	533	394	240	29
Total aboveground dead C	1 015	742	394	255	307
Total aboveground C	1 602	1 277	749	252	371
Roots					
0–15 cm	7 166	6 011	5 763	1 073	NS
15–30 cm	1 244	1 646	1 312	NS	NS
30–60	379	504	346	NS	NS
Total root C	8 789	8 161	7 421	NS	NS
Total plant C	10 391	9 438	8 170	1 259	1517
Soil profile					
0–3.8 cm	9 595	12 675	12 000	1 309	1929
3.8–7.6 cm	5 906	7 457	8 478	660	793
7.6–15 cm	12 662	15 009	15 472	1 573	1896
Total soil C (0–15 cm)	28 163	35 141	35 950	2 188	3224
15–30 cm	19 761	22 847	22 348	2 485	NS
Total soil C (0–30 cm)	47 924	57 988	58 298	2 463	3629
30–45 cm	22 932	20 353	25 281	NS	NS
45–60 cm	17 291	13 595	17 689	NS	NS
Total soil C (0–60 cm)	88 147	91 936	101 268	11 853	NS
Total ecosystem C					
(to 30 cm)	58 315	67 426	66 468	4 334	6565
(to 60 cm)	98 538	101 374	109 438	NS	NS

basis), and blue grama increased from 17 to 27% of PSC, under CH compared to CL grazing (Manley et al. 1997). The PSC under CL grazing was comparable to that in the EX, but the plant compositions of the two treatments differed. The dominant species under CL grazing was western wheatgrass (45% of PSC), whereas in the EX, forbs were dominant. Surface litter biomass was significantly greater in the EX compared to both grazing treatments. Standing dead biomass was comparable in the EX and CL grazed pastures, but absent under CH grazing (Hart et al. 1988). Root biomass in the surface soil (0–15 cm) of the EX and CH grazed pasture was similar, and the EX had significantly greater root biomass than the CL grazing treatment (Table 1).

Trends in the distributions of C and N in the aboveground vegetation components (Tables 3 and 4) were similar to the trends seen for total aboveground biomass, i.e., decreasing masses of C and N with increasing grazing pressure. However, the masses of root C and N in the 0–15 cm depth were significantly higher in the EX than with either grazing treatment (Tables 3 and 4).

Soil response

Total organic C and N masses in the surface 30 cm of the soil profile were significantly lower in the EX than in either grazing treatment (Tables 3 and 4). In the 30–60 cm soil depth, soil organic C and N concentrations were low, and C and N masses were quite variable. The lower masses of C and N in the surface 30 cm of the soil profile of EX were due both to the significantly lower surface soil (0–7.5 cm) bulk density in the EX compared to the grazed pastures (1.00 vs. 1.14 and 1.17 g/cm^3 in the EX, CL, and CH treatments, respectively) and to lower concentrations (milligrams per kilogram) of C and N in the surface 15 cm of the soil profile in the EX than in the grazing treatments (data not shown). Mean bulk densities for the 7.5–30 cm depth were 1.37, 1.31, and 1.44 g/cm^3 in the EX, CL, and CH, respectively. Bulk densities for the 30–60 cm depth averaged 1.39, 1.26, and 1.47 g/cm^3 in the EX, CL, and CH, respectively.

The inorganic N content of the soil profile at the July sampling was low and did not vary significantly among treatments. Nitrate-N concentrations were consistently <1 mg/kg in the soil profile, while NH_4-N concentration were <5 mg/kg. While these data represent a single measurement in time, they are consistent with past studies that have demonstrated that nitrate and ammonium levels in unfertilized grassland soils are almost universally very low (Richardson 1938, Walker 1956, Woodmansee et al. 1978).

Total C and N masses of the system

An evaluation of total C and N masses in the surface 30 cm of plant–soil system, the depth that includes >90% of the root biomass, revealed that (1) total C and N were significantly lower in the EX than in either grazing treatment, and (2) total mass of C was comparable under the two grazing treatments, but total mass of N was significantly larger under CL grazing than

TABLE 4. Mass of N from vegetation components and soil (0–60 cm profile) as affected by stocking rate (NS = not statistically significant).

System components	Exclosure (kg/ha)	Continuous light grazing (kg/ha)	Continuous heavy grazing (kg/ha)	Least significant differences	
				P = 0.10	P = 0.05
Above ground					
Live biomass	18	15	12	5	NS
Standing dead	5	4	0	1.4	1.6
Litter	33	20	15	7	11
Total above ground dead N	38	24	15	6	9
Total above ground N	56	39	27	8	13
Roots					
0–15 cm	308	237	233	50	60
15–30 cm	44	56	52	NS	NS
30–60 cm	10	14	11	NS	NS
Total root N	362	307	296	54	NS
Total plant N	418	346	323	59	71
Soil profile					
0–3.8 cm	684	939	840	26	39
3.8–7.6 cm	488	673	665	95	115
7.6–15 cm	1171	1460	1298	191	230
Total soil N (0–15 cm)	2343	3073	2802	488	636
15–30 cm	1936	2442	2005	233	329
Total soil N (0–30 cm)	4279	5515	4807	204	301
30–45 cm	1865	1736	1692	NS	NS
45–60 cm	1510	1091	1260	273	329
Total soil N, 0–60 cm	7654	8342	7760	NS	NS
Total ecosystem N					
(to 30 cm)	4697	5861	5130	254	362
(to 60 cm)	8072	8688	8083	NS	NS

under CH grazing (Tables 3 and 4). However, when the full 0–60 cm soil depth was evaluated, 89–93% of the system C and 95–96% of the N were stored in soil organic matter within the soil profile. Less than 10% of the C was found in the vegetation component, and 85–91% of vegetation C was in the root mass. Less than 5% of the system N was found in the vegetation component, with 87–92% of vegetation N in the roots. When the soil and plant components were combined for C and N accounting, statistically significant differences across grazing treatments were no longer evident, primarily because C and N concentrations were low and highly variable in the 30–60 cm depth of the soil profile.

Discussion

We found that 12 yr of livestock grazing, after >40 yr of exclusion of both fire and livestock, resulted in a significant increase in the masses of soil C and N in the root zone (0–30 cm) of the soil profile. The surface 30 cm of the soil was 6000–9000 kg/ha higher in C and 450–700 kg/ha higher in N in the grazed treatments than in the EX (Tables 3 and 4). These increases in soil C and N with grazing are probably due to redistributions of C and N within the plant–soil (0–60 cm) system, increases in C and N cycling rates between system components, and reduced losses of C and N from the plant–soil system.

The heavy stocking rate, 135% of that recommended by the Natural Resources Conservation Service, could be expected to affect soil C negatively because of plant physiological responses to the increased grazing pressure. Grasses can respond to defoliation by increasing C allocation to new leaves while decreasing allocation to roots (Detling et al. 1979). Repeated and frequent grazing results in decreased root elongation and biomass (Schuster 1964, Davidson 1978), and hence lower C inputs into the soil from the roots (Holland and Detling 1990). Simulation models also have predicted decreasing soil C levels with increased grazing rates (Parton et al. 1987). In contrast, our data indicate that 12 yr of grazing increased the total mass of soil organic C in the 0–30 cm profile, but did not affect the total mass of C in the plant–soil system to 60 cm depth (Table 3). The heavy stocking rate altered plant composition, which may account for a portion of the change in the distribution of C among the system components. Blue grama, with a typically dense but shallow rooting system, increased under heavy grazing. This change is reflected in the higher root : shoot biomass ratio under the heavy grazing treatment (41:6) compared to the other treatments (Table 1), but it is not reflected in the root biomass or root C or N masses. Coupland and Van Dyne (1979) reported that blue grama-dominated grasslands transfer more of the energy contained in net primary production to underground plant parts than does mixed-grass prairie. Likewise, Frank et al. (1995), who reported similar findings on a North Dakota mixed-grass prairie, suggested that blue grama may partition more C belowground than other species in a mixed-grass ecosystem. Other research has shown that grazing stimulates greater aboveground phytomass production

(Mutz and Drawe 1983, Dodd and Hopkins 1985), increased tillering (Floate 1981), and increased rhizome production (Schuman et al. 1990), and possibly stimulates root respiration and root exudation rates (Dyer and Bokhari 1976). Increased production rates and greater C allocation to the belowground portions of the system may explain the patterns we observed.

Although the mass of soil (0–30 cm) organic C under CH grazing was comparable to that under CL grazing, the mass of organic N was lower (Table 4). Carbon lost from the plant–soil system by herbivory can be replenished by increased photosynthesis and production, but N losses by defoliation are replaced primarily by increased atmospheric N_2 fixation; in our study nitrogen-fixing species represent an extremely small component (<2%) of the mixed-grass ecosystem and did not change with grazing. In the EX, 72% of the aboveground phytomass was in the form of litter and standing dead plant material. Bauer et al. (1987) found lower mass of soil N in relict (nongrazed) than in grazed grasslands and suggested that there is an increased potential for volatilization of NH_3 from plants, and increased opportunity for denitrification in the cooler and more moist conditions of the nongrazed soil profile. Coupland and Van Dyne (1979) reported that ~15% of net primary production of a Canadian mixed-grass prairie was not transferred to litter, but rather was lost via decomposition within the dead-shoot component of the canopy. They also reported losses in the litter layer from photochemical decomposition. Such C losses from the system should be greater in the exclosures where a large aboveground plant C pool exists.

Grazing stimulates C and N cycling from aboveground plant components to the soil. The apparent annual rate of turnover of shoots in the exclosures is 28% (PSC production of 1330 kg/ha divided by mean aboveground standing crop of 4673 kg/ha), compared to 36 and 39% with light and heavy grazing. Animal traffic in the grazed treatments may be enhancing physical breakdown, soil incorporation, and rate of decomposition of litter. Aboveground immobilization of C and N in standing dead plant materials in the EX treatment may also contribute to the lower soil C and N observed. Compared to the grazed treatments, ~275–675 kg/ha more C and 15–25 kg/ha more N are immobilized in the dead plant material of the exclosures instead of being recycled back into the surface soil. These levels of immobilized C and N account for 8% or less of the C deficit, and 6% or less of the N deficit in the surface 30 cm of the exclosure soil profiles. However, over a period of 12 yr of livestock grazing, the enhanced transfer of litter C and N into the soil has resulted in a significantly higher accrual of C and N in the soil of the grazed treatments than in the exclosures.

Grazing of these northern mixed-grass rangelands has not resulted in a reduction of soil C and N resources. In fact, grazing has led to increased levels of soil C and N through enhanced incorporation and decomposition of the litter and standing dead plant material. Transfer of net primary production to belowground plant parts may also account for a portion of the observed increase of soil C and N in the 0–30 cm soil depth, even though root biomass has not exhibited the significant increase typically observed when species composition is changed in response to grazing. The observed increases in soil C and N in the 0–30 cm soil zone have important implications in determining management strategies for these grasslands. Removing livestock from these lands could over the long term reduce soil C and N cycling and potentially the productivity of the systems. These ecosystems developed under grazing; the fact that soil resources are enhanced with grazing suggests that grazing is an important part of ensuring long-term sustainability of these grassland systems.

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