

Grazing Effects on Carbon Dynamics in the Northern Mixed-Grass Prairie

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ABSTRACT / The role of rangelands in the regulation of atmospheric CO₂ concentrations is a critical issue in global climate change research. Rangelands are complex ecosystems that occupy about 50% of the land area in the world and USA. We studied the effects of seasonal grazing on CO₂ flux on small plots located on a silty range site in the northern mixed-grass prairie with an Epa fine loam soil. Treatments were no grazing or short-duration intensive grazing during mid-May or mid-July in 1996, 1997, and 1998. Data were collected from mid-

April to mid-October at about 30-day intervals to estimate standing crop, leaf area, soil organic C, root mass to a 30-cm soil depth, and diurnal variation of CO₂ flux and soil respiration (at 08:00, 12:00, 16:00, and 24:00 hr) in closed chambers. Uptake of CO₂ was greatest during spring and early summer, peak periods of precipitation and green biomass. Grazing removed an average of about 70% of the green standing crop with a subsequent reduction in CO₂ uptake of 175% in May and 109% in July. Grazing in May reduced CO₂ uptake for 30 days in two of the three years, whereas, grazing in July reduced CO₂ flux only in 1998. Residual effects of grazing, however, declined in late summer and autumn with the onset of plant maturation. The potential C sink in the mixed-grass prairie of the Northern Great Plains appears to be small and will vary through time with intensity and timing of grazing as it interacts with climatic conditions.

Rangelands (including grasslands, shrublands, deserts, and tundra) occupy about 50% of the world's land area and contain more than 33% of aboveground and belowground terrestrial C reserves (Allen-Diaz 1996). Follett and others (2001) suggest that, given the size of the C pool in US rangeland, a better understanding is needed of the current and potential effects of management practices on C storage. Since 1990 researchers have been actively studying the potential role of grasslands for C sequestration with research in seeded pastures (Franzluebbers and others 2000); tall grass prairie (Verma and others 1989, 1992, Kim and others 1992, Ham and Knapp 1998, Mielnick and Dugas 2000, Dugas and others 1999, Rice and Owensby 2001, Suyker and Verma 2001); mixed-grass prairie (Dormaar and others 1995, Frank and others 1995, 2001, Manley and others 1995, Schuman and others 1999, 2001, 2002, LeCain and others 2000, Meyers 2001, Frank and Dugas 2001, Sims and Bradford 2001, Frank 2002, Reeder and Schuman 2002; shortgrass

steppe (Reeder and Schuman 2002; Reeder and others this issue); and sagebrush steppe (Angell and others 2001). Inherent in all rangeland ecosystems are both diurnal and seasonal variation in CO₂ flux, with the direction of flux controlled by the balance between photosynthesis and respiration during the growing and dormant seasons (Norman and others 1992, Bremer and others 1998, Dugas and others 1999, Mielnick and Dugas 2000, Frank and Dugas 2001, Frank 2002). Rangelands are also resource limited, particularly for nitrogen and water (Willms and Jefferson 1993). Severity, duration, and timing of grazing and drought in relation to plant phenology are important in determining the status of prairie vegetation as a C source or sink.

Inconsistent responses of soil organic C to grazing have been reported on rangelands. Many of these differences appear to be the result of variations in climate, soil properties, landscape position, plant community composition, grazing management practices, soil organic matter, depth of soil profile, and depth of the soil profile sampled (Johnston and others 1971, Smoliak and others 1972, Dormaar and others 1977, Bauer and others 1987, Milchunas and Lauenroth 1993, Frank and others 1995, Manley and others 1995, Biondini and Manske 1996, Derner and others 1997, Povirk and others 2001, Schuman and others 1999, Wienhold and others 2001, Reeder and Schuman 2002). Some have suggested that grazing leads to an increase in soil microbial biomass that is related to changes in root exu-

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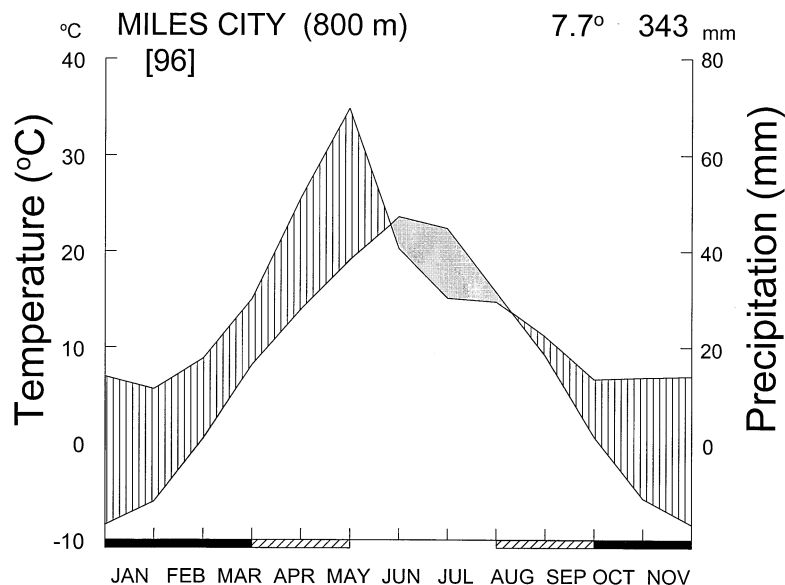


Figure 1. Climate diagram developed for a 96-year period for Miles City, Montana. Mean monthly temperature (°C) and precipitation (mm) indicate mesic spring, early summer, and autumn periods interrupted by late summer and early autumn drought (stippling). Winter precipitation occurs as snow. Months shaded in black have average minimum temperatures < 0°C. Those with diagonal lines have absolute minimum temperatures < 0°C. Figure follows standard form of Walter (1985).

dation patterns following defoliation (Guitian and Bardgett 2000, Hamilton and Frank 2001). Grazing can also affect the redistribution of C within the system (Reeder and Schuman 2002) through changes in rate of recycling aboveground plant C into the soil, changes in plant species composition, and the rate of incorporation of litter into the soil (Naeth and others 1991). Excluding grazing allows litter to accumulate, which may reduce rate of C incorporation into the soil. Litter accumulation will also affect soil temperature (LeCain and others 2000) and soil water content, which in turn will affect soil organic matter decomposition rates, and C and N cycling (Reeder and others 2001). Lateral and vertical spatial variability on rangelands associated with soil organic matter, soil aggregation, and other resources poses challenges and opportunities for managers trying to enhance C storage (Bird and others 2001).

The objective of this research was to determine the impact of short-duration intensive grazing in May or July on CO₂ flux and C dynamics in the Northern Great Plains. We hypothesized that intensive short-duration grazing in May or July would have no effect on CO₂ flux or C dynamics relative to environmental stress.

Study Area

Research was conducted at the Fort Keogh Livestock and Range Research Laboratory (46°22'N 105°5'W) near Miles City, Montana, USA. Regional topography varies from rolling hills to broken badlands with small intersecting ephemeral streams flowing into rivers in broad, nearly level valleys. The area is representative of

the semi arid mixed-grass prairie of the Northern Great Plains. Indigenous vegetation on the 22,500-ha research station is a grama-needlegrass-wheatgrass (*Bouteloua-Stipa-Agropyron*) mix (Küchler 1964). Annual precipitation averages 343 mm, with about 60% received from April through September (Figure 1). Daily temperatures range from > 38°C during summer to below -40°C during winter. The average frost-free growing season is 150 days.

This 1-hectare study site was a nearly level silty range site, which is a common range site in the Northern Great Plains. Soil was an Eapa (fine-loamy, mixed, superactive, frigid Aridic Argiustoll). Vegetation was dominated by a C3 annual grass, Japanese brome (*B. japonicus* Thunb.); C3 perennial grasses, prairie Junegrass [*Koeleria macrantha* (Ledeb.) J.A.], needleandthread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth], and western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Love]; a C3 sedge, thread-leaf sedge (*Carex filifolia* Nutt.); C4 perennial grasses, blue grama [*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths] and red threeawn [*Aristida purpurea* Nutt. var. *longiseta* (Steud.) Vasey]; a succulent, prickly pear (*Opuntia* spp.); half-shrubs, fringed sagewort (*Artemisia frigida* Willd), common sagewort (*A. campestris* L.), and phlox (*Phlox hoodii* Richards); and forbs, western salsify (*Tragopogon dubius* Scop.) and hairy goldaster [*Heterotheca villosa* (Pursh.) Shinners var. *villosa*]. Perennial cool-season grasses and sedges generally made up greater than 60% of the green standing crop during April through July each year. Perennial warm-season grasses and sagesworts be-

gin to increase in dominance during July. Elevation at the study site was 719 m.

Methods

Environment

Long-term and current precipitation and temperature records were obtained from a weather station located at Frank Wiley Field, Miles City, MT, 12.5 km from the study site. Precipitation data for 1996 and early 1997 were also obtained from a study area located 6 km from the study site. These supplemental data were used because malfunction of the nearby Bowen Ratio system prevented continuous precipitation measurements during 1996 and 1997. Precipitation was monitored on site during the remainder of 1997 and 1998. Soil water was estimated during measurement periods on an adjacent site using gravimetric methods for the 0- to 8-cm depth and a dielectric soil water probe for the 15-, 30-, 60-, and 90-cm depths. Gravimetric samples were oven-dried at 105°C for 48 hr.

Treatments

Three treatments were imposed on replicated plots. Treatments were: no grazing (control), intensively grazed by sheep in mid-May (May), and intensively grazed by sheep in mid-July (July). Treatments were arranged in a randomized complete-block design with four blocks of three treatment plots (15 m × 15 m). The study was conducted during 1996, 1997, and 1998. Sheep (28–35 head) were used to impose grazing treatments. Grazing events were normally about 3 hr in duration beginning early morning (05:00 to 08:00 hr). The desired level of grazing (60–70% removal) was generally attained in one grazing bout, and only rarely were the plots grazed again the next morning. Two of the four blocks were grazed during the same week, thus requiring two weeks to complete the treatment application in May and July each year.

Measurements

Seasonal and diurnal effects of grazing and environment were measured from mid-April to mid-October (weather permitting) at about 30-day intervals each year. As with the application of grazing treatments, two blocks were sampled during the same week during each 30-day period.

CO₂ flux. Net CO₂ flux between the soil surface and atmosphere was measured over one randomly located 1-m² sampling quadrat per replication. The 1-m² area was located at the beginning of the study in early spring of 1996, and the same plot was used each year. The plot

was delineated by pressing a 1-m² angle iron frame into the soil. At 08:00, 12:00, 16:00, and 24:00 hr on designated days, we sampled CO₂ flux with a portable CO₂ measurement system (LI-COR 6200, LI-COR Inc., Lincoln, NE, USA) connected to a 1-m³ chamber placed over each plot (Angell and Svejcar 1999, Angell and others 2001). We also measured CO₂ flux at 12:00 hr on control and grazed plots the day of grazing. The chamber was constructed and operated according to methods presented in Angell and Svejcar (1999). An air-tight seal was maintained by setting the chamber on a gasket of closed cell foam resting on the angle iron frame and sealing any gaps around the metal angle iron frame by tamping loose soil. Before obtaining a measurement, the chamber was placed on the foam gasket, the chamber fan was turned on, and ventilation doors were left open to maintain near-ambient conditions within the chamber until data logging was initiated.

To obtain a measurement, the doors were closed and after a 30-sec mixing interval, the measurement period began, and CO₂ concentration was measured for three 20-sec or two 30-sec periods. During measurements of CO₂ concentration, we monitored leaf and air temperature with thermocouples and photosynthetic active solar radiation (PAR) with a quantum sensor. Measurement periods were brief to minimize chamber effects, and the chamber was covered when moving between plots to reduce heating. Net CO₂ fluxes above the canopy (positive flux values indicating movement of CO₂ from the atmosphere to the terrestrial surface) were calculated from rate of change in CO₂ concentration.

Soil CO₂ flux was measured just before the large chamber measurements using a 1-liter LI-COR 6000-09 soil respiration chamber (Norman and others 1992) connected to a LI-COR 6200 infrared gas analyzer. Measurements were taken in two soil respiration rings (polyvinyl chloride 10.4-cm diameter, 5-cm depth) per replication. These were located near the 1-m² frames. After CO₂ was drawn below ambient concentrations within the chamber, the CO₂ concentration was measured for four 15-sec or three 20-sec periods. Rings were pressed into the soil in a new location each spring to a depth of 2.5 cm, and then left in place during the entire April–October sampling period. Emerging seedlings were plucked from inside each ring at least 48 hr before taking measurements. Soil temperature was measured using a temperature probe placed 8 cm deep at the time of soil flux measurements. Soil samples were collected to a 4-cm depth from each replication for gravimetric soil water determinations on each sample date. Samples were oven-dried at 105°C for 48 hr.

Aboveground biomass. On each sample date, standing crop was clipped to ground level and sorted by plant species, within one 0.25-m² quadrat (50 × 50 cm) randomly located within each replication. Litter was also collected from this same plot. The standing crop sample was refrigerated and sorted into live, current dead (i.e., this year's senesced biomass), and dead (i.e., previous year's senesced biomass) tissue. Leaf area of the green standing crop was then determined with a LI-COR 3050-A leaf area meter for determination of leaf area index (LAI). Biomass samples were dried at 60°C for 48 hr and then ground before laboratory analyses. During 1996, quadrats were located randomly throughout the entire study area prior to grazing. Sampling began in the individual May and July plots after grazing. The assumption was made that these samples collected before grazing were representative of the biomass in plots. During 1997 and 1998, samples were collected within each plot on all dates before and after grazing.

Belowground biomass. On each sample date two soil cores were obtained (4.2-cm diameter, 30-cm depth) within each 0.25-m² frame to estimate root mass. Additional soil cores were obtained to a 60-cm depth within each 0.25-m² frame in July each year to determine bulk density, root biomass, and soil C. Bulk density was determined by the core method (Blake 1965). Roots were washed from each soil core using a hydropneumatic root washer, dried at 60°C for 48 hr, and ground prior to laboratory analysis. Soil samples for C determinations were stored in a freezer until they were processed by removal of roots from soil by gentle grinding and sieving of samples through a 1-mm screen. Small root particles passing through the screen were removed by hand.

Laboratory analyses of soils and biomass. All samples were removed from storage and dried at 60°C for 16 hr before they were weighed for chemical analyses. Soil and plant samples were analyzed for total C with a Carlo/Erba automated dry combustion analyzer, and inorganic soil C was determined by the modified pressure-calimeter method (Sherrod and others 2002). Root samples were ashed, and weights corrected for organic matter content. Soil C values were corrected for bulk density. Net primary production of total C was determined for aboveground biomass by summing increases in C in live and current dead biomass.

Data Summary and Analysis

The fundamental design of the experiment was a randomized complete block with repeated observations collected through time. Data were analyzed using analysis of variance models in which block, treatment, and

block × treatment interactions comprised the whole plot. The significance of treatment effects was tested using the mean square of the block × treatment interaction. The subplot varied according to the sampling strategy for the particular dependent variable, as described previously. In general, the subplot contained a set of nested effects describing the time course of data collection (e.g., year, date within year, time within date within year for those data collected more than once per day), each of which interacted with the treatment effects.

Results

Impact of Environment

The amount and distribution of precipitation varied during the three years of our study (Figure 2). Precipitation was above average at Frank Wiley Airfield during January, March, May, October, and November in 1996; April and July in 1997; and March, June, July, August, and October in 1998. Although May 1996 was very wet, precipitation was below average thereafter until the following October. Precipitation was below average in May and June in 1997 and from August 1997 through February 1998. April and May were dry in 1998, but rainfall was above average the remainder of the summer. Average monthly temperatures were near normal during all three years of our study. Soil water varied by sample date (Figure 3) in response to wet and dry periods.

Impact of Grazing

Grazing immediately reduced leaf area index (LAI), aboveground biomass, and net CO₂ flux. Leaf area index was reduced from 0.29 ± 0.03 before grazing to 0.06 ± 0.03 after grazing. Live aboveground biomass was reduced ($P < 0.05$) with grazing in all three years whether grazing occurred in May or July (Table 1). Current dead was similar before and after grazing in May but was reduced by grazing in July. Dead biomass was reduced ($P < 0.05$) from 26 ± 2 to 9 ± 2 g/m² averaged across years. Grazing did not affect ($P > 0.05$) litter.

CO₂ flux measurements, taken before and after grazing events on both May and July plots and the corresponding control plot at 12:00 hr, revealed variation among years (Table 2). There were, however, no significant ($P > 0.05$) differences in CO₂ flux between control plots and May or July treatment plots before grazing, and no differences between control plots measured before or after grazing (Table 2). In contrast, CO₂ flux was significantly reduced by grazing in May and July.

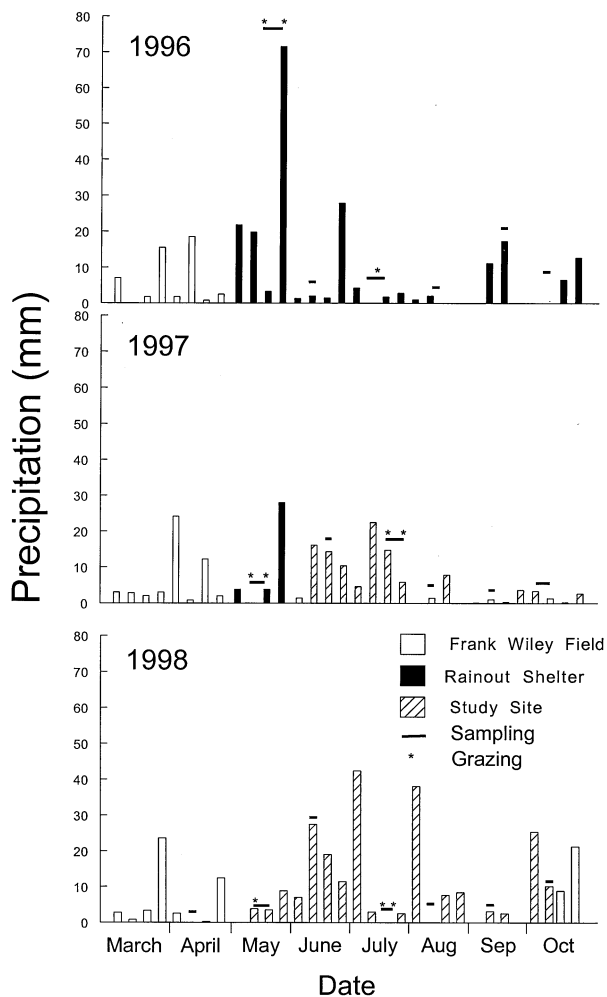


Figure 2. A combination of precipitation data recorded at the Frank Wiley Airfield (National Oceanic and Atmospheric Administration 1996–1998) located about 12.5 km from the study site, on another study area located 6 km from the study site, and onsite during 1996, 1997, and 1998. Horizontal lines above the precipitation bars denote time of sampling, and asterisks denote time of grazing.

Seasonal and Diurnal CO₂ Fluxes

Net. April fluxes, measured at 12:00 and 24:00 hr in 1998, averaged 0.8 ± 0.2 and $-0.6 \pm 0.2 \mu\text{m CO}_2/\text{m}^2/\text{sec}$, with no differences among treatments. In May 1996, fluxes that were measured only at 12:00 hr were greater than fluxes measured at 12:00 hr in 1997 or 1998 (Figure 4). Grazing in May reduced ($P < 0.05$) CO₂ fluxes for at least 30 days in 1996 and 1998, but not in 1997. Grazing in July only reduced ($P < 0.05$) CO₂ flux for at least 30 days in 1998. Fluxes were only greater in grazed than control plots in July 1997. Seasonal fluxes were generally greatest in May and June, intermediate in July, and near or below zero in August,

September, and October. Diurnal fluxes (Figure 5) were generally greatest at 08:00 hr, intermediate at 12:00 and 16:00 hr, and least at 24:00 hr. The greatest difference in diurnal measurements occurred during May, June, and July, whereas diurnal measurements were similar during August, September, and October.

Soil. Seasonal soil flux varied significantly with treatment \times date-within-year ($P < 0.05$) and time-within-date and year ($P < 0.05$). April fluxes at 12:00 and 24:00 hr in 1998 averaged -0.9 ± 0.1 and $-0.6 \pm 0.1 \mu\text{m CO}_2/\text{m}^2/\text{sec}$, with no differences among treatments. Some treatment differences occurred during May, June, and July, when soil flux was less on grazed than nongrazed plots in June and July 1997 and 1998. Although the differences were significant ($P < 0.05$), they were small, averaging -2.6 vs $-2.2 \mu\text{m CO}_2/\text{m}^2/\text{sec}$ in June 1997, -2.8 vs $-2.6 \mu\text{m CO}_2/\text{m}^2/\text{sec}$ in July 1997, and -1.6 vs $-1.4 \mu\text{m CO}_2/\text{m}^2/\text{sec}$ in both June and July 1998. Variation among times was related to season of the year (Figure 6). During spring and autumn, highest rates were generally during the warmer periods at 12:00 and 16:00 hours, but during summer no clear trends were found. The significant ($P < 0.05$) date-within-year interaction accounted for 67% of the total sum of squares. Respiration was generally greatest in June and July. Although the relationships between soil flux and soil temperature and soil water were significant ($P < 0.05$), less than 20% of the variation was explained by either variable.

Leaf area index (LAI). Average LAI was reduced ($P < 0.05$) from 0.18 ± 0.01 with no grazing to 0.14 ± 0.01 with May grazing and 0.12 ± 0.01 with July grazing. Leaf area index varied significantly ($P < 0.05$) among dates within years (Figure 7). Maximum values were generally recorded during May, June, and July. During 1998, however, LAI in June was significantly lower than in May or July.

Carbon Dynamics

Aboveground C. The live component of ungrazed and July-grazed treatments peaked in May, June, and July (Figure 8). Current dead (CDED) increased as the growing season progressed in nongrazed and May-grazed plots, but increased early and then decreased abruptly after grazing in July. The dead component was greatest early in the season, then gradually decreased through time without grazing, and decreased abruptly after grazing events in May or July.

Grazing reduced the live component for at least 60 days after grazing in May and 90 days in July (Figure 8). Compared to nongrazed control plots, grazing in May and July reduced current dead for the remainder of the season. July-grazed plots contained less dead than con-

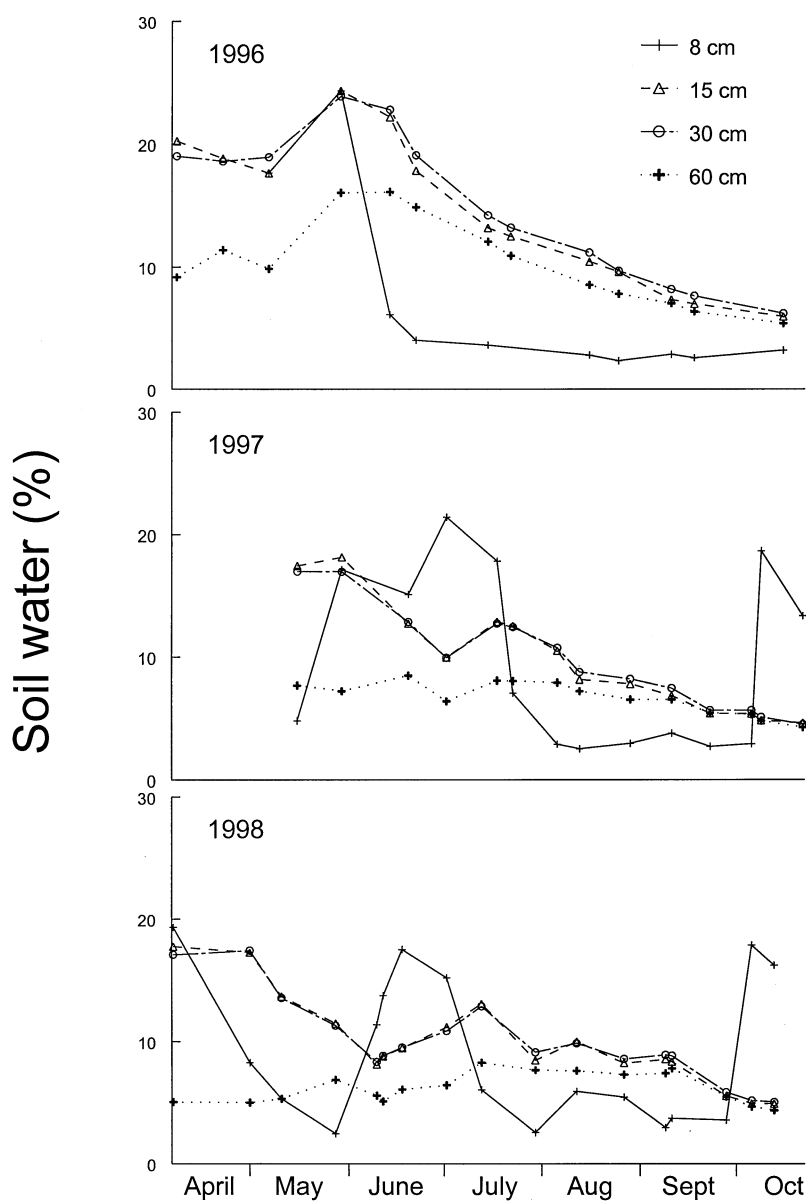


Figure 3. Percent soil water as measured on adjacent Bowen Ratio plots. Soil water for the 0 to 8-cm depth was determined gravimetrically from cores. Soil water at the 15, 30, and 60 cm depths was determined with a dielectric soil water probe. Sampling occurred on selected dates in 1996, 1997, and 1998.

tol plots for the entire season, whereas May grazing reduced this component from June onward. Litter was similar ($P > 0.05$) in the nongrazed control (15.5 ± 0.6 g C/m²) and May-grazed plots (14.8 ± 0.6 g C/m²), but was reduced with grazing in July (12.7 ± 0.6 g C/m²). In general, the amount of aboveground C was greatest in 1996 and least in 1997 or 1998, particularly for live biomass and current dead (Figure 9). No clear trends were found for the dead component, but litter was consistently less in 1998. Net primary production of C was similar ($P > 0.05$) among grazing treatments for the May to October period (49.6 ± 4.3 g C/m²). Significantly more carbon was, however, produced in 1996

(66.8 ± 4.3 g C/m²) than in 1997 (46.2 ± 4.3 g C/m²) or 1998 (35.8 ± 4.3 g C/m²).

Belowground C. Due to missing data it was not possible to examine the effects of belowground C in 1996. As a result, only the data for 1997–1998 root C and soil organic C were analyzed. Both the date \times treatment-within-year interaction and date \times depth-within-year interaction were significant ($P < 0.05$) for root C biomass. Treatment differences occurred in only 20% of the comparisons for the three years, and no consistent trends were detected in these differences. When means for the date \times depth-within-year interaction were compared, we found greater root C biomass in the 0- to

Table 1. Immediate effect of grazing in May or July on aboveground biomass

Biomass component (g/m ²) at time of measurement relative to grazing		
year/treatment date	Before	After
Live ^a		
1996	71	17
1997	44	14
1998	41	9
SE	3	
Current dead ^b		
1996		
May	7	4
July	39	17
1997		
May	4	1
July	17	5
1998		
May	6	2
July	10	4
SE	2	

^aLeast-square means and standard error (SE) for the significant timing/year interaction for the live biomass component.

^bLeast square means and standard error (SE) for the significant timing/treatment/year interaction for the current dead biomass component.

Table 2. Immediate effects of grazing in May and July on CO₂ flux^a

Year/treatment date	(CO ₂ μm m ² /sec) at Time of measurement relative to grazing	
	Before	After
1996 Control ^b	3.0	3.2
May	3.5	-0.9
1997 Control	1.5	1.2
May	1.2	-0.4
1998 Control	2.0	1.1
May	2.2	-0.3
SE	0.4	
Control ^c	0.6	0.7
July	0.6	-1.0
SE	0.2	1.0

^aMeasurements taken at 12:00 hr the day before and the day of grazing in May or July.

^bLeast-square means and standard error (SE) for the significant year/treatment/timing interaction for the control and May grazing treatment.

^cLeast square means and standard errors (SE) for the treatment/timing interaction for the control and July grazing treatment.

10-cm depth compared to the 10- to 30-cm depth in 65% of the comparisons. The average root C content for 1997–1998 was 313 ± 9 g C/m² in the 0- to 10-cm depth and 156 ± 9 g C/m² in the 10- to 30-cm depth.

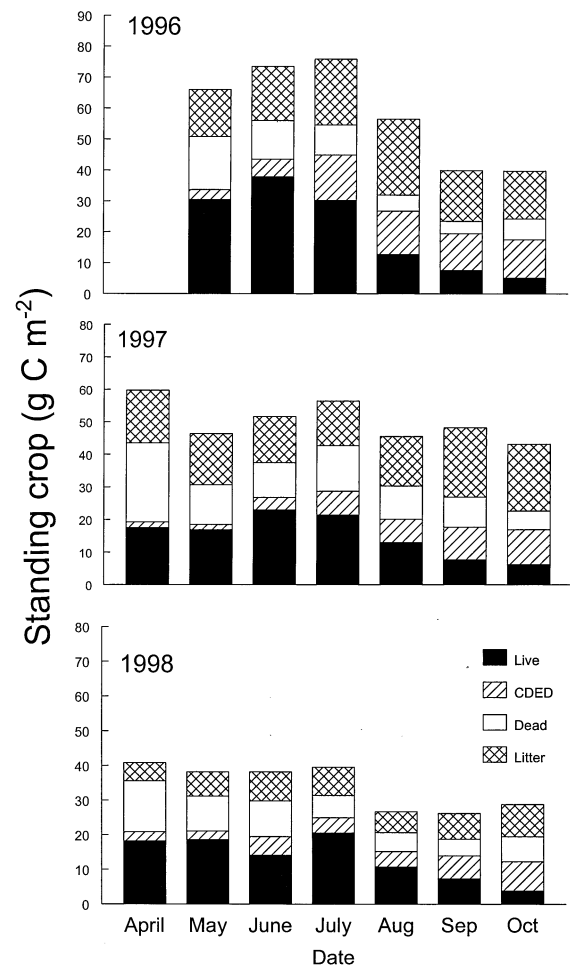


Figure 4. Least-square means for CO₂ flux ± standard errors as affected by the significant treatment/date-within-year ($P < 0.05$) interaction. May 1996 value is only for 12:00 hr.

Soil organic C measured from soil samples collected in July each year was not affected ($P > 0.05$) by grazing treatment. The depth × year interaction was significant ($P < 0.05$) (Table 3).

Discussion and Conclusions

Short-duration intensive grazing reduced potential CO₂ uptake in this study. Maximum CO₂ flux generally coincided with periods of maximum green biomass, which agrees with findings of others (Kim and others 1992, Dugas and others 1999, LeCain and others 2000, Sims and Bradford 2001, Frank 2002, this issue). In our study, as in others, green biomass and CO₂ flux increased in early spring, peaked in early to mid-summer, and decreased during mid-summer to early autumn. Soil flux in this study followed similar patterns to those

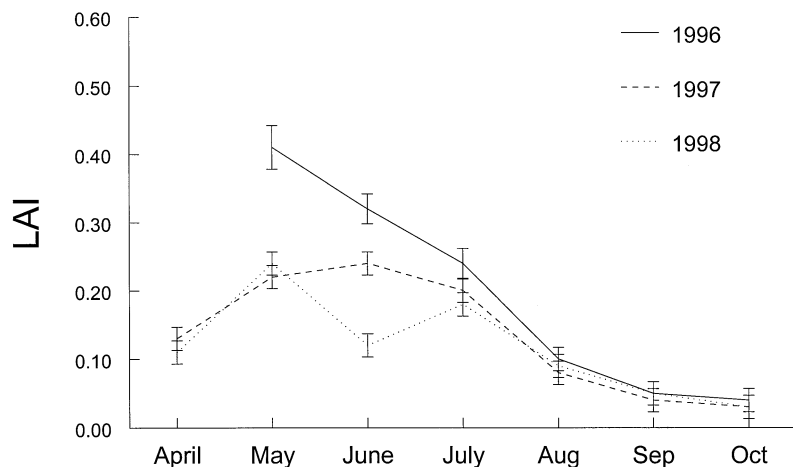


Figure 5. Least-square means for CO₂ flux \pm standard errors as affected by the significant time-within-date and -year ($P < 0.05$) interaction.

found by Frank and others (2002), where soil CO₂ flux peaked with biomass production in late June and July in central North Dakota. Whether due to defoliation or senescence, once green biomass is reduced, CO₂ uptake is at least temporarily reduced. This reduction may be mitigated, however, if grazing enhances photosynthesis by increasing the amount of light reaching green tissue and occurs when soil water and temperature are optimum for plant regrowth (LeCain and others 2000). Timing and intensity of defoliation are also important in determining response to grazing. Haferkamp and others (1998) found western wheatgrass regrowth measured in July was twofold greater for plots clipped in May compared to plots clipped in June. They found that clipping or grazing at an earlier date allowed plants to replace leaf area sooner, whereas delayed clipping gave plants a longer period of uninterrupted growth. This is similar to responses observed in the current study. As LAI increased, photosynthesis and growth rate presumably increased, if environmental conditions were conducive for growth.

The magnitude of the reduction in CO₂ flux from grazing in May or July varied seasonally and annually, due to variation in solar radiation, temperature, and precipitation. The importance of annual climate can not be ignored, since it may be as important as grazing for limiting CO₂ sequestration in this region of the Northern Great Plains. Many have shown a reduction of CO₂ flux with the onset of drought (Kim and others 1992, Verma and others 1992, Meyers 2001, Sims and Bradford 2001, Suyker and Verma 2001, Frank 2002, this issue). Environment may override the effects of grazing, as occurred on most dates in 1997 and after August of most years of this study. The potential period for growth is relatively short in the Northern Great Plains, as reported by Frank and others (2002) and

shown in Figure 1. Most herbaceous plants in this area grow during late spring and early summer, and normally an average of 91% of the year's perennial cool-season grass production and 76% of the perennial warm-season grass production is completed by the end of June (R. K. Heitschmidt unpublished file data, USDA-ARS, Miles City, MT, USA). The region also frequently experiences periods of below average precipitation (Hurt 1951, Reed and Peterson 1961, Olson and others 1985, Haferkamp and others 1993, Heitschmidt and others 1995, 1999). The impact of environmental stress on reducing plant growth in this region cannot be overemphasized and has been documented by others (Sims and Singh 1978, Olson and others 1985, White 1985, Sala and others 1988, Frank 1988).

Data from this study do not totally agree with data collected on grazed and ungrazed rangelands in other locations in the mixed-grass prairie (LeCain and others 2000) and shortgrass steppe (LeCain and others 2002). They found that early season CO₂ exchange rates were generally greater in grazed pastures than in nongrazed areas. In contrast, we generally found a sharp decline in CO₂ uptake with grazing. They did not report sharp declines in CO₂ uptake with continuous season-long grazing as we observed with intensive short-duration grazing. The most likely reasons for differences among locations are variations in season and severity of defoliation and availability of soil water for potential regrowth. Heavy stocking rates reported by LeCain and others (2000, 2002) only removed about 50% of the forage during the growing season on the mixed-grass prairie and 60% of the forage on the shortgrass steppe. With these grazing regimes half the leaf blades were never grazed and many were grazed only once. Precip-

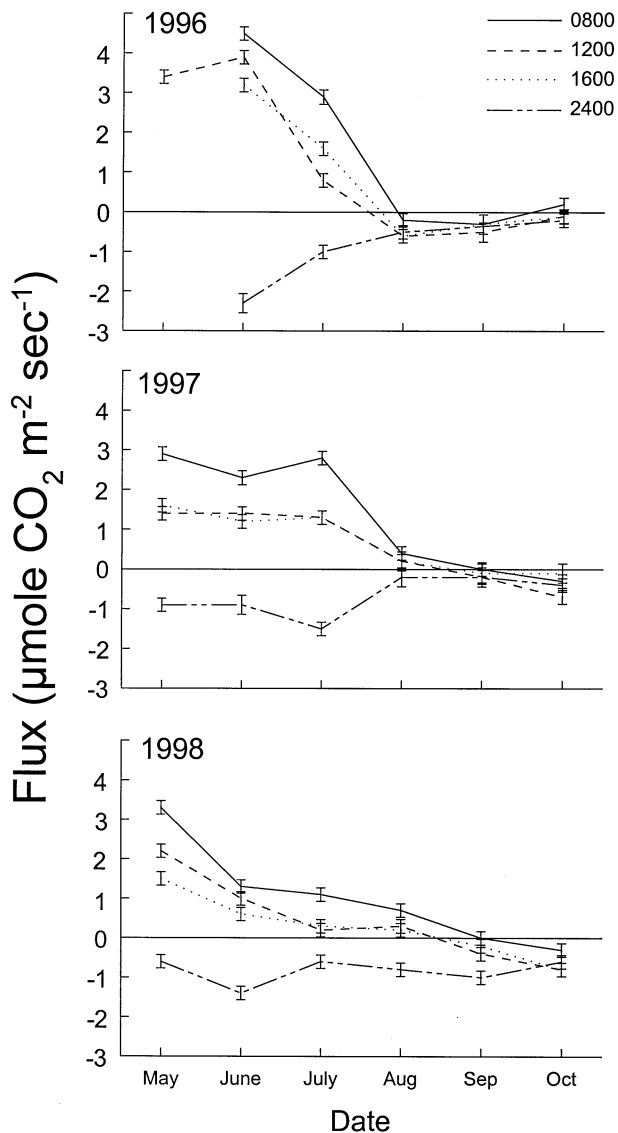


Figure 6. Least-square means for soil CO₂ flux \pm standard errors as affected by the significant time within date and year ($P < 0.05$) interaction.

itation at the Colorado sites of LeCain and others (2002) was at or above normal for the study period.

Environmental differences and their effects on biomass production were the likely causes for the smaller CO₂ fluxes in this study than at other locations in the mixed-grass prairie (LeCain and others 2000, Sims and Bradford 2001, Frank 2002, this issue), shortgrass steppe (LeCain and others 2002), and tall-grass prairie (Kim and others 1992, Verma and others 1992, Dugas and others 1999, Suyker and Verma 2001). We cannot make direct comparisons because our measurements were made in a closed chamber at several points in

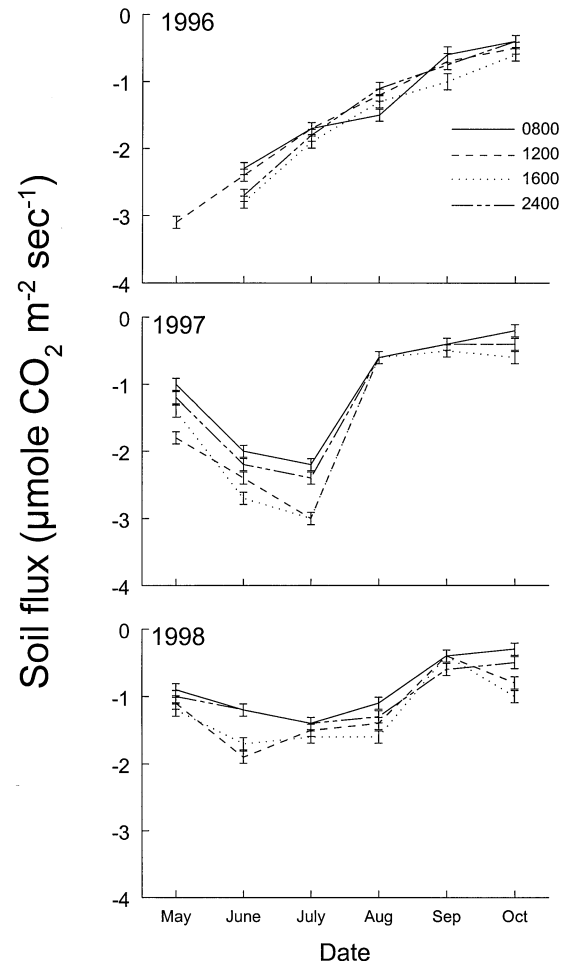


Figure 7. Least-square means for leaf area index (LAI) \pm standard errors as affected by the significant date-within-year ($P < 0.05$) interaction.

time, whereas data from other studies, except LeCain and others (2000, 2002), were from continuous measurements derived from Bowen Ratio energy balance or eddy correlation methods. We assumed that pressure within the large chamber allows total respiration from the soil surface. Based on Norman and others (1992), this assumption may be flawed. Although the magnitude of any single value may be biased upward by our assumption, all treatments were treated similarly. Angell and others (2001) also cautioned that chamber effects may be increased when temperatures are high and soil water is low, thus increasing plant stress to a level that causes stomata to close. Although this may have been a factor during measurements at 12:00 and 16:00 hr during July and August, treatments were contrasted in similar conditions.

We did not detect greater amounts of soil C due to grazing during the three-year study, as has been re-

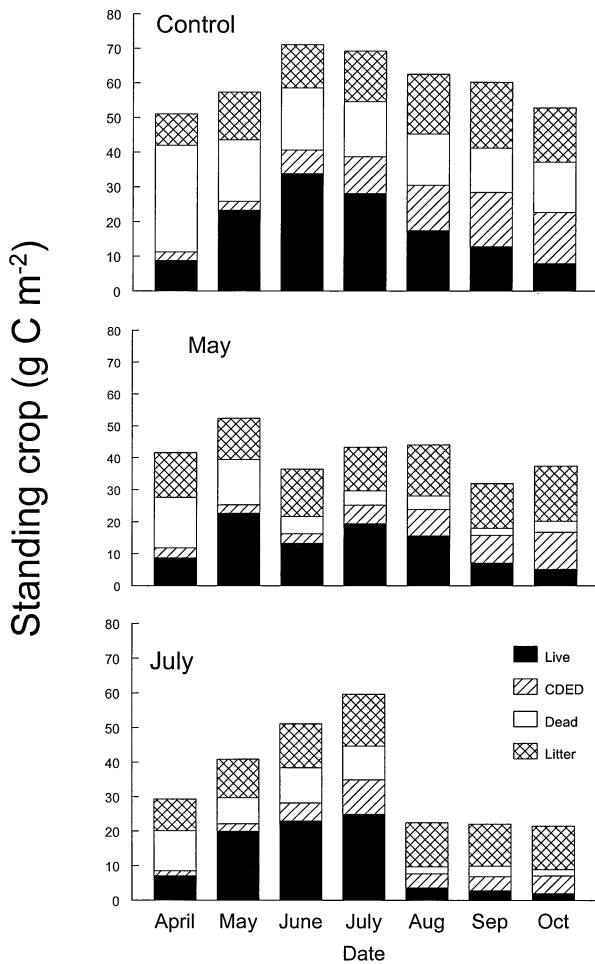


Figure 8. Least-square means for C standing crop as affected by the significant treatment/date ($P < 0.05$) interaction for aboveground biomass components. CDED refers to current year's senesced material and dead refers to previous year's senesced material. Litter was the only component for which the interaction was not significant.

ported by others comparing areas that had been grazed for longer periods of time (Frank and others 1995, Manley and others 1995, Schuman and others 2001, Reeder and Schuman 2002). As discussed earlier many differences reported on the impact of grazing on soil C appear to be the result of variations in climate, soil properties, landscape position, plant community composition, and grazing management practices, as well as variations in soil organic matter, and depth of soil profile. In the short-time span of three years in our study, reduced green, current dead, and dead biomass as well as reduced CO₂ flux after intensive short-duration grazing suggest that intensive grazing could lead to reduced soil C after many years. Fluxes at 12:00 hr decreased to below zero with grazing in either May or

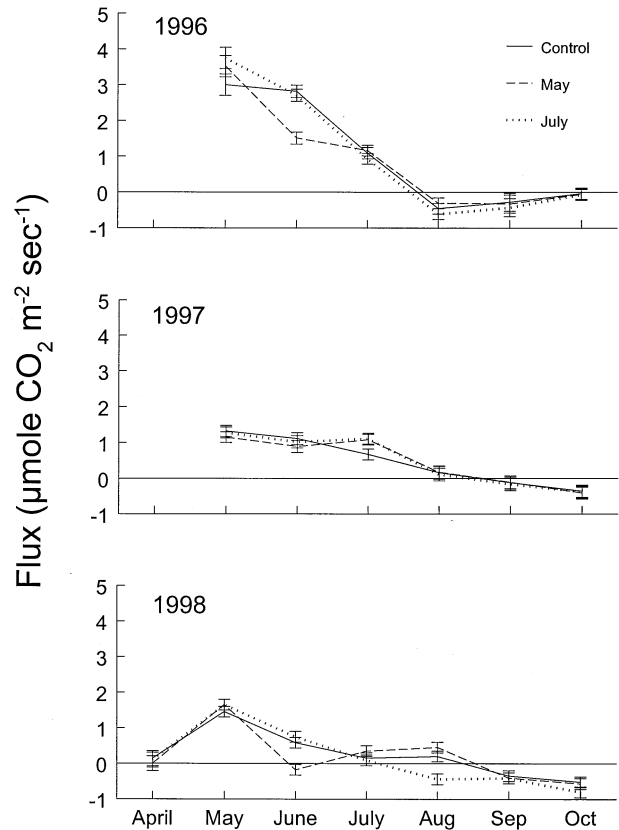


Figure 9. Least-square means for C standing crop as affected by the significant date-within-year ($P < 0.05$) interaction for aboveground biomass components. CDED refers to current year's senesced material and dead refers to previous year's senesced material.

Table 3. Effects of year and depth on soil organic C^a

Depth (cm)	(C g/m ²)	
	1997	1998
0–10	1419	1155
10–30	1805	1824
30–60	1620	2068
SE	93	

^aLeast-square means and standard error (SE) for the significant year/depth interaction.

July. Average fluxes for the May-grazed plots tended to rebound during the next 30–60 days, whereas fluxes from July-grazed plots remained near or below zero. Although we found reductions in various vegetation components due to grazing, we did not measure C inputs from livestock defecation, which could increase C content in soils through time. Baron and others (2002) found that adding estimated fecal C to the

residual soil C significantly increased total C on a grazed pasture of meadow brome grass (*Bromus riparius* Rhem).

Grazing may reduce or cause little change in C sequestration in the mixed-grass prairie of the Northern Great Plains. The exact influence on CO₂ flux will depend upon the degree of defoliation and its interaction with climatic variables, particularly temperature and precipitation. Based on findings from this and other studies (Frank 2002, this issue), the potential C sink in the mixed-grass prairie of the Northern Great Plains appears to be small and will vary in time with intensity and timing of grazing and its interaction with climate.

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