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Changes in Plant Functional Groups, Litter Quality, and Soil Carbon and Nitrogen Mineralization With Sheep Grazing in an Inner Mongolian Grassland

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Abstract

This study reports on changes in plant functional group composition, litter quality, and soil C and N mineralization dynamics from a 9-year sheep grazing study in Inner Mongolia. Addressed are these questions: 1) How does increasing grazing intensity affect plant community composition? 2) How does increasing grazing intensity alter soil C and N mineralization dynamics? 3) Do changes in soil C and N mineralization dynamics relate to changes in plant community composition via inputs of the quality or quantity of litter? Grazing plots were set up near the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) with 5 grazing intensities: 1.3, 2.7, 4.0, 5.3, and 6.7 sheep $ha^{-1} \cdot yr^{-1}$. Plant cover was lower with increasing grazing intensity, which was primarily due to a dramatic decline in grasses, *Carex duriuscula*, and *Artemisia frigida*. Changes in litter mass and percentage organic C resulted in lower total C in the litter layer at 4.0 and 5.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with 2.7 sheep $ha^{-1} \cdot yr^{-1}$. Total litter N was lower at 5.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with 2.7 sheep $ha^{-1} \cdot yr^{-1}$. Litter C:N ratios, an index of litter quality, were significantly lower at 4.0 sheep $ha^{-1} \cdot yr^{-1}$ relative to 1.3 and 5.3 sheep $ha^{-1} \cdot yr^{-1}$. Cumulative C mineralized after 16 days decreased with increasing grazing intensity. In contrast, net N mineralization ($NH_4^+ + NO_3^-$) after a 12-day incubation increased with increasing grazing intensity. Changes in C and N mineralization resulted in a narrowing of CO_2-C:net N_{min}ratios with increasing grazing intensity. Grazing explained 31% of the variability in the ratio of CO_2-C:net N_{min}. The ratio of CO_2-C:net N_{min} was positively correlated with litter mass. Furthermore, there was a positive correlation between litter mass and *A. frigida* cover. Results suggest that as grazing intensity increases, microbes become more C limited resulting in decreased microbial growth and demand for N.

Resumen

Este estudio reporta los cambios en la composición de grupos funcionales de plantas, calidad del mantillo y la dinámica de mineralizacián del C y N del suelo en un estudio de 9 años de apacentamiento con ovinos en el interior de Mongolia. Las preguntas planteadas fueron: 1) ¿Como el aumento de la intensidad de apacentamiento afecta la composición de la comunidad vegetal?; 2) ¿Como el aumento en la intensidad de apacentmaiento altera la dinámica de mineralización del C y N? y 3) ¿Se relacionan los cambios en la mineralización del C y N con los cambios de la composición de la comunidad vegetal via la calidad o cantidad del mantillo?. Las parcelas para el apacentamiento se Establecieron cerca de la Estación Experimental de Ecosistemas de Pastizal del Interior de Mongolia (IMGERS); ahí se evaluaron cinco intensidades de apacentamiento: 1.3, 2.7, 4.0, 5.3 y 6.7 borregos ha^{-1} $año^{-1}$. La cobertura vegetal disminuyó al incrementar la intensidad de apacentamiento, lo cual se debio principalmente a una dramática disminución de los zacates *Carex duriuscula* y *Artemisia frigida*. Los cambios observados en la masa de mantillo y el porcentaje de carbón orgánico fueron que se tuvo un menor contenido de C total en la capa de mantillo en las intensidades de apacentamiento de 4.0 y 5.3 borregos ha^{-1} $año^{-1}$ en comparación con la de 2.7 borregos ha^{-1} $año^{-1}$. El N total del mantillo fue menor en la intensidad de 5.3 borregos ha^{-1} $año^{-1}$ en relación a la de 2.7 borregos ha^{-1} $año^{-1}$. Las relaciones de C:N, un indice de calidad del mantillo fueron significativamente menores en la intensidad de 4.0 borregos ha^{-1} $año^{-1}$ en en relación con las intensidades de 1.3 y 5.3 borregos ha^{-1} $año^{-1}$. El C mineralizado acumulado despues de 16 días disminuyœ al incrementar la intesnsidad de apcentamiento. En contraste, la mineralización neta del N ($NH_4^+ + NO_3^-$), despues de 12 días de incubación, aumentó al incrementar la intensidad de apacentamiento. Los cambios en la mineralización del C y N resultaron que al aumentar la inensidad de apacentamiento se reducen las tasas de CO_2-C:neto N_{min}. El apacentamiento explicó el 31% de la variabilidad de la relación de CO_2-C:neto N_{min}, la cual estuvo positivamente correlacionada con la masa de mantillo. Además, hubo una correlación positiva entre la masa de mantillo y la cobertura de *A. frigida*. Los resultados suguieren que conforme la intensidad de apacentamiento incrementa los microbios vienen a estar más limitados de C resultando en una disminución del crecimiento microbiano y de la demanda por N.

Key Words: *Stipa grandis*, *Artemisia frigida*, typical steppe

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Introduction

Human population growth and changes in land use practices are rapidly increasing livestock grazing pressure in the steppe region of Inner Mongolia in northern China, where livestock numbers nearly tripled from 1952 to 1989 (Ellis 1992). Studies con-

Figure 1. Site location of the Inner Mongolian Grassland Research Station within the Inner Mongolian Autonomous Region, China. The field site location is designated by a ★.

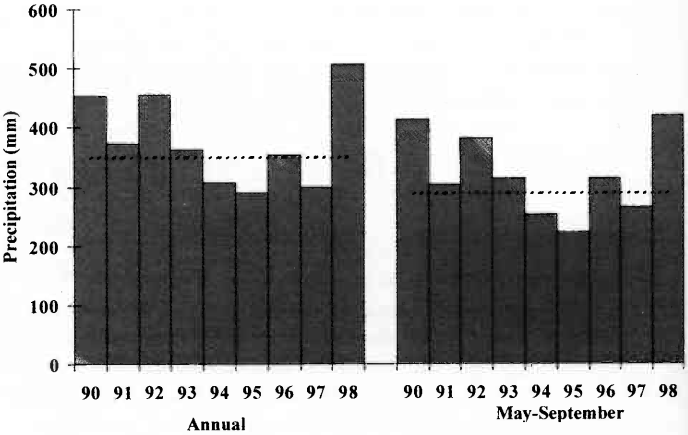

Figure 2. Annual and May–September precipitation received at the Inner Mongolia Grassland Ecosystem Research Station, Xilinhot, Inner Mongolia Autonomic Region, China, 1990 to 1998. Dotted line denotes long-term average, 1970–1998.

ducted in this region during the 1990s indicate that grassland productivity decreased by 30% in some areas, and up to 55% of Inner Mongolian grasslands are now considered to be unusable or deteriorated (see review by Ellis 1992). From 1990 to 1998 livestock numbers in the Xilin River Basin, the area of this study, increased by 184% (W. Shiping, personal communication, November 2003).

Declines in plant productivity and functional changes in plant community composition can have large effects on soil C and N cycling. In central Inner Mongolia 12% of the soil organic carbon (SOC) in the top 20 cm was estimated to be lost over a 40-year period as a result of overgrazing (Li et al 1998). Another study in the same region indicated that 17 years of grazing had no effect on SOC (Wang and Chen 1998). These data suggest that grazing effects on soil C and N dynamics may be observed only after several decades, with no discernible differences occurring in the shorter term. Livestock grazing affects SOC and soil organic N storage via changes in litter quality and quantity (Fuhlendorf et al 2002; Mapfumo et al 2002; Olofsson and Oksanen 2002; Reeder and Schuman 2002; Willms et al 2002), belowground biomass (Biondini et al 1998; Wang and Wang 1999; Johnson and Matchett 2001; Frank et al 2002), soil microclimate (Rietkerk et al 2000; Wan et al 2002), and wind and water erosion (Bach 1991; Bird et al 1992).

Increased offtake by animals often results in decreased litter inputs (Huang et al 1997), whereas selective foraging may cause changes in litter quality as a result of changes in plant community composition (eg, Pastor et al 1993; Olofsson and Oksanen 2002). Four years after the initiation of a 9-year sheep grazing study in Inner Mongolia, standing aboveground biomass decreased by 50% under high-intensity grazing as compared with moderate grazing (Wang et al 1999). Furthermore, after 4 years, cover of the dominant grass species, *Agropyron michnoi* and *Leymus chinensis*, decreased dramatically with increasing grazing intensity, whereas cover of *Potentilla* spp. (*P. acaulis* and *P. tanacetifolia*), an indicator of overgrazing, increased at the highest grazing intensities (Wang and Chen 1998; Li et al 1999). Given these changes in aboveground biomass and plant community composition, we hypothesized that changes in litter quantity and quality after 9 years under varying grazing intensities alters soil C and N mineralization dynamics.

This study reports on changes in plant functional group composition, litter quality, and soil C and N mineralization dynamics from a 9-year grazing study in Inner Mongolia. We addressed these questions: 1) How does increasing grazing intensity affect plant functional group composition? 2) How does increasing grazing intensity affect soil C and N mineralization dynamics? 3) Do changes in soil C and N mineralization dynamics relate to changes in plant functional group composition via inputs of the quality and quantity of litter?

Methods

Site Description

Study sites were located in the Xilin River Basin near the Inner Mongolian Grassland Ecosystem Research Station (IMGERS), Inner Mongolia Autonomous Region (IMAR), China (lat, 43°38′N, long, 116°42′E, Fig. 1). Mean annual temperature in this region is 0°C, with warm summers and cold winters dominated by northern arctic fronts. Annual precipitation ranged between 290 and 507 mm/yr between 1990 and 1998 with up to 80% of annual precipitation occurring from May through September (Fig. 2). Vegetation is characterized as typical steppe, which is dominated by *Artemisia frigida*, *Carex duriuscula*, and the grasses *Stipa grandis*, *L. chinensis*, and *A. michnoi* (Wu and Loucks 1992; Li et al 1999). Soils are coarse-textured with a mean of 71% sand, 15% silt, and 9% clay across all experimental plots. One-hectare plots were established 9 years prior to this study in 1989. Plots were set up as a restricted complete block design with 5 grazing intensities of 1.3, 2.7, 4.0, 5.3, and 6.7 sheep $ha^{-1} \cdot yr^{-1}$ within 3 blocks, except during the 1st year of the experiment (1989) when

Table 1. Changes in plant cover with livestock grazing (9 years). Values are mean percentage cover ($N = 40$) for each vegetation type ± 1 SE. When a different letter appears within a row there was significant effect of grazing level on cover at $P < 0.05$ (post hoc Newman-Keuls).

	Grazing intensity (sheep $ha^{-1} \cdot yr^{-1}$)				
Plants	1.3	2.7	4.0	5.3	6.7
Potentilla spp.	13.5 (1.3) a	19.0 (1.9) b	19.0 (1.9) b	25.5 (2.6) c	25.0 (2.5) c
Grass	12.4 (1.5) a	6.5 (0.6) b	6.1 (0.7) b	8.1 (0.7) b	1.2 (0.3) c
Carex spp.	14.1 (1.5) a	8.3 (0.9) b	9.2 (0.8) b	0.2 (0.1) c	3.9 (0.4) d
Artemisia frigida	17.7 (1.2) a	11.9 (0.9) b	8.5 (0.9) c	8.7 (0.9) c	3.7 (0.7) d
Total	53.3 (1.7) a	45.9 (1.8) b	39.6 (1.7) c	47.6 (2.4) b	36.8 (2.1) c

grazing intensities within the plots were 1.3, 2.0, 2.7, 3.3, and 4.0 sheep $ha^{-1} \cdot yr^{-1}$. Sheep grazing levels were targeted to use 20%–70% of available forage, which was based on primary productivity data. The lowest and highest grazing levels used approximately 20% and 70% of available forage, respectively, with the intermediate grazing level (4.0 sheep $ha^{-1} \cdot yr^{-1}$) using approximately 50% of available forage. The grazing schedule was 15 days on/30 days off rotation from May 20 to October 5 each year.

Plant Cover at 9 Years

Plant functional groups were surveyed within the grazing plots in July of 1998. Four transects were delineated within each plot. At 10 equally spaced points along each transect, percentage cover of 4 groups was estimated for *A. frigida*, *Potentilla* spp. (*P. acaulis* and *P. tanacetifolia*), *C. duriuscula*, and total grass. Cover was estimated using a 25 × 25-cm gridded quadrat with a total of 16 point hits within a quadrat. This was performed at 10 locations every 10 m along 4 random lines for a total of 40 quadrats in each 1-ha grazing plot.

Soil Carbon and Nitrogen Mineralization

The impact of grazing was explored on soil C and N mineralization with a laboratory experiment. Three soil cores were collected from each depth of 0–5, 5–10, and 10–20 cm within each plot. Since we were primarily interested in laboratory C and N mineralization potentials and not field rates of C and N mineralization, soils were immediately air dried and stored at room temperature for several months. To measure net N mineralization, a double chamber sterile filtration unit was used to leach the soils for inorganic N (NH_4^+ and NO_3^-). The upper chamber was lined with a Whatman glass fiber filter, and 50 g of dry soil was placed into the chamber. Soil samples were leached with 100 ml of 0.01 M $CaCl_2$ as described by Wedin and Pastor (1993) on days 12, 29, 45, 109, and 151 after the initial wet up. The salt solution was allowed to equilibrate with the soil for 1 hour. After this time a vacuum was applied to the lower chamber to remove excess solution. The leachate was then stored in polypropylene bottles and frozen. Ammonium and NO_3^- concentrations were analyzed colorimetrically using an Alpchem autoanalyzer (Perstorp Analytical). Soils were subsampled a 2nd time for total C and N analysis. To removed inorganic C, 2 N HCl was added to each sample and left to sit overnight. The next day samples were centrifuged and rinsed with deionized water 3 times. Samples were dried at 70°C. Total C and N were measured on a Leco Carbon-Hydrogen-Nitrogen analyzer.

Soil respiration was measured at 4, 16, and 29–43 days after the initial wet up on the same soil samples. On sample days 4 and 16, soils were incubated for 24 hours. Soil CO_2 fluxes were low by day 29; therefore CO_2 concentrations were allowed to build up in the chamber over 12 days. Filtration units were placed in 1.9-L glass jars with metal screw top lids. Each lid was equipped with a Wheaton septum in order to withdraw gas samples from the jar. Before each sample period each chamber was purged with compressed air of a known concentration of CO_2. CO_2 gas samples were drawn from the jars using polypropylene disposal syringes and analyzed on an infrared gas analyzer (Licor-6252). On each sample date, 6 jars were randomly chosen and initial CO_2 concentrations were measured immediately after the jars were capped. Mean CO_2 concentration was calculated from these jars, which was used as the initial CO_2 concentration for all samples.

Litter Quantity and Quality

To determine the effect of increasing grazing intensity on litter quality and quantity, two 90-m transects were established within each 1-ha plot in July 1999. Litter was sampled from the soil surface at 10 equally spaced stops along each transect at grazing intensities of 1.3, 2.7, 4.0, and 5.3 sheep $ha^{-1} \cdot yr^{-1}$. We were unable to collect adequate litter samples from the

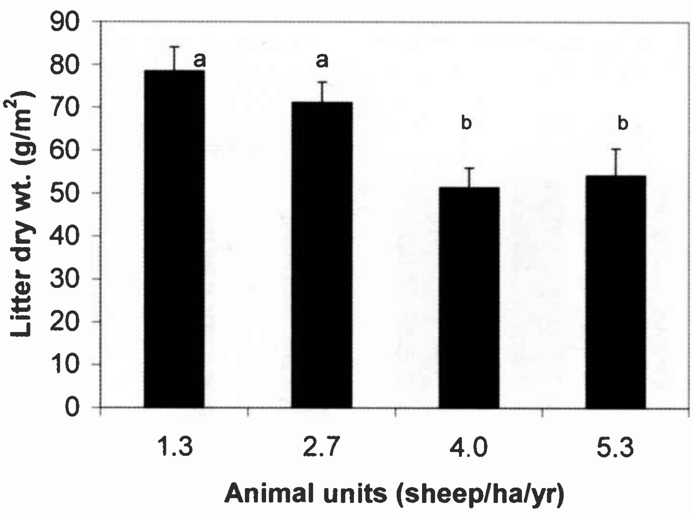

Figure 3. Soil surface litter mass. Values are mean litter mass within each grazing treatment ± 1 SE ($N = 20$). There was a significant effect of grazing at $P < 0.05$ where a different letter appears above 2 treatment means (post hoc Newman-Keuls).

Table 2. Carbon and nitrogen in the surface litter layer. Values are means per grazing treatment ± 1 SE in brackets. When a different letter occurs within a column there was a significant effect of grazing at $P < 0.05$ (post hoc Newman-Keuls).

Animal units (sheep $ha^{-1} \cdot yr^{-1}$)	Litter C (%)	Litter N (%)	Litter C (g/m^2)	Litter N (g/m^2)	Litter C:N Ratio
1.3	31.6 (1.2) a	1.36 (0.06) a	24.3 (3.7) ab	1.1 (0.18) ab	23.3 (0.82) a
2.7	28.2 (1.1) ab	1.37 (0.06) a	26.5 (4.5) a	1.3 (0.20) a	20.7 (0.59) ab
4.0	26.1 (1.2) b	1.44 (0.07) a	14.9 (2.5) b	0.84 (0.15) ab	18.7 (1.06) b
5.3	29.5 (1.8) ab	1.26 (0.06) a	13.0 (3.7) b	0.56 (0.15) b	23.9 (1.81) a

highest grazing intensity of 6.7 sheep $ha^{-1} \cdot yr^{-1}$ because of the paucity of surface litter. Litter was collected from a 10 × 10-cm area at each stop along the transects. The litter samples were immediately air dried in the field and then dried in a 65°C oven once they were transported back to the laboratory. The free-living soil cyanobacteria (*Nostoc commune*) and the soil lichen (*Xanthoparmelia camtschadalis* [Ach.] Hale) were removed from the litter samples. The remaining organic material was considered surface litter material. After weighing the litter samples, 4 samples (2 from each transect) were chosen from within each plot to measure total C and N. Litter samples were ground with a mortar and pestle and analyzed for total C and N on a Leco CHN-1000 elemental analyzer.

Statistical Analysis

Soil C and N mineralization data were analyzed using an analysis of covariance (ANCOVA) with grazing as the main effect and blocking as a covariate. Litter and vegetation cover data were analyzed using a 2-way analysis of variance (ANOVA) with the 2 main effects of grazing and block and their interaction because there were significant grazing × block interactions using the ANCOVA. Overall F tests were considered significant at $P < 0.05$. Newman-Keuls post hoc test was used to evaluate differences among individual grazing treatments in the 2-way ANOVA.

Results

Grazing treatments resulted in changes in total plant cover (Table 1; $F_{2,493} = 8.8$, $P = 0.0001$). Under the lowest grazing intensity, mean percentage cover was 53.3%, which was greater than the highest grazing intensity that averaged 36.8%. However, plant cover did not decrease with increasing grazing intensity at the intermediate levels of grazing. Total plant cover was higher at grazing levels of 2.7 and 5.3 sheep $ha^{-1} \cdot yr^{-1}$ relative to 4.0 and 6.7 sheep $ha^{-1} \cdot yr^{-1}$. This effect was primarily due to greater *Potentilla* spp. cover, which nearly doubled at higher grazing intensities. *Potentilla* spp. made up 25% of the ground cover at grazing levels of 5.3 and 6.7 sheep $ha^{-1} \cdot yr^{-1}$ as compared with only 13% at 1.3 sheep $ha^{-1} \cdot yr^{-1}$ (Table 1). In contrast to *Potentilla* spp., cover of all other groups was lower at the higher grazing intensities. Grasses were heavily impacted by increasing grazing intensity with a 10-fold lower grass cover at 6.7 sheep $ha^{-1} \cdot yr^{-1}$ compared with 1.3 sheep $ha^{-1} \cdot yr^{-1}$ (Table 1). Even moderate grazing levels impacted grass cover. Grass cover was 50% lower at 2.7 sheep $ha^{-1} \cdot yr^{-1}$ compared with the lowest grazing level of 1.3 sheep $ha^{-1} \cdot yr^{-1}$. Grazing had a similar impact on *A. frigida* and *C. duriuscula*; cover was 4–5-fold higher at 1.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with 6.67 sheep $ha^{-1} \cdot yr^{-1}$ (Table 1).

Changes in plant cover altered both quantity (ie, mass) and quality (ie, C content) of surface litter. Litter mass was lower at the higher grazing intensities of 4.0 and 5.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with the 1.3 and 2.7 sheep $ha^{-1} \cdot yr^{-1}$ intensities (Fig. 3). Changes in litter mass in combination with percentage C in the litter led to lower total C in the litter layer at 4.0 and 5.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with 2.7 sheep $ha^{-1} \cdot yr^{-1}$ (Table 2). A similar pattern was observed in total litter N, which was lower at 5.3 sheep $ha^{-1} \cdot yr^{-1}$ compared with 2.7 sheep

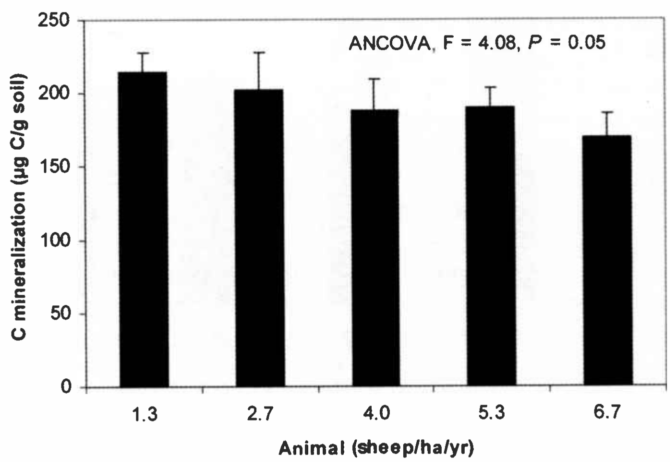

Figure 4. Soil cumulative C mineralization after 16 days. Values are mean C mineralized (µg C/g soil) ± 1 SE from 0–5-cm depth soils.

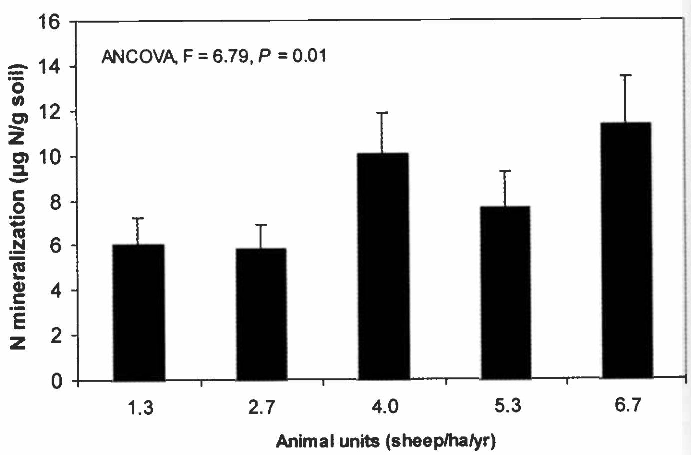

Figure 5. Soil net N mineralization after 12 days in the lab. Values are means (± 1 SE) of total mineral N ($NO_3^- + NH_4^+$) from 0–5-cm depth soils.

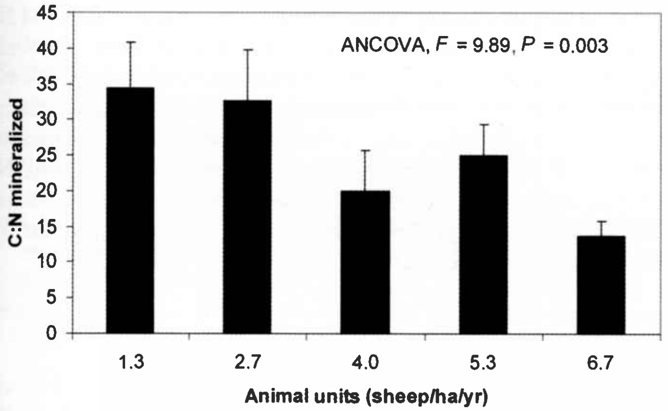

Figure 6. CO_2-C:net N_{min} ratios. Ratio of C mineralized as CO_2 after 16 days to net N mineralized ($NO_3^- + NH_4^+$) after 12 days. Values are means within each grazing treatment ± 1 SE.

$ha^{-1}{\bullet}yr^{-1}$ (Table 2). Litter C:N ratios were lower at 4.0 sheep $ha^{-1}{\bullet}yr^{-1}$ relative to 1.3 and 5.3 sheep $ha^{-1}{\bullet}yr^{-1}$ (Table 2). The lower C:N ratios at 4.0 sheep $ha^{-1}{\bullet}yr^{-1}$ were mainly driven by higher percentage C in the litter layer (Table 2), since no significant differences were observed in percentage N under different grazing intensities.

Grazing impacted C and N mineralization in surface soils (0–5 cm). Cumulative C mineralized after 16 days decreased with increasing grazing intensity (Fig. 4; ANCOVA, grazing, $F_{1,44} = 4.08$, $P = 0.05$). In contrast, net N mineralization ($NH_4^+ + NO_3^-$) after a 12-day incubation increased with increasing grazing intensity (Fig. 5; ANCOVA, grazing, $F_{1,44} = 6.79$, $P = 0.01$). Changes in C and N mineralization resulted in a narrowing of CO_2-C:net N_{min} ratios with increasing grazing intensity (Fig. 6; ANCOVA, grazing, $F_{1,39} = 9.89$, $P = 0.003$). Grazing explained 31% of the variability in the ratio of CO_2-C:net N_{min} (Fig. 6). The ratio of CO_2-C:net N_{min} was positively correlated with litter mass, which explained 94% of the variability in the ratio (Fig. 7).

Table 3. Soil organic C and N in the top 5 cm. Values are means (± 1 SE).

Animal units (sheep $ha^{-1}{\bullet}yr^{-1}$)	Soil organic C (%)	Soil organic N (%)
1.3	1.66 (0.12)	0.16 (0.01)
2.7	1.56 (0.09)	0.16 (0.01)
4.0	1.49 (0.14)	0.15 (0.01)
5.3	1.45 (0.11)	0.15 (0.01)
6.7	1.43 (0.13)	0.15 (0.01)

After the 1st 2 weeks of the incubation, there was no effect of grazing on C and N mineralization in surface 0–5-cm soils. In addition, grazing had no effect on C and N mineralization in subsurface soils (5–10 cm and 10–15 cm) or total organic C and N in surface soils (Table 3). *A. frigida* appears to have a differential impact on surface litter as compared with other groups. Surface litter was positively correlated with *A. frigida* cover, where percentage cover of *A. frigida* explained 94% of the variability in litter mass (Fig. 8).

Discussion

Results from this study suggest that C quality for microbial decomposition was enhanced under low-intensity grazing as compared with high-intensity grazing. High CO_2-C:net N_{min} ratios reflect growth in the microbial population by immobilization of N, whereas lower ratios under high-intensity grazing indicate low N demand and microbial growth (Schimel 1986; Burke et al 1989; Holland and Detling 1990). In a Colorado grassland, Holland and Detling (1990) observed an increase in CO_2-C:net N_{min} ratios with increasing grazing intensities and suggested the decrease in root biomass along a grazing sequence was a result of decreased C allocated belowground resulting in C limitation of the microbial community. Both aboveground and belowground biomass decreased after 7 years of grazing at the Inner Mongolia sites (Wang and Wang 1999; Wang et al

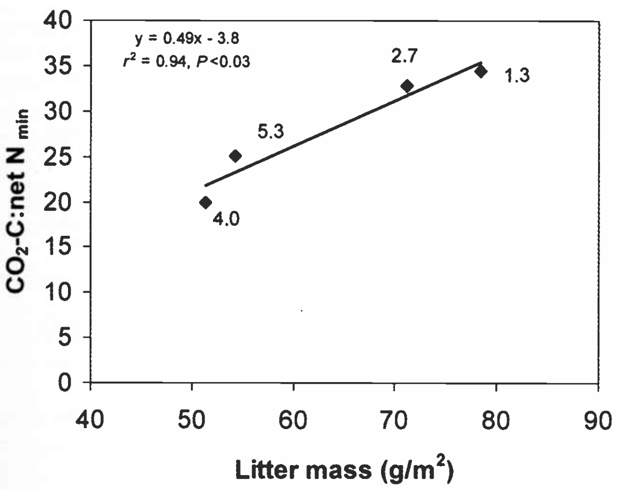

Figure 7. Ratio of CO_2-C:net N_{min} as a function of litter mass. Values are treatment means with numbers next to the triangle representing the grazing treatment.

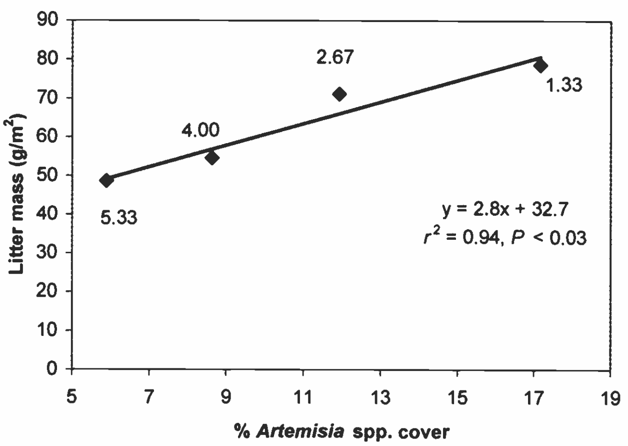

Figure 8. Litter mass as a function of *A. frigida* cover. Values are treatment means, with the numbers next to the triangle representing the grazing treatment.

1999), which may partially explain the higher CO_2-C:net N_{min} ratios with increasing grazing intensity in this study.

The decline in C quality for microbial decomposition was driven more by litter quantity (ie, mass) as compared with litter C or N content. Litter quantity at the soil surface, which decreased with increasing grazing intensity, was the best predictor of C quality as reflected in CO_2-C:net N_{min} ratios. As grazing intensity increases, microbes become more C limited, resulting in lower microbial growth, which may result in a lower demand for N. Indeed, 4 years after the initiation of the grazing experiment, microbial biomass and numbers decreased with increasing grazing intensity in these sites (Zhao 1999). Field data on available N also support the results from the laboratory incubation, which showed increasing N availability with increasing grazing intensity (Zhao 1999).

Lower microbial demand for inorganic N results in higher plant available N in soils. During times of low plant N demand, N may also be more easily lost via gaseous and leaching pathways. After 4 years of experimental grazing at the Inner Mongolia sites, percentage soil organic N decreased in the top 10 cm of soil for the highest grazing intensity relative to light and moderately grazed plots (Zhao 1999). Whether this was due to decreased inputs as a result of declines in N-fixing organisms (Belnap, unpublished data, 1999) or increased outputs via changes in leaching or gaseous N loss is not clear. In this study, however, there were no differences in total soil N in the top 5 cm of soil.

Carbon and N mineralization dynamics were not correlated with litter C:N ratios, an index of litter quality. Litter mass did explain a large amount of the variability in CO_2-C:net N_{min} ratios. C:N ratios of the surface litter pool are integrated over several years, and a narrower C:N ratio may reflect not only a difference in litter quality but microbial decomposition of litter. Microbial decomposition of litter results in a narrowing of C:N ratios where C is lost as CO_2 but N is retained in the soil. As a result, C:N ratios of fresh litter may be a better indicator of litter quality than surface litter pools, used in this study.

Potentilla spp. are used as an indicator of overgrazing in grassland ecosystems (Li et al 1999). In addition to the presence of *Potentilla* spp., *A. frigida* cover may also be used to predict changes in soil C and N mineralization dynamics via changes in litter quantity. *A. frigida* cover explains a large amount of the variability in the surface litter pools, which is positively related to C and N mineralization dynamics. Based on these relationships, long-term monitoring of *A. frigida* can be used as an indicator of changes in C quality and subsequent effects on soil C and N mineralization dynamics in typical steppe regions of Inner Mongolia.

Conclusions

Future increases in livestock grazing on the Inner Mongolian steppe, and the resulting transition from a grass and sagebrush community to one that is dominated by *Potentilla* spp., may impact soil C and N mineralization dynamics. As grazing intensity increases, litter quantity decreases, resulting in C limitation to soil microbial communities. Since there was a positive relationship between litter quantity and *A. frigida* cover, long-term monitoring of *A. frigida* can be used as an indicator of litter inputs and subsequent changes in soil C and N mineralization dynamics. Even though C limitation of microbes results in lower N immobilization and higher plant available N pools, there is also greater potential for N loss from these pools by leaching and gaseous loss pathways. Even though we present evidence that litter quantity plays a role in soil C and N mineralization dynamics, other factors such as changes in allocation to belowground biomass may also be important in contributing to these changes.

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Literature Cited

Bach, A. J. 1991. Assessing conditions leading to severe wind erosion in the Antelope Valley, California, 1990–1991. *Professional Geographer* 50:87–97.

Biondini, M. E., B. D. Patton, and P. E. Nyren. 1998. Grazing intensity and ecosystem processes in a northern mixed-grass prairie, USA. *Ecological Applications* 8:469–479.

Bird, P. R., D. Bichnell, P. A. Bulman, S. J. A. Buke, J. F. Leys, and J. N. Parker. 1992. The role of shelter in Australia for protecting soils, plants, and livestock. *Agroforestry Systems* 20:59–86.

Burke, I. C., W. A. Reiners, and D. S. Schimel. 1989. Organic matter turnover in a sagebrush steppe landscape. *Biogeochemistry* 7:11–31.

Ellis, J. E. 1992. The grazinglands of northern China: ecology, society, and land use. *In:* J. E. Ellis [ed.]. Grassland and grassland sciences in northern China. Washington, D.C.: National Academy Press. p 9–36.

Frank, D. A., M. M. Kuns, and D. R. Guido. 2002. Consumer control of grassland plant production. *Ecology* 83:602–606.

Fuhlendorf, S. D., H. Zhang, T. R. Tunnell, D. M. Engle, and A. F. Cross. 2002. Effects of grazing on restoration of southern mixed prairied soils. *Restoration Ecology* 10:401–407.

Holland, E. A., and J. K. Detling. 1990. Plant response to herbivory and belowground nitrogen cycling. *Ecology* 71:1040–1049.

Huang, D. H., C. J. Yin, and Z. Z. Chen. 1997. Litter formation, accumulation and decomposition in the typical steppe grassland of Inner Mongolia (in Chinese). Inner Mongolia Grassland Ecosystem Research Station. *Grassland Ecosystem Research* 5:179–189.

Johnson, L. C., and J. R. Matchett. 2001. Fire and grazing regulate belowground processes in tallgrass prairie. *Ecology* 82:3377–3389.

Li, Y., Z. Chen, S. Wang, and D. Huang. 1999. Grazing experiment for sustainable management of grassland ecosystem of Inner Mongolia steppe. *Acta Agrestia Sinica* 7:173–182.

Li, L., X. Liu, and Z. Chen. 1998. Study on the carbon cycle of *Leymus chinensis* steppe in Xilin river basin. *Acta Botanica Sinica* 40:955–961.

Mapfumo, E., M. A. Naeth, V. S. Baron, A. C. Dick, and D. S. Chansyk. 2002. Grazing impacts on litter and roots: perennial versus annual grasses. *Journal of Range Management* 55:16–22.

Olofsson, J., and L. Oksanen. 2002. Role of litter decomposition for the increased primary production in areas heavily grazed by reindeer: a litterbag experiment. *Oikos* 96:507–515.

Pastor, J., B. Dewey, R. J. Naiman, P. F. McInnes, and Y. Cohen. 1993. Moose browsing and soil fertility in the boreal forest of Isle-Royale National Park. *Ecology* 74:467–480.

Reeder, J. D., and G. E. Schuman. 2002. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. *Environmental Pollution* 116:457–463.

Rietkerk, M., P. Ketner, J. Burger, B. Hoorens, and H. Olff. 2000. Multiscale soil and vegetation patchiness along a gradient of herbivore impact in a semi-arid grazing system in West Africa. *Plant Ecology* 148:207–224.

Schimel, D. S. 1986. Carbon and nitrogen turnover in adjacent grassland and cropland ecosystems. *Biogeochemistry* 2:345–357.

Wan, S., Y. Luo, and L. L. Wallace. 2002. Changes in microclimate induced by experimental warming and clipping in tallgrass prairie. *Global Change Biology* 8:754–768.

Wang, Y., and Z. Chen. 1998. Distribution of soil organic carbon in the major grasslands of Xilinguole, Inner Mongolia, China. *Acta Phytoecologica Sinica* 22:545–551.

Wang, S., Y. Li, and Z. Chen. 1999. The optimal stock rate on grazing system in Inner Mongolia steppe. *Acta Agrestia Sinica* 7:192–197.

Wang, Y., and S. Wang. 1999. Influence of different stocking rates on belowground biomass in Inner Mongolia steppe. *Acta Agrestia Sinica* 7:198–203.

Wedin, D. A., and J. Pastor. 1993. Nitrogen mineralization dynamics in grass monocultures. *Oecologia* 96:186–193.

Willms, W. D., J. F. Dormaar, B. W. Adams, and H. E. Douwes. 2002. Response of the mixed prairie to protection from grazing. *Journal of Range Management* 55:210–216.

Wu, J., and O. Loucks. 1992. Xilingele. *In:* J. E. Ellis [ed.]. Grasslands and grassland sciences in northern China. Washington, D.C.: National Academy Press. p 67–84.

Zhao, J. 1999. Effect of stocking rates on soil microbial number and biomass in steppe. *Acta Agrestia Sinica* 7:223–227.