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Short communication

Soil response to long-term grazing in the northern Great Plains of North America

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Abstract

Grazing management affects ecosystem function through impacts on soil condition. We investigated the effects of long-term (over 70 years) grazing on soil properties and nitrous oxide (N_2O) emission within a moderately grazed native vegetation pasture (MGP), heavily grazed native vegetation pasture (HGP), and a fertilized crested wheatgrass (*Agropyron desertorum* (Fisch. ex. Link) Schult.) pasture (FCWP) near Mandan, ND, USA. Grazing-induced changes in species composition and N fertilizer application contributed to differences in soil properties and N_2O emission between pastures. Soil organic C (SOC) was 5.7 Mg ha^{-1} greater in FCWP and HGP than MGP at 0–5 cm, whereas HGP had 2.4 Mg ha^{-1} more SOC than FCWP and MGP at 5–10 cm. At 30–60 cm, SOC in FCWP was 4.0 and 7.5 Mg ha^{-1} greater than in HGP and MGP, respectively. Particulate organic matter (POM) C and N in the surface 5 cm of FCWP were three- and five-fold greater, respectively, than in HGP and MGP. Acidification from N fertilization in FCWP decreased soil pH and cation exchange capacity compared to HGP and MGP in the surface 5 cm. Annual N_2O emission was over three-fold greater in FCWP compared to HGP and MGP, and was positively associated with POM-C across all pastures ($P \leq 0.0001$; $r^2 = 0.85$). Results from this study suggest fertilized crested wheatgrass enhances deep storage of SOC, but contributes to surface acidification and greater N_2O emission relative to native non-fertilized pastures in the northern Great Plains.

Keywords: Soil properties; Soil organic carbon; Acidification; Nitrous oxide emission; Northern Great Plains

1. Introduction

Grazing lands represent the largest land resource in the world. In the USA alone, grazing lands occupy over 30% of the total land surface area across a diversity of climates and soils (Sobecki et al., 2001). Through their utilization by ruminant animals, grazing lands provide goods and services of economic and social importance. Grazing lands also affect numerous ecosystem functions, which, in turn, influence environmental quality at multiple spatial scales (Schlesinger et al., 1990).

Soils perform many ecosystem functions that directly influence biological productivity and environmental quality (Daily et al., 1997). Sustainable use of grazing lands requires management strategies that do not compromise the capacity of soil to function over the long-term. Both positive and negative effects of grazing on soil attributes can occur, the extent of which depends on ecosystem resilience and disturbance feedbacks (Franzluebbers and Stuedemann, 2003). Generally, grazing has been found to affect near-surface soil physical condition by hoof action (Donkor et al., 2002) and nutrient storage and cycling potential through grazing intensity and urine and dung deposition (Russelle, 1992; Carran and Theobald, 2000). Accordingly, changes in soil attributes resulting from grazing affect vegetation composition, forage quality, and movement of water within and across landscapes.

Abbreviations: EC, electrical conductivity; IPM, identifiable plant material; N_2O, nitrous oxide; POM, particulate organic matter; SIC, soil inorganic carbon; SOC, soil organic carbon; TN, total nitrogen

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Evaluation of grazing management effects on soil attributes often requires decades before measurable differences are detectable. In 1916 and 1932, long-term grazing trials were established near Mandan, ND, USA, on mixed-grass prairie vegetation and a seeded crested wheatgrass (*Agropyron desertorum* (Fisch. ex. Link) Schult.) pasture. Though the trials were originally established to assess the effects of grazing intensity on vegetation characteristics and animal performance (Sarvis, 1941; Rogler, 1951), the age of the trials and the consistency of the applied treatments over time make them an ideal setting to evaluate grazing management effects on soil. Previous evaluations on the trials have quantified grazing management effects on soil C and N (Frank et al., 1995) and soil quality (Wienhold et al., 2001). The evaluation reported in this manuscript sought to quantify long-term grazing effects on soil chemical properties within the historical grazing trials at Mandan. Furthermore, emission of nitrous oxide – an important greenhouse gas – was measured in this evaluation and related to near-surface soil properties.

2. Materials and methods

Experimental sites were located within the Missouri Plateau approximately 6 km south of Mandan (46°46′12″ N, 100°54′57″ W). The site is on gently rolling uplands (0–3% slope) with a silty loess mantle overlying Wisconsin age till. Predominant soils at the site are Temvik–Wilton silt loams (FAO: Calcic Siltic Chernozems; USDA: fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). Particle-size distribution for these soils average 280 g kg^{-1} sand and 190 g kg^{-1} clay in the surface 30 cm, and 330 g kg^{-1} sand and 240 g kg^{-1} clay in the 30–100 cm depth. From 1914 to 2002, annual precipitation averaged 414 mm, with over 75% of the total received during the growing season from April through September. Average annual temperature is 4 °C, though daily averages range from 21 °C in the summer to −11 °C in the winter.

Three grazing treatments were evaluated for their effects on soil properties and N_2O emission. Two native vegetation pastures, a moderately grazed pasture (MGP) and heavily grazed pasture (HGP), were established in 1916 with stocking rates of 2.6 and 0.9 ha $steer^{-1}$, respectively. Vegetation composition in MGP at the time of sampling included a mixture of blue grama [*Bouteloua gracilis* (H.B.K.) Lag. Ex Griffiths], needle-and-thread (*Stipa Comata* Trin. and Rupr.), western wheatgrass (*Pascopyrum smithii* (Rybd) Löve), prairie junegrass (*Koeleria pyramidata* (Lam) Beauv.), Kentucky bluegrass (*Poa pratensis* L.), and carex (*Carex filifolia* Nutt. and *Carex heliophila* Mack.). Within HGP, blue grama and carex were the dominant plant species. A fertilized crested wheatgrass (*A. desertorum* (Fisch. ex. Link) Schult.) pasture (FCWP) was seeded in 1932 into plowed native range. Stocking rates within FCWP were 0.4 ha $steer^{-1}$ in late-spring/early-summer and 0.9 ha $steer^{-1}$ for the remainder of the grazing season. The FCWP has been fertilized in the fall of each year since 1963 with NH_4NO_3 at 45 kg N ha^{-1}. Additional plant species within FCWP include blue grama. The grazing season for all three pastures extends from about mid-May to early-October using yearling steers. Grazing occurred every year since pasture establishment except during times of severe drought when forage production was inadequate to support livestock grazing. Of the three grazing treatments, MGP and HGP are reflective of the predominant forms of grassland management in the northern Great Plains.

Soil samples were collected in October 2003 from each grazing treatment on the same soil type. Samples were collected in four locations of each treatment to 100 cm in depth increments of 0–5, 5–10, 10–20, 20–30, 30–60, and 60–100 cm using a 3.5 cm (i.d.) Giddings hydraulic probe (Giddings Machine Co., Windsor, CO). Eight soil cores at 0–5 and 5–10 cm, four soil cores at 10–20 and 20–30 cm, and two soil cores at 30–60 and 60–100 cm were collected at each location and composited by depth. Each sample was saved in a double-lined plastic bag and placed in cold storage at 5 °C until processing.

Gravimetric soil water content was determined for each sample using a 15–20 g sub-sample by measuring the difference in mass before and after drying at 105 °C for 24 h (Gardner, 1986). Whole samples were then dried at 35 °C for 3–4 days and ground by hand to pass a 2.0 mm sieve. Identifiable plant material (>2.0 mm) was removed during sieving. Laboratory analyses conducted on the soil samples included electrical conductivity (EC), pH, exchangeable cations, total C and N, inorganic C, and particulate organic matter (POM) C and N. Electrical conductivity and pH were estimated from a 1:1 soil–water mixture (Whitney, 1998; Watson and Brown, 1998). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were estimated by atomic absorption spectrometry with the sum taken to reflect cation exchange capacity (Sumner and Miller, 1996). Total soil C and N was determined by dry combustion on soil ground to pass a 0.106 mm sieve (Nelson and Sommers, 1996). Using the same fine-ground soil, inorganic C was measured on soils with a pH $\geq$ 7.2 by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with $FeCl_2$ (Loeppert and Suarez, 1996). Soil organic C (SOC) was calculated as the difference between total C and inorganic C. Particulate organic matter was estimated for the 0–30 cm depths only by determining the C and N content of material retained on a 0.053 mm sieve (Gregorich and Ellert, 1993). Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density (Blake and Hartge, 1986). All data were expressed on an oven-dry basis.

Measurement of nitrous oxide (N_2O) emission began in October 2003, 1 week after soil sampling. Measurements were made every other week from October until mid-March, and then at least once per week from mid-March through September 2004. Static chamber methodology was employed to collect gas samples as outlined by Hutchinson and Mosier (1981). Within each grazing treatment, gas samples were collected from six two-part chambers consisting of a permanent polyvinyl chloride (PVC) pipe anchor (20.3-cm i.d.; 5.0-cm height) and a PVC cap (20.3-cm i.d.; 10.0-cm height) with a vent tube and sampling port. Gas samples from inside the chambers were collected with a 20 ml syringe at 0, 15, and 30 min after installation (approximately 10:00 a.m. each sampling day). Gas samples were then injected into 12 ml evacuated glass vials sealed with butyl rubber septa. The concentration of N_2O inside each vial was estimated by gas chromatography using a Shimadzu GC-17A gas chromatograph equipped with an electron capture detector (Shimadzu Scientific Instruments, Kyoto, Japan). Nitrous oxide emission was calculated from the increase in concentration in the chamber headspace over time (Hutchinson and Mosier, 1981). Annual N_2O emission rates were calculated for each chamber within a grazing treatment by linearly interpolating data points and integrating the underlying area.

Grazing management effects on soil properties and annual N_2O emission were evaluated with PROC MIXED using a randomized complete block design (Littell et al., 1996). The four sampling locations in each grazing treatment were considered to be replicates, as the grazing treatments themselves were not replicated. Though not ideal, justification for using this approach hinges upon the value of the long-term status of the grazing treatments (Frank et al., 1995; Wienhold et al., 2001). Soil properties were evaluated by depth, and treatment means were compared using least significant differences (LSD) at $P < 0.05$. Associations between soil properties and annual N_2O emission were identified using Pearson correlation analysis.

3. Results and discussion

Grazing management effects on soil bulk density were confined to the surface 10 cm depth (Table 1). Soil bulk density was greater in FCWP than HGP and MGP at 0–5 cm, and greater in FCWP than HGP at 5–10 cm. A higher spring stocking rate in FCWP as well as greater vegetative cover from sod-forming grasses in HGP and MGP likely accounted for differences in soil bulk density between pastures. In all pastures, soil bulk density values would not be expected to restrict root growth within the sampling depth. Soil bulk density values ranged from 0.31 to 0.60 Mg m^{-3} higher for the 0–5 cm depth than that observed by Wienhold et al. (2001) for the same grazing treatments. Differences in sampling methodology accounted for discrepancies in soil bulk density between evaluations, as Wienhold et al. excavated blocks of soil by hand to a 15 cm depth, while samples in this evaluation were collected using a standard soil coring device. It is likely that Wienhold et al. collected more roots per unit volume of sample with the excavation method, as sampling directly above plant crowns was avoided in this evaluation. Soil bulk densities in this evaluation did compare favorably to that measured by Frank et al. (1995), who used the same coring method but with a different diameter probe tip.

Table 1
Effect of grazing management systems on soil bulk density and selected soil chemical properties

Soil depth (cm)	Fertilized crested wheatgrass	Heavily grazed	Moderately grazed
Soil bulk density (Mg m^{-3})			
0–5	1.02 a[†]	0.92 b	0.87 b
5–10	1.34 a	1.14 b	1.20 ab
10–20	1.23	1.12	1.09
20–30	1.28	1.17	1.18
30–60	1.28	1.32	1.26
60–100	1.44	1.43	1.40
Soil pH ($-\log[H^+]$)			
0–5	5.10 a	6.62 b	6.44 b
5–10	5.80 a	6.65 b	6.46 b
10–20	6.39 a	6.70 b	6.63 b
20–30	6.70	6.79	6.81
30–60	7.15	6.98	7.06
60–100	7.73	7.69	7.70
Exchangeable Ca (cmol kg^{-1})			
0–5	6.39 b	12.06 a	11.37 a
5–10	11.19	11.94	11.10
10–20	12.30	12.32	11.94
20–30	12.70	11.71	11.86
30–60	15.47	13.12	13.26
60–100	20.49	21.29	20.97
Exchangeable Mg (cmol kg^{-1})			
0–5	2.64 c	4.84 a	4.50 b
5–10	4.35 b	5.01 a	4.49 b
10–20	5.22	5.93	5.27
20–30	6.41	6.70	6.05
30–60	8.16	8.80	7.44
60–100	12.47	10.80	10.10
Exchangeable K (cmol kg^{-1})			
0–5	1.31	1.26	1.38
5–10	1.19	1.04	1.06
10–20	0.94	0.93	0.92
20–30	0.67	0.83	0.79
30–60	0.49 b	0.63 a	0.55 ab
60–100	0.51 a	0.49 a	0.42 b
Exchangeable Na (cmol kg^{-1})			
0–5	0.10	0.06	0.04
5–10	0.11	0.06	0.05
10–20	0.11 a	0.11 a	0.04 b
20–30	0.15 a	0.10 b	0.06 c
30–60	0.16 a	0.13 ab	0.07 b
60–100	0.49 a	0.30 b	0.11 b
Cation exchange capacity (cmol kg^{-1})			
0–5	10.44 b	18.21 a	17.29 a
5–10	16.82	18.04	16.71
10–20	18.56	19.29	18.16
20–30	19.91	19.34	18.75
30–60	24.27	22.67	21.32
60–100	33.95	32.87	31.61

[†] Means in a row with unlike letters differ ($P < 0.05$).

Electrical conductivity did not differ between grazing treatments and all values were categorized as non-saline (range = 0.18–0.48 dS m^{-1}). Soil pH was significantly lower at 0–20 cm in FCWP compared to HGP and MGP (Table 1). Categorically, soil pH in FCWP ranged from strongly to slightly acid in the surface 20 cm, while HGP and MGP ranged from neutral to slightly acid across the same depths. Differences in soil pH between pastures were greatest at 0–5 cm, where pH in FCWP was on average 1.4 units lower than the other two pastures. Greater acidification of surface soil depths within FCWP was driven by annual application of N fertilizer, which by the time of the 2003 sampling totalled 1747 kg N ha^{-1} over the course of the experiment. Soil pH in FCWP decreased by 0.1 units for each 122 kg N ha^{-1} applied. Smika et al. (1961) reported a pH decrease of 0.1 units for each 151 kg N ha^{-1} applied, when a total of 907 kg N ha^{-1} was applied over 9 years to a mixed grass prairie biome.

Trends in exchangeable cations between pastures varied by cation valence with depth (Table 1). Grazing treatments tended to impact divalent cations at 0–10 cm, whereas treatment effects on monovalent cations occurred below 10 cm. Exchangeable Ca^{2+} was nearly two-fold higher in HGP and MGP compared to FCWP at 0–5 cm. Exchangeable Mg^{2+} was greater in HGP compared to MGP and FCWP in the order of HGP > MGP > FCWP at 0–10 cm. Together, trends in exchangeable Ca^{2+} and Mg^{2+} accounted for differences in cation exchange capacity (CEC) between pastures, where CEC was greater in HGP and MGP by an average of 7.31 cmol kg^{-1} as compared to FCWP at 0–5 cm (Table 1). Trends in divalent cations between pastures were presumably driven by differences in displacement of Ca^{2+} and Mg^{2+} by H^+ on exchange sites, with the most displacement occurring in FCWP where acidification was greatest. It is likely the displaced Ca^{2+} and Mg^{2+} in FCWP was taken up by plant roots or followed the wetting front to lower soil depths to precipitate as calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$).

Grazing management effects on exchangeable K^+ were observed at 30–60 cm, where HGP had greater exchangeable K^+ than FCWP (Table 1). At 60–100 cm, exchangeable K^+ was greater in FCWP and HGP than MGP, though the absolute difference was small (<0.1 cmol kg^{-1}). Exchangeable Na^+ tended to be greatest in FCWP and least in MGP, with significant differences between pastures below 10 cm. Elevated levels of exchangeable Na^+ in FCWP may be caused by a stocking effect, resulting in greater deposition of Na^+ through feces and urine followed by subsequent distribution throughout the soil profile.

Grazing management effects on soil organic C occurred at both near- and sub-surface soil depths. At 0–5 cm, SOC was greater in FCWP and HGP as compared to MGP by an average of 5.7 Mg C ha^{-1} (Table 2). Wienhold et al. (2001) observed a similar trend in SOC between pastures, though absolute differences in SOC were smaller. Soil organic C was greater in HGP as compared to FCWP and MGP by

Table 2
Effect of grazing management systems on soil organic C, total N, and particulate organic matter

Soil depth (cm)	Fertilized crested wheatgrass	Heavily grazed	Moderately grazed
Soil organic C (Mg ha^{-1})			
0–5	28.6 a[1]	28.4 a	22.8 b
5–10	16.7 b	19.1 a	16.7 b
10–20	26.0	26.4	24.2
20–30	20.9	19.4	18.4
30–60	44.1 a	37.1 b	36.6 b
60–100	48.2	45.9	48.6
Total N (Mg ha^{-1})			
0–5	2.33 a	2.08 a	1.76 b
5–10	1.54	1.56	1.43
10–20	2.45	2.32	2.14
20–30	2.01	1.79	1.72
30–60	4.00	3.64	3.81
60–100	3.12	3.18	3.04
Particulate organic matter C (Mg ha^{-1})			
0–5	11.20 a	3.54 b	3.15 b
5–10	1.62 a	1.26 ab	0.94 b
10–20	1.63 a	1.17 b	0.97 b
20–30	1.37 a	0.83 b	0.87 b
Particulate organic matter N (Mg ha^{-1})			
0–5	0.66 a	0.13 b	0.12 b
5–10	0.10 a	0.06 b	0.06 b
10–20	0.13 a	0.08 b	0.09 b
20–30	0.12 a	0.07 b	0.08 b

[1] Means in a row with unlike letters differ ($P < 0.05$).

2.4 Mg C ha^{-1} at 5–10 cm. Elevated levels of SOC in FCWP and HGP relative to MGP at near-surface soil depths likely occurred by different mechanisms. For FCWP, greater SOC was caused by greater biomass production from N fertilizer application, whereas for HGP, greater SOC was caused by the predominance of blue grama, a mat-forming grass that transfers most of its photosynthate belowground to root biomass. Frank et al. (1995) found SOC in HGP to be 10 Mg C ha^{-1} greater than MGP in the surface 30.4 cm, primarily as a result of a grazing-induced shift toward more blue grama over time. In the surface 30 cm of this evaluation, SOC was 11.2 Mg C ha^{-1} greater in HGP than MGP. Grazing management effects on total N were limited to the surface 5 cm. Total N trends between grazing treatments were similar to SOC, with greater total N under FCWP and HGP than MGP (Table 2).

Differences in SOC between grazing treatments at subsurface depths was confined to 30–60 cm, where SOC in FCWP was 4.0 and 7.5 Mg C ha^{-1} greater than in HGP and MGP, respectively (Table 2). While increased SOC at lower depths can often be explained by greater root biomass, this explanation is inadequate as crested wheatgrass has been found to have lower live root biomass below 30 cm than native vegetation (Power, 1980; Redente et al., 1989). It is possible, however, that C allocation to roots and subsequent rhizodeposition may contribute to increased SOC in FCWP below 30 cm. Redente et al. (1989) observed crested wheatgrass to allocate 85% of fixed C belowground over a depth of 100 cm. Though the amount of rhizodeposited C from crested wheatgrass is not known, Kuzyakov (2002) has estimated that up to 25% of belowground allocated C is exuded from roots to soil, reflecting an important source of labile C for potential incorporation into soil organic matter.

Over the 0–100 cm depth, SOC was greatest in FCWP (185 Mg C ha^{-1}), intermediate in HGP (176 Mg C ha^{-1}), and least in MGP (167 Mg C ha^{-1}) ($P = 0.1413$). Though MGP had the least SOC of the three grazing treatments, previous research has found it to be a C sink. Measurement of CO_2 fluxes over a period of 6 years by Frank (2002) found MGP to sequester approximately 300 kg C ha^{-1} per year. Using this C accrual rate as a baseline and SOC differences between MGP and the other two grazing treatments, C sequestration rates for HGP and FCWP would be about 400 and 550 kg C ha^{-1} per year, respectively. It is important to recognize, however, that C accrual rates for all grazing treatments are highly variable due to annual climatic variation, which drives biomass production.

Assessments of soil inorganic C (SIC) are needed in arid and semiarid ecosystems to provide an accurate accounting of soil–plant C balance. In the shortgrass steppe of Colorado, Reeder et al. (2004) observed significantly more (16.3 Mg C ha^{-1}) SIC in a heavily grazed treatment than in an ungrazed treatment at 0–90 cm. In this evaluation, SIC was present in all grazing treatments below 30 cm (data not shown). However, treatment differences in SIC were not observed, though there was a numerical trend toward greater SIC in FCWP (70.3 Mg C ha^{-1}) compared to HGP (48.0 Mg C ha^{-1}) and MGP (51.8 Mg C ha^{-1}) at 60–100 cm ($P = 0.1734$).

Particulate organic matter is considered an intermediately labile pool of C and N with greater sensitivity to changes in management than total soil organic matter (Cambardella and Elliott, 1992). Particulate organic matter C and N was consistently greater in FCWP than HGP and MGP at 0–30 cm (Table 2). Differences between pastures were most pronounced at 0–5 cm, where POM-C and POM-N were over three- and five-fold greater, respectively, in FCWP compared to the average of HGP and MGP. Surface accumulation of POM in FCWP was likely caused by greater biomass production in the form of roots and deposited aboveground plant residues in response to N fertilization and deposition of cattle feces.

Annual N_2O emission was over three-fold greater in FCWP compared to HGP and MGP (Fig. 1). Addition of fertilizer N, greater deposition of cattle urine and feces, and mineralization of N-enhanced plant residue likely contributed to increased emission of N_2O in FCWP. This latter mechanism is supported by Wienhold et al. (2001), who observed seven-fold greater N mineralization within FCWP as compared to HGP and MGP. Mineralization of plant residues with high N content has been shown to be a significant source of N_2O in agro-ecosystems (Kaiser et al.,

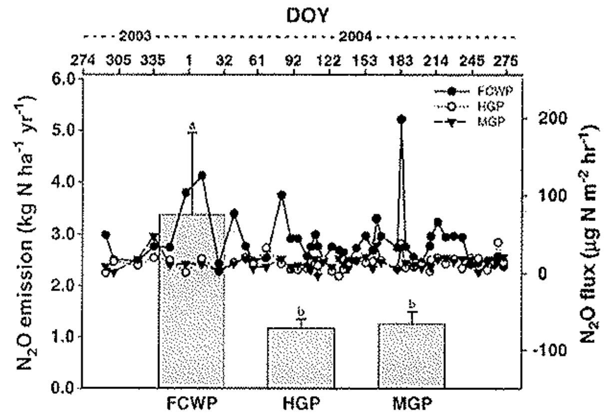

Fig. 1. Nitrous oxide emission/flux from long-term grazing management systems near Mandan, ND. Annual N_2O emission is given using units on the left y-axis, ±1 S.E. Bars with unlike letters differ ($P < 0.05$). Temporal variation of N_2O flux throughout sampling period is given using units on the right y-axis.

1998; Baggs et al., 2000). Major N_2O emission events throughout the measurement time were associated with thawing periods in late winter and early spring as well as instances during the growing season when the soil was at or above field capacity (data not shown). The magnitude of N_2O emission from all three historical pastures was intermediate of that observed in shortgrass steppe and tallgrass prairie (Liebig et al., 2005).

Annual N_2O emission was correlated with soil pH, SOC, total N, and POM-C and POM-N at 0–5 cm (Table 3). Particulate organic matter C, in particular, was strongly associated with annual N_2O emission ($P \leq 0.0001$; $r^2 = 0.85$) (Fig. 2). As a labile pool of organic matter, and therefore a source of N for nitrification and dentrification, POM may act as a useful soil-based indicator of potential N_2O emission within grazing management systems. This finding deserves further investigation as others have found POM to function as an N storage pool recycled by microbial biomass with little net N mineralization (Yakovchenko et al., 1998). Significant correlations between N_2O emission and other soil properties were less direct, driven by trends among pastures in acidification (for soil pH) and soil organic matter (for SOC and TN). The negative correlation between N_2O emission and soil pH, in

Table 3
Correlation coefficients between soil properties at 0–5 cm and annual emission of N_2O

Indicators	Annual N_2O emission, r
Electrical conductivity	−0.31
Soil pH	-0.75^{***}
Soil organic C	0.54^{*}
Total N	0.70^{**}
Particulate organic matter C	0.92^{***}
Particulate organic matter N	0.91^{***}

*,**,*** Correlation significant at $P < 0.1$, 0.05, and 0.01, respectively.

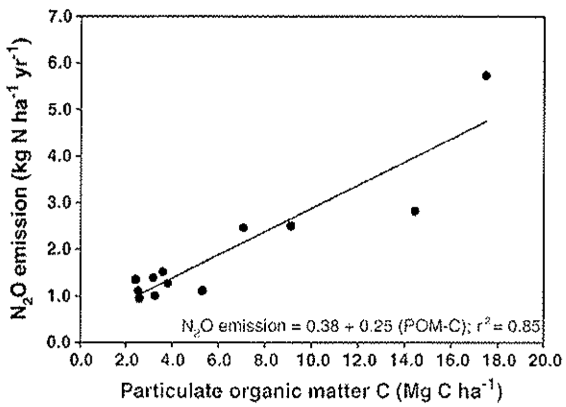

Fig. 2. Relationship between particulate organic matter C (0–5 cm) and annual N_2O emission for long-term grazing management systems near Mandan, ND.

particular, unlikely reflects a causal relationship as dentrification has been observed to increase up to a pH of 8.3 (Šimek et al., 2002).

4. Conclusions and management implications

Grazing management systems affect soil attributes, which, in turn, impact ecosystem function. Within this evaluation, soil attributes were affected by long-term (over 70 years) grazing management systems in the northern Great Plains of North America. Of the management variables evaluated, ecosystem function was most impacted by N fertilization within the crested wheatgrass pasture. Specifically, N fertilization caused a marked increased in soil acidification, with concomitant decreases in CEC and exchangeable Ca^{2+} and Mg^{2+} in near-surface soil depths. Soil pH and CEC are surrogate indicators of nutrient cycling and storage potential, and when lowered past threshold levels result in nutrient loss. Management practices to counter acidification such as liming are necessary to maintain soil pH within an optimum range for plant growth and nutrient cycling. Nitrogen fertilization also contributed to greater N_2O emission within the crested wheatgrass pasture relative to the native vegetation pastures. Given the global warming potential of this greenhouse gas (296 times that of CO_2 over a 100 year period), alternative management strategies to minimize emissions are needed. Options include: (a) changing fertilizer N application from fall to early spring, thereby decreasing the amount of available N present in soil during late winter/early spring, when most emission of N_2O occurs and (b) using slow-release N fertilizers and/or nitrification inhibitors. Of these two options, the first is more economically viable for grazing management systems in the northern Great Plains. The effects of N fertilization were partially offset by increased SOC at near- and subsurface (>30 cm) soil depths within the crested wheatgrass pasture relative to native vegetation pastures. Among the soil properties measured, particulate organic matter C was strongly associated with N_2O emission, indicating its usefulness as a soil-based indicator of potential N_2O emission within grazing management systems.

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