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Full Length Research Paper

Effects of grassland management on soil organic carbon density in agro-pastoral zone of Northern China

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The objective of this study was to estimate the soil organic carbon (SOC) in grasslands with different management measures including: (1) uncontrolled or free grazing grassland (FG); (2) grassland enclosured, excluding grazing and mowing (EG); (3) grassland enclosured and mowed early in October every year (MG) and (4) grassland enclosured under controlled grazing (CG) by examining soil bulk density and SOC content from 0 to 50 cm soil depth in agro-pastoral ecotone, Northern China. The results showed that, by implementing CG, EG and MG practices, the grasslands in agro-pastoral ecotone of Northern China achieved higher SOC storage on decade scales when compared to FG field. CG field had the highest SOC density in 0 to 50 cm soil layer, while the least SOC density was displayed by FG. However, SOC density was similar between MG and EG plots. CG increased SOC concentration by 56.08% and SOC density by 4.96 kg/m^2 when compared to FG practice. In addition, it was likely to give positive financial returns in providing livestock products when compared to EG practice. CG therefore was the most feasible and benign short-term grassland management option which could deposit even higher carbon dioxide in agro-pastoral ecotone in Northern China.

Key words: Agro-pastoral zone, soil organic carbon density, grassland management, Northern China.

INTRODUCTION

In the biosphere, the terrestrial ecosystems contains, almost three times, more carbon (C) than that of the atmosphere (Schimel, 1995), and C in terrestrial ecosystems was mainly distributed in the soil organic matter (SOM) (Burke et al., 1995; Schimel, 1995), which was twice or three times higher than that in living vegetation (Post and Kwon, 2000). C in SOM made up 80% of the terrestrial carbon pool and was regarded as an important potential C sink to mitigate the greenhouse effect (Bolin and Sukumar, 2000). Soil C sequestration had the potential to increase organic matter in soils that have been depleted by past land management practices (Lal et al., 1998).

In general, the importance of land utilization and management strategies on soil C stocks has been noted in many studies (Lal et al., 1998; Sperow et al., 2001). However, the literatures about the impacts of grassland management on the soil C reservoir were largely incomeplete and inconsistent in many cases (Milchunas and Lauenroth, 1993). Many studies have demonstrated that changes in ecosystem management strategies influenced the soil C storage in grasslands (Lugo and Brown, 1993; Post and Kwon, 2000; Murty et al., 2002; Soussana et al., 2004). A variety of manage-ment techniques that increased or decreased the soil C storage of the region's grasslands could have significant effects on the global C budget (Ojima et al., 1993), in that proper management could sustain or increase soil C sequestration and contribute to the mitigation of atmo-spheric CO_2 increase in grassland system (Abril and Bucher, 2001; Derner et al., 2006; Derner and Schuman, 2007). To assess C sequestration potential of grassland ecosystems for mitigating global climate change, it is important to have a comprehensive database on soil C storage with

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Abbreviations: C, Carbon; **SOC,** soil organic carbon; **FG,** uncontrolled or free grazing grassland; **EG,** grassland enclosured, excluding grazing and mowing; **MG,** grassland enclosured and mowed early in October every year; **CG,** grassland enclosured under controlled grazing.

different management strategies.

There were various studies of C storage and C sinks in different grassland management measures at specific regional or nation-wide scales to global scales (Scurlock and Hall, 1998; Wang et al., 1998; Wang et al., 2001; Ni, 2002; Liu and Tong, 2003; Wu et al., 2003; Liu et al., 2004; Ni, 2004; He et al., 2008). However, most of these studies were conducted almost on the typical steppe (Fang et al., 1996; Ni, 2002; Wu et al., 2003; Fan et al., 2008) and as such, limited attention had been paid to the grassland in agro-pastoral ecotone of Northern China.

The agro-pastoral ecotone in Northern China, as a vast natural ecological transition zone, was one of the distinguished ecological ecotones in the world, covering 6.9×10^5 km^2 area and approximately 6.7×10^7 population (Huang et al., 2007). The land utilization ratio was 82%, with grassland accounting for 43% and farmland 29% (Huang et al., 2007). As a dominant form of landscape and an integral component of the Eurasian continent, the grasslands in the agro-pastoral zone in Northern China play an important role as a sink of atmospheric C. The effect of different grassland management practices on C cycle of grassland ecosystems in this region needs to be further understood.

Thus, the main objective of this research was to gain insight into the effects of grassland management measures including free grazing, grassland enclosure and other management practices on SOC stocks in the grasslands of Northwest Hebei province, in the typical agro-pastoral ecotone, Northern China. Our two hypotheses were: (1) SOC density by grassland enclosure treatment is higher than that by grasslands uncontrolled or free grazing, and (2) SOC density by grassland enclosured and ungrazed is higher than that by grassland enclosured including grazing or mowing. We then suggested efficient grassland managements for preventing SOC loss from the grassland in this region.

MATERIALS AND METHODS

Research area descriptions

The experiment was conducted in the National Grassland Ecosystem Observation and Research Station, which lies in the typical agro-pastoral ecotone in Guyuan county, Hebei province, Northern China (115°41´E, 41°46´N), along the Southeast inner Mongolia plateau that connects with the Xilin Gol steppes. There are 1.4×10^3 km^2 natural grasslands in Guyuan county and it is characterized by a continental, semi-arid, monsoon climate in the temperate zone, with windy and 'dry winter and spring', warm and comparatively rain-rich 'summer' followed by short and cool 'fall'. The average annual temperature ranged from 1 to 2℃, the frost-free period was about 80 to 110 days and ≥10℃ annual accumulated temperature was 1,500 to 2,200℃ per year. Long-term annual average precipitation ranged from 350 to 450 mm, 80% of which occurred during June through September growing season, and the average annual potential evaporation was 1,700 to 2,300 mm. Geomorphologically, the region was characterized by open flat lands alternating with undulating hilly lands and the elevations of the site ranged from 1,300 to 1,450 m. The soil was a chestnut type (that is, Calcic Kastanozems, which was equivalent to Calcic-orthic aridisol in the U.S. soil taxonomy classification system).

Representative texture reported as percentage sand/silt/clay for the soil was 53.1/40.0/7.0, 38.2/59.8/2.0 and 63.5/35.4/1.1 for profile depths of 0 to 20 cm, 21 to 40 cm and 40 to 60 cm, respectively (Liu et al., 2009). Acidity of the saturated soil (pH) for these same profiles were 7.79 - 8.25, 7.83 - 8.31, 8.10 - 8.49, respectively (Guo et al., 2010).

The plant community was dominated mainly by *Leymus chinensis, Stipa grandis, Cleistogenes squarrosa, Agropyron michnoi,* and *Koeleria cristata*. The *L. chinensis* community represented the most widely distributed grassland communities in the Eurasian steppe region, which was the largest contiguous grassland area in the world (Chen and Wang, 2000). The plants reached their maximum aboveground biomass in July and August, when the air temperature and precipitation were the highest of the year.

For the fact that the agricultural yield was very low, many of the local residents opted for sheep and ox herding for improved income. Overgrazing by livestock had historically been an extensive management practice for the grasslands in this region. Almost all the grasslands in this region were open perennial grasslands that were used with continuous season-long grazing at a heavy stocking rate prior to 2000 years. Nowadays, improved grassland management, particularly grassland enclosured, was a common measure to protect the *L. chinensis* grasslands that were widely distributed in this region. A study by Chen and Zhu (2001) showed a more detailed description of grassland in this region.

Experimental plots

Four categories of managed grassland were identified as common in the region: (1) uncontrolled or free grazing grassland (FG); (2) grassland enclosured, excluding grazing and mowing (EG); (3) grassland enclosured and dry grass was mowed early in October every year (MG) and (4) grassland enclosured under control grazing (CG). Plot FG had been exposed to long-term free grazing, except from March 1st to May 1st because of the government's restriction, with an estimated 60 ~ 80% of aboveground biomass consumed by livestock each year. Plot EG was established in 1999, by fencing 10 ha of previously free-grazing grassland, with grazing and mowing excluded. Plot MG was established in 2000 by fencing 10 ha of previously free-grazing grassland. As such, the dry grass was harvested early in October and then bundled, while the average yield was about 8,500 kg per ha. Plot CG was established in 1999, by fencing 15 ha of previously free-grazing grassland, with an estimated 40 ~ 60% of aboveground biomass consumed by livestock each year. Fields were selected based on the availability of reliable information about grassland use and management history under the same environmental conditions. The four experimental plots were contiguous, and some characteristics of these plots are described in Table 1.

Soil sample collection and analysis

Soil samples were collected at the peak of the standing crop during the second week of August, 2009. Within each treatment, three 50 × 50 m sampling locations (spaced at least 50 m apart) were demarcated and hereafter regarded as field replicates. At each location, all live vegetation and litter were clipped to the ground level and removed prior to collection of the soil's core. Soil samplings were conducted by using a soil sampler (diameter, 6 cm). The soil samples were collected from 10 points and from 5 layers at depths of 0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm and 40 to 50 cm, then were mixed together to obtain a composite sample, at each location. Soil samples were air-dried in a ventilation room

Table 1. Characteristics of experimental plots.

Treatment	Description	Dominant species	Grassland condition
EG	10-ha plot was enclosured and grazing was excluded since 1999.	*Leymus chinensis, Hordeum spontaneum. Iris lactea* var. *chinensis (Fish) Koidz.*	Excellent
MG	10-ha plot was enclosured and dry grass was mowed early in October every year since 2000.	*Leymus chinensis, Potentilla lancinata,* Carex *capricornis Meinsh.*ex *Maxim., Iris lactea* var. *chinensis (Fish) Koidz.*	Light degradation
CG	15-ha plot was enclosured since 1999, with an estimated 40~60% aboveground biomass consumed by livestock each year.	*Leymus chinensis, Thermopsis lanceolata, Ixeris polycephala Cass., Puccinellia altaica Tzvel., Stellera chamaejasme*.	Moderate degradation
FG	20-ha plot was subjected to uncontrolled and intense year-round grazing by cattle, sheep, goats and donkeys, and approximately 60~80% of ANPP was removed	*Leymus chinensis, Iris lactea* var. *chinensis (Fish) Koidz, Stellera chamaejasme*.	Severe degradation

and grounded, then were sieved with a 2 mm mesh to remove stones, root fragments and other organic debris. Sub-samples were sieved with 100 mesh and were ground to a fine powder before total carbon determination.

Soil bulk density was measured with a volumetric (100 cm^3) steel ring from the five layers, with three replicates for each site and was determined by drying the soil samples at 105℃. The measurement of soil bulk density at different depths allowed us to estimate the mass of SOC density at each site.

The SOM and SOC contents were analyzed by external heating method following the standard procedures (Bao, 2000). Briefly, 0.5 g of the soil samples were digested with 1 N $K_2Cr_2O_7$ (10 ml) and were concentrated with H_2SO_4 (20) ml for 30 min. This was followed by an addition of distilled water (250 ml) to the sample, and then was titrated with standardized 0.5 N $FeSO_4$.

Since SOC content varied along soil profile, SOC density (kg m^{-2}) was calculated as follows:

$$\text{SOC density} = \frac{\sum_{i=1}^{n} D_i \times \rho_i \times SOCC_i}{10}$$

Where, i is the number of soil horizons, D_i is the depth interval (cm) of the horizon i from the top and down soil, ρ_i is the BD (g cm^{-3}) in the horizon i and $SOCC_i$ is the mean SOC content (%) in the horizon *i.*

Statistical analysis

Although the experiments were pseudo-replicate, it can be regarded that the sampling distance between sampling locations was sufficient to ensure adequate variation estimation within each treatment. We followed the approach of Frank et al. (1995) and considered each of the three plots as a replication of the summary statistics. Each variable of the three locations was averaged for statistical analysis. All data except soil bulk density were expressed as mean ± SE. Analysis of variance was used to assess the effect of grassland management on soil bulk density, SOC content and density. Duncan's multiple comparison tests were used to determine the significant difference in the mean soil bulk density, SOC content and density, among the depth intervals and different grassland management at $p < 0.05$. All the statistical analyses were performed by SPSS v. 16.0.

RESULTS

Soil bulk density

The soil bulk density showed a similar change in the 0 to 50 cm soil layer for the four grasslands after conducting different management measures (Table 2). Bulk density increased significantly with soil depth across all the four treatments. Moreover, there was no difference in soil bulk density between 30 to 40 cm and 40 to 50 cm soil layers ($p > 0.05$), but the soil bulk densities were different significantly among 0 to 10 cm, 10 to 20 cm and 20 to 30 cm at $p < 0.05$ in the experimental fields. As such, there was no difference in the soil surface (0 to 30 cm) bulk density between CG and FG and EG and MG management practices. The grasslands under grazing management (FG and CG treatments) had significantly higher soil bulk densities than those under ungrazed managements among 0 to 10 cm, 10 to 20 cm and 20 to 30 cm (EG and MG treatments) at $p < 0.05$.

Soil organic carbon content

The different grassland management practices also affected SOC content (Table 3), in that SOC content was highest at the top surface soil and decreased with soil depth increment across the four grassland management practices. The grassland enclosured with managed grazing practice (CG) has higher SOC content than those in MG, EG and FG treatments from 0 to 50 cm, but there were no significant difference between the CG and EG

Table 2. Soil bulk density ($g.cm^{-3}$) in different grassland management fields (mean ± SD).

Soil layer treatment (cm)	EG	MG	CG	FG
0 - 10	$1.25±0.03^{bE}$	$1.23±0.02^{bE}$	$1.36±0.02^{aC}$	$1.33±0.01^{aD}$
10 - 20	$1.34±0.02^{bD}$	$1.35±0.02^{bD}$	$1.39±0.02^{aC}$	$1.37±0.02^{abC}$
20 - 30	$1.40±0.02^{bC}$	$1.41±0.01^{bC}$	$1.48±0.02^{aB}$	$1.48±0.02^{aB}$
30 - 40	$1.45±0.02^{aB}$	$1.46±0.01^{aB}$	$1.52±0.06^{aB}$	$1.49±0.02^{aB}$
40 - 50	$1.60±0.02^{aA}$	$1.56±0.03^{aA}$	$1.59±0.02^{aA}$	$1.57±0.02^{aA}$

Values followed by the same letter (a - b) within a row were not statistically different at the 5% error level for the grassland management effect. Values followed by the same letter (A - E) within a column were not statistically different at the 5% error level for the soil depth effect.

Table 3. Soil organic carbon content ($g\ kg^{-1}$) in different grassland management fields (mean ± SE).

Soil layer treatment (cm)	EG	MG	CG	FG
0 - 10	$27.51±1.12^{a}$	$24.81±0.63^{b}$	$28.97±0.61^{a}$	$24.27±0.69^{b}$
10 - 20	$18.99±0.84^{ab}$	$21.80±1.38^{a}$	$22.50±0.71^{a}$	$12.48±0.56^{c}$
20 - 30	$13.89±0.43^{ab}$	$16.68±3.11^{a}$	$18.12±1.12^{a}$	$8.81±0.38^{b}$
30 - 40	$13.36±0.14^{a}$	$8.96±0.26^{b}$	$13.87±0.44^{a}$	$8.00±0.14^{b}$
40 - 50	$8.50±0.28^{ab}$	$7.09±0.20^{b}$	$8.97±0.21^{a}$	$5.66±0.14^{c}$

Values followed by the same letter (a - c) within a row were not statistically different at the 5% error level for the grassland management effect.

Table 4. Soil organic carbon density ($kg\ m^{-2}$) in different grassland management fields (mean ± SE).

Soil layer treatment (cm)	EG	MG	CG	FG
0 - 10	$3.44±0.14^{bA}$	$3.05±0.08^{cA}$	$3.94±0.08^{aA}$	$3.23±0.09^{bcA}$
10 - 20	$2.54±0.11^{bB}$	$2.94±0.19^{abAB}$	$3.13±0.10^{aB}$	$1.71±0.08^{cB}$
20 - 30	$1.94±0.06^{bC}$	$2.35±0.44^{abB}$	$2.68±0.17^{aBC}$	$1.30±0.06^{cC}$
30 - 40	$1.94±0.20^{aC}$	$1.31±0.04^{bC}$	$2.11±0.07^{aC}$	$1.19±0.06^{bD}$
40 - 50	$1.36±0.05^{aD}$	$1.11±0.03^{bC}$	$1.43±0.03^{aD}$	$0.89±0.02^{bD}$
0 - 50	$11.23±0.30^{b}$	$10.76±0.69^{b}$	$13.28±0.37^{a}$	$8.32±0.14^{c}$

Values followed by the same letter (a - c) within a row were not statistically different at the 5% error level for the grassland management effect. Values followed by the same letter (A - D) within a column were not statistically different at the 5% error level for the soil depth effect.

plots in all the soil layers from 0 to 50 cm. In general, the average SOC content in 0 to 50 cm soil layers of FG treatment was 11.84 $g\ kg^{-1}$. For decades, CG, EG and MG increased the SOC content by 56.08, 38.89 and 33.98%, respectively, when compared to FG in 0 to 50 cm soil layers.

Soil organic carbon density

The SOC density in the four plots followed the same trend as the SOC content (Table 4). The patterns of SOC density with soil depth were slightly different among the different grassland management measures, but SOC density displayed similar profiles, which declined at each successive increment from 0 to 50 cm depth across the four treatments, with the relative distribution greatly skewed towards the top layers. As such, the top 10 cm accounted for more than 30% of the total C.

The results of the ANOVA analyses showed that there were significant effects of grassland management practices on SOC density ($p < 0.05$). As such, CG treatment had the highest SOC density in the 0 to 50 cm soil layer, while the lowest SOC density was displayed by FG, and SOC density was similar between MG and EG treatments. Overall, CG, EG and MG treatments increased SOC density by 59.62, 34.98 and 29.33%, respectively, when compared to FG in 0 to 50 cm soil layer.

DISSCUSION

Our findings showed significant difference in topsoil C and bulk density levels among the management categories in that grazing fields, whether enclosured or not, generally exhibited higher level of bulk density, and enclosured fields, whether grazed and mowed or un-grazed and non-mowed, generally exhibited higher level of C.

Soil bulk density was a good indicator of soil physical quality, in that it highly correlated with many soil processes (Doran and Jones, 1996; Brady and Weil, 2002; Murphy et al., 2004). The main effects of grassland management practices on soil bulk density in this study can be inferred from Table 2. Grasslands, under grazed management (FG and CG treatments), increased soil bulk density from 0.08 to 0.13, 0.02 to 0.05 and 0.07 to 0.08 g cm^{-3} when compared to the ungrazed management (MG and EG treatments) in the 0 to 10 cm, 10 to 20 cm and 20 to 30 cm soil layers, respectively, while the underlying horizon (40 to 50 cm) was not affected much. The changes apparently related to the effects of animal hooves in grazing management grassland decreased soil porosity, and it became compacted by the weight. As the soil surface was compacted, the volume of pore space in the top surface soil was reduced, therefore, its dry bulk density increased. One potential mechanism that could explain the lower bulk density in ungrazed fields was an increase in the activity of burrowing mammals within the enclosures, which was our casual observation in the ungrazed places. Another mechanism was that high level of residual dry matter within the enclosures increased soil surface organic matter (Kenneth et al., 2004). Mean soil bulk densities of the grazed sites were much higher than those of non-grazed sites, in that the enclosured fields and mowing grasslands could be found in several other rangeland studies (Assaeed, 1982; Kenneth et al., 2004). However, to gain more insight into how specific management measures affect soil bulk density, long-term field experiments are needed which simultaneously consider several groups of organisms and/or soil processes (Wardle et al., 2001).

There were conflicting reports on the effect of grazing on SOC. Higher soil C content has been reported in grazed pastures than in un-grazed grassland (Reeder and Schuman, 2002). Others reported that grazing neither had any effect (Dormaar et al., 1977; Milchunas and Lauenroth, 1993) nor decreased soil C (Frank et al., 1995; Derner et al., 1997; Snyman and Du-Preez, 2005). The difference in the response of soil C to grazing may reflect the difference in climate, inherent soil properties, landscape position, plant community composition and grazing management practices (Reeder and Schuman, 2002). The results of this study suggested that management practice influenced grassland soil C, in that free grazing management of grasslands caused loss of SOC in the agro-pastoral ecotone of Northern China in the study. Reductions in SOM content in the free grazing fields from domestic livestock was attributed to the removal of aboveground herbaceous plant material and a reduction in the rooting density and depth. Many other studies also showed that heavy grazing under improper management led to grassland degradation (Noellemeyer et al., 2006). Disruption of soil aggregate structure and surface soil crust due to stamping by livestock increased the decomposition of SOM and renders the soil susceptible to water and wind erosion (Belnap, 2003; Liu et al., 2004; Neff et al., 2005). Hence, grasslands were historically over-utilized or heavily grazed according to loose SOM (Lal, 2002).

Management improvements increased the soil C, whereas enclosured management (CG, EG and MG) increased the mean SOC content by about 56.08, 38.89 and 33.98% in the horizon of 0 to 50 cm compared to the uncontrolled field (FG), respectively. However, in all the three enclosured fields, CG had the highest SOC content than those of MG and EG treatments from 0 to 50 cm. The grassland under controlled grazing increased SOC in this region of the study and the result was consistent with the findings of some other studies (Frank et al., 1995; Hiernaux and Turner, 1996; Derner et al., 1997; Hiernaux et al., 1999a; Snyman and Du-Preez, 2005; Klein et al., 2007) due to the fact that the controlled grazing could be beneficial for vegetation production by stimulating growth, thereby compensating for moderate exports of forage organic C, promoting floral and faunal biodiversity (Bilotta et al., 2007) and increasing C sequestration and allocation to soils (Derner and Schuman, 2007). It has also been found that exclosure of livestock did not benefit grassland soil C sequestration in some semi-arid rangeland (Nosetto et al., 2006; Shrestha and Stahl, 2008) and Savanna contexts (Moussa et al., 2007). Many grasslands increased the biomass production in response to frequent grazing which when managed appropriately, could increase the input of organic matter to grassland soils (Klein et al., 2007). Enclosure of grasslands from livestock grazing may also restrict the access of livestock keepers to functional grazing lands, which adversely affect herders' incomes and displace grazing intensity onto unenclosed lands (Williams, 1996). The lower C in the EG field compared to the CG plot in our study was attributed to immobilization of C in excessive aboveground plant litter, and an increase in annual forbs and grasses which lack dense fibrous rooting systems conducive for soil organic matter formation and accumulation. As such, the lower C in MG fields compared to the CG plots in our study was likely attributable to the removal of aboveground biomass as green-fodder. However, there was absence of faeces and urine deposition (Hiernaux et al., 1999b).

Conclusion

By implementing CG, EG and MG practices, the grasslands in the agro-pastoral ecotone of Northern China achieved higher C storage on decade scales compared to FG fields in the context of mitigating global climate change. The most effective option for increasing SOC content and density was grassland enclosed with controlled grazing practice (CG), which had the effect of increasing SOC content by 56.08% and SOC density by 4.96 kg/m^2, compared to the free grazing practice (FG). In addition, CG was likely to give positive financial returns in providing livestock products when compared to EG practice. CG therefore was the most feasible and benign short-term soil rehabilitation option which could deposit even higher carbon dioxide. These results could be useful to those making rangeland management decisions directed at maximizing C sequestration in this region.

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