Soil organic matter stabilization in degraded semi-arid grasslands after grazing cessation

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Abstract

Soils in semi-arid grasslands are considered to store significant amounts of soil organic carbon (SOC) and to be of global importance for carbon sequestration. However, land use changes, in particular overgrazing, caused a large release of SOC in the last decades. The aim of this study was to investigate the sequestration potential of degraded grasslands after grazing cessation in terms of soil organic matter (SOM) stabilization. Intensively grazed as well as short- and long-term ungrazed grasslands were sampled in Inner Mongolia, Northern China, and analyzed for amount, spatial distribution and stabilization of SOM. Grazing exclusion led to a significant increase of SOC in the topsoil after three years and resulted in 35% higher amounts after 30 years. This increase is based on higher input of particulate organic matter (POM) and on increased amount of labile SOM physically protected within soil aggregates. This was evident as carbon mineralization of grazed sites with lower amounts of aggregate occluded POM was considerably higher compared to ungrazed sites. Analysis of the spatial distribution of SOM showed a heterogeneous pattern for ungrazed sites and a homogeneous distribution for grazed sites. Apparently, the recovery after grazing cessation starts with the formation of "islands of fertility", where a higher input of water and organic matter promotes the development of vegetation and associated SOM patches. We conclude that grazing exclusion in degraded semi-arid grasslands has a high potential to immediately sequester atmospheric carbon and mitigate climate change.

Key Words

Soil organic carbon stocks, carbon mineralization, soil aggregates, steppe degradation, overgrazing, China.

Introduction

Degradation of semi-arid grasslands is a global environmental problem, particularly in Northern China, where 2.1 – 2.6 million km² are regarded as degraded steppe (Yang *et al.* 2005). In some regions of Inner Mongolia, up to 72% of the total area are classified as degraded steppe (Tong *et al.* 2004). The main cause of grassland degradation in Northern China is overgrazing as a result of increasing stocking rates after the change from a sustainable nomadic culture to a static grazing management in the last 50 years. Intensification of grazing was accompanied by a considerable loss of SOC in the grassland soils (Xie *et al.* 2007). Grasslands play a crucial role within the storage of global SOC containing approximately 15% of total SOC stocks (Lal 2004). The degradation of steppe soils can be attributed to lower input of organic matter (OM) into the soil as grazing decreases biomass input (Steffens *et al.* 2009b). Furthermore, animal trampling leads to soil compaction associated with a destruction of soil aggregates that in turn enhances soil erodibility. Formerly protected OM within aggregates is released and mineralized. In order to investigate the degradation of steppes and find solutions for a sustainable grassland management the sino-german research group MAGIM (Matter fluxes in grasslands of Inner Mongolia as influenced by stocking rate) was established in 2004. The study area is located in a semi-arid grassland in Inner Mongolia where continuously grazed plots as well as ungrazed plots, that were fenced in 1979 and 2005 were investigated. Our main research focus was the recovery of degraded semi-arid grasslands after cessation of grazing in terms of amount, spatial distribution and stabilization of SOM compared to continuously grazed steppes.

Material and methods

The study sites are located in the Xilin River Basin (43°38' N, 116°42' E, 1270 m a.s.l.) in the autonomous province Inner Mongolia, P.R. China. The region is part of the continental semi-arid grasslands of the Central Asian steppe ecosystem, with a dry and cold middle latitude climate. Mean annual temperature is 0.7 °C and mean annual precipitation is around 350 mm, with the highest values in the summer from June to August. The vegetation period from May to September is relatively short (<150 days). Zonal vegetation types are *Leymus chinensis* dominated steppe communities at areas with relatively wet soil conditions and

Stipa grandis dominated communities in drier regions. Soils are classified as *Calcic Chernozems* (IUSS 2006) which developed from aeolian sediments. They are characterized by a dark, carbonate-free Ah horizon followed by an Ach horizon with secondary calcium carbonate nodules.

In order to determine short-term effects of grazing cessation, a controlled grazing experiment was established at a *Leymus* dominated site in 2005. Topsoil samples were taken in 2005 and again in 2008 from ungrazed (UG), moderately grazed (MG) and heavily grazed plots (HG) with stocking rates of 4.5 and 7.5 sheep units per hectare, respectively, and analyzed for bulk density (BD), SOC, total nitrogen (N_{tot}), total sulphur (S_{tot}) and pH values. The effects of long-term grazing exclusion were investigated in detail for both steppe types at ungrazed sites that were fenced in 1979 (UG79) and compared to adjacent continuously grazed sites (CG) with a stocking rate of around 1.2 sheep per ha. For basic soil properties 3 soil pits were sampled at all study sites and analyzed for soil texture, BD, SOC, N_{tot}, S_{tot}, pH values and carbon isotope ratios ($\delta^{13}C$). To elucidate the spatial structure of selected topsoil parameters at the field scale, 100 grid points with spacings of 5 m and 15 m were sampled. For detection of small-scale variability at the plant scale, 40 randomly selected points were sampled inside areas of 2 m × 2 m at each plot. Semivariances were calculated for BD, SOC, N_{tot} and S_{tot}. To quantify the contribution of single SOC fractions to carbon sequestration a combined density and particle size fractionation was applied that separated bulk soil samples in POM and mineral fractions. Carbon mineralization was determined in an incubation experiment for a period of one month for UG79 and CG from *Leymus* dominated sites. For a detailed description of all investigations see (Steffens *et al.* 2009a; Steffens *et al.* 2009b; Steffens *et al.* 2008; Wiesmeier *et al.* submitted; Wiesmeier *et al.* 2009).

Results

Results from the controlled grazing experiment showed that SOC, N_{tot} and S_{tot} stocks calculated for the first 4 cm of the topsoil from all plots were comparable in 2005 with amounts of 1.0 kg/m^2 for SOC, 0.1 kg/m^2 for N_{tot} and 0.015 kg/m^2 for S_{tot}. In 2008, UG plots revealed significantly ($P < 0.05$) higher SOC, N_{tot} and S_{tot} stocks whereas MG and HG sites tended to show lower elemental stocks, but differences were not significant.

Table 1. SOC, N_{tot} and S_{tot} stocks determined in 2005 and 2008 for the first 4 cm of the topsoil of ungrazed (UG), moderately grazed (MG) and heavily grazed (HG) sites (standard deviation in parentheses, n = 40 for UG, n = 10 for MG and HG).

Site/year	UG 2005	UG 2008	MG 2005	MG 2008	HG 2005	HG 2008
SOC (kg/m^2)	1.04±0.23	1.11±0.24	1.03±0.14	0.88±0.05	1.01±0.19	0.81±0.09
N_{tot} (kg/m^2)	0.107±0.02	0.113±0.02	0.106±0.01	0.092±0.01	0.104±0.02	0.090±0.01
S_{tot} (kg/m^2)	0.015±0.0	0.016±0.0	0.015±0.0	0.013±0.0	0.015±0.0	0.013±0.0

Analysis of basic topsoil properties showed no significant differences for soil texture (sand 55–68%, silt 14–21%, clay 18–24%), pH values (6.6–6.9) and $\delta^{13}C$ (-23.3 – -24.0‰) between UG79 and CG sites. Stocks for SOC, N_{tot} and S_{tot} calculated from 100 sampling locations for each site revealed a significant increase (25–45%) for UG79 compared to CG from both steppe types. BD decreased after grazing cessation and was approximately 20% lower compared to CG. In general, *Stipa* sites showed significantly ($P<0.01$) lower stocks of SOC, N_{tot}, S_{tot} and higher BD than *Leymus* sites.

Table 2. SOC, N_{tot}, S_{tot} stocks, BD, pH (n = 100 for *Stipa*, n = 123 for *Leymus* CG, n = 98 for *Leymus* UG79) and soil texture (n = 3) of continuously grazed (CG) and ungrazed (UG79) *Stipa* and *Leymus* dominated steppe types.

Site	SOC (kg/m^2)	N_{tot} (kg/m^2)	S_{tot} (kg/m^2)	BD (g/cm^3)	pH ($CaCl_2$)	Sand (mg/g)	Silt (mg/g)	Clay (mg/g)
Stipa CG	0.72±0.10	0.08±0.01	0.009±0.0	1.35±0.04	6.9±0.3	676±11	145±6	179±6
Stipa UG79	0.98±0.16	0.10±0.01	0.012±0.0	1.10±0.08	6.9±0.2	642±31	180±24	178±6
Leymus CG	0.87±0.16	0.09±0.02	0.011±0.0	1.17±0.07	6.6±0.4	548±52	211±35	242±21
Leymus UG79	1.17±0.21	0.12±0.02	0.016±0.0	0.94±0.10	6.6±0.2	642±55	135±41	223±17

The spatial distribution of SOM at the field scale showed generally a more heterogeneous pattern for UG79 sites and a homogeneous distribution at CG sites. However, semivariograms for SOC, N_{tot} and S_{tot} indicated a high spatial variability at smaller scales <5 m. This was confirmed by the analysis of the spatial SOM patterns at the plant scale. All semivariograms of both UG79 sites revealed semivariances approximately one order of magnitude higher compared to grazed sites, pointing towards a much stronger spatial dependence.

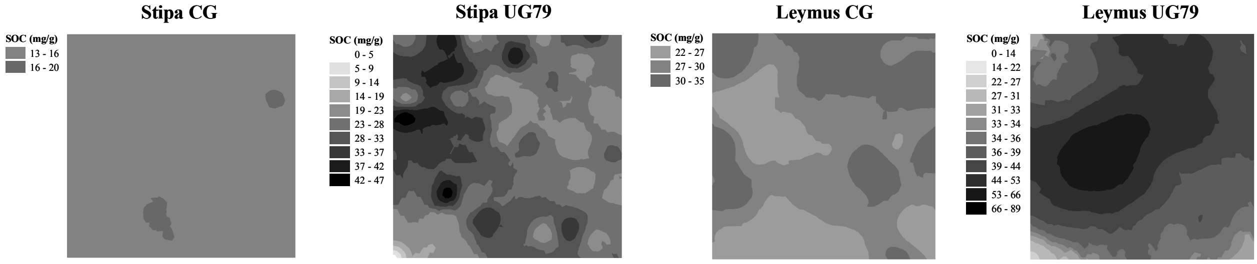

Figure 1. Spatial distribution of SOC at the plant scale (2 m × 2 m) of continuously grazed (CG) and ungrazed (UG79) *Stipa* and *Leymus* dominated sites.

The differences in terms of semivariance between grazed and ungrazed sites were more pronounced at the plant scale than the field scale. Ranges of spatial dependence at UG sites were about 23 cm for *Stipa* UG79 and 90 cm for *Leymus* UG79. Mean concentrations for SOC, N_{tot}, S_{tot} and BD determined at the plant scale for CG sites (40 sampling points) and for UG sites (20 points under bare soil areas and 20 points under vegetation patches) showed highly significant ($P < 0.001$) differences between vegetation patches and bare soil at both UG sites. CG sites and bare soil areas from UG sites revealed comparable values.

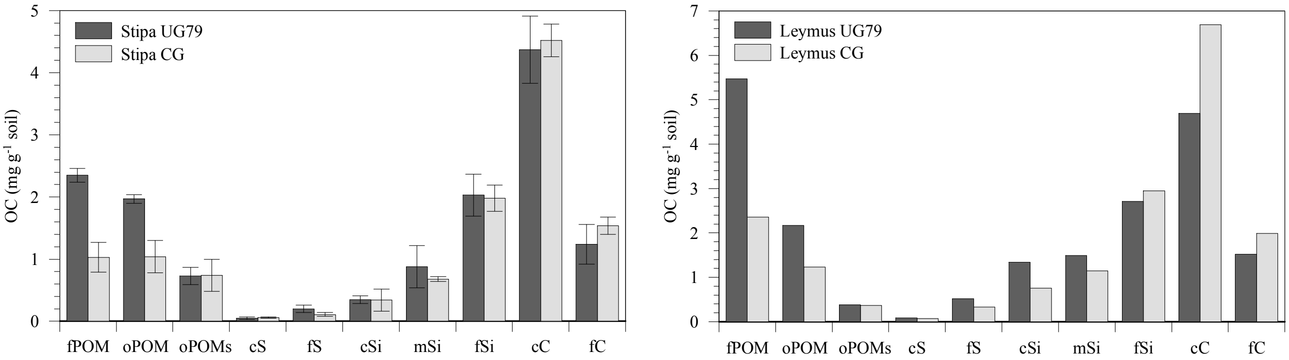

Figure 2. Contribution of OC from SOC fractions to the bulk soil of continuously grazed (CG) and ungrazed (UG79) *Stipa* (n = 3) and *Leymus* (n = 2) dominated sites (cS, fS, cSi, mSi, fSi, cC, fC = mineral fractions).

Results from the physical fractionation showed considerable higher amounts of SOC in free (fPOM) and in aggregate occluded particulate organic matter (oPOM) fractions for UG79 sites compared to CG sites. Grazing cessation had no effect on mineral fractions. Incubation of bulk topsoil samples from *Leymus* dominated sites showed a significantly higher carbon mineralization (+59%) for CG compared to UG79.

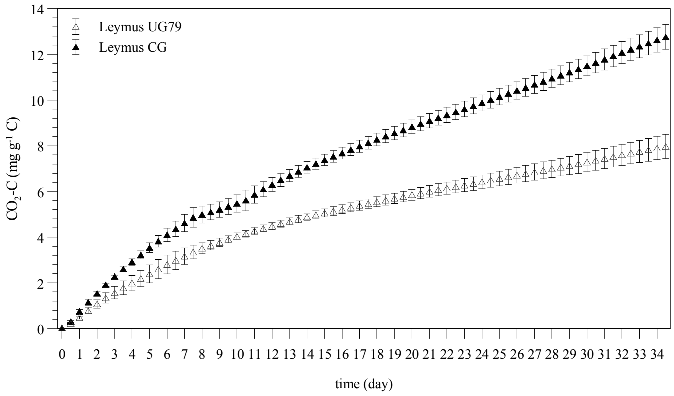

Figure 3. Carbon mineralization of continuously grazed (CG) and ungrazed (UG79) *Leymus* dominated sites.

Discussion and conclusions

Grazing exclusion for 3 years resulted in a significant increase of SOC (7%) (Table 1). Obviously, the recovery of degraded steppe soils starts with the cessation of grazing. After 30 years of grazing exclusion SOC stocks were approximately 35% higher for both *Stipa* and *Leymus* dominated steppe types compared to CG sites (Table 2). The ongoing carbon sequestration at long-term ungrazed grasslands indicates a high potential of degraded semi-arid steppes for mitigation of climate change after cessation of grazing. Increasing SOC stocks at ungrazed sites can be attributed to a higher input of organic matter into the soil as above- and belowground primary production is significantly higher there (Gao *et al.* 2008; Wiesmeier *et al.* submitted). This was confirmed by considerably higher amounts of POM at UG79 sites (Figure 2). The enhanced input of organic matter also promotes the formation of soil aggregates associated with a physical protection of labile SOC within aggregates. This was indicated by higher amounts of SOC in aggregate occluded POM at UG79 sites (Figure 2). Furthermore, a decrease of BD as a consequence of reduced mechanical stress was observed at ungrazed sites that probably supports soil aggregation. As a result of an enhanced physical proctection of SOM within soil aggregates, carbon mineralization is much lower at UG79 compared to CG (Figure 3). The increase of SOC after grazing exclusion starts with the formation of single resource patches. Analysis of the spatial distribution of SOC showed a homogeneous pattern for CG and a heterogeneous distribution for UG79. This patchy pattern can be explained by the development of "islands of fertility" under grass tussocks after grazing exclusion. This was apparent as the ranges of the spatial dependence of SOC were congruent with the extension of grass tussocks (Figure 1). Precipitation water as well as aeolian deposits are redistributed from bare soil areas with low infiltration to vegetation patches with higher infiltration. A higher input of water, which is the limiting factor in semi-arid steppes, and an increased accumulation of eroded materials at UG79 sites (Hoffmann *et al.* 2008) enhance primary production at single locations and create a heterogeneous pattern of vegetation and SOM. We conclude that these heterogeneous patterns are essential for carbon sequestration and productivity of semi-arid grasslands.

References

Gao YZ, Giese M, Lin S, Sattelmacher B, Zhao Y, Brueck H (2008) Belowground net primary productivity and biomass allocation of a grassland in Inner Mongolia is affected by grazing intensity. *Plant and Soil* **307**, 41-50.

Hoffmann C, Funk R, Wieland R, Li Y, Sommer M (2008) Effects of grazing and topography on dust flux and deposition in the Xilingele grassland, Inner Mongolia. *Journal of Arid Environments* **72**, 792-807.

IUSS (2006) World reference base for soil resources 2006. World Soil Resources Reports No. 103, FAO, Rome.

Lal R (2004) Carbon sequestration in dryland ecosystems. *Environmental Management* **33**, 528-544.

Steffens M, Kölbl A, Giese KM, Hoffmann C, Totsche KU, Breuer L, Kögel-Knabner I (2009a) Spatial variability of topsoil and vegetation in a grazed steppe ecosystem in Inner Mongolia (PR China). *Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernährung und Bodenkunde* **172**, 78-90.

Steffens M, Kölbl A, Kögel-Knabner I (2009b) Alteration of soil organic matter pools and aggregation in semi-arid steppe topsoils as driven by organic matter input. *European Journal of Soil Science*, doi: 10.1111/j.1365-2389.2008.01104.x.

Steffens M, Kölbl A, Totsche KU, Kögel-Knabner I (2008) Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (PR China). *Geoderma* **143**, 63-72.

Tong C, Wu J, Yong S, Yang J, Yong W (2004) A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. *Journal of Arid Environments* **59**, 133-149.

Wiesmeier M, Kreyling O, Steffens M, Schoenbach P, Wan H, Gierus M, Taube F, Kölbl A, Kögel-Knabner I (submitted) Soil and vegetation indicators for degradation of steppes due to short-term grazing in Northern China. *Journal of Arid Environments*.

Wiesmeier M, Steffens M, Kölbl A, Kögel-Knabner I (2009) Degradation and small-scale spatial homogenization of topsoils in intensively grazed steppes of Northern China. *Soil & Tillage Research* **104**, 299-310.

Xie ZB, Zhu JG, Liu G, Cadisch G, Hasegawa T, Chen CM, Sun HF, Tang HY, Zeng Q (2007) Soil organic carbon stocks in China and changes from 1980s to 2000s. *Global Change Biology* **13**, 1989-2007.

Yang X, Zhang K, Jia B, Ci L (2005) Desertification assessment in China: An overview. *Journal of Arid Environments* **63**, 517-531.