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Effects of fencing and grazing on the temporal dynamic of soil organic carbon content in two temperate grasslands in Inner Mongolia, China

X. Y. Ping and T. M. Wang

Research Center of Grassland Resource and Ecology, Beijing Forestry University, Beijing, China

ABSTRACT

This study aimed to investigate the impact of long-term grassland management on the temporal dynamic of SOC density in two temperate grasslands. The top soil SOC density, soil total nitrogen density and soil bulk density (0–20 cm) under long-term fencing and grazing treatments, the aboveground net primary productivity of fenced plots and the associated climatic factors of *Leymus chinensis* and *Stipa grandis* grasslands in Inner Mongolia were collected from literatures and analyzed. The results showed that the SOC density increased linearly with fenced duration but was insensitive to grazed duration in both grasslands. Compared with long-term grazing, fenced plots had larger potential for carbon sequestration, and the accumulation rate of SOC density was 29 and 35 g $Cm^{-2}y^{-1}$ for *L. chinensis* and *S. grandis* grasslands. Fenced duration and mean annual temperature jointly contributed large effect on temporal pattern of SOC density. Climate change and grazed duration had little influence on the inter-annual variance of SOC density in grazed plots. Our results confirmed the enhancement effect of long-term fencing on soil carbon sequestration in degraded temperate grassland, and long-term permanent plot observation is essential and effective for accurately and comprehensively understanding the temporal dynamic of SOC storage.

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Temporal pattern; carbon sequestration; climate change; grassland management; soil organic carbon

1. Introduction

Up to 70% of grassland carbon stock is stored belowground in soils (Scurlock and Hall 1998; He et al. 2008). Therefore, small changes in such large pools of soil carbon would have profound impact on global carbon cycle and positive feedback on climate change (Davidson and Janssens 2006; He et al. 2013). The soil carbon storage is controlled by the balance between carbon input through net primary productivity (NPP) and outputs through decomposition, harvest, fire, erosion, and leaching (Jobbágy and Jackson 2000). Many factors have been found to influence the input/output process in grassland ecosystem such as species

CONTACT X. Y. Ping pingxy@bjfu.edu.cn

composition, climate change, land-use change, and management practices (Wu et al. 2008; Wang et al. 2015; Bradford et al. 2016).

It has been widely accepted that appropriate management practices such as grazing, mowing, fertilization, and irrigation could increase soil carbon sequestration (He and Yu 2016; Song et al. 2014). Fencing (grazing enclosure) has been proven beneficial for increasing SOC storage in degraded grassland (Zhou et al. 2002; Golluscio et al. 2009; Wang et al. 2015). However, the effect of grazing on SOC storage is largely dependent on the grazing intensity. High grazing intensity always induces decline in SOC storage (Golluscio et al. 2009), while no significant reduction or even increase in SOC storage could be detected under light or moderate grazing intensity (Martinsen et al. 2011).

Permanent plot observation and chronosequence are two most commonly used methods for studying the temporal dynamic of soil properties (Bakker et al. 1996; Knops and Tilman 2000; Manies et al. 2016). Chronosequence method is often used to identify changes in species composition and soil properties during community succession (Knops and Tilman 2000; He et al. 2009; Wang et al. 2015). While permanent plot observation method is considered as the most accurate method for detecting the temporal changes in soil carbon storage and could give detailed description of soil properties during succession process (Bakker et al. 1996). However, very few studies have been consistently observed for multiple periods of time. Therefore, it is relatively difficult to determine the temporal dynamic of SOC contents during long-term ecological process (Poeplau et al. 2011).

This study addressed the issue of temporal dynamic of SOC densities under long-term fencing and grazing treatments in two temperate grasslands: *L. chinensis* and *S. grandis* grasslands, which were considered as the two most widely distributed grassland types in the Eurasia steppe region. We aimed to (1) investigate the long-term effects of fencing and grazing treatments on the temporal dynamic of SOC density, (2) identify the main factors controlling the temporal dynamic of SOC density, and (3) determine the annual change rate of SOC densities under long-term fencing and grazing treatments.

2. Materials and methods

2.1. Study area

This study was conducted in the Inner Mongolia Grassland Ecosystem Research Station (IMGERS, 116°42′E, 43°38′N, 1200 m) of the Chinese Academy of Sciences in Inner Mongolia, China. This area belongs to the Eurasian steppe region and is described as semi-arid continent climate. The mean annual temperature (MAT) of the study site is 0.7 °C and the mean annual precipitation is 331 mm, with most of the precipitation (86%) falls within the growing season (May–September). There was significant positive trend in the MAT in the past 23 years (1984–2007) ($r = 0.66$, $p = 0.002$, Figure 1(a)), which accounted for an increase of 2.0 °C during the research period, while the mean annual precipitation showed a slight decrease ($r = 0.41$, $p = 0.07$, Figure 1(b)).

The field experiments were conducted at two typical temperate grasslands: *L. chinensis* and *S. grandis* grasslands. Before 1979, the two study sites belonged to permanent pasture and had been freely grazed by sheep and cattle for thousands of years. The two fenced plots were established in 1979, since then never under any grazing practice. The fenced *L. chinensis*

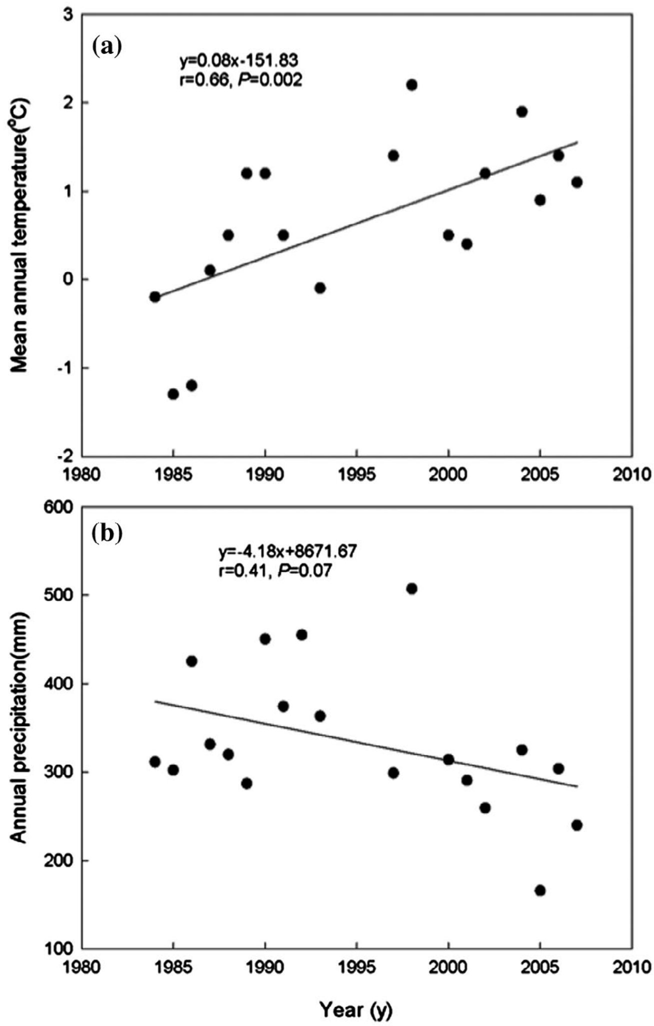

Figure 1. Temporal dynamics of MAT (mean annual temperature, a) and AP (annual precipitation, b) of the study area during 1984–2007.
Notes: Mean annual temperature (°C) and annual precipitation (mm) were obtained from China Meteorological Data Sharing Service System (Xilinhot). The AP slightly decreased during the past 23 years ($r = 0.41$, $p = 0.07$, Figure 1(b)), while the MAT increased significantly with a rate of 0.8 °C per decade ($r = 0.66$, $p = 0.002$, Figure 1(a)).

plot (116°40′E, 43°32′N) is about 24 ha. The soil type is classified as typical chestnut soil (Calcic-orthic Aridisol). The dominant species is *L. chinensis,* other species like *S. grandis*, *Agropyron cristatum*, and *Cleistogenes squarrosa* are companion species.

The fenced *S. grandis* plot (116°33′E, 43°32′N, 1070 m) located adjacent to fenced *L. chinensis* plot with an area of 25 ha. The soil type belongs to typical chestnut (Calcic-orthic Aridisol). The companion species included *L. chinensis, A. cristatum*, and *C. squarrosa*.

The two grazing plots were established adjacent to the fenced plots with area of more than 200 ha. Moreover, both grazing plots were used as pasture with light grazing intensity. The livestock consume about 65% of the aboveground biomass each year with the vegetation cover ranged from 25 to 30% (Cui et al. 2005).

2.2. Experimental design

The data from literatures conducted in the fenced and grazed *L. chinensis* and *S. grandis* plots from 1984 to 2007 were listed in Table 1. Overall, 69 measurement data of soil properties were collected from 11 individual experiments. In addition to SOC content, soil total nitrogen (TN) content, soil bulk density, measurement techniques, MAT, annual precipitation (AP), and aboveground net primary productivity (ANPP) were recorded when presented. All the samples were taken from the same study site and only differed in the sampling year, which could reduce the spatial heterogeneity of SOC content as much as possible.

2.3. Data analyses

The SOC and TN densities (0–20 cm) were calculated based on the following equations (Yang et al. 2007):

$$\mathrm{SOCD} = \mathrm{D} \times \mathrm{BD} \times \mathrm{SOC} \tag{1}$$

$$\mathrm{TND} = \mathrm{D} \times \mathrm{BD} \times \mathrm{TN} \tag{2}$$

where SOCD and TND represented the densities of soil organic carbon (kgC m^{-2}) and total nitrogen (kg Nm^{-2}), and D, BD, SOC, and TN represented the soil layer thickness (cm), soil bulk density (g cm^{-3}), SOC content (%), and soil TN content (%), respectively.

If the SOC content was expressed as percent C by weight without the measurement of soil bulk density (29 of the 69 measurements), empirical relationship between soil bulk density and SOM content developed by Yang et al. (2007) was used to estimate soil bulk density (Equation (3)). The verification result based on the measured soil bulk density showed that Equation (3) could give reliable estimation of soil bulk density ($y = 1.02x$, $n = 40$, $R^2 = 0.46$, $p < 0.001$).

$$\mathrm{BD} = 0.29 + 1.20\mathrm{exp} - 0.08\mathrm{SOM} \tag{3}$$

where BD represented the soil bulk density (g cm^{-3}) and SOM referred to soil organic matter content (SOC/0.58) (%).

Table 1. Data characteristics used in this study.

References	Grassland type	Management practices	Sampling year
Wang (2006)	*L. chinensis, S. grandis*	Fencing, Grazing	1984–1988, 1996, 2002, 2005
Guan et al. (1999)	*L. chinensis, S. grandis*	Fencing, Grazing	1989–1993
Li (1999)	*L. chinensis, S. grandis*	Fencing, Grazing	1997
Geng et al. (2001)	*L. chinensis, S. grandis*	Fencing, Grazing	1998
Cui et al. (2005)	*L. chinensis, S. grandis*	Fencing, Grazing	2000
Dong et al. (2005)	*L. chinensis*	Fencing	2001
Li et al. (2005)	*L. chinensis, S. grandis*	Grazing	2001
Li et al. (2004)	*S. grandis*	Fencing, Grazing	2001
Zhao et al. (2010)	*L. chinensis*	Fencing	2004
Yan et al. (2008)	*L. chinensis, S. grandis*	Fencing, Grazing	2006
He et al. (2009)	*L. chinensis*	Fencing, Grazing	2007

2.4. Statistical analyses

Kolmogorov–Smirnov test was used to check the normality of variables. Paired t-test and independent *t*-test were used to detect the difference in SOC density between fenced and grazed plots and two grasslands. Correlation analysis, partial correlation analysis and multiple stepwise regression analysis were conducted relating SOC density to climatic variables, treatment duration, ANPP, and soil nitrogen content to determine the main factors regulating the temporal dynamic of SOC density. Partial correlation analyses were used to identify the relative importance of individual variables on the temporal dynamic of SOC density. Coefficients of variation (CVs, standard deviation/mean) of SOC density were used to detect the temporal variability of SOC density. All the statistical analyses were carried out using R Statistical Software (version 2.14.0). The level of significance for all the tests was $p < 0.05$.

3. Results

3.1. Temporal dynamics of SOC density under long-term fencing and grazing treatments

The SOC density showed a significant positive correlation with fencing duration for both two grasslands (*L. chinensis* $r = 0.58$, $p < 0.01$, Figure 2(a); *S. grandis*, $r = 0.63$, $p < 0.01$, Figure 2(c));

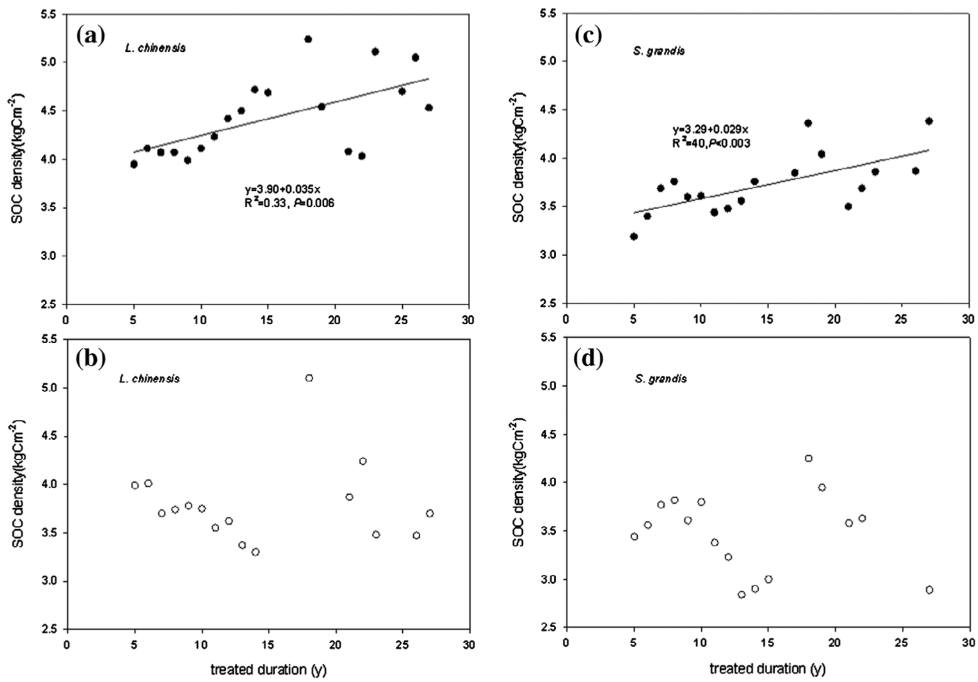

Figure 2. Temporal patterns of soil organic carbon (SOC) density under long-term fencing and grazing treatments in two temperate grasslands.

Notes: Filled circle represents fenced plots and empty circle represents grazed plots. There were significant positive liner relationships between SOC densities with fencing duration for both fenced plots (Figure 2(a) and (c)). As for grazed plots, the SOC density was insensitive to grazing duration (Figure 2(b) and (d)). The two fenced plots were both established in 1979 and since then never under any management scheme. While the grazed plots were established adjacent to the two fenced plots and had been lightly grazed for thousands of years.

as for grazed plots, the SOC density was insensitive to grazing duration (Figure 2(b) and (d)). The fenced plots had greater SOC densities compared with the grazed plots (Figure 3), and it was significant for *L. chinensis* grassland (4.37 ± 0.10 vs. 3.79 ± 0.11 kg Cm^{-2}, $t = 4.44$, df = 15, $p < 0.001$).

L. chinensis grassland had significant higher SOC densities than *S. grandis* grassland for both fenced and grazed plots (fenced plot: 4.37 ± 0.10 vs. 3.72 ± 0.07 kg Cm^{-2}, $t = 5.91$, df = 35, $p < 0.001$; grazed plot: 3.79 ± 0.11 vs. 3.48 ± 0.10 kg Cm^{-2}, $t = 2.11$, df = 30, $p = 0.04$).

Compared with the grazed plots, fencing treatment could reduce the interannual variability (coefficients of variation, CVs) of SOC density for both grasslands. The CVs for SOC density were 9 and 11% for fenced and grazed *L. chinensis* grassland, and were 8 and 12% for fenced and grazed *S. grandis* grassland.

3.2. Factors affecting temporal dynamics of SOC density under long-term fencing and grazing treatments

Fenced duration and MAT had significant positive correlation with SOC densities in both fenced *L. chinensis* grassland (fenced duration: $r = 0.61$, $p = 0.006$; MAT: $r = 0.50$, $p = 0.04$, Table 2) and *S. grandis* grassland (fenced duration: $r = 0.66$, $p = 0.003$; MAT: $r = 0.56$, $p = 0.02$, Table 2). There were significant positive relationships between treated duration and MAT in the four plots ($r = 0.61$–0.65, $p < 0.01$). In order to quantify the single effect of treated duration on SOC density, partial correlation coefficient analyses were conducted and the results showed that fenced duration had significantly positive effect on SOC density (*L. chinensis*

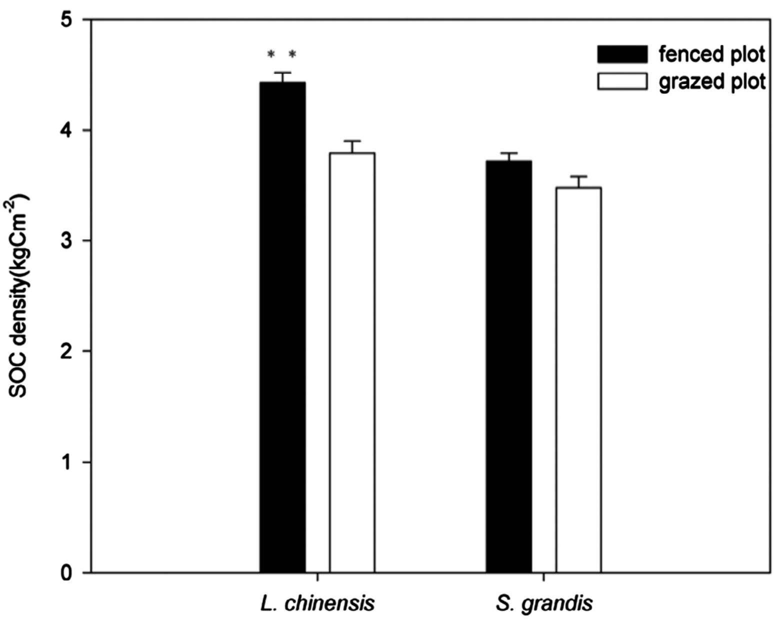

Figure 3. The mean SOC densities of fenced and grazed plots in two temperate grasslands during 1984–2007.

Notes: The values are expressed as means ± SE. Statistical differences in SOC density between fenced and grazed plots in *L. chinensis* ($t = 4.44$, df = 15, $p < 0.001$) and *S. grandis* grasslands ($t = 1.87$, df = 15, $p = 0.08$) were detected by paired *t*-test. **Denotes $p < 0.01$.

Table 2. Pearson correlation coefficients (lower triangle) and partial correlation coefficients (upper triangle) among SOC density, TN density, treated duration, and climatic factors in two fenced grasslands.

Grassland type		SOCD (kg Cm^{-2})	TND (kg Nm^{-2})	ANPP (gm^{-2}y^{-1})	Treated duration (y)	MAT (°C)	AP (mm)
Fenced *L. chinensis* grassland	SOCD		0.36	−0.04	0.68**	0.49*	−0.30
	TND	0.22		0.34	−0.10	−0.12	−0.09
	ANPP	−0.02	0.36		−0.33	−0.07	0.48*
	Treated duration	0.61**	−0.10	−0.39		0.63**	−0.35
	MAT	0.50*	−0.11	−0.11	0.65**		0.06
	AP	−0.25	−0.02	0.51*	−0.34	0.06	
	C:N ratio	0.45	−0.76**	−0.34	0.51*	0.52*	−0.19
Fenced *S. grandis* grassland	SOCD		−0.40	−0.25	0.85**	0.56*	−0.06
	TND	−0.18		0.23	−0.55*	−0.39	0.07
	ANPP	−0.07	0.20		−0.14	0.03	0.96**
	Treated duration	0.66**	0.02	−0.32		0.69**	0.10
	MAT	0.56*	−0.09	0.01	0.61**		0.16
	AP	−0.12	−0.30	0.83**	−0.35	0.01	
	C:N ratio	0.70**	−0.82	−0.33	0.44	0.40	0.07

Notes: $n = 19$ and 18 for *L. chinensis* and *S. grandis* grasslands, respectively. SOCD and TND represent the soil organic carbon density (kg Cm^{-2}) and soil total nitrogen density (kg Nm^{-2}) of the surface soil (0–20 cm), which were calculated based on the soil organic carbon content (%), total nitrogen content (%) and soil bulk density (g cm^{-3}). Treated duration represents the fencing year (y), MAT represents the mean annual temperature (°C), while AP represents the annual precipitation (mm). **Denotes $p < 0.01$, while *Denotes $p < 0.05$.

$r = 0.68$, $p = 0.003$; *S. grandis* $r = 0.85$, $p < 0.001$). ANPP, soil TN density and AP played minor role in regulating the temporal pattern of SOC density for both fenced grasslands. ANPP was significantly positively correlated with AP for both fenced plots (partial correlation coefficients: *L. chinensis* $r = 0.48$, $p = 0.04$; *S. grandis* $r = 0.96$, $p < 0.001$).

A positive correlation between SOC density and soil TN density was found in two grazed plots, and this trend was statistically significant in grazed *S. grandis* grassland ($r = 0.53$, $p = 0.04$) (Table 3). The SOC density was insensitive to grazed duration and climate change in two grazed plots. The soil TN density was significantly negatively correlated with grazed

Table 3. Pearson correlation coefficients (lower triangle) and partial correlation coefficients (upper triangle) among the SOC density, TN density, treated duration, and climatic factors in two grazed grasslands.

Grassland type		SOCD (kg Cm^{-2})	TND (kg Nm^{-2})	Treated duration (y)	MAT (°C)	AP (mm)
Grazed *L. chinensis* grassland	SOCD	–	0.29	0.01	0.12	−0.22
	TND	0.38	–	−0.83**	−0.45*	0.41
	Treated duration	0.01	−0.79**	–	0.64**	−0.57*
	MAT	0.12	−0.42	0.62*	–	−0.36
	AP	−0.22	0.31	−0.51**	−0.32	–
	C:N ratio	0.76**	−0.30	0.53**	0.41	−0.48
Grazed *S. grandis* grassland	SOCD	–	0.48*	−0.16	0.19	−0.13
	TND	0.53*	–	−0.87**	−0.40	0.09
	Treated duration	−0.14	−0.84**	–	063**	−0.02
	MAT	0.19	−0.45	0.61**	–	0.16
	AP	−0.14	0.27	−0.35	0.01	–
	C:N ratio	0.43	−0.53*	0.74**	0.58*	−0.23

Notes: $n = 16$ for both *L. chinensis* and *S. grandis* grasslands. Treated duration represents the grazing year (y), MAT represents the mean annual temperature (°C), while AP represents the annual precipitation (mm). **Denotes $p < 0.01$, while *Denotes $p < 0.05$.

duration for both plots (partial correlation coefficients: *L. chinensis* $r = 0.83$, $p < 0.001$; *S. grandis* $r = 0.87$, $p < 0.001$).

Multiple stepwise linear regression analyses showed that the SOC density was mainly controlled by fenced duration and soil TN density in fenced *L. chinensis* grassland ($R^2 = 0.60$, $p = 0.002$). Fenced duration was the determinant factor for predicting SOC density in fenced *S. grandis* grassland ($R^2 = 0.70$, $p = 0.004$) (Table 4). While in grazed plots, grazed duration and SOC density were the two major determinants for soil TN density (*L. chinensis*: $R^2 = 0.75$, $p < 0.001$; *S. grandis*: $R^2 = 0.85$, $p < 0.001$). ANPP was co-controlled by fenced duration and SOC density for fenced *S. grandis* grasslands ($R^2 = 0.97$, $p < 0.001$).

4. Discussion

4.1. Long-term impacts of fencing and grazing treatments on the SOC density

Grazing exclusion (fencing treatment) resulted in linear increase in SOC density in both fenced plots, and the accumulation rates of SOC density were 29 and 35 g $Cm^{-2}y^{-1}$ for *L. chinensis* and *S. grandis* grasslands, respectively. Compared with other management practices in temperate grasslands, i.e. abandonment or convert from cropland to grassland, fencing treatment showed a relatively higher efficiency in carbon accumulation (Knops and Tilman 2000; Wang et al. 2015). Studies based on chronosequence method at the same site showed that the SOC and TN density increased logarithmically with fenced duration in *L. chinensis* grassland, and attained stable condition after 20 years of grazing enclosure (Wu et al. 2008; He et al. 2009). However, the accumulation of SOM is a relatively slow process and will require quite long time to recovery. At least 100 and 230 years or even longer time is required for sink saturation of soil carbon in Minnesota sand plain and temperate grasslands (Knops and Tilman 2000; Poeplau et al. 2011). The interannual variation of SOC density was generally low in our study site (8–12%). Furthermore, fencing treatment could reduce the temporal variability of SOC density. Such small inter-annual variability would require relatively long-term duration to quantify the temporary dynamic of SOC storage (Saby et al. 2008). These results suggested that 30 years were relatively too short for soil carbon to reach the sink saturation (a new equilibrium), and there was still large potential for carbon sequestration in the two temperate grasslands after 30 years of fencing management.

Our result is consistent with previous reports indicating that fencing is a simple and effective method for restoring soil carbon in degraded grasslands (Knops and Tilman 2000;

Table 4. Multiple stepwise linear regression relationships for predicting the SOC and TN density in fenced and grazed *L. chinensis* and *S. grandis* grasslands.

Grassland type	Independent variables	Regression equation	$R^2_{Adjusted}$	*P* value
Fenced *L. chinensis* grassland	SOC density (kg Cm^{-2})	$y = 0.04$fenced duration + 3.40TN + 2.07	0.60	0.002
Fenced *S. grandis* grassland	SOC density (kg Cm^{-2})	$y = 0.05$fenced year + 3.11	0.70	<0.001
	ANPP ($gm^{-2}y^{-1}$)	$y = -3.18$fenced duration + 1.11AP − 3.10	0.97	<0.001
Grazed *L. chinensis* grassland	Soil TN density (kg Nm^{-2})	$y = -0.005$grazed duration + 0.032SOC + 0.42	0.75	<0.001
Grazed *S. grandis* grassland	Soil TN density (kg Nm^{-2})	$y = -0.007$grazed duration + 0.05SOC + 0.38	0.85	<0.001

Notes: In fenced plots, the predicting factors including fenced duration, mean annual temperature (MAT), annual precipitation (AP), and aboveground net primary productivity (ANPP); as for grazed plots, ANPP was not included in the analysis.

He et al. 2009; Knops and Bradley 2009; Wang et al. 2015). Moreover, compared with the *S. grandis* grassland, *L. chinensis* grassland had greater potential to sequester topsoil carbon. The mean SOC density increased 15 and 7% for *L. chinensis* and *S. grandis* grasslands, respectively compared with grazed plots. Fencing had been considered with great potential to restore the SOC density in heavily degraded grasslands (33% in desert sandy grassland, 55% in southern Great Plain) (Wu et al. 2008; Golluscio et al. 2009).

There were two possible explanations for the unchanged SOC density in two grazed plots. Firstly, more than 60% of the aboveground biomass was consumed by livestock each year in two grazed plots, such decrease in litter input would lead to decline in SOC density (Pineiro et al. 2010); besides that, it has been well demonstrated that the soil bulk density would increase with long-term grazing due to soil compaction caused by livestock trampling. The increase in soil bulk density would further lead to elevated SOC density (Cui et al. 2005). The trade-off between these two aspects might result in unchanged SOC density under long-term grazing treatments. Secondly, unchanged SOC density in grazed plots was probably due to well-adapted plant species composition under long-term grazing. This study site had been continuously grazed for thousands of years. Therefore, the vegetation was mostly composed of grazing-tolerant species (Cui et al. 2005; Li et al. 2008). The adaptation to long-term grazing resulted in unchanged SOC density.

4.2. Factors contributing to the temporal dynamic of SOC density in fenced plots

Previous reviews have demonstrated that the processes controlling input and output of SOC storage, i.e. climate change, grassland management, land-use change, site fertility, hydrology, and species composition would have large impact on soil carbon sequestration (Poeplau et al. 2011; Wang et al. 2015). Our results showed that climatic variables, grassland management practices, treated duration and grassland type all affected the temporal dynamic of SOC density. Partial correlation analysis showed that compared with MAT, fenced duration had greater impact on the temporal dynamic of SOC density ($r = 0.68, 0.85$ vs. $r = 0.49, 0.56$ for *L. chinensis* and *S. grandis* grasslands, Table 2). Furthermore, 48 and 70% of the interannual variance of SOC density in *L. chinensis* and *S. grandis* grasslands could be explained by fenced duration (Table 4).

However, contrary to other studies, ANPP and AP had little influence on the temporal dynamic of SOC density in two fenced plots (Table 2). It has been demonstrated that the spatial pattern of SOC density was positively correlated with AP and negatively correlated with MAT over large spatial scales (Jobbágy and Jackson 2000; Zhou et al. 2002; Liu et al. 2011). Our results indicated that there were differences in controlling factors of SOC density between spatial and temporal scales.

The potential response of SOC storage to global warming has recently received considerable attention for its impact on global carbon cycle and the potential feedbacks to atmospheric composition (Jobbágy and Jackson 2000; Davidson and Janssens 2006). The SOC density increased linearly with increasing MAT in our study sites, which was different from previous reports indicating that the reduction in soil carbon storage was mainly due to accelerated decomposition in warming condition (Kirschbaum 2000; Davidson and Janssens 2006; He and Yu 2016). Ma et al. (2010) reported that increasing temperature significantly increased the aboveground biomass (21.8%) in early growing season (May) in fenced plots during 1982–2003. The stimulation of grassland plant growth in early spring might increase the soil carbon density in fenced grasslands. Moreover, variations of organic matter input due to changes in the allocation scheme of NPP with greater root: shoot ratios might contribute to the temporal dynamic of SOC density (Poeplau et al. 2011). Plants would allocate more carbon to belowground when confront with drought stress (Litton and Giardina 2008). The larger proportion of carbon allocated to belowground with increased MAT might result in higher litter input into soil and consequently increased the SOC density. However, at present, given the difficulty of calculating belowground net primary productivity (BNPP), which would restrict the accurate assessment of global carbon budget in response to climate change (Ma et al. 2010).

4.3. Factors contributing to the temporal dynamic of SOC density in grazed plots

The small changes in temporal dynamic of SOC density in grazed plots might be caused by the following two aspects. Firstly, the community species composition of the grazed plots was relatively stable after thousands of years grazing. Secondly, the SOC density was the consequences of trade-off between changes in carbon allocation scheme and constrained plant growth. Water deficiency resulted from increased MAT and slightly decreased AP in the study site would influence the allocation scheme of NPP. More carbon would allocate to belowground and subsequently increase the SOC density. Meanwhile, the accumulation of SOC was constrained by limited plant growth due to soil nutrition deficiency as the TN density decreased linearly with grazing duration (Tables 2 and 3). Moreover, such reduction would be aggravated by ammonia volatilization from animal manure in grazed plots (Bakker et al. 2004).

5. Conclusions

Compared with grazed plots, fencing treatment had greater potential for carbon sequestration, which indicated that fencing treatment could be beneficial for restoring soil carbon storage in degraded grassland. Moreover, it usually requires hundreds of years for soil carbon to reach new equilibrium due to slow process in accumulation of SOM. Therefore, we suggest that there is still large potential for carbon sequestration in the two fenced grasslands.

Fencing duration had large impact on the temporal dynamic of SOC density, and MAT had positive effect while AP played a minor role in regulating the temporal pattern of SOC density in fenced plots. The soil carbon response function based on fencing duration provides an easy and efficient way for predicting the dynamic of SOC under long-term fencing. However, the interactions between management practices and climatic factors make it difficult for us to accurately predict temporal dynamic of SOC density along with grassland management. Therefore, more attentions should be paid to separate the effect of climate change and management practices on the temporal dynamic of SOC storage in the future. Long-term grazing had little influence on the SOC density in both two grasslands, which was largely due to well-adapted plant species composition in grazed plots. However, the soil nitrogen content decreased continuously under long-term grazing, which would have a profound influence on the carbon cycling in the semi-arid temperate grassland.

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Disclosure statement

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