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Grazing exclusion significantly improves grassland ecosystem C and N pools in a desert steppe of Northwest China

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ABSTRACT

Grazing exclusion is often implemented as an effective management practice to increase the sustainability of grassland ecosystems. However, it remains unclear if grazing exclusion can improve ecosystem services related to carbon (C) and nitrogen (N) sequestration in grassland ecosystems. We investigated the effects of 11 years of grazing exclusion on plant biomass and diversity, soil properties (pH, soil water content (SWC), bulk density (BD), soil organic carbon (SOC), total nitrogen (TN), and C/N ratio), and the C and N stocks of plants and soils in a desert grassland of Northwest China. Grazing exclusion improved plant aboveground biomass and diversity, as well as SWC, SOC, and TN contents, but lowered the belowground biomass, root/shoot ratio, pH, and BD. Moreover, grazing exclusion strongly influenced the C and N stocks of the ecosystem, and the annual mean ecosystem C and N sequestration rates were 0.47 and 0.09 Mg ha^{-1} yr^{-1}, respectively, over 11 years of grazing exclusion. Soil C stocks were most dynamic in the top 30 cm of the soil, and N stocks mainly changed in the top 20 cm after grazing exclusion. Our results indicated that grazing exclusion is an effective measurement on improving the ecosystem C and N pools in desert steppe of Northwest China.

1. Introduction

Carbon (C) and nitrogen (N) are key nutrients for all living organisms on earth and play important roles in regulating both the structure and function of terrestrial ecosystems (Elser et al., 2010). Grasslands account for approximately 25% of the land surface of the earth and 10% of global carbon stocks and are thus vital to global carbon cycling (Scurlock et al., 2002; Yang et al., 2010).

Grazing is an important type of disturbance and a critical controlling factor of ecosystem functioning in natural grasslands (Pineiro et al., 2009; Zhou et al., 2010; Hafner et al., 2012). Overgrazing severely reduces grassland productivity, vegetation cover, and the proportion of forage grasses (Evju et al., 2009; Schonbach et al., 2011). Many pastures have become degraded as a result of heavy grazing (Stavi et al., 2008; Steffens et al., 2008), which increases the risk of soil erosion and desertification (Zhao et al., 2005; Zhou et al., 2010). Furthermore, overgrazing may reduce the C and N stocks of grassland ecosystems (Shrestha and Stahl, 2008; Pineiro et al., 2009; Wang et al., 2014). Conversely, grazing exclusion could improve plant diversity, C and N stocks, and other soil properties of such ecosystems (Wu et al., 2010; Qiu et al., 2013; Deng et al., 2014a).

Globally, grazing exclusion has been used effectively to increase the sustainability of grassland ecosystems (Mcsherry and Ritchie, 2013). Grasslands have high inherent soil C pools and N contents that supply plant nutrients; increase soil aggregation, cation exchange, and water holding capacities; and limit soil erosion (Kool et al., 2007). Soil C and N contents in rangelands are highly relevant for carbon sequestration. However, the effects of grazing exclusion on ecosystem services related to C and N pools are inconsistent; exclusion promotes C and N pools in some cases (Deng et al., 2014a; Zhou et al., 2011), decreases them in other studies (Hafner et al., 2012; Shi et al., 2013), and in some experiments has no effect (Medina-Roldan et al., 2012; Yang et al., 2010). Due to the low productivity and small distribution area, the desert grassland ecosystem in Asia has been paid with less attentionas compared to the prairie in North America and Savanna in Africa (Collins and Calabrese, 2012; Eby et al., 2014; Koerner et al., 2014; Tagesson et al., 2015). However, the desert grassland ecosystem has a great importance in terms of preventing the expansion of desertification and also improving the regional ecological environment (Zhao et al., 2005). Moreover, the extremely low soil organic matter and nitrogen content in desert grassland ecosystem might induce different response sensitivities to grazing exclusion as compared to other grassland ecosystem (Wen et al., 2013). Yet very few data are available regarding grazing effects on C and N pools in natural desert grassland systems.

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In China, approximately 0.39 M km^2 of land has become desertified, of which 28.3% is associated with overgrazing (Zhao et al., 2005). Grazing exclusion is regarded as the most effective method for restoring degraded grasslands and reversing grassland desertification. Several previous studies have investigated the vegetation succession (Jing et al., 2013), species diversity (Deng et al., 2014b), and soil microbial structure (Huang et al., 2011) of typical temperate steppes under grazing exclusion. However, comparably less information is available on the effects of grazing exclusion on plant diversity and productivity, soil properties, and C and N stocks in desert grassland ecosystems. Therefore, additional research is necessary to examine the direct effects of grazing exclusion on the plant and soil C and N pools in desert grasslands.

In the present study, we assessed the effects of 11 years of grazing exclusion on vegetation biomass, plant diversity, soil properties, and the C and N pools of a grassland ecosystem in a desert steppe of Northwest China. This study aimed to better understand the effects of grazing exclusion on the (i) plant community properties, (ii) soil physical and chemical properties, and (iii) C and N stocks of desert grassland ecosystems.

2. Material and methods

2.1. Study area

The study was conducted in a desert steppe at an altitude of 1420 m near the town of Gaoshawo (37°56′ N, 107°01′ E) in Yanchi County, Ningxia Province, China. Historical data for the period 1981–2010 show that the mean annual temperature for this area was 8.6 °C, ranging from −7.9 °C in January to 23.1 °C in July, and the mean annual precipitation was 282.4 mm, the majority of which occurred in summer and autumn. The terrain is gentle hilly with the slope generally less than 10°. The soil type is aridisols (USDA) which developed from loess parent materials. The soil texture is sandy loam with the sand content being more than 70%. Soil pH ranges from 8.0–9.0 and calcium carbonate is more than 10%. The vegetation is typical of desert steppes and is dominated by *Agropyron mongolicum* (Poaceae), *Lespedeza potaninii* (Leguminosae), *Glycyrrhiza uralensis* (Leguminosae), and *Peganum multisectum* (Zygophyllaceae).

Since 1999, the grasslands in this area have been improved by the Chinese government's implementation of the "Returning Grazing Land to Protected Grassland" project. The local government implements the project in this area by prohibiting grazing and fencing large areas of the grasslands. Therefore, many fenced grasslands are maintained to ensure sustainable pasture management.

2.2. Sampling and measurements

2.2.1. Experimental design

The experiment was conducted in blocks of fenced grassland (FG) and grazing grassland (GG) located outside the fence (Fig. 1). The FG block, comprising an area of over 100 ha, was established as a grassland conservation district by the local government 11 years ago (in 2000). Since this point, the area has been constantly fenced and has not experienced grazing. Outside the fence, the grassland suffered different grazing intensities, ranging from three to eight cattle per ha. The FG and GG blocks were close to each other in our study.

The experiment was conducted in early August 2011, when the grassland biomass was at its peak. Throughout each block, ten 20 m × 20 m plots were selected randomly following the line transect method (Fig. 1). Four plots were chosen in each side transect, and two plots in the middle transect. Within the center and four corners of each plot, five 1 m × 1 m quadrats were chosen to survey the community cover and height, plant composition and height, density (number of individuals per taxon) and aboveground biomass of individual species, belowground

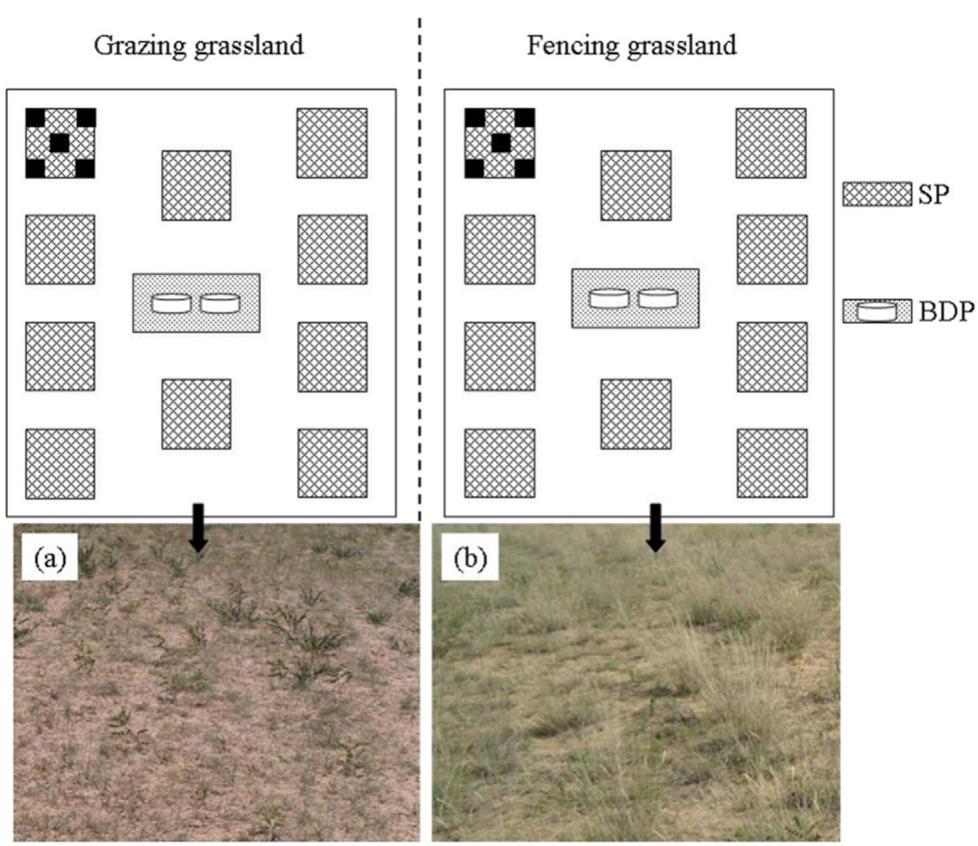

Fig. 1. The design of the samplings in the fencing and grazing grasslands. Note: five 1 m × 1 m quadrats within the center and four corners were chosen in each plot. Photos (a) and (b) showed the community profile of grazing and fencing grasslands, respectively. SP, sampling plots, BDP, soil bulk pit.

biomass, litter, and soil properties from 0 to 100 cm. Additionally, in the center of the FG and GG blocks, we dug a pit to sample soil bulk density (BD) (Fig. 1).

2.2.2. Biomass measurement

In each quadrat, all green aboveground parts of individual species were cut, collected from the ground, put into envelopes, and tagged, as was all litters. To measure belowground biomass, soil sampling was conducted at three points in each quadrat using a 9 cm diameter root auger at depths of 0–5, 5–10, 10–20, 20–30, and 30–50 cm. The root biomass below 50 cm was too low to be measured, and was negligible. These three points were in the corners and at the center of each quadrat along a diagonal direction, and samples from the same layer were then mixed together to make one sample. The majority of the roots were found in the soil samples and were isolated using a 2 mm sieve. The remaining fine roots taken from the soil samples were isolated by spreading the samples in shallow trays, overfilling the trays with water, and allowing the outflow from the trays to pass through a 0.5 mm mesh sieve. No attempts were made to distinguish between living and dead roots. All isolated roots were oven-dried at 65 °C and weighed. Due to the large sizes of the aboveground biomass samples, they were first weighed fresh, and then a part of each sample was dried and weighed. The aboveground biomass of the samples was calculated by multiplying the ratio of the dry/fresh weight ratio by the fresh weight. The total aboveground biomasses of the quadrats represented the sum of the aboveground biomasses for each species.

2.2.3. Species diversity

Species richness indicates the number of species in each quadrat. The richness index (*R*), Shannon–Wiener diversity index (*H*), and evenness index (*E*) of the fenced and grazed grassland communities were calculated as follows:

Richness index (*R*):

$$R = S \tag{1}$$

Shannon–Wiener diversity index (*H*):

$$H = -\sum_{i=1}^{s} (Pi \ln Pi) \tag{2}$$

Evenness index (*E*):

$$E = \frac{H}{\ln S} \tag{3}$$

where *S* is the total number of species in the grassland community, *H* is the Shannon–Wiener diversity index, and *Pi* is the density proportion of species *i*.

2.2.4. Soil sampling and determination

Soil samples were taken at three points along the diagonal direction opposite to that used for root sampling in each quadrat. The litter layer was removed before soil sampling. A soil drilling sampler (5 cm inner diameter) was used to sample at 0–5, 5–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm in depth. Samples from the same layer were then mixed together to make one sample. All samples were sieved through a 2 mm mesh, and the roots and other debris were removed. Each sample was air-dried and stored at room temperature until the determination of soil physical and chemical properties. The soil bulk density (g cm^{-3}) at different soil layers (0–5, 5–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm) was measured using a 100 cm^3 soil bulk sampler in the center of the FG and GG blocks. We gathered ten replicates in each sampling pit.

Soil water content was measured gravimetrically and expressed as a percentage of soil water to dry soil weight. Soil pH was determined using a soil:water ratio of 1:5 (PHS-3C pH acidometer, Shanghai, China). Soil BD was calculated from the inner diameter of the core sampler, sampling depth, and the oven-dried weight of the composite soil samples. SOC content was assayed by dichromate oxidation (Nelson and Sommers, 1982), and soil TN content was assayed using the Kjeldahl method (Bremner, 1996). Two replicates were conducted for each analysis.

2.3. Calculation of C and N stocks

2.3.1. Plant C and N stocks

The following equations were used to calculate the plant C and N stocks:

$$C_P = \frac{B \times C_f}{100} \tag{4}$$

$$N_P = \frac{B \times N_f}{100} \tag{5}$$

where C_p and N_p are the vegetation C and N stocks (Mg ha^{-1}), respectively; B is the vegetation biomass (g m^{-2}); and C_f and N_f are the plant biomass C and N contents, respectively.

2.3.2. Soil C and N stocks

It should be noted that no coarse fraction (>2 mm) was found in any of the sample soils. The term (1-coarse fragment (%)) could thus be omitted from our calculations. We used the following equation to calculate soil C stocks (Cs):

$$Cs = BD \times SOC \times D \times 10 \tag{6}$$

where Cs is the soil C stocks (Mg ha^{-1}), BD is the soil bulk density (g cm^{-3}), SOC is the soil organic carbon content (g kg^{-1}), and D is the soil thickness (cm).

The following equation was used to calculate soil N stocks (Ns):

$$Ns = BD \times TN \times D \times 10 \tag{7}$$

where Ns is the soil N stocks (Mg ha^{-1}), BD is the soil bulk density (g cm^{-3}), TN is the soil TN content (g kg^{-1}), and D is the soil thickness (cm).

2.4. Statistical analysis

All data were expressed as the mean ± standard deviation (SD) of the mean for ten blocks. After a normal distribution test for data, one-way analysis of variance (ANOVA) was performed to test for differences of biomass, plant diversity, soil properties, and plant, soil, and grassland ecosystem (plant and 0–100 cm soil) C and N storage between fenced and grazed grasslands, thereby assessing the effects of grazing exclusion on aboveground and belowground ecosystem properties and soil C and N storage. Significant differences were evaluated at the $P < 0.05$ level. When significance was observed, the LSD (least significant difference) post-hoc test was used to conduct multiple comparisons. All statistical analyses were performed using the software program SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Plant properties

The aboveground biomass (AGB) ($P < 0.001$) and litter biomass (LB) ($P < 0.001$) of FG were significantly increased over those in GG (Table 1), but the belowground biomass (BGB) (<50 cm in soil depth) decreased under FG, from 490.1 ± 82.9 g m^{-2} to 361.5 ± 121.2 ($P < 0.05$), thus leading to greater total biomass (TB: sum of AGB, LB and BGB) and

Table 1
Effects on plant properties in grassland communities of either fencing or grazing (n = 10). Note: AGB, aboveground biomass; LB, litter biomass; BGB, belowground biomass; TB, total biomass; R/S, root/shoot; R, species richness; H, Shannon–Wiener diversity index; E, evenness. Values (mean ± SD) are means of ten squares; significant differences between fenced and grazed grasslands are indicated by symbols: ***$P < 0.001$, *$P < 0.05$.

Treatments	AGB (g m^{-2})	LB (g m^{-2})	BGB (g m^{-2})	TB (g m^{-2})	R/S	Coverage (%)	Height (cm)	R	H	E
GG	48.6 ± 11.5	29.0 ± 9.1	490.1 ± 82.9	567.6 ± 103.5	10.5 ± 2.5	45.0 ± 4.2	36.7 ± 3.2	5.6 ± 1.0	2.2 ± 0.1	1.0 ± 0.01
FG	91.4 ± 13.9	47.5 ± 5.8	361.5 ± 121.2	500.4 ± 140.9	4.1 ± 1.8	57.0 ± 4.3	49.8 ± 9.2	8.0 ± 1.3	2.5 ± 0.1	1.3 ± 0.02
	*Sig.****	*Sig.****	*Sig.**	*Sig.**	*Sig.****	*Sig.****	*Sig.****	*Sig.****	*Sig.****	*Sig.****

root/shoot (R/S) ratio in GG than in FG ($P < 0.05$; Table 1). Additionally, the coverage ($P < 0.001$), height ($P < 0.001$), Richness index ($P < 0.001$), Shannon–Wiener diversity index ($P < 0.001$), and Evenness index ($P < 0.001$) of the grassland community were significantly higher in FG than in GG (Table 1).

3.2. Soil physical and chemical properties

FG was associated with reductions in soil pH and soil BD compared with GG (Fig. 2a, c). Fencing also increased the soil water content, although only in the top soil depth (0–50 cm), and this difference was significant between FG and grazed grassland (Fig. 2b). Meanwhile, fencing significantly increased SOC ($P < 0.001$) and soil TN ($P < 0.01$) throughout the soil compared with GG (Fig. 3a, b). Except in the surface soil (0–5 cm) ($P < 0.05$), soil C/N was not significantly different in the underlying soils of FG and GG (Fig. 3c).

3.3. Plant C and N pools

Fencing significantly increased C and N storage in the AGB and LB (Fig. 4a). The C stocks in the AGB and LB averaged 118.1% ($P < 0.001$), and 82.5% ($P < 0.01$) higher in FG than in GG, respectively, while the N stocks were 123.6% ($P < 0.001$) and 46.0% higher ($P < 0.05$), respectively (Fig. 4b). The C ($P < 0.01$) and N ($P > 0.05$) stocks of the BGB were lower in FG than in GG. Moreover, the total plant C was significantly lower, by 21.3% ($P < 0.05$), in FG compared to GG (Fig. 4a), while FG had a higher N stock in the TB than did GG, but this difference was not significant ($P > 0.05$) (Fig. 4b).

3.4. Soil C and N pools

Fencing significantly increased soil C and N pools in the surface soil layers (0–20 cm) ($P < 0.05$), while insignificant increases were observed from 20 to 100 cm ($P > 0.05$; Fig. 5a, b). The cumulative soil C stock in the top 100 cm soil was significantly greater in FG, by 15.2%, than in GG ($P < 0.05$) (Fig. 6a). The cumulative N stock from 0 to 100 cm was not significantly greater in FG than in GG, but it was significantly greater in the top 20 cm ($P < 0.05$, Fig. 6b).

3.5. Grassland ecosystem C and N pools

Grassland ecosystem C and N stocks in FG were higher than in GG ($P < 0.05$, Fig. 7a, b). According to the increases of ecosystem C and N sequestration over the 11 years of the experiment, we estimated that the mean annual ecosystem C and N sequestration rates were 0.47 and 0.09 Mg ha^{-1} yr^{-1}, respectively, under fencing compared to grazed grassland.

4. Discussion

In this study, grazing exclusion had significantly improved the canopy cover, height and biodiversity of desert grassland ecosystem (Table 1), which was supported by previous studies in other grassland types (Golodets et al., 2010; Fensham et al., 2011; Louhaichi et al., 2012; Deng et al., 2014b). Grazing exclusion could enhance the ability of grassland to recover after disturbance due to the removal of grazing pressures which it would benefit to the regeneration of soil seed bank and increasing of species composition recovery (Liang et al., 2009; Golodets et al., 2010). Moreover, grazing exclusion had positive effects on AGB and LB but negative effects on BGB, which decreased TB

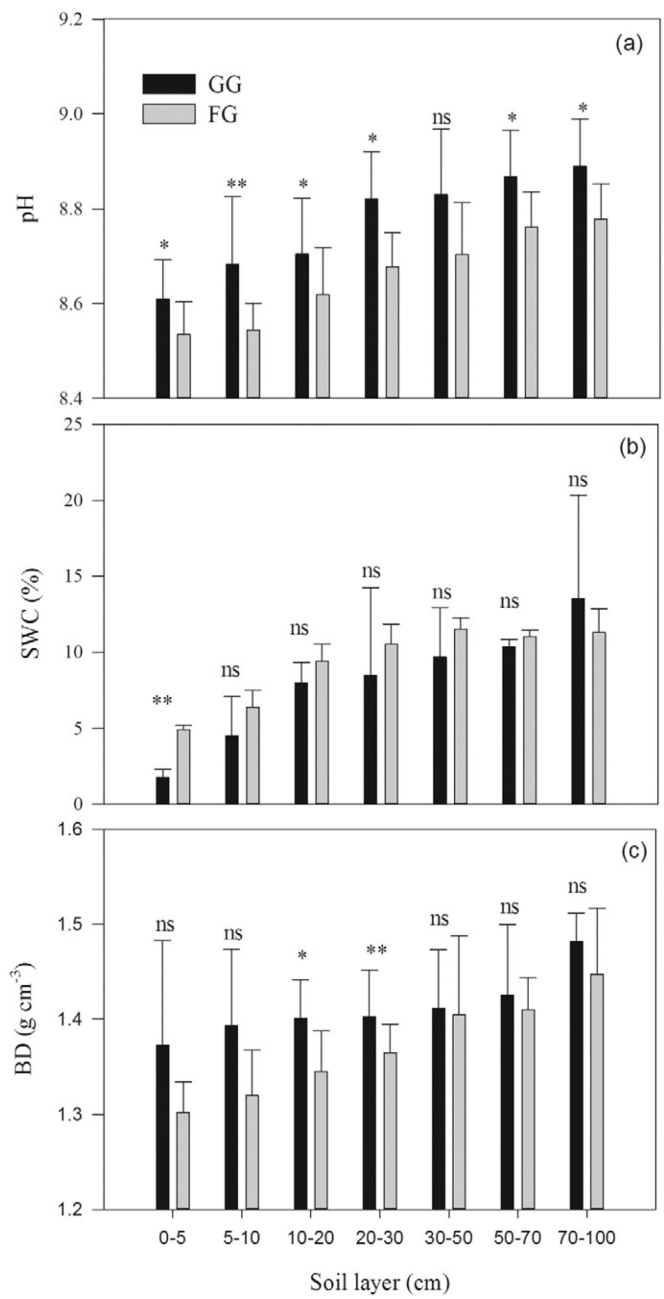

Fig. 2. Effect of grazing exclusion after fencing (FG) and grazing (GG) on (a) soil pH, (b) soil water content (SWC) and (c) soil bulk density (BD) in each soil layer. Note: values (mean ± SD) are means of ten squares; significant differences are indicated by symbols above the bars: **$P < 0.01$, *$P < 0.05$, ns, no significant difference.

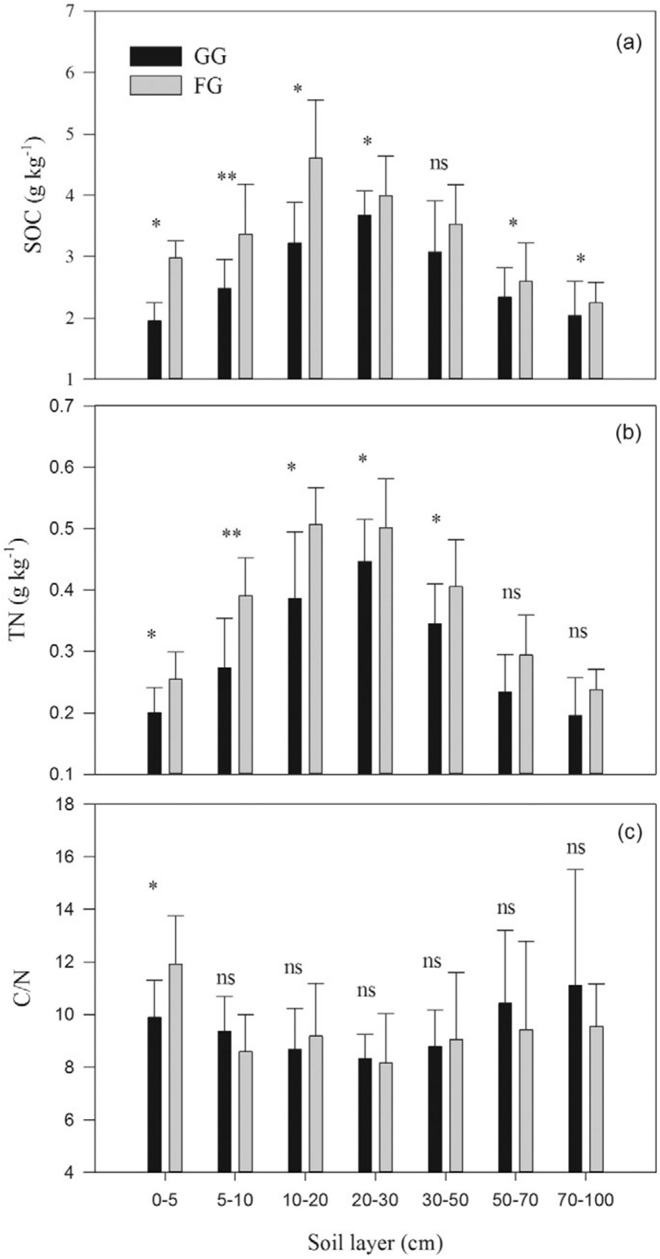

Fig. 3. Effect of grazing exclusion after fencing (FG) and grazing (GG) on (a) SOC, (b) TN and (c) C/N in each soil layer. Note: values (mean ± SD) are means of ten squares; significant differences are indicated by symbols above the bars: $^{**}P < 0.01$, $^{*}P < 0.05$, ns, no significant difference.

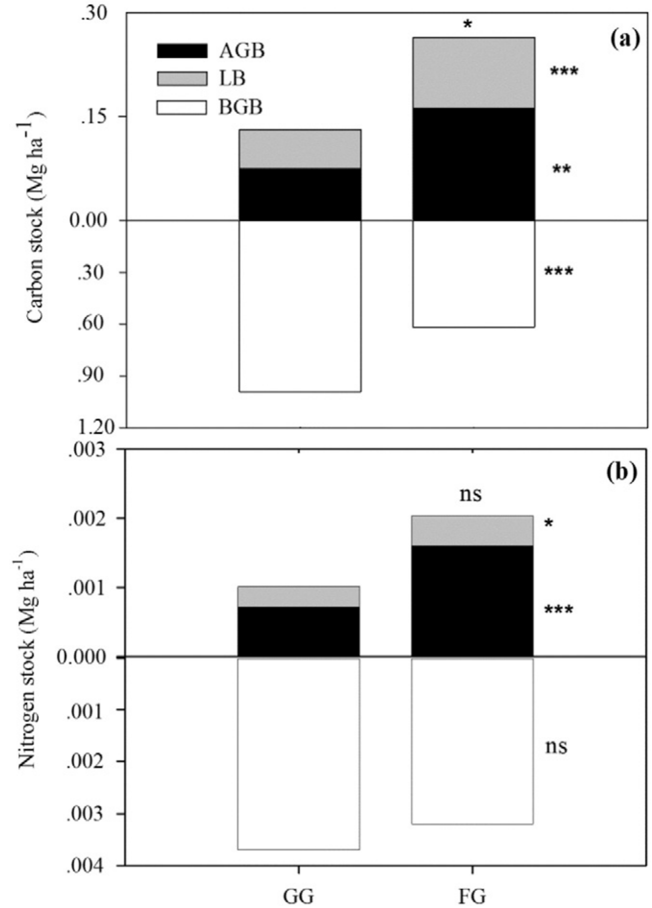

Fig. 4. Effect of grazing exclusion after fencing (FG) and grazing (GG) on the plant carbon (C) pool and the plant nitrogen (N) pool in the aboveground biomass (AGB), litter (LB), belowground biomass (BGB) and total biomass (TB). Note: values (mean ± SD) are means of ten squares; significant differences in C or N pools from different sources between FG and GG treatments are indicated by symbols next to or above the bars: $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, ns, no significant difference.

(Table 1, Fig. 8). The observed increases in AGB and LB were consistent with those found in previous studies (Deng et al., 2014b; Wang et al., 2014). In grazing grasslands, the continuous removal of standing biomass by herbivory would induce the decrease of AGB and LB (Schonbach et al., 2011). Apart from the loss or deterioration of plant tissue by defoliation (Ferraro and Oesterheld, 2002) and trampling or reductions in soil water content (Zhao et al., 2007), changes in species composition can also cause significant declines in AGB and LB (Bakker et al., 2009). Conversely, grazing exclusion can improve the structure and function of grassland ecosystems through increases of vegetation coverage, diversity, biomass production, and soil moisture and nutrition (Jing et al., 2013; Wang et al., 2014; Wu et al., 2010). We also observed that vegetation coverage and diversity (Richness index, Shannon–Wiener diversity index, and Evenness index) significantly increased ($P < 0.001$) under FG compared to GG (Table 1). Gallego et al. (2004) have reported that palatable grasses have greater competitive ability than unpalatable grasses and show a marked increase in abundance in grasslands where livestock are excluded for ten or more years. This may be the reason for explaining higher species richness was found in the FG grassland, which agreed with the findings in the temperate grassland (Deng et al., 2014b) and alpine grassland (Wu et al., 2010). Deng et al. (2014b) reported that grazing exclusion increased BGB in a temperate grassland; however, we found that fencing clearly decreased BGB in the studied desert steppe (Table 1; Fig. 8). Plants reduce the outflow of energy from their aboveground parts to livestock by allocating more assimilation products to the roots as storage for regrowth after grazing (Hafner et al., 2012; Deng et al., 2014b), which explains why BGB and R/S were greater in GG than FG in our study (Table 1). Similarly, many studies have also reported that grazing has mainly stimulatory, or at least no detrimental, effects on BGB all over the world (Frank et al., 2002; Pucheta et al., 2004; Pineiro et al., 2009).

Fencing had significant effects on pH value, soil BD, and soil moisture (Fig. 2). The large coverage of the community and accumulation of litter may have increased the soil water retention, and the reduced trampling due to fencing may have reduced the BD (Deng et al., 2014b). Bach et al. (2012) reported that grassland restoration improved phospholipid fatty acid (PLFA) contents in soils, and PLFA had a significant negative correlation with soil pH ($P < 0.05$) (Huang et al., 2011); grazing exclusion thus reduced soil pH, as was observed in the present study (Fig. 2a). Previous studies have indicated that long-term fencing led to marked increases in SOC and TN (Deng et al., 2014b; Shrestha and Stahl, 2008;

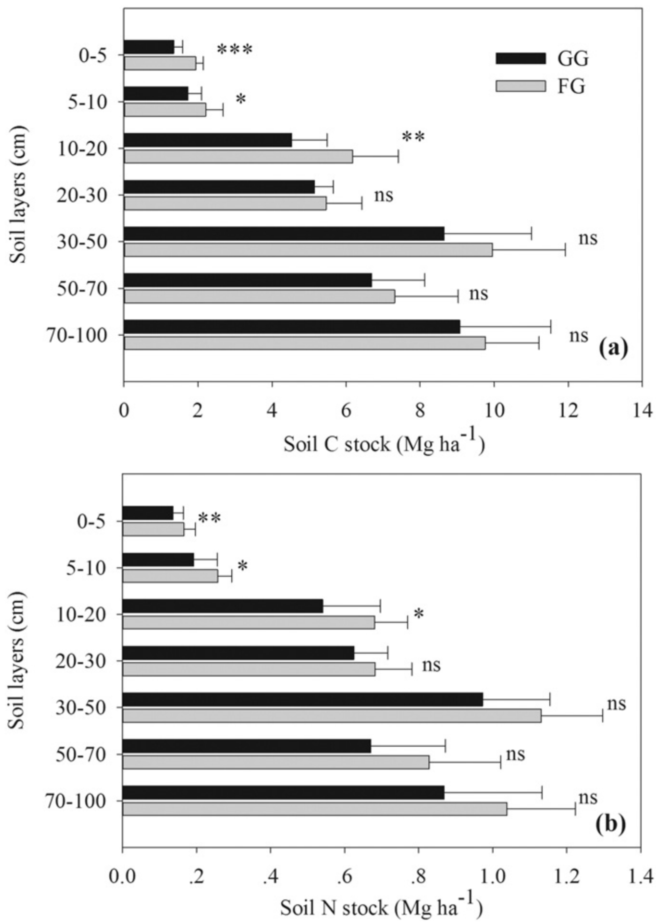

Fig. 5. Effect of grazing exclusion after fencing (FG) and grazing (GG) on (a) soil C stock and (b) soil N stock in each soil layer. Note: values (mean ± SD) are means of ten squares; significant differences are indicated by symbols above the bars: $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, ns, no significant difference.

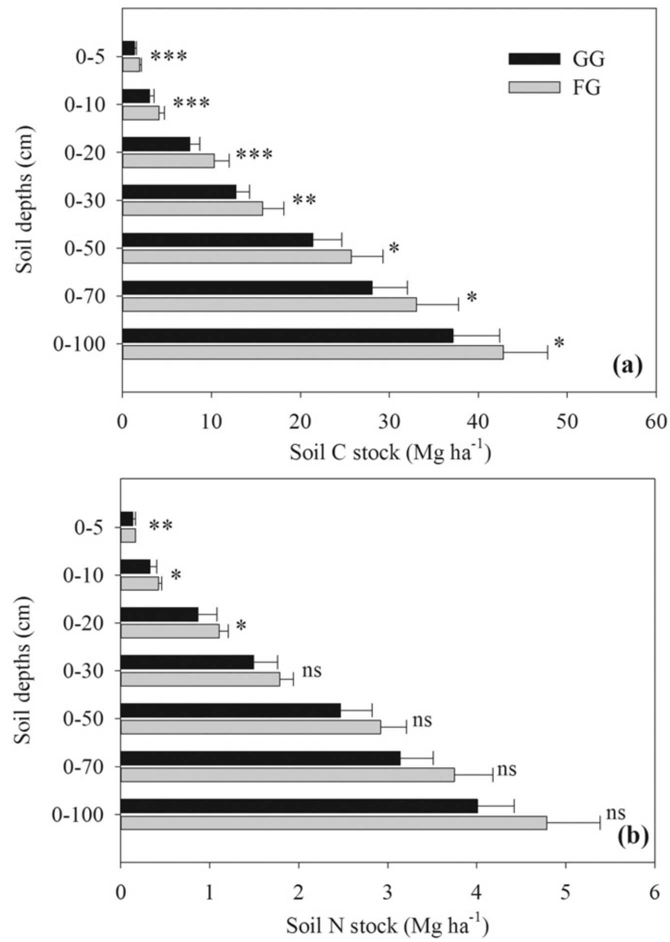

Fig. 6. Effect of grazing exclusion after fencing (FG) and grazing (GG) on (a) cumulative soil C stock and (b) cumulative soil C stock in each soil depth. Note: values (mean ± SD) are means of ten squares; significant differences are indicated by symbols above the bars: $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, ns, no significant difference.

Wu et al., 2010). In our study, we also found significantly higher levels of SOC ($P < 0.05$, 0–100 cm) and soil TN ($P < 0.05$, 0–50 cm) in FG than in GG (Fig. 3). Greater organic matter (litter, dead roots, mycorrhizae, and exudates) input to the soils leads to increases of SOC and TN through vegetation recovery (Prietzel and Bachmann, 2012). Conversely, grazing generally leads to greater soil OC and N losses by the greater removal of photosynthetic tissue and subsequent respiration of assimilated C by grazers, which reduces potential C and N inputs to soil organic matter (Derner and Schuman, 2007; Klumpp et al., 2009). In our study, except at the surface soil (0–5 cm) ($P < 0.05$), soil C/N was not significantly different in the underlying soils between FG and GG (5–100 cm) ($P > 0.05$) (Fig. 3). This result may indicate the close coupling between soil C and N, in agreement with the results of Deng et al. (2014b).

Plant carbon stocks are mainly determined by biomass. In this study, we found that after 11 years of grazing exclusion, the C stocks in the AGB and LB averaged 118.1% ($P < 0.001$) and 82.5% ($P < 0.01$) higher in FG than in GG, respectively. Wang et al. (2014) also observed that aboveground biomass carbon stocks increased by 107% after 8 years of grazing exclusion, which is consistent with the results of several studies in which reduced herbivore densities led to the recovery of plant community structure and composition, thus increasing vegetation carbon pools (Shrestha and Stahl, 2008; Tanentzap et al., 2009; Wu et al., 2010). In our study, the N stocks in the AGB and LB were 123.6% ($P < 0.001$) and 46.0% higher ($P < 0.05$) in FG than in GG, respectively (Fig. 4), as was similar to Wang et al.'s (2014) results. However, the C ($P < 0.01$) and N ($P > 0.05$) stocks of BGB were lower in FG than in GG; moreover, the total plant C was significant lower, by 21.3% ($P < 0.05$), in FG than in GG, which was inconsistent with the results of other studies (Qiu et al., 2013; Deng et al., 2014b). Qiu et al. (2013) observed that after 17 years of grazing exclusion, the C and N in the belowground biomass from 0 to 80 cm in soil depth increased by approximately 50%–75% and 55%–106%, respectively, in a temperate grassland of the Loess Plateau. This difference may have occurred because of the variation of the belowground biomass response to grazing exclusion across a precipitation gradient. A previous study has revealed that the belowground biomass was higher in ungrazed sites than in grazed sites at moderately humid locations (400–850 mm of mean annual precipitation) but lower in ungrazed sites at humid and dry locations (Pineiro et al., 2009). Moreover, less C was lost by shoot respiration, and more C was translocated into belowground biomass, in grazed grassland (Hafner et al., 2012). These phenomena may also have caused the lower C stocks of BGB in FG than in GG as observed in the present study.

Additionally, in our study, fencing significantly increased soil C stocks in the top 100 cm soil and N stocks from 0 to 20 cm compared with those of GG, and soil N stocks from 0 to 100 cm showed a non-significant increase ($P > 0.05$) (Fig. 6). Similar results have been observed in previous work. For example, Deng et al. (2014b) have reported that long-term fencing (30 years) significantly improved soil C and N stocks at 0–100 cm in soil depth compared to those of grazed areas in temperate grassland. Zhou et al. (2011) reported that the soil C and N storage of the top 30 cm of the soil increased by 13.6- and 5.4-fold, respectively, after 26 years of grazing exclusion in a desert shrubland. However, in a different study area (the northeastern Qinghai–Tibetan Plateau) with different grassland types, Shi et al. (2013) found the opposite result; under grazing exclusion, less C input from root-associated

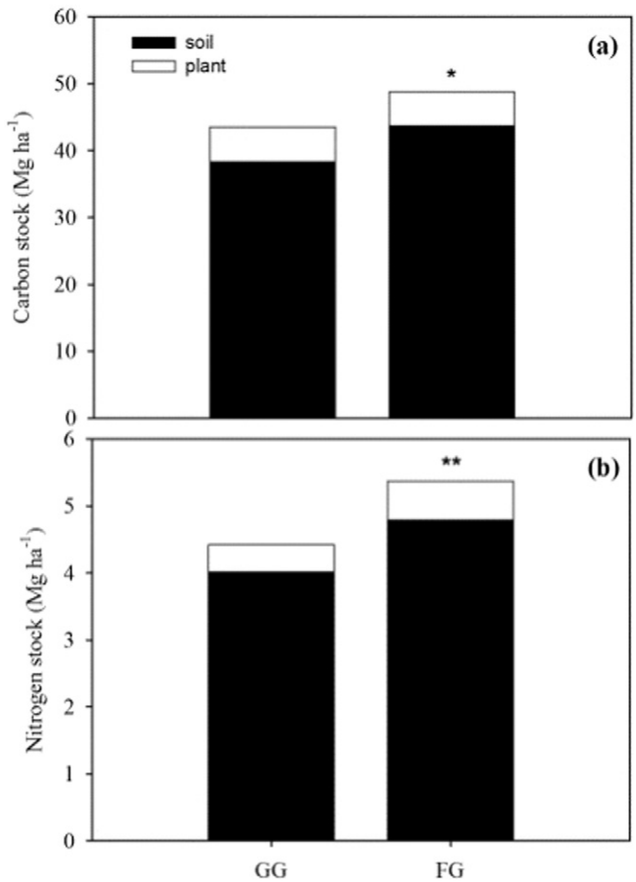

Fig. 7. Effect of grazing exclusion after fencing (FG) and grazing (GG) on the grassland ecosystem carbon (C) pool and the plant nitrogen (N) pool in plant and 0–100 cm soil. Note: values (mean ± SD) are means of ten squares; significant differences in C or N pools from different sources between FG and GG treatments are indicated by symbols above the bars: $^{**}P < 0.01$, $^{*}P < 0.05$.

sources and possibly greater C output through heterotrophic respiration might have reduced various soil OC stocks. However, Shi et al. (2013) also reported that due to decreased plant N demand and uptake and changes in N mineralization and/or immobilization, a significant increase in the soil N pool was found under ungrazed conditions

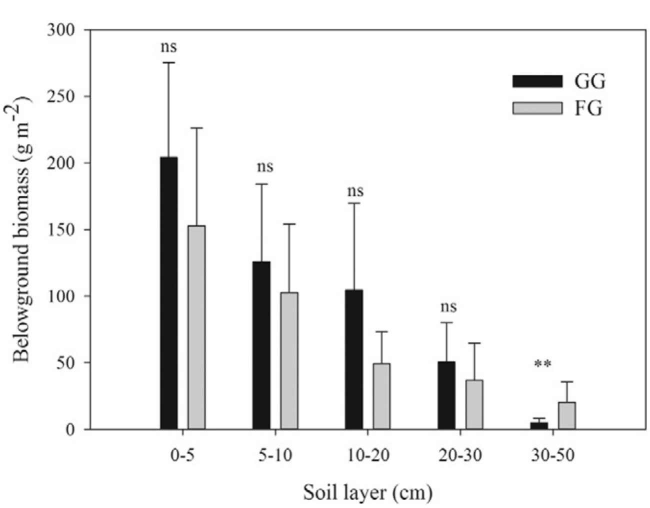

Fig. 8. The belowground biomass of grazing exclusion after fencing (FG) and grazing (GG) grasslands. Note: significant differences in belowground biomass from different sources between FG and GG treatments are indicated by symbols above the bars: $^{**}P < 0.01$, ns, no significant difference.

compared to grazed conditions. Pineiro et al. (2009) also found that grazing exclusion in the Riodela Plata grasslands increased soil C and soil N stocks in upland soils; in all cases, SOC and STN variations were largely derived by changes in SOM stocks that maintained their C:N ratios unchanged. Soil C and N stocks in the GG and FG grasslands depending on soil properties, including texture, pH and soil depth, and vegetation type, particularly allocation patterns and C:N ratios of different plant species (Pineiro et al., 2009). Those situations may explain our finding that grazing exclusion improved soil N stocks. Overall, grazing exclusion significantly improved the C and N stocks of the studied desert grassland ecosystem in China (Fig. 7). Therefore, grazing exclusion should be considered for restoring degraded grasslands in this region.

5. Conclusions

Grazing exclusion improved community coverage, height, diversity, plant aboveground biomass, and SWC, OC, and TN contents, but decreased belowground biomass, root/shoot ratio, pH, and BD. Moreover, grazing exclusion strongly influenced the C and N stocks of the ecosystem, and the mean annual ecosystem C and N sequestration rates were 0.47 and 0.09 Mg ha^{-1} yr^{-1}, respectively, over 11 years of fencing. The dynamics of soil C stocks mainly occurred in the top 30 cm of the soil, while N stocks mainly changed in top 20 cm of the soil after grazing exclusion. Soil cumulative C stocks in the top 100 cm of the soil were 15.2% greater in FG than GG, but cumulative N stocks in the top 100 cm were not significantly different. Our results indicated that grazing exclusion is an effective measurement on improving the ecosystem C and N pools in desert steppe. The findings are important for assessing the resilience of these grazed-disturbed ecosystems and developing a more effective strategy by means of fencing for the management of degraded desert grassland from a long-term perspective.

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