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Effects of Grazing Exclusion on Plant Productivity and Soil Carbon, Nitrogen Storage in Alpine Meadows in Northern Tibet, China

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Abstract: Grazing exclusion is widely adopted in restoring degraded alpine grasslands on the Qinghai-Tibetan Plateau. However, its effectiveness remains poorly understood. In this study, we investigated the effects of grazing exclusion on plant productivity, species diversity and soil organic carbon (SOC) and soil total nitrogen (STN) storage along a transect spanning from east to west of alpine meadows in northern Tibet, China. After six years of grazing exclusion, plant cover, aboveground biomass (AGB), belowground biomass (BGB), SOC and STN were increased, but species diversity indices declined. The enhancement of AGB and SOC caused by grazing exclusion was correlated positively with mean annual precipitation (MAP). Grazing exclusion led to remarkable biomass increase of sedge species, especially *Kobresia pygmaea*, whereas decrease of biomass in forbs and no obvious change in grass, leguminous and noxious species. Root biomass was concentrated in the near surface layer (10 cm) after grazing exclusion. The effects of grazing exclusion on SOC storage were confined to shallow soil layer in sites with lower MAP. It is indicated that grazing exclusion is an effective measure to increase forage production and enhance soil carbon sequestration in the studied region. The effect is more efficient in sites with higher precipitation. However, the results revealed a tradeoff between vegetation restoration and ecological biodiversity. Therefore, carbon pools recover more quickly than plant biodiversity in the alpine meadows. We suggest that grazing exclusion should be combined with other measures to reconcile grassland restoration and biodiversity conservation.

Keywords: aboveground biomass; belowground biomass; soil organic carbon (SOC); soil total nitrogen (STN); biodiversity; grazing exclusion; precipitation; alpine meadow

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1 Introduction

Livestock grazing is one of the most essential and pivotal means in the utilization of grassland worldwide (Watkinson and Ormerod, 2001). Overgrazing is considered as the main cause leading to grassland degradation around the world (Conant and Paustian, 2002), particularly in the developing countries (Han *et al.*, 2008). Grazing exclusion has been widely adopted as the cost-effective way in enhancing forage production and improving soil quality in degraded grasslands (Su *et al.*, 2005; Wu *et al.*, 2010; Mekuria and Veldkamp, 2012). In China, due to widespread degradation of natural grasslands (Akiyama and Kawamura, 2007), the national ecological program of 'Returning Grazing Land to Grassland' was implemented in temperate and alpine grasslands in eight provinces (or autonomous regions) since 2003. Until 2012, the area of grazing excluded

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grasslands reached 6.08 × 10^7 ha in China (http://english.agri.gov.cn). Release from grazing by exclosure could influence plant community structure, species diversity, soil quality, carbon storage, and nutrients cycling within the plant-soil system (Schuman *et al.*, 1999; Altesor *et al.*, 2006; Wu *et al.*, 2009). Exclosure may, therefore, potentially aid to restore degraded grasslands caused by overgrazing. The response of species composition, biomass and soil carbon and nitrogen storage to grazing exclusion have been extensively studied in the northern China, however, few field studies have examined the effects of grazing exclusion on grassland restoration and soil carbon, nitrogen storage in Tibet.

One-third of the grasslands on the Qinghai-Tibetan Plateau were estimated to be degraded (Gao *et al.*, 2011) mostly due to excessive livestock grazing (Harris, 2010). About 1.73 × 10^7 ha, ca. 16% of natural grasslands have been grazing excluded on the Qinghai-Tibetan Plateau since 2003 (http://english.agri.gov.cn). The natural alpine meadows, accounting for 35% of the land area in the plateau (Zheng, 2000), are among the highest carbon stock in 18 grassland types (Ni, 2002). So grazing exclusion of the degraded alpine meadow may have great potential for promoting carbon sequestration. In recent years, pair-compared studies, i.e., grazed vs. un-grazed samplings, indicated positive effects of grazing exclusion on plant productivity, soil carbon and nitrogen storage in eastern edge of the Qinghai-Tibet Plateau (Wu *et al.*, 2009; Shi *et al.*, 2010; Wu *et al.*, 2010; Gao *et al.*, 2011). For example, Wu *et al.* (2010) found that nine-year of grazing exclusion of meadows significantly improved vegetation cover, aboveground biomass, increased soil organic carbon (SOC) and total nitrogen (STN) content in soil depth of 0–30 cm. While Gao *et al.* (2011) reported that the amounts of SOC in the 0–10 cm soil were 1.4 and 2.0 times higher in the five- and ten-year grazing exclusion sites, respectively, than in the grazed sites, and STN was 1.3 to 1.8 times higher. However, little investigation was explored in Tibetan alpine meadow.

In this paper, we assessed changes induced by grazing exclusion for plant canopy cover, plant height, species biodiversity, aboveground biomass (AGB), belowground biomass (BGB), SOC and STN storage in a transect of alpine meadows in the northern Tibet. The aims were to evaluate the effects of grazing exclusion on alpine meadow community and soil properties, in order to determine whether grazing exclusion can efficiently restore degraded alpine meadows in the northern Tibet.

2 Materials and Methods

2.1 Study area

We chose four exclosure sites spanning the main distribution of alpine meadows in Nagqu Prefecture, northern Tibetan Autonomous Region of China (Fig. 1). The four study sites were located in Seqing village (SQ) and Nyainrong Town (NR) of Nyainrong County, Zharen Town (ZR) of Amdo County, and Nameqie village (NMQ) of Nagqu County. The mean annual precipitation (MAP) of the four sites ranged from 410 mm to 480 mm (Table 1). But very limited mean annual temperature (MAT) ranging from –1.2℃ to –0.6℃ existed. The grazing exclusion program was implemented for 6 years since 2006 at all sites (Table 1). The overgrazing rates of the four study sites are approximately 75% (Gao *et al.*, 2005). The average elevation for the four sites ranged from 4575 m to 4680 m. Vegetation in all sites is alpine meadow dominated by sedge species (*Kobresia pygmaea*), associated with some forbs (mainly consisting of *Potentilla bifurca*, *Leontopodium leontopodioides*, *Lagotis brachystachya*), grass species (mainly including *Stipa purpurea*, *Trisetum spicatum*), Leguminous species (mainly consisting of *Oxytropis stracheyana*, *Oxytropis microphylla*) and noxious species (mainly including *Gentian aristata* and *Ranunculus tanguticu*). The proportions of *K. pygmaea* biomass in the total AGB were 43.9% in SQ, 42.9% in NR, 36.8% in ZR and 34.1% in NMQ, respectively. Forb covered a large part of the biomass, accounting for 39.2%–49.8% in the four study sites. Soils are classified as Cambisols, i.e., alpine meadow soil for all sites.

2.2 Experimental design and field sampling

The terrain in this study area is flat with relatively homogeneous vegetation and soil in each sampling site. We selected one representative plot within exclosure and free grazing area respectively to investigate the effect of grazing exclusion in each site. The plots inside the exclosure were the grazing excluded (GE) treatments while those outside were the grazed (G) treatment. Field survey indicated that the grazed plot and grazing excluded plot are floristically and topographically similar at the beginning of the project in each site. Thus, we

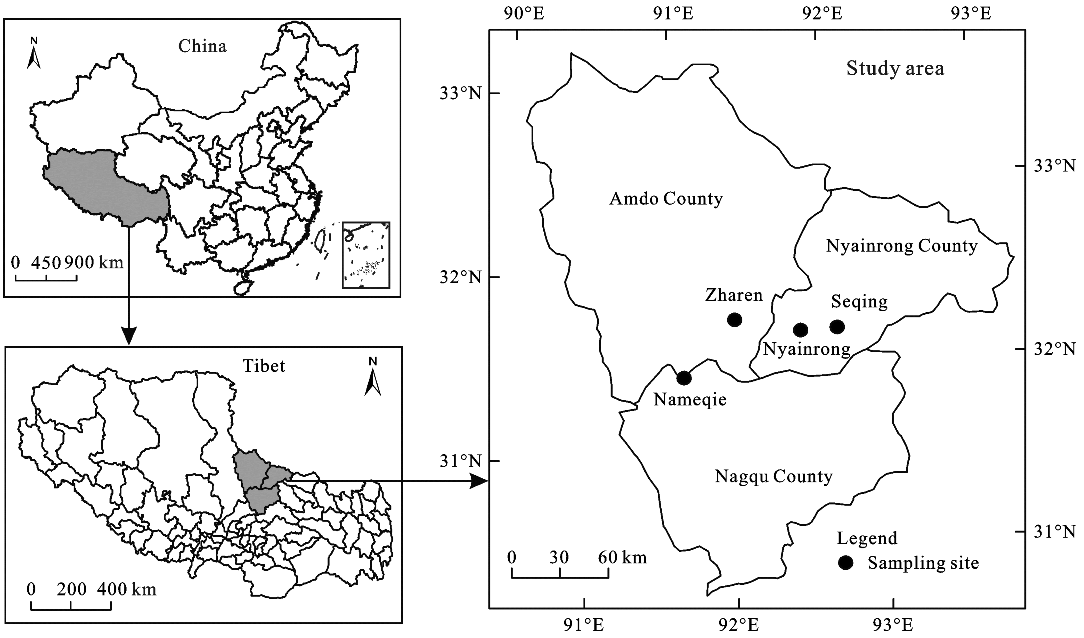

Fig. 1 Location of study area and distribution of sampling sites

Table 1 Characteristics of four exclosure sites in this study

Site	Longitude	Latitude	Proportion of *K. pygmaea* (%)	Elevation (m)	MAP (mm)	MAT (℃)	Area (ha)
SQ	92°24′10″	31°59′35″	43.9	4680	480.5	–1.2	15.5
NR	92°09′44″	31°57′07″	42.9	4575	470.2	–1.0	26.2
ZR	91°43′14″	31°57′32″	36.8	4645	435.0	–0.9	25.0
NMQ	91°26′16″	31°36′12″	34.1	4650	410.0	–0.6	10.8

Notes: SQ, Seqing; NR, Nyainrong; ZR, Zharen; NMQ, Nameqie; MAP, mean annual precipitation; MAT, mean annual temperature

believe that grazing exclusion is the major cause for the difference inside and outside the exclosure.

In August 2012, we established five sampling quadrats (0.5 m × 0.5 m) at 20 m intervals along a 100-m line transect inside and outside the exclosure in each of the four sampling sites. Within each quadrat, plant species were identified and recorded. Plant cover and plant height were assessed by species. Live plants in each quadrat were harvested and dried by species respectively. The dry biomass of all species in each quadrat is accumulated as aboveground biomass (AGB). AGB was divided into five functional groups: sedge species (SG); grass species (GG); forbs species (FG); leguminous species (LG); and noxious species (NG) (Wu *et al.*, 2009). Belowground biomass (BGB) was measured to 50 cm depth. After AGB harvested, four soil cores at five depths (0–5 5–10 10–20 20–30 30–50 cm) were taken using auger with diameter of seven centimeter. Four soil cores at the same depth in each quadrat were mixed together, and immediately washed by using 0.5-mm mesh screen to remove soil. The dry mass of all plant samples were determined by oven-drying at 60℃ to constant weight over 48 hours. BGB was calculated as the total dry mass of soil profile.

Composite soils consisting of 5 soil cores were taken using a soil auger with 4 cm in diameter from the same quadrats after AGB harvested and root cores taken. Soil cores were taken at the same five depths as root sampling. Soil samples were prepared for chemical analysis after air-dried and then passing through a 0.149-mm sieve. Additionally, a soil profile (150 cm in length, 50 cm in width and 50 cm in depth) was also excavated in each plot in both grazed and grazing excluded treatments of the four sites. Three soil cores were taken in different aspect of the soil profile with a steel cylinder (100 cm^3 in volume) at five depths (mentioned above) to determine soil bulk density.

2.3 Methods

2.3.1 Calculation of Species importance and biodiversity

In this study, we used the Shannon-Wiener diversity index (H), Simpson dominance index (D) and Pielou evenness index (E) to describe the biodiversity traits of the alpine meadow community. Species importance value (N_i) and species relative importance values (P_i) were used to calculate the above diversity indices (Zhang *et al.*, 2000).

The Species importance value (N_i) was calculated as:

$$N_i = (C_{ri} + H_{ri}) / 2 \tag{1}$$

where C_{ri} and H_{ri} are the relative coverage and height of species i, respectively.

The species relative importance values (P_i) was calculated as:

$$P_i = N_i / \sum_{i=1}^{S} N_i \tag{2}$$

where S is the total number of species.

The Shannon-Wiener index (H) was calculated as:

$$H = -\sum_{i=1}^{S} P_i \ln P_i \tag{3}$$

The Simpson dominance index (D) was calculated as:

$$D = 1 - \sum_{i=1}^{S} P_i^2 \tag{4}$$

The Pielou evenness index (E) was calculated as:

$$E = H / \ln S \tag{5}$$

2.3.2 Soil carbon and nitrogen analysis

SOC concentration was measured by using the oil bath-$K_2Cr_2O_7$ titration method, and STN concentration was determined with the Kjeldahl procedure (ISSCAS, 1978). The SOC density (SOC_d, Mg/ha) and STN density (STN_d, Mg/ha) of the five soil layers in each quadrat was calculated by the following equation (Xie *et al.*, 2007):

$$SOC_d = SOC_i \times \rho_i \times H_i \times 10^{-1} \tag{6}$$

$$STN_d = STN_i \times \rho_i \times H_i \times 10^{-1} \tag{7}$$

where SOC_i, STN_i, ρ_i and H_i represent soil organic carbon concentration (g/kg), soil total nitrogen concentration (g/kg), soil bulk density (g/cm^3) and soil thickness (cm) in the layer i, respectively.

2.3.3 Statistical analyses

Statistical analyses were conducted by using SPSS software (SPSS ver. 13.5 for Windows, Chicago, IL, USA). Independent-sample t test was employed to identify significant differences between the grazed and grazing excluded treatments.

3 Results

3.1 Plant canopy cover and biodiversity

Grazing exclusion significantly increased plant canopy cover by 31.7%, 31.2%, 26.1% and 25.5%, respectively in SQ, NR, ZR and NMQ sites (Table 2). There were no significant differences in the species richness between grazed and exclusion plots in all sites. However, Shannon-Wiener index and Simpson index were significantly lower in the grazing excluded plots than in the adjacent grazed plots at all sites.

3.2 Aboveground and belowground biomass

Grazing exclusion had significantly positive effects on AGB in all sites. After six years grazing exclusion, AGB increased by 69.0%, 57.0%, 32.2% and 25.0% in SQ, NR, ZR and NMQ, respectively (Table 3). The increment of AGB increased positively with MAP ($R^2 = 0.95$, $p < 0.01$). The biomass fraction was significantly increased in sedge species, but decreased in forb species in grazing excluded sites. After grazing exclusion, the biomass of sedge species in SQ, NR, ZR and NMQ increased by 171.9%, 170.5%, 154.5% and 131.6%, respectively, while those of forb species decreased by

Table 2 Comparison of plant canopy cover, species richness and species diversity in grazed and grazing excluded plots

	SQ		NR		ZR		NMQ	
	G	GE	G	GE	G	GE	G	GE
Canopy cover (%)	$74.7±2.8^b$	$98.3±3.7^a$	$74±2.9^b$	$97.1±1.0^a$	$73.2±3.3^b$	$92.3±2.9^a$	$72.1±3.0^b$	$90.5±1.5^a$
Number of species	10	11	12	10	11	10	10	9
Shannon-Wiener diversity index (H)	$2.31±0.12^a$	$1.99±0.11^b$	$2.08±0.25^a$	$1.67±0.31^b$	$2.01±0.23^a$	$1.91±0.35^b$	$2.03±0.09^a$	$1.82±0.19^b$
Simpson dominance index (λ)	$0.87±0.02^a$	$0.81±0.01^b$	$0.85±0.05^a$	$0.72±0.06^b$	$0.86±0.04^a$	$0.82±0.06^b$	$0.82±0.02^a$	$0.76±0.04^b$
Pielou evenness index (E)	0.91±0.02	0.87±0.03	0.91±0.04	0.86±0.03	0.89±0.01	0.86±0.03	0.85±0.04	0.83±0.03

Notes: Different lowercase letter within the same row for each study site indicates significant difference of biodiversity index at 0.05 level. G, grazed plots; GE, grazing excluded plots

Table 3 Aboveground biomass of different functional groups under grazed and grazing excluded conditions in each site (g/m^2)

Functional group	SQ		NR		ZR		NMQ	
	G	GE	G	GE	G	GE	G	GE
Sedge species group	50.1^{b}	136.2^{a}	46.5^{b}	125.8^{a}	36.7^{b}	93.4^{a}	32.6^{b}	75.5^{a}
Grass species group	4.7	0.8	4.3	2.5	6.8	0.5	4.7	1.4
Forbs species group	38.3^{a}	20.9^{b}	39.3^{a}	21.8^{b}	40.2^{a}	22.0^{b}	32.1^{a}	18.1^{b}
Leguminous species group	4.2	7.0	2.5	–	5.4	0.3	8.3	2.4
Noxious species group	0.5	0.4	4.2	1.8	–	1.6	0.2	–
Total	97.8^{b}	165.3^{a}	96.8^{b}	151.9^{a}	89.1^{b}	117.8^{a}	77.9^{b}	97.4^{a}

Notes: '–' denotes no this species group in the plot. Different lowercase letter within the same row for each study site indicates significant difference of aboveground biomass at 0.05 level

45.4%, 44.5%, 45.3% and 43.6%, respectively (Table 3). There were no obvious effects of exclusion on the biomass of grass species (GG), leguminous species (LG) and noxious species (NG) (Table 3). The proportion of the sedge biomass approximated 41.2%–51.2% in the grazed sites, while increased to 77.5%–82.8% in the grazing excluded sites. The biomass of *K. pygmaea* accounted for most of the biomass of sedge species, ranging from 85.6% to 94.2% and from 84.6% to 98.6% inside and outside the exclusion plots, respectively.

The means of BGB were significantly greater in grazing excluded plots than in adjacent grazed plots in all sites (Fig. 2). Grazing exclusion significantly increased root biomass in the 20-cm depth at SQ, NR and ZR and in the 10-cm depth at NMQ. The top 10 cm of soil contained most of the BGB, accounting for 63.8%–74.0% of the total BGB in the study sites. The proportion was significantly higher in grazing excluded plots than in grazed plots. The total BGB increased by 44.9% in SQ, 42.1% in NR, 30.9% in ZR and 28.6% in NMQ, respectively in exclusion plots compared with grazed plots (Fig. 3a).

The root∶shoot (R∶S) ratio ranged from 8.1 in SQ grazing excluded plots to 10.4 in NMQ grazing excluded plots. R∶S ratio was significant higher in grazed plots than in exclusion plots in SQ and NR, but no difference was found in ZR and NMQ site (Fig. 3b).

3.3 Soil organic carbon and total nitrogen

SOC concentration decreased with increase of soil sampling depth in all sites (Fig. 4). The means of soil carbon storage in soil profiles were significantly greater in grazing excluded plots than in grazed plots at all sites. The positive effects of grazing exclusion on SOC concentration and storage were significant in the 0–30 cm soil depth at SQ and NR, in the 0–20 cm soil depth at ZR and only in the 0–10 cm soil depth at NMQ. Soil carbon storage in soil profiles (0–50 cm) were increased by 27.9%, 27.4%, 15.1% and 11.4% in grazing excluded sites at SQ, NR, ZR and NMQ, respectively (Fig. 5a). The

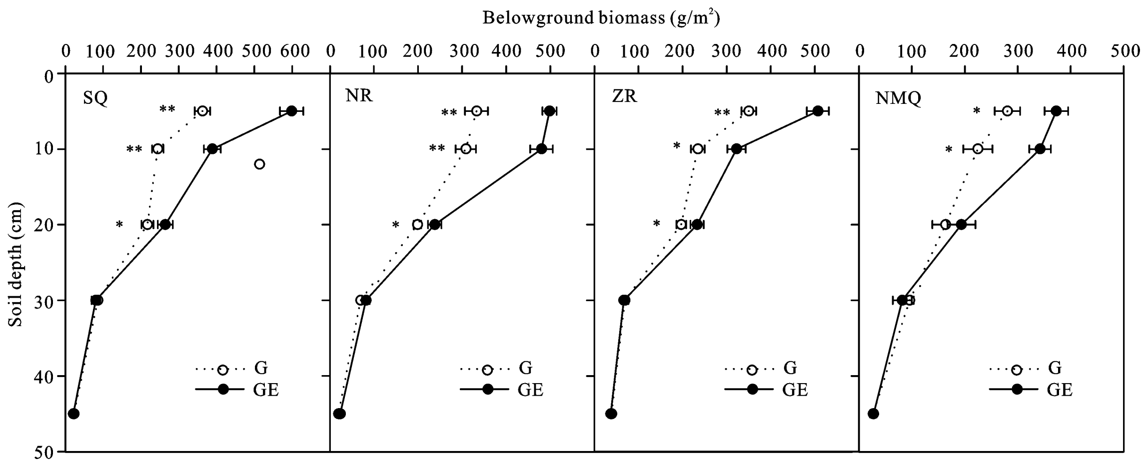

Fig. 2 Vertical distribution of belowground biomass under grazed (G) and grazing excluded (GE) conditions in all sites. Error bars represent standard errors. SQ, Seqing; NR, Nyainrong; ZR, Zharen; NMQ, Nameqie. Statistical differences (*t*-test) between grazed and grazing excluded sites for each depth are indicated as ** $p < 0.01$; * $p < 0.05$

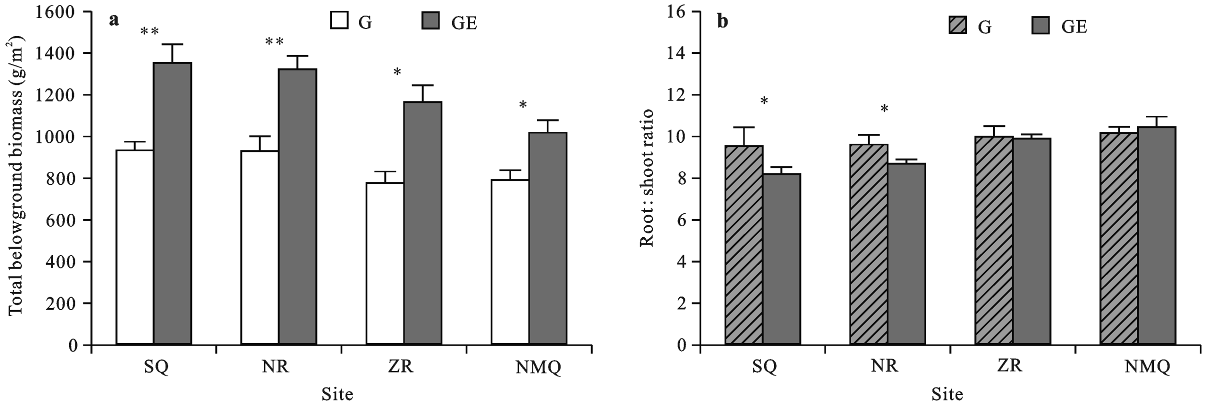

Fig. 3 Total belowground biomass (0–50 cm) (a) and root : shoot (R : S) (b) ratio in grazed (G) and grazing excluded (GE) plots in each site. Error bars represent standard errors. Significant difference between grazed and grazing excluded sites are indicated by symbols, ** $p < 0.01$; * $p < 0.05$

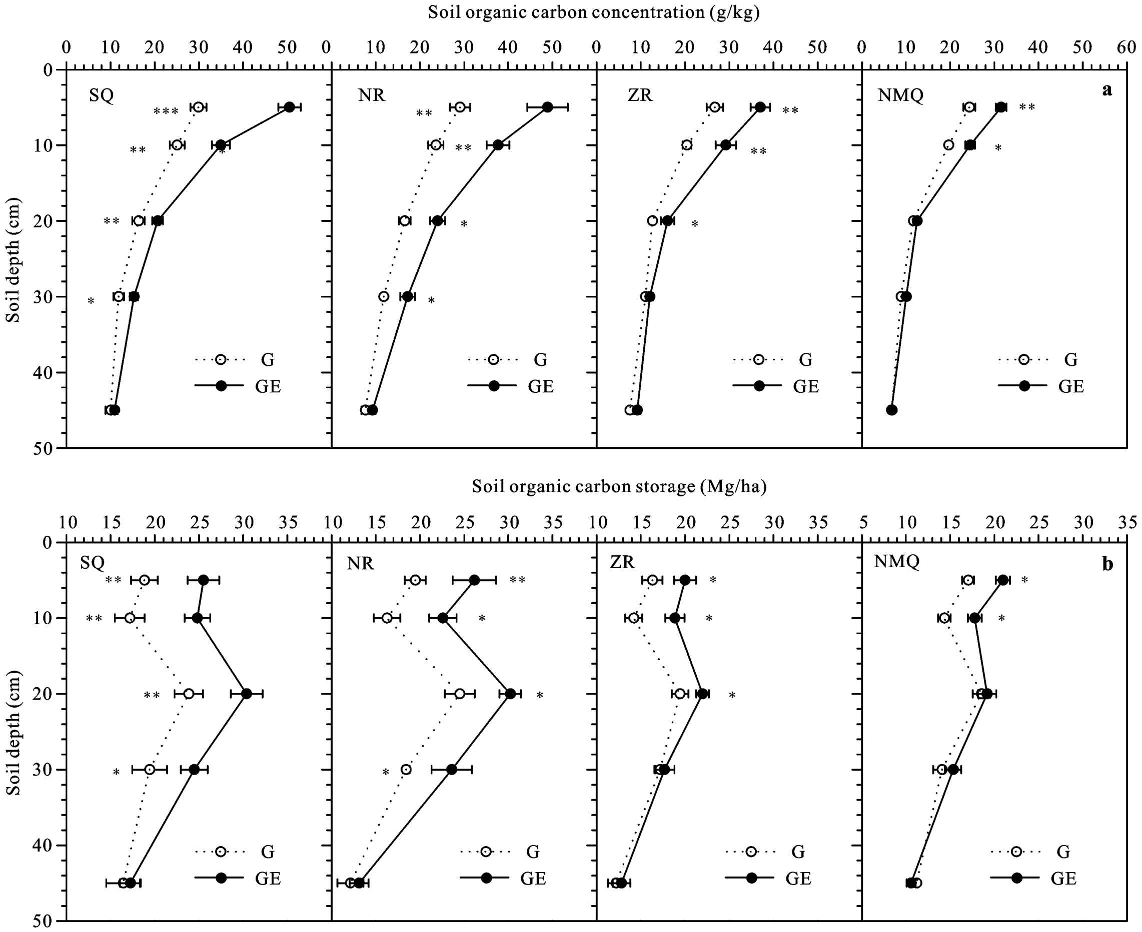

Fig. 4 Vertical distribution of soil organic carbon concentration (a) and storage (b) under grazed (G) and grazing excluded (GE) for all sites. Error bars represent standard errors. Statistical differences (*t*-test) between grazed and grazing excluded plots for each depth are indicated as *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

change of total SOC storage (0–50 cm) increased positively with MAP levels ($R^2 = 0.97$, $p < 0.01$).

The vertical distribution of STN concentration was similar to that of SOC in soil profiles. The positive effects of grazing exclusion on STN concentration were significant in the 0–20 cm soil depth at SQ and NR and in the 0–10 cm soil depth at ZR and NMQ (Fig. 6a). Grazing exclusion increased STN storage in the 10–20 cm depth at SQ, and in the 5–10 cm depth at NMQ (Fig. 6b). Increase in STN storage for the whole soil profile (0–50 cm depth) between grazed plots and grazing excluded plots was only significant at SQ (Fig. 5).

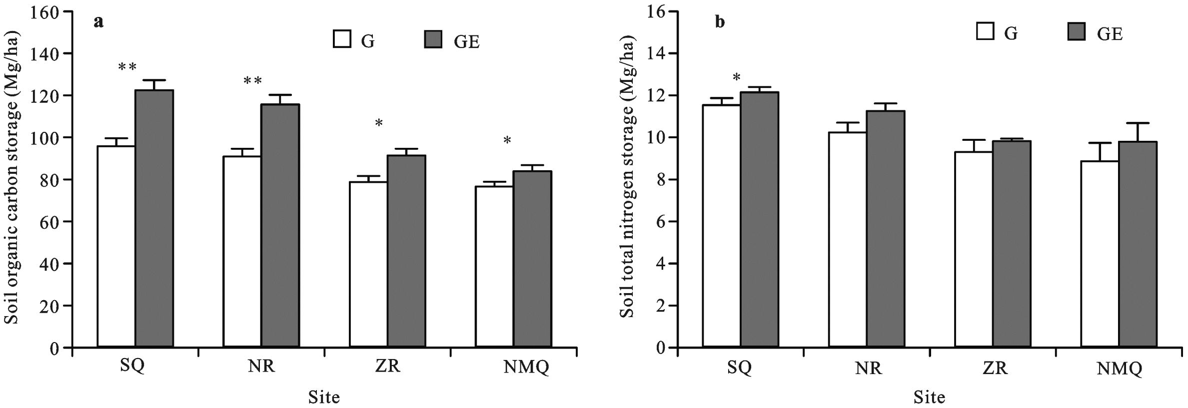

Fig. 5 Soil organic carbon (a) and total nitrogen storage (b) (0–50 cm) under grazed (G) and grazing excluded (GE) conditions for all sites. Error bars represent standard errors. Statistical differences (*t*-test) between grazed and grazing excluded plots for each depth are indicated as ** $p < 0.01$; * $p < 0.05$

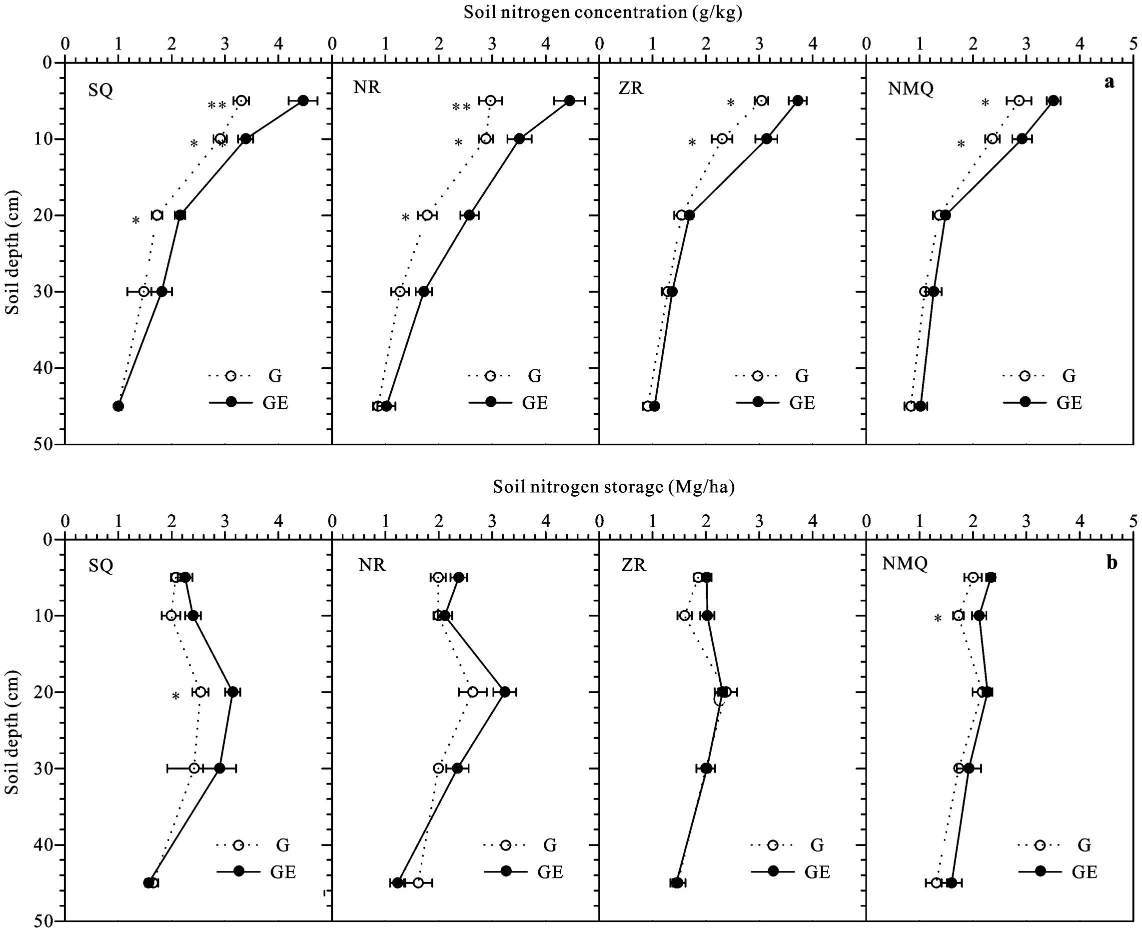

Fig. 6 Vertical distribution of soil total nitrogen concentration (a) and storage (b) under grazed (G) and grazing excluded (GE) conditions for all sites. Error bars represent standard errors. Statistical differences (*t*-test) between grazed and grazing excluded plots for each depth are indicated as ** $p < 0.01$; * $p < 0.05$

4 Discussion

4.1 Effects of grazing exclusion on plant cover and species diversity

Plant canopy cover is a key indicator to evaluate the degree of grassland degradation (Liu *et al.*, 1998). In agreement with many other exclosure experiments (Cheng *et al.*, 2011; Mekuria and Veldkamp, 2012), our study indicated that grazing exclusion had significantly positive effects on plant canopy cover of the alpine meadows in the northern Tibet. The results support the viewpoint that exclusion of livestock grazing is a simple and effective measure for restoring degraded grasslands (Spooner *et al.*, 2002; Wu *et al.*, 2009; Shi *et al.*, 2010). However, negative effect of grazing exclusion on biodiversity was observed. Wu *et al.* (2009) observed similar result of negative consequences of grazing exclusion on biodiversity due to reduction of plant density and species diversity. Plant diversity loss in high-productivity grassland may result from greater competition for canopy resources, for example, light (Huston, 1994) or/and nutrient availability (van der Wal *et al.*, 2004). Some species with lower competitive ability reduce their densities or even disappear because of competition for resources (Grime, 1998). In this study, removal of livestock grazing caused a surge of dominant *K. pygmaea* with strong tillering ability in the study sites. This change would, in turn, inhibit the growth of other plants species and diminish species richness. The present results raised a practical question of contradiction between increase of biomass yields and loss of species diversity after grazing exclusion. Thus, we suggest that grazing exclusion should be combined with other measures, for example, mowing, periodic grazing or reseeding in the process of grassland restoration.

4.2 Effects of grazing exclusion on aboveground and belowground biomass

Our findings indicated that grazing exclusion significantly increased the total AGB of the meadow community, while the biomass of different plant functional groups showed inconsistent responses to grazing exclusion. We observed an increase of palatable sedge species while a decrease of unpalatable forbs after grazing exclusion, the results are in line with previous studies which reported that palatable grasses have greater competitive ability than unpalatable grasses in grazing excluded grasslands (Gallego *et al.*, 2004; Diaz *et al.*, 2007). Palatable sedges are the dominant species in the study area. After six years of grazing exclusion, the low proportions of forbs, leguminous species and noxious species render them competitive inferiority. The dominant sedge species, *K. pygmaea* accounted for a large proportion of sedge biomass. Thus, the massive increment of *K. pygmaea* biomass primarily attributed to the increment of the total AGB. After grazing exclusion, the degraded meadow was restored with characters of biomass increase of *K. pygmaea* and decrease of forbs.

BGB is an important component of belowground carbon (Langley and Hungate, 2003). In our study, grazing exclusion significantly increased BGB in all sites. The change in root biomass is consistent with other studies that showed increase in BGB after grazing exclusion (Kauffman *et al.*, 2004; Cheng *et al.*, 2011). Commonly, continuous grazing reduced source size of carbon assimilating organs and intensified re-translocation of root carbohydrates to shoot meristems (Gao *et al.*, 2008), thus the grazing excluded plots showed a greater BGB compared with grazing plots. The response of root biomass to grazing exclusion may relate to precipitation and vegetation types. Pineiro *et al.* (2009) found that higher BGB in un-grazed sites than in grazed sites commonly observed at mesic conditions with MAP from 400 mm to 850 mm (Schuman *et al.*, 1999; Fuhlendorf *et al.*, 2002; Xie and Wittig, 2004; Derner *et al.*, 2006; Gao *et al.*, 2008). In our study, relative higher MAP ranging from 410 mm to 480 mm may be beneficial for BGB accumulation in the mesic meadows. Our result indicated that a large part of the root biomass was concentrated in the surface soil layer (0–10 cm), which is in agreement with previous study in east edge of the Qinghai-Tibetan Plateau (Shi *et al.*, 2007). Grazing exclusion seemed to potential changed the vertical distribution of BGB, as the proportions of root biomass stored in top soil layers were higher in exclosure plots than in grazed plots. This change may be attributed to the remarkable increase of dominant species *K. pygmaea*, with its root biomass mainly distributed in shallow layer (Hu *et al.*, 2005).

Yang *et al.* (2009) revealed an isometric relationship between AGB and BGB at community level in Tibetan grasslands. But in our case, significant greater R∶S ratio were observed in grazing plots in more humid sites of SQ and NR. The results are consistent with that of van der Maarel and Titlyanova (1989) who observed increasing R∶S ratio with grazing intensity in steppe. It may attribute to an increase in the allocation of resources to BGB under overgrazing condition.

4.3 Effects of grazing exclusion on soil carbon and nitrogen

Our results showed that excluding livestock grazing can increase SOC concentration and storage and STN concentration in alpine meadows in the northern Tibet. Calculated STN storage did not show the same significant increase as STN content, mainly due to lower soil bulk density in exclosures than in grazing plots. Grazing exclusion predominantly increased soil carbon and nitrogen contents in the top soil layers. Wu *et al.* (2010) observed results similar to ours that the SOC and STN concentration in the 0–30 cm soil depth increased by 23.0% and 26.3%, respectively, after nine years grazing exclusion in a degraded alpine meadow. Fan *et al.* (2013) also observed significant increase in SOC and STN concentration and storage after five and ten years of grazing exclusion in alpine meadow. Since the SOC is determined by carbon input mainly from aboveground litter production, root turnover and animal excreta, and carbon output through soil respiration, soil erosion and leaching (Cui *et al.*, 2005). The following mechanisms may attribute to the significant increase in SOC levels after removal of grazing in the study sites. First, the increment of SOC storage can be mainly ascribed to the increase in AGB and BGB caused by grazing exclusion, as primary productivity is the main driver of soil carbon sequestration (de Deyn *et al.*, 2008). Overgrazing decreased the input of organic matter from aboveground and roots (Johnson and Matchett, 2001). As a consequence, removal of grazing would reduce the outflow of energy from soil-plant system to consumers (Wu *et al.*, 2009) and increase carbon and nitrogen storage. Second, grazing exclusion increased plant cover and prevented livestock trampling from degraded grassland, which can protect aggregate structure of soil, rendering soil less susceptible to water and wind erosion and loss of carbon and nitrogen (He *et al.*, 2008). Moreover, animal manure as fuel energy is widely adopted in the study area. For example, it is estimated that about 80% of yak dung are combusted for energy in the northern Tibetan Plateau (Xu *et al.*, 2013). This would decrease nutrient availability, limit vegetation regeneration and reduce input of organic matter into soils, consequently decrease carbon and nitrogen pools in the grazed sites.

The effect of grazing exclusion on SOC is usually attributed to climatic factors, edaphic factors and grazing history. In our study, grazing intensities and soil bio-physical conditions were similar among study sites. Difference in precipitation appeared the key factor to affect the effect of grazing exclusion on soil carbon storage. First, the increment of the AGB and the SOC caused by the grazing exclusion increased with MAP levels, while the 0.6℃ variation of MAT among sites are not likely enough to cause large variation of carbon storage. It is coincided with the viewpoint of Conant and Paustian (2002), who found a positive linear relationship between potential carbon sequestration and MAP. Second, the effects of grazing exclusion on soil carbon storage at NMQ site were confined to shallower soil than at SQ, NR and ZR sites. The results suggest that grazing exclusion may be more efficient in facilitating soil carbon sequestration at sites with favorable precipitation.

5 Conclusions

In this paper, we carried out a field survey to evaluate the effectiveness of grazing exclusion project in restoring degraded alpine meadows in the northern Tibet. We mainly focused on the differences in plant production and soil properties between grazed sites and grazing excluded sites. Our investigation revealed that six years of grazing exclusion significantly improved forage production, plant canopy cover, BGB and SOC and STN storage in the northern Tibet. The results suggest that grazing exclusion can facilitate soil carbon sequestration and is an effective way to restore the degraded alpine meadows. Grazing exclusion led to dramatic increase of palatable grasses and a decrease in inedible grasses. Concentrated surface distribution of the increased root biomass and soil carbon storage, especially in lower precipitation area suggested potentially instable carbon storage and the increment in SOC may susceptible to loss with disturbance. Since the enhancement of grazing exclusion on biomass and carbon sequestration was amplified by favorable precipitation condition, it is demonstrated that grazing exclusion is more efficient in forage yield and carbon sequestration in the eastern area of alpine meadows with more precipitation. Nevertheless, our findings also indicated negative effects of grazing exclusion on species diversity of the alpine meadow community, which caused a tradeoff between carbon storage and biodiversity conservation. Therefore, carbon pools recover more quickly than plant biodiversity. We suggest that the implementation of grazing exclusion project should combine with other measures, for example, periodical grazing, in order to reconcile restoration of degraded grassland and biodiversity conservation.

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