REGULAR ARTICLE

Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China

Gao-Lin Wu · Zhen-Heng Liu · Lei Zhang · Ji-Min Chen · Tian-Ming Hu

Abstract Overgrazing significantly affects alpine meadows in ways similar to grasslands in other areas. Fencing to exclude grazers is one of the main management practices used to protect alpine meadows. However, it is not known if fencing can improve soil properties and soil organic carbon storage by restraining grazing in alpine meadows. We studied the long-term (nine-year) effects of fencing on soil properties, soil organic carbon and nitrogen storage compared with continued grazing in an alpine swamp meadow of the Qinghai–Tibetan Plateau, NW China. Our results showed that fencing significantly improved vegetation cover and aboveground biomass. There were significant effects of fencing on pH value, soil bulk density, and soil moisture. Long-term fencing favored the increase of soil total nitrogen, soil organic matter, soil organic carbon, soil microbial biomass carbon and soil carbon storage compared with grazed meadows. Our study suggests that long-term fencing to prevent disturbance could greatly affect soil organic carbon and nitrogen storage with regard to grazed meadows. Therefore, it is apparent from this study that fencing is an effective restoration approach of with regard to the soil's storage ability for carbon and nitrogen in alpine meadow of the Qinghai–Tibetan Plateau.

Keywords Alpine swamp meadow · Fencing · Grazing · Soil properties · Soil carbon storage

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Introduction

Soils play an important role in the carbon and nitrogen cycles and storage in grassland ecosystems (Tiessen et al. 1994; Neill et al. 1997; Lal 2004; Piao et al. 2009). Soil carbon storage represents a significant sink of carbon from the atmosphere (Neill et al. 1997), and changes to surface soil organic carbon and nitrogen stocks and cycling patterns are also important indicators of soil fertility and utilization potential (Tiessen et al. 1994). Human alteration of natural ecosystems for

agriculture is an important component of disturbance, and has the potential to alter soil carbon and nitrogen storage.

The grassland ecosystem is an important carbon-sink or source and soils are the largest source of uncertainty in the terrestrial carbon balance (Piao et al. 2009). Grassland ecosystems can influence global environmental change through their strong potentials for carbon and nitrogen sequestration (Wright et al. 2004). But, overgrazing may reduce soil carbon sequestration and storage in grassland ecosystem (Shrestha and Stahla 2008) and forest ecosystem (Abril et al. 2005). Soil management of ecosystems also can influence the rate of soil organic carbon sequestration (Lal 2004). Improved grazing methods have been considered as an important strategy to renew degraded grassland and to increase the soil carbon pool (Lal 2004). The exclusion of livestock through the use of mesh fencing to create large-scale enclosures has become a common grassland management strategy throughout the world in recent decades (Reeves 2000; Smith et al. 2000; Shrestha and Stahla 2008; Wu et al. 2009). Fencing to exclude stock has been widely regarded as a simple restoration method for degraded grassland and the fenced remnants have typically been thought to 'look after themselves' (Reeves 2000). Recent research has focused on the effects of fencing on aboveground vegetation succession and community structure (Pettit et al. 1995; Gibson et al. 2001; Spooner et al. 2002; Wu et al. 2009). Such management measures present a dilemma between grazing utilization and biodiversity protection for grassland (Smith et al. 2000). However, less information is available on effects of long-term fencing on soil organic carbon and nitrogen stocks in a grassland ecosystem, especially in alpine swamp meadow of the Qinghai–Tibetan Plateau.

In this paper, we examine changes in soil organic carbon, nitrogen stocks and other soil properties of a nine-year fenced swamp meadow relative to grazed meadow. The aim of this study was to better understand the effects of excluding grazing herbivores through fencing on high altitude meadow soil in the Qinghai–Tibetan Plateau and to determine whether long-term fencing can significantly advance soil carbon sequestration and storage as a grassland management tool. Specifically we examined the effects of long-term fencing on: (1) soil properties; and (2) soil organic carbon and nitrogen storage. Our long-term hope is that

the study should contribute to the restoration of carbon and nitrogen sequestration ability in degraded grasslands in the Qinghai–Tibetan Plateau.

Methods

Study area

This experiment was conducted in alpine meadow at 3,500 m a.s.l. in the eastern Qinghai–Tibetan Plateau at Manrima village of the Maqu Wetland Protection Area (33°45′ N, 102°04′ E) in Gansu Province, PR China (Fig. 1). The mean daily air temperature is 1.2°C, ranging from −10°C in January to 11.7°C in July. Mean annual precipitation is 620 mm, mainly falling during the short, cool summer. The monthly mean temperature and precipitation, annual average precipitation and annual accumulated temperature (≥0°C) from 1969 to 2005 in Maqu County were reviewed in Wu et al. (2009). The annual cloud-free solar radiation is about 2,580 h. The vegetation is typical alpine meadow and is dominated by clonal *Kobresia* sp. (Cyperaceae), *Festuca ovina*, *Poa poophagorum*, *Roegneria nutans*, *Agrostis sp.* (Poaceae), *Saussurea sp.* (Asteraceae), and *Anemone rivularis* (Ranunculaceae) (Wu et al. 2009). The total Maqu Wetland Protection Area had 85.87×10^4 ha alpine meadow. The soil type of the study area was an alpine meadow soil.

Experimental design and soil sampling

An alpine swamp meadow dominated by *Kobresia tibetica*, *Carex muliensis* and including grasses and some forbs was selected for this study. The dominant botanical components and their biomass, and litter biomass in fenced and grazed meadows are showed in Table 1. Grazed meadow had lower total biomass and higher plant density, but ungrazed meadow had higher total biomass and lower plant density (Wu et al. 2009). This showed that ungrazed meadow had the larger individuals than grazed meadow. We selected five 50 m×50 m blocks in each the grazed and fenced meadows using the line transect method (Fig. 1). This resulted in a total of 10 blocks for the study. Grazed meadows had become degraded because they were undergoing nomadic grazing from a medium density of Tibetan sheep and yaks (the approximate proportion of

Fig. 1 Map of the Maqu Wetland Protection Area showing the location of the study sampling sites. It is located in the south of Gansu Province and lie in the eastern Qinghai–Tibetan Plateau, China. *Red circles* are sampling sites and *open squares* are sampling quadrats. Five blocks were selected respectively in grazed meadow and fenced meadow and five quadrats were determined for soil sampling collection in each block. Total 50 squares (1.0 m×1.0 m) were included in this study
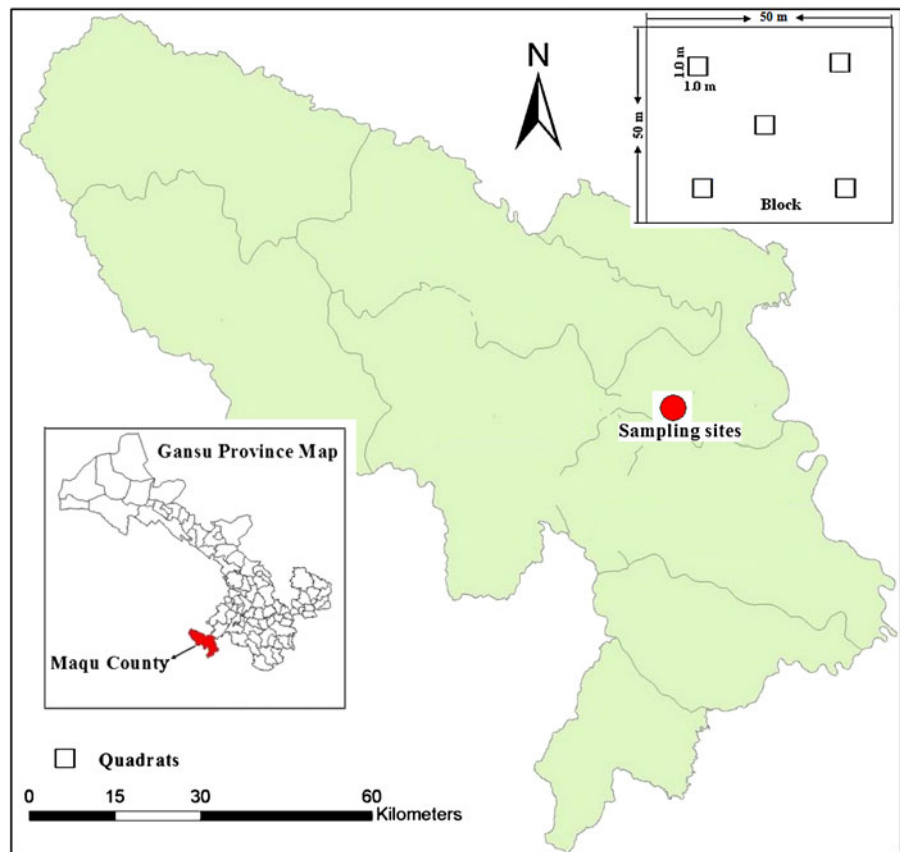
sheep vs yaks was about 1.6:1) all the time. And, fenced meadows were fenced from 1999 to now because of Natural Forest Protection Project of China. The fence completely excluded livestock grazing during the plant growth-season from April to October and slight grazing was done only during the hay-stage in winter.

We established five zonal random sampling quadrats (1 m × 1 m) per block in both the five grazed blocks and five fenced blocks. The quadrats were randomly arranged in every sampling block. Samples were taken in mid-August of 2008, when biomass had reached its highest. The covers, aboveground biomass and litter

Table 1 Dominant species and their biomass, total cover, aboveground total biomass and litter biomass in fenced and grazed meadows in this study. Values (±SE) are means of 25 squares

Management types	Dominant species	Biomass (g/m^2)	Total cover (%)	Aboveground total biomass (g/m^2)	Litter biomass (g/m^2)
Fenced meadow	*Koeleria tibetica*	73.47±11.23	91.96±5.5	391.51±63.82	33.85±8.54
	Blysmus sinocompressus	46.19±6.12			
	Carex muliensis	31.43±6.61			
	Poa poophagorum	39.54±5.32			
	Kobresia humilis	11.41±3.04			
Grazed meadow	*Potentilla anserine*	43.23±8.92	66.32±8.5	220.54±45.74	17.06±4.72
	Kobresia humilis	33.42±9.32			
	Aster tongolensis	24.54±4.21			
	Elymus nutans	15.65±4.17			
	Stipa aliena	11.32±3.51			

biomass were measured for these meadow communities. Meanwhile, we collected five soil samples by bucket auger within each quadrat from each sampling block in each the fenced and grazed blocks, then mixed five homogenised soil samples as a soil sample. Five mixed soil samples at depths of 0–30 cm in each sampling quadrat of each block were used to analyze soil properties. A total of 25 mixed soil samples were collected respectively for grazed meadow and fenced meadow.

All soil samples were air-dried and then passed through a 0.14 mm sieve. Soil pH was determined using a soil–water ratio of 1:5, soil water content before air drying was obtained by the oven-drying method, soil bulk density was measured using the soil cores (volume, 100 cm^3) by the volumetric ring method (Soil Science Society of China 1983); soil total nitrogen and soil organic matter were measured by the $K_2Cr_2O_7$ method using the modified Kjeldahl wet digestion procedure of Miller and Keeney (1982); the organic carbon content in the soil samples was measured using a Mebius method by the Walkley–Black acid digestion (Nelson and Sommers 1982); microbial biomass carbon was measured by the method of Vance et al. (1987). The content of each soil property was calculated by the proportions of its account for per soil dry weight. We calculated the total soil organic carbon storage density (TSOC, g cm^{-2}) by the method of He et al. (2008) on a ground area basis up to a 30-cm depth as follows:

$$TSOC = \sum D_i \times P_i \times OM_i \times S$$

where D_i, P_i, OM_i, and S represent, respectively, the soil thickness (cm), bulk density (g cm^{-3}), organic carbon concentration (%), and cross-sectional area (cm^{-2}) of the ith layer; i=1, 2, and 3.

Data analyses

All data were expressed as mean±1 standard error of mean. The mixed soil samples data for the 0–30-cm soil layer were used to analyze the soil properties and soil organic carbon storage potentials of the grazed and fenced meadows. ANOVA tests (followed by Tukey's) were performed to test for differences of aboveground vegetation covers, aboveground biomass, litter biomass, soil properties and soil organic carbon storage between fenced and grazed meadows to assess the effects of long-term fence on aboveground and belowground properties and soil organic carbon storage. Significant differences for all statistical tests were evaluated at the level of $P \leq 0.05$. All statistical analyses were performed using the software program SPSS, ver. 13.0 (SPSS Inc., Chicago, IL, USA).

Results

ANOVA analyses showed that the fenced meadows had greater total vegetation cover (F=3.954, P<0.001), aboveground biomass (F=2.259, P<0.001) and litter biomass (F=1.433, P<0.001) in comparison to the grazed meadows. Fencing the meadow for nine years increased respectively 72.94%, 57.66% and 98.42% on vegetation covers, aboveground biomass and litter biomass than grazed meadows (Table 1). Meanwhile, the long-term fencing significantly altered soil properties in alpine meadow. Long-term fencing of the meadows was associated with a reduction in pH from 7.67 to 7.20 (F=4.828, P<0.01) and in soil bulk density from 1.12 to 0.86 g cm^{-3} (F=4.514, P<0.001) compared with grazed meadows.

Long-term fencing of the meadows significantly increased soil water content (from 23.26% to 33.78%, F=2.473, P<0.001), soil total nitrogen (from 5.21 to 6.58 g kg^{-1}, F=1.327, P<0.05), soil organic matter (from 106.09 to 158.58 g kg^{-1}, F=6.385, P<0.001), soil organic carbon (from 62.94 to 77.44 g kg^{-1}, F=4.246, P<0.01) and soil microbial biomass carbon (from 1.32 to 1.51 g kg^{-1}, F=2.647, P<0.05) in the 0–30 cm soil depth compared with grazed meadows (Table 2). Nine-year-fencing of meadows significantly increased soil carbon storage in the surface 0–30 cm of soil from 2.97 in the grazed meadows to 3.55 kg m^{-2} (F=3.541, P<0.001) (Table 2), and the increased carbon storage due to reduced grazing for the area were estimated about 49.80×10^8 kg in 85.87×10^4 ha alpine meadow.

Discussion

Effects of fencing on ecosystem properties except soil carbon

Our results showed that the fenced meadow had higher aboveground biomass, litter biomass, vegetation cover,

Table 2 Comparison of (mean±SE) of soil pH value, Soil water content (%), Soil bulk density (g cm^{-3}), Soil total nitrogen(g kg^{-1}), Soil organic matter(g kg^{-1}), Soil organic carbon(g kg^{-1}), Soil microbial biomass carbon(g kg^{-1}) and Soil carbon storage(kg m^{-2}) over the depth of 0~30 cm for grazed and fenced meadows

Soil property parameters	Management types	
	Grazed meadows	Fenced meadows
pH value	7.67±0.22	7.20±0.13
Soil water content	23.26±1.60	33.78±3.19
Soil bulk density	1.12±0.07	0.86±0.09
Soil organic matter	106.09±6.53	158.58±9.23
Soil total nitrogen	5.21±0.26	6.58±0.32
Soil organic carbon	62.94±2.48	77.44±3.58
Soil microbial biomass carbon	1.32±0.08	1.51±0.04
Soil carbon storage (0~30 cm)	2.97±0.12	3.55±0.07

soil carbon, soil microbial biomass, soil moisture, soil nitrogen and soil organic matter, but a lower pH value and soil bulk density. The reduced disturbance had a direct effect on the dominant species of vegetation, vegetation cover and aboveground biomass, and reduced trampling may have resulted in a reduction in bulk density. Long-term trampling by livestock can lead to soil compaction, reduced soil infiltration rates, soil porosity, increased soil bulk density, and limited oxygen concentrations. These result in a decline of activity of edaphon in soil of grazed meadow (Holt 1997).

There is a buildup of litter in the ungrazed treatment due to the more grass and the less herbs, as offtake by herbivores is reduced. However, this build up has been slow suggesting that the increase in litter production may be offset by a more rapid litter decomposition rate in the moist, more neutral acidic and less dense soil of fenced meadow (Geissen and Guzman 2006). This may have contributed to the higher soil organic matter and carbon contents in the fenced areas.

Fenced meadows also had higher soil microbial biomass carbon than the grazed meadows; consistent with the results of Gu et al. (2007) which showed that overgrazing significantly reduced soil microbial biomass carbon in typical grasslands in Inner Mongolia of China. It has been interpreted by Iyyemperumala et al. (2007) that changes in soil properties provide a mosaic of environments for soil microbes and likely alters microbial ecophysiology and their mediated nutrient transformations. In addition, soil microbial biomass serves as a sink and source of N and thus plays an important role in regulating soil available N and preventing undesirable N loss from soil systems (Iyyemperumala et al. 2007). So, higher soil nitrogen

contents may be related to higher soil microbial biomass carbon in fenced meadow. However, excretal returns of dung and urine from grazing animals can also result in the accumulation of soil nitrogen (Thomas et al. 2006). As well as increasing soil nitrogen, fencing also results in increased soil total phosphorus and available phosphorus (Wu et al. 2009).

Effects of fencing on soil carbon storage

Although aboveground vegetation plays an important role in regulating the biogeochemistry of ecosystems by fixing carbon and nutrients and preventing the loss of nutrients under disturbances (Bormann and Sidle 1990), it is clear from these results that management of alpine swamp meadows also has great impact on soil carbon and nitrogen storage. Fencing increased soil carbon sequestration and storage: with the assumption that past grazing has resulted in carbon losses from this system. Our results showed that soil organic carbon, soil microbial biomass carbon and soil carbon storage all increased after fencing for nine years; increases were of 23.04%, 14.39% and 19.53% compared to the grazed meadow, respectively. Similar studies have reported that there was positive contribution for soil carbon sequestration under exclosure conditions in degraded sandy grassland (e.g. Li et al. 2006).

There may be a range of potential mechanisms through which soil carbon increased in the fenced meadows. Firstly, the return of carbon from increased aboveground biomass and litter. As soil carbon input is mainly derived from litter, so that primary productivity is the main driver of soil carbon sequestration (De Deyn et al. 2008), even in alpine meadows of the Qinghai–

Tibetan Plateau with a short growing season. Excluding grazing reduced the outflow of energy and nutrient from soil–plant system to consumers (livestock), especially for palatable grasses (Moretto and Distel 1997), Poaceae spp. and Cyperaceae spp. which are dominant species in this study area. Above-ground plant resources may be returned to the soil when litter layers decompose (Bardgett and Wardle 2003) in fenced meadow.

Secondly, belowground biomass (dead roots, mycorrhizae, and exudates) is an important element of soil carbon sequestration (Langley and Hungate 2003). Belowground biomass appears to be significantly decreased by grazing (Li et al. 2006), so grazing removal may potentially increase the amount of soil carbon sequestered in this way.

Thirdly, changes in vegetation composition and dominant plant functional group could affect soil carbon sequestration (De Deyn et al. 2008). The presence of C4 grasses in combination with other species has also been shown to increase soil C accumulation and biomass production in other grasslands (Fornara and Tilman 2008). So, we suggest the increase of C3 plant functional group species, *Potentilla anserine*, *Elymus nutans*, *Kobresia humilis* and decrease of C4 plant functional group species, Cyperaceae spp. and Poaceae spp. also may be a reason why there are higher soil C and N accumulation in fenced meadow soils than grazed meadow soils.

Grassland carbon management

Grasslands play an important role in the global carbon (C) cycle. Grassland in good condition should be in balance in terms of carbon input and carbon output or in the state where carbon input is greater than carbon output. At least one study has shown that carbon output is greater than carbon input in grazed grassland (Li et al. 2006). Our results indicate that fenced meadow results in higher soil carbon storage than grazed meadow. All these suggest that fencing is an effective restoration measure in that it favors of soil carbon sequestration and storage in this type of grassland.

Conclusions

Soil carbon, nitrogen and water content, soil organic matter and soil microbial biomass carbon and soil organic carbon storage were all increased by fencing meadow communities to prevent grazing. Higher soil organic carbon, soil total nitrogen and soil microbial biomass carbon storage may be attributed to the increase in plant aboveground vegetation and changes in soil physical characteristics after grazing is removed. Therefore, it is apparent from this study that fencing is an effective restoration approach of storage ability for soil carbon and nitrogen stocks in alpine meadow of the Qinghai–Tibetan Plateau. This may be true of other grassland without a long history of grazing. Although the soil sampling replications were sufficient for this alpine swamp meadow in this study, however, additional researches at more sites should be sampled to extend the findings in this study. However, it should be borne in mind that management for carbon may result in reductions in biodiversity, as both may not be maximized under the same management regime.

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