Environ Earth Sci (2016) 75:1471
DOI 10.1007/s12665-016-6178-0

ORIGINAL ARTICLE

Characteristics of soil water percolation and dissolved organic carbon leaching and their response to long-term fencing in an alpine meadow on the Tibetan Plateau

Yongsheng Yang[1] · Hongqin Li[1] · Li Zhang[2] · Jingbin Zhu[1,3] · Huidan He[1,3] · Yaxi Wei[1,3] · Yingnian Li[1,4]

Received: 14 March 2016 / Accepted: 7 October 2016 / Published online: 25 November 2016

Abstract Fencing is an important method for restoring and reconstructing degraded grasslands on the Tibetan Plateau. Understanding the characteristics of soil water percolation and soil dissolved organic carbon (DOC) leaching and their response to long-term fencing (10 years) could provide a scientific basis for the management of soil water resources and carbon sinks in alpine grasslands. In this study, grazing plots and plots fenced for 10 years were selected in an alpine meadow, and soil bulk density, soil organic carbon (SOC) density, vegetative carbon (VC) density, soil water percolation and DOC leaching were monitored regularly in the two treatments. The results were as follows: (1) Long-term fencing reduced the soil bulk density and improved carbon sequestration in the alpine meadow. The soil bulk density at a depth of 0–20 cm in the fenced plots was significantly lower than that of the grazing plots ($p < 0.05$), and SOC density and VC density at a depth of 0–40 cm were higher than those of the grazing plots to a different degree. (2) During the non-frozen period (from May to September), total soil water leakage at a depth of 40 cm in the grazing plots was 9.6 mm, which accounted for 2.2% of the total rainfall in this period. After fencing for 10 years, soil water leakage was increased by 53.1%. (3) From May to September, total DOC leaching from the grazing plots was 34.6 gC m^{-2}, and total DOC leaching from the fenced plots was increased by 55.5% compared to the grazing plots. Our results demonstrated obvious soil water percolation and DOC leaching in the alpine meadow. The DOC entered into the groundwater system with the percolation water and finally flowed into lakes and rivers, which represents an important soil carbon loss pathway in alpine meadows.

Keywords Long-term fencing · Alpine meadow · Soil water percolation · DOC leaching · Soil organic carbon density

Introduction

The Tibetan Plateau is the main functional area providing ecosystem security and water source conservation in China and is known as the “Chinese water tower.” As one of the main components of the water source conservation region of the Tibetan Plateau, the alpine meadow is a widespread land cover type comprising the representative vegetation of the plateau (Cao et al. 2004), and it plays a very important ecological role in maintaining the development of the regional economy, protecting water sources and preserving biodiversity in the Tibetan Plateau ecosystem (Bu et al. 2007; Wang et al. 2012). Because the soil layer in alpine meadows is relatively thin and the soil below 40 cm is usually a sand-gravel layer with high water permeability (Wang et al. 2003), soil water easily enters into the groundwater system by the process of percolation, which is closely related to the leaching of soil nutrients and soil salinity (Feng et al. 2005; Robert and Bruce 1990). Studying the characteristics of soil water percolation in

✉ Yingnian Li
ynli@nwipb.cas.cn

[1] Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining 810001, China

[2] Ecological Environment Monitoring Center of Environmental Protection Bureau of Qinghai, Xining 810001, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

[4] Key Laboratory of Adaptation and Evolution of Plateau Biota, China Academy of Sciences, Xining 810001, China

alpine meadows would provide basic data to elucidate the water cycle and nutrient transfer in this region. Until now, research on soil water percolation has mainly focused on arid, semiarid and humid regions at low altitudes (De and Bootsma 1997; Heng et al. 2001; Mack et al. 2005), but little research has been conducted on the fragile ecological environment of high-altitude alpine meadows.

Due to the detailed research on the topic of global warming, the global carbon cycle is becoming one of the most important issues that must be studied by environmental scientists (Booth et al. 2012). As one of main carbon sinks in the natural environment, soil carbon can be released into the atmosphere in the form of greenhouse gases (CO_2, CH_4) (Cao et al. 2004; Hannu et al. 1995) as well as leached into the groundwater in a water-soluble form (Jette et al. 1996). Reimo et al. (2011) found that the net carbon losses from cropland soils was increased by 25% due to carbon leaching, but leaching hardly affected the actual net ecosystem carbon balance of forest soils. Research from Ireland determined that the leaching losses of biogenic dissolved inorganic carbon from non-inversion tillage plus a cover crop was 34.0 g m^{-2} $year^{-1}$ (David et al. 2011), which was significantly higher than that for conventional tillage. Therefore, it can be inferred that dissolved organic carbon (DOC) leaching is very important for the natural carbon cycle. Alpine meadows account for 35% of the area of the Tibetan Plateau (Song et al. 2010) and are a very important ecosystem component of this region. To date, research on DOC leaching in alpine meadows is still lacking, so its study in these habitats would be of important scientific significance and contribute to a deeper understanding of the carbon cycle and the change in carbon sequestration on the Tibetan Plateau.

Fencing is an effective rehabilitation measure for degraded pastures, and it has been widely used in grassland management in China. Researchers have studied the ecological restoration effects of fencing on degraded grasslands on the Tibetan Plateau. Wu et al. (2010) demonstrated that fencing could enhance the coverage and above-ground vegetation biomass but significantly decrease the species richness of alpine grassland vegetation (Wu et al. 2009), and other research has found that fencing could improve the soil physicochemical properties of alpine meadows (Li et al. 2013). However, while fencing has been shown to affect the growth of the vegetation and soil properties in alpine meadows, whether it affects water percolation and DOC leaching is unknown. If it does, to what degree? Exploring the effects of fencing on soil water percolation and DOC leaching in alpine meadows is an important contribution to research on the global water and C cycles.

Based on the above reasons, this research focused on a typical alpine grassland in the source region of the three rivers on the Tibetan Plateau as a study area and determined the effects of long-term fencing on soil water percolation and DOC leaching through long-term positioning observations. Based on these analyses, we examined the effects of long-term fencing on the soil water and carbon cycles in an alpine grassland and expected that the results could provide an experimental basis and basic data to inform the effective utilization of water resources and improve carbon sequestration management in alpine grasslands.

Materials and methods

Study site and management

The study site was located in Maqin Country in Guoluo Prefecture of Qinghai Province (N 34°28′47.52″, E 100°12′05.37″) at an elevation of 3763 m. This area experiences a typical plateau continental climate with long harsh winters and short cool summers. The annual average temperature is −0.5 °C, and the annual cumulative temperature above 0 °C is 914.3 °C. The mean annual precipitation is 514 mm with 445.0 mm of rainfall from May to September (Wang et al. 2007). The vegetation is typical of an alpine meadow dominated by *Kobresia myosuroides* (Villars) Foiri, and the main associated plant species are *Festuca ovina* Linn, *Poa annua* Linn, *Elymus nutans* Griseb *and Ptilagrostis dichotoma*. The vegetation coverage ranges from 50 to 80%, and the soil type is mainly alpine meadow soil. Due to climate change and overgrazing, the grassland in the study site was severely degraded (Yi et al. 2012).

Experimental design

We selected a block of a meadow in Maqin Country that was fenced in 2003 as a fenced plot in March 2013; the fence completely excluded livestock grazing during the plant growing season from June to October. Slight grazing was allowed during the hay-stage in winter at an intensity of approximately 1.00 sheep per hm^2. The grazing plot was established 500 m away from the fenced plot enclosure (CK), and the grazing intensity was 1.36 sheep per hm^2. The sizes of the fenced and grazing plots were 60 m × 60 m.

Index measurements and analysis

Collection of soil water leakage

Three soil water percolation observation systems (Fig. 1) were established in the middle of both the fenced plot and grazing plot in May 2013, and the spacing between

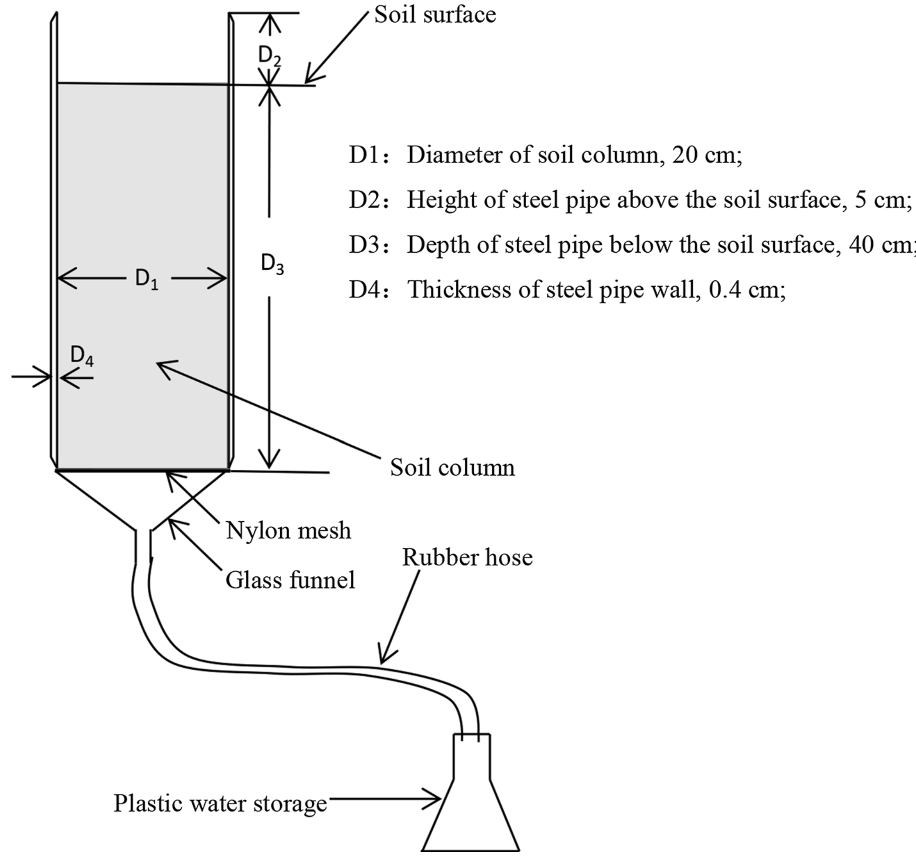

Fig. 1 Schematic representation of the soil water percolation experimental setup used in the study

adjacent soil water percolation observation systems was 15 m. The detailed soil water percolation observation system installation procedure was as follows. First, six steel pipes were cut so that their height, inner diameter and wall thickness were 45, 20 cm and 4 mm, respectively. The top and bottom edges of the steel pipes were like blades; so to maintain the natural structure of the soils, the pipes were pounded vertically into the soil with a rubber hammer. The small gaps between the soil and the inner walls of the pipes were filled by air-dried fine soil particles with a thin bamboo stick. To prevent water flowing between the inner and outer walls of the pipes, which would have influenced the accuracy of the experiment, the top edge was 5 cm higher than the soil surface, and the remaining 40 cm was buried in the soil. A sand-gravel layer usually occurs at a depth of 40 cm in alpine meadows, so the soil water leakage measured in this research is from a depth of 40 cm. Each treatment was replicated three times. After the steel pipes were pounded into the soil, a tunnel of 120 cm (length) × 80 cm (width) × 100 cm (depth) was dug beside each steel pipe, and the distance between the steel pipe and the side of the tunnel was 50 cm. A parallelogram-shaped pit reaching the bottom edge of each steel pipe, a depth of 40 cm, was dug on the inner side of the tunnel. Then, a glass funnel was connected to the bottom of each steel pipe, and the point of connection between bottom edge of the pipe and the funnel was sealed with tape. To prevent the soil in the steel pipe from being dropped into the funnel, which would have influenced the normal fluidity of the soil water, a layer of nylon mesh was tightly bound to the outside of each steel pipe. A rubber hose with an inner diameter of 0.6 cm was connected to the outlet of the funnel, and leakage water was stored in a plastic water container. The space below the bottom edge of the steel pipe and around the funnel was filled with soil under the assumption that the water in the rubber hose could flow normally. Lastly, the four sides of the tunnel were reinforced with moisture-proof, insulating material with a thickness of 3 cm, and a panel made from moisture-proof, insulating material was used to cover the tunnel; the size of the panel was 230 cm (length) × 90 cm (width). A schematic representation of the soil water percolation measurement setup is shown in Fig. 1.

The soil water leakage was measured with a measuring cup on the 8th, 18th and 28th of each month during the non-frozen period (from May to September). To avoid the overflow of leakage water from the plastic water storage container when long rains occurred, observations were added when lone-time or heavy rainfall events occurred. After measuring the amount of soil water percolation, the

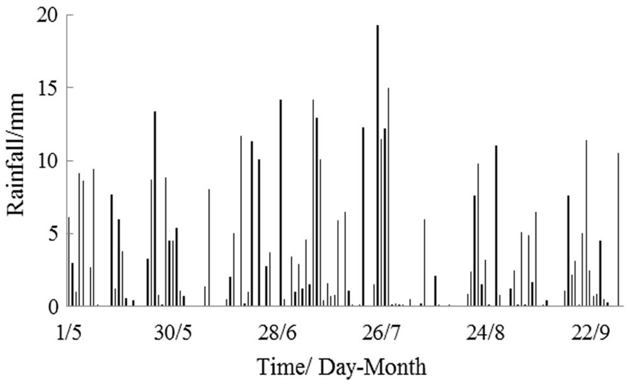

Fig. 2 Daily rainfall in Maqin country from May to September in 2013

leakage water was brought to the laboratory in clean plastic bottles. The daily rainfall from May to September in 2003 was measured by the weather bureau of Maqin Country and is shown in Fig. 2.

Determinations of DOC leaching

DOC concentrations of the soil leakage water samples, in mgC/g, were analyzed using Pt-catalyzed, high-temperature combustion (680 °C) with a TOC-VCPH/CPN (Shimadzu Corporation, Kyoto, Japan) (Reimo et al. 2011; Forrester et al. 2013). Prior to analysis, the inorganic carbon was stripped off by adjusting the pH to 2 with HCL and sparging with CO_2-free synthetic air. Then, DOC leaching per unit area was calculated according to the following equation:

$$Q = \frac{Q_1 S}{1000}$$

where Q is the DOC leaching per unit area in gC/m^2; Q_1 is the DOC concentrations of soil water in mgC/g; S is the amount of leakage water, g/m^2; and 1000 is the conversion coefficient between mg and g.

Determinations of soil bulk density and soil organic carbon (SOC) density

Undisturbed soil samples were collected from depths of 0–10, 10–20 and 20–40 cm in fenced and grazing plots with a soil wreath knife (both the inner diameter and height were 5 cm) in August 2013. Each treatment was replicated three times. Undisturbed soils were placed in an oven at 105 °C until they reached constant weight, and the dry undisturbed soil was then weighed. Soil bulk density was calculated using the following equation:

$$D = \frac{m_1 - m}{v}$$

where D is the soil bulk density in g/cm^3; m_1 is the dry weight of the undisturbed soil and the soil wreath knife in g; m is the weight of the soil wreath knife in g; and v is the volume of the soil wreath in m^3.

After the soil samples were air-dried, the roots and gravel in the soil samples were carefully removed, and the soil was sifted through a 0.25-mm sieve. The SOC content of each soil layer was measured by the heated dichromate titration method (Wang et al. 2011).

SOC density is the storage of SOC per unit area, the SOC density of a certain soil profile is the sum of the SOC densities of all of the soil layers in the profile; and SOC density was calculated with the following equation (Du et al. 2011):

$$\mathrm{SOC} = \sum_{i=1}^{k} \mathrm{SOC}_i = \sum_{i=1}^{k} C_i O_i D_i (1 - V_i)/100$$

where SOC is the SOC density in kg/m^2; C_i is the SOC content in the i soil layer in g/kg^1; O_i is the soil bulk density in the i soil layer in g/kg; D_i is the thickness of soil in the i soil layer in cm; and V_i is the volume ratio of gravel with diameters >2 mm in the i soil layer in %.

Determinations of vegetation carbon (VC) density

First, the vegetation biomass was determined using the "harvest" method. Five 0.25-m^2 (0.5 m × 0.5 m) quadrats in the fenced and grazing plots were randomly chosen in August 2010, and the above-ground part of the vegetation within each quadrat was cut and collected in a paper bag. Soils in the quadrats, which contained the roots of the vegetation, at the depths of 0–10, 10–20 and 20–40 cm were dug by shovel and knife, and they were collected in the mesh bags. The roots were washed off in the river, and little stones were removed in this process. The biomass samples were dried in an oven at 80 °C until they reached a constant weight to determine the vegetation biomass per unit area. VC density was calculated with the following equation:

$$\mathrm{DVC}_t = \sum_{i=1}^{k} \mathrm{DVC}_i = \sum_{i=1}^{k} C_i O_i$$

where $\mathrm{DVC_t}$ is the VC density in g/m^2, and k is the vegetation biomass layer. From the top to the bottom, the vegetation biomass was divided into four layers including the above-ground biomass and the below-ground biomass at the depths of 0–10, 10–20 and 20–40 cm. C_i is the conversion coefficient of vegetation biomass to carbon content. For the above-ground biomass, C_i is 0.45, and it is 0.40 for the below-ground biomass (Fan et al. 2008). Finally, O_i is the vegetation biomass per unit area in g/m^2.

Data analysis

Data were expressed as the mean ± SE. Data were analyzed for significance with a t test, one-way analysis of variance and least significance difference test in SPSS 12.0 (SPSS Inc., Chicago, IL, USA), and the analysis of correlations among the different index values was performed in SAS 9.0 (SAS Institute, Inc., Cary, North Carolina).

Analysis and results

Soil bulk density

Soil bulk density values at different depths in the fenced and grazing plots are shown in Fig. 3, and the results indicated that the soil bulk density in the fenced and grazed regions in the alpine meadow significantly increased with increasing soil depth. Long-term fencing significantly decreased the soil bulk density from 0 to 20 cm in depth, but there were no effects on soil bulk density from 20 to 40 cm. Compared with the grazing plot, the soil bulk density at depths of 0–10 and 10–20 cm in the fencing plot was decreased by 59.2 and 18.2%, respectively, and the differences were significant ($p < 0.05$).

SOC density

SOC density at the different soil depths in the grazing and fenced plots is shown in Fig. 4. The results indicated that, compared with the grazing plot, SOC density was increased by fencing to varying degrees, especially in the deep soil layers. SOC density at 0–10, 10–20 and 20–40 cm in the fencing plot increased by 16.4, 23.2 and 118.3%, respectively, compared with that of the grazing plot. The difference between the two treatments at 20–40 cm was significant ($p < 0.05$).

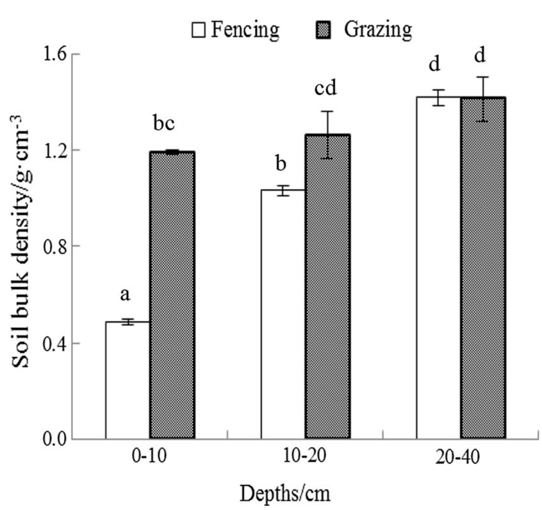

Fig. 3 Soil bulk density of plots with fencing and grazing in an alpine meadow. *Note Different lowercase letters* indicate significant differences among the different treatments, $p < 0.05$. The same applies below alpine meadow

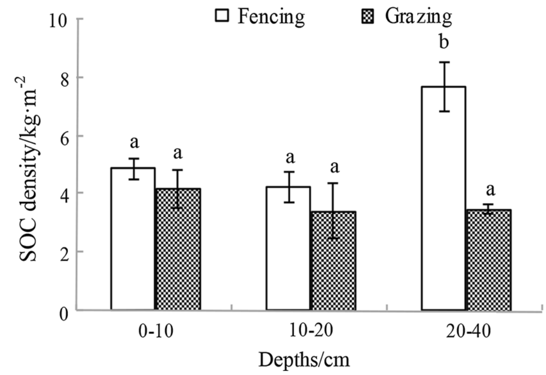

Fig. 4 SOC density of plots with fencing and grazing in an alpine meadow

VC density

The above-ground and below-ground VC densities at different depths under fencing and grazing plot in the alpine meadow are shown in Fig. 5. The total VC density, which was the sum of the above-ground density and that at the different depths, of the fenced plot (2469.9 gC/m^2) was increased by 147.2% compared with the grazing plot. The above-ground and below-ground VC density at soil depths of 0–10, 10–20 and 20–40 cm in the fenced plot increased by 186.8, 144.8, 153.2 and 103.2%, respectively, compared with that of the grazing plot. The statistical analysis confirmed that the differences between the two treatments above-ground and at the 0–10 cm depth were significant ($p < 0.05$), whereas the differences at 10–20 and 20–40 cm were not significant ($p > 0.05$). These findings indicated that long-term fencing enhanced the carbon storage ability of the vegetation and increased the carbon stock in the alpine meadow ecosystem.

Soil water leakage

The change in soil water leakage in the 0–40 cm soil layer during the non-frozen period (from May to September) in 2013 is shown in Fig. 6. The trend in the change in soil

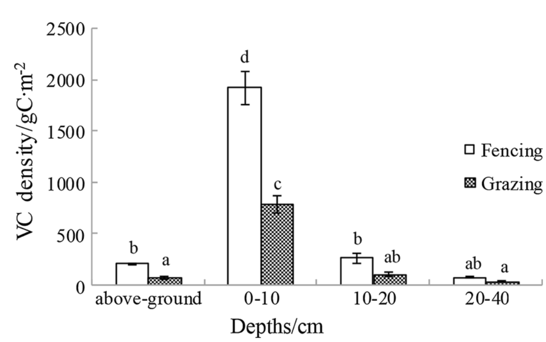

Fig. 5 VC density of above-ground and different depths in plots with fencing and grazing in an alpine meadow

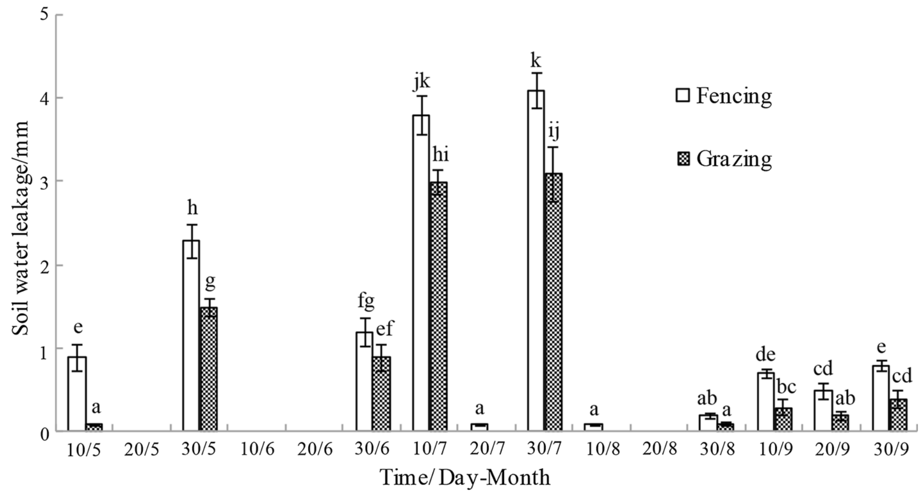

Fig. 6 Soil water leakage in plots with fencing and grazing in an alpine meadow from May to September

water leakage in the grazing plot was consistent with that of the fenced plot; both were low from May to June and August to September and reached peak values in July. The results also indicated that fencing significantly increased soil water leakage in alpine meadow. The soil water leakage from the grazing and fenced plots from May to September lies between 0.0 to 3.1 mm and 0.0 to 4.1 mm, respectively, and the average soil water leakage during this period was 0.6 and 1.0 mm, respectively. The total soil water leakage under fencing (14.7 mm) from May to September was increased by 53.1% compared with grazing (9.6 mm) ($p < 0.05$), and the values for both treatments account for 3.4 and 2.2% of the total rainfall (423.6 mm), respectively, during the same period. The correlation analysis showed that there was a significant positive relationship between soil water leakage and rainfall under both fencing ($r = 0.87643$, $p < 0.001$) and grazing ($r = 0.83789$, $p < 0.001$).

DOC leaching

DOC leaching under grazing and fencing in the alpine meadow from May to September is shown in Fig. 7. These results indicated that fencing significantly increased soil DOC leaching under grazing and fencing, which lies between 0.0 and 13.8 gC/m^2 and 0.0 and 10.5 gC/m^2, respectively, and the average values for the two treatments were 3.6 and 10.5 gC/m^2. Total DOC leaching of the fenced plot (53.8 gC/m^2) from May to September was increased by 55.5% compared with that of the grazing plot ($p < 0.05$). DOC leaching under both grazing and fencing from May to July was significantly greater than from August to September ($p < 0.05$). The average values were 5.2 and 3.6 gC/m^2, respectively, from May to July and 1.2 and 0.4 gC/m^2 from August to September. There was a significant positive relationship between DOC leaching and soil leakage in both the fenced ($r = 0.98579$, $p < 0.001$) and grazing plots ($r = 0.99008$, $p < 0.001$).

Discussion

Effect of long-term fencing on soil bulk density in an alpine meadow

Soil bulk density is considered to be an important factor affecting soil water infiltration, and the results of our research confirmed that long-term fencing significantly reduced soil bulk density from 0 to 20 cm in depth ($p < 0.05$), which was consistent with Wu et al. (2010). This phenomenon could be explained by (1) decreased soil compaction under long-term fencing due to the prevention of repeated livestock trampling (Castellano and Valone 2007). (2) Long-term fencing decreased livestock grazing on plants and significantly improved the growing conditions for the vegetation; root growth thus increased, which caused the increase in soil porosity within the root zone of the vegetation, especially at depths of 0–20 cm (Li et al. 2011). These results suggested that long-term fencing would improve the soil infiltration in alpine meadows, but in contrast to our results, Li et al. (2013) found that fencing had no significant effect on soil bulk density at depths of 0–20 cm in an alpine meadow. The reason for these contradictory results could be related to the difference in fencing time. The fencing time in this study and Wu et al. (2010) was 10 and 9 years, respectively, but it was only 3 years in the study by Li et al. (2013). This indicated that the difference in fencing time could lead to contradictory results when determining the effects of fencing on soil bulk.

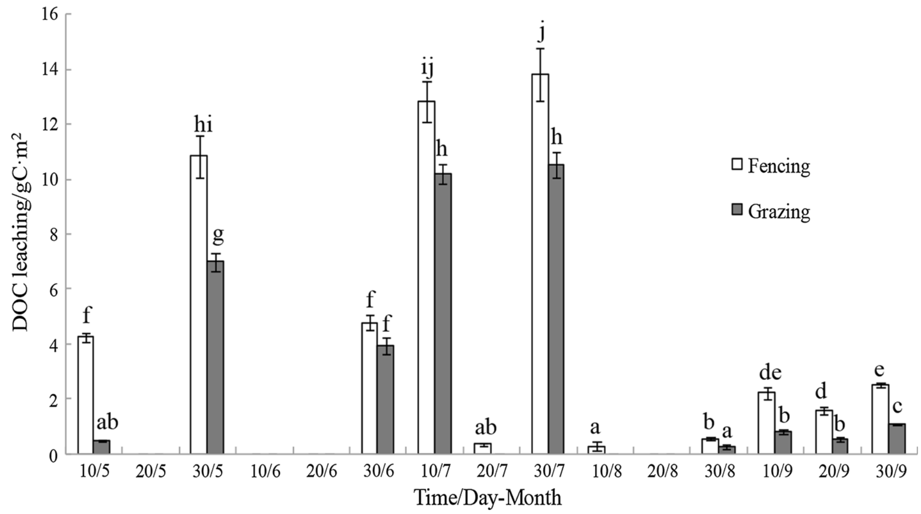

Fig. 7 SOC leaching in plots with fencing and grazing in an alpine meadow from May to September

Effects of long-term fencing on soil-vegetation carbon density

Because fencing reduced livestock trampling and herbivory, which enhanced the leaf area index of the plant community (Sala et al. 1986), it increased the above-ground vegetation biomass. Meanwhile, fencing improved the below-ground biomass of plants in the alpine meadow (Zeng et al. 2015; Xiong et al. 2014a), which would promote an increase in the carbon fixation ability of the vegetation (Zou et al. 2013; Dong et al. 2013). Thus, long-term fencing significantly increased the VC density in the alpine meadow, which was similar to findings for the Loess Plateau (Deng et al. 2014). The results of our research showed that the carbon storage of the soil-vegetation ecosystem, which was the sum of the soil carbon density and the below-ground C density of the vegetation, under fencing (2.3 kgC/m^2) was far lower than that of a natural alpine meadow (17.1 kgC/m^2) (Han et al. 2011) and the average carbon storage of the overall soil-vegetation ecosystem in China (8.0–11.9 kgC/m^2) (Wu et al. 2003). This study confirmed that recovering alpine meadow on the Tibetan Plateau had great carbon sequestration potential.

The roots and vegetation litter were the main source of SOC (Cao et al. 2004). Although livestock dung was decomposed by microorganisms under grazing conditions, which supplied SOC to the shallow soil to some degree, the roots and litter of vegetation obviously increased under long-term fencing, and they significantly enhanced the input of SOC (Berendse 1990). Additionally, the coverage and height of the alpine meadow vegetation was rapidly increased after fencing (Wu et al. 2010), and soil water evaporation was decreased. This resulted in the soil water content of the top soil layer of the fenced plot to be greater than that of the grazing plot, which increased the decomposition rate of surface litter under fencing (Estavillo et al. 2002). Third, soil respiration was increased by grazing, which accelerated the emission of C from the soil to the atmosphere (Hiernaux et al. 1999; Risser et al. 1981). Consequently, SOC from depths of 0–40 cm under long-term fencing plot was greater than that of the grazing plot, and this result was supported by the research by Holt (1997). Because the soil bulk density of the shallow soil layers was significantly decreased by long-term fencing, the infiltration ability of the soil in fencing plot was greater than that in the grazing plot; it caused the DOC leaching from the shallow soil to the deep soil in the fenced plot to be greater than that of the grazing plot. Therefore, the SOC in the deep soil (20–40 cm) of the fencing plot was significantly greater than that of the grazing plot. In contrast to our results, Berg et al. (1997) and Binkley et al. (2003) found that long-term fencing had no significant effects on SOC in a sand hill rangeland, and other researchers (Reeder and Schuman 2002; Reeder et al. 2004) found that fencing could decrease the SOC in short grass steppes. These differences may be due to the different soil types examined in the different studies. The results of this research show that long-term fencing not only significantly enhanced VC density, but it also significantly increased the SOC in deep soil, which indicated that long-term fencing could enhance carbon sequestration in alpine meadow ecosystems and once again confirmed that fencing is the one of the most effective management measures to realize the carbon sequestration effect of alpine meadows (Xiong et al. 2014b).

Soil water percolation and its response to long-term fencing

Soil water percolation is one of the most important pathways for soil water loss, and it is also one of the important links in transformation process of rainfall, surface water, soil water and groundwater (Marios 2002). The frozen soil in the alpine meadow was just completely thawing in May, so the soil water content was relatively high (Guo et al. 2011). Moreover, the rainy season in alpine meadow began in May, so the alpine meadow soil was easily saturated, and soil water constantly percolated at depths of 40 cm. With the decrease in rainfall at the end of the rainy season (from August to September), especially in August (Fig. 2), the soil water content decreased, and soil water percolation was reduced rapidly. Our research found that the soil water percolation process in the alpine meadow had the following characteristics: (1) soil water leakage up to a depth of 40 cm had a significant positive relationship with rainfall. (2) Soil water leakage from May to June and August to September was relatively low, and it reached its peak value in July. (3) During the non-frozen period (from May to September), the total soil water leakage up to a depth of 40 cm was 9.6 mm, which accounted for 2.2% of the total rainfall during the same period. Different with our results, Yang et al. (2014) reported that the soil water leakage in Mu Us sandland and Ulan Buh desert reached 508.4, 23.8 mm, which accounted for 58.4, 13.9% of the concurrent rainfall, respectively. This difference was caused by the different rainfall and soil texture in the two studies. The alpine meadow area on the Tibetan Plateau was 6.37×10^5 km^2 (Ni 2002), and it can be deduced that the soil water leakage in the alpine meadow during the non-frozen period could have reached 6.1×10^9 m^3, which would have accounted for 2.7% of annual (from 1919 to 2010) average surface runoff of the upper Yellow River (226.3×10^9 m^3) (Li et al. 2014). Fencing increased the coverage of the vegetation (Wu et al. 2010), decreased the soil bulk density and enhanced the soil infiltration ability (Naeth et al. 1990), and these effects caused the soil water leakage under fencing to be higher than that of the grazing plot. Because the roots of the alpine meadow vegetation were mainly distributed from 0 to 30 cm in depth (Yang et al. 2009), it was difficult for the soil water below 40 cm to be absorbed by the vegetation. Thus, moderate grazing in alpine meadows would be beneficial for reducing the loss of soil water and increasing the soil water use efficiency in this region. Grazing intensity and grazing time must be researched in future studies.

DOC leaching and its response to long-term fencing

The results of the DOC leaching experiment showed that there was an obvious DOC leaching phenomenon in the alpine meadow, and it was significantly greater from May to July than from August to September. From May to September, the DOC leaching in the grazing plot in the alpine meadow was between 0.0 and 10.5 gC/m^2, and the total DOC leaching was 34.6 gC/m^2. DOC leaching in the alpine meadow had a significant positive relationship with soil water percolation. After fencing for 10 years, total DOC leaching in the alpine meadow increased by 55.5%, and the main reasons were as follows: (1) Long-term fencing enhanced the density of the SOC and VC, and it increased the source of the carbon that could be leached. (2) Long-term fencing improved the soil water infiltration ability, which increased soil water leakage. Compared with the low-altitude regions, the annual mean temperature in alpine meadow was relatively low and the accumulation of soil organic matter was relatively high (Tao et al. 2007), which caused the source of carbon that could be leached in alpine meadow was greater than that in low-altitude regions. Thus, the DOC leaching of alpine meadow was much greater than that of forest, grassland (Reimo et al. 2011) and cropland (David et al. 2011). These results indicated that the DOC leaching was varied under different environmental and soil characteristics. Except the alpine meadow, alpine steppe and alpine swamp were also the important components of Tibetan Plateau (Wang et al. 2002). To comprehensively understand the DOC leaching condition on the Tibetan Plateau, it is necessary to study the characteristics of DOC leaching in alpine steppe and alpine swamp in the future.

At the end of the twentieth century, Scholes (1999) estimated the value of the net carbon sink of a terrestrial ecosystem to be 2 Pg a^{-1} and predicted that the carbon storage in terrestrial ecosystems would reach saturation. On the contrary, Ji et al. (2008) believed that the carbon storage of the semiarid region in the eastern Tibetan Plateau would not reach carbon saturation until the end of the 21st century, and these regions would still play a role in carbon sequestration. Combined with total DOC leaching in the grazing plot in our study and the alpine meadow area on the Tibetan Plateau (6.37×10^5 km^2) (Ni 2002), the total DOC leaching in alpine meadow during the non-frozen period could reach 2.20×10^7 t which accounted for 7.5% of the carbon fixed annually by the alpine meadow vegetation (Zhang et al. 2003). Because of the thin soil layer, whose thickness was mainly maximized between 30 and 60 cm (Wang et al. 2003), in the alpine meadow, the DOC in this region would be constantly infiltrated into the groundwater system with the leakage water and flow into the river and lakes. Ultimately, this would cause the alpine meadow soils to always have some degree of space for carbon sequestration. This result indirectly supported the view of Ji et al. (2008), and it also explained, to some degree, the reason for the strong carbon sequestration function of the alpine meadow soil.

Previous researchers mainly focused on soil respiration (Cao et al. 2004) when they discussed the soil carbon emission from the alpine grassland on the Tibetan Plateau, but little research has been concerned with the carbon emission in the form of the DOC leached with leakage water. This study confirmed that the total DOC leaching in the alpine meadow during the non-frozen period reached 34.6 gC m^{-2}, which accounted for 18.1% of the annual average alpine meadow soil respiration flux (Tao et al. 2007). This result indicated that DOC leaching is an important form of soil carbon emission in alpine meadows, and it has important significance for the comprehensive understanding of the process of carbon loss in alpine grasslands.

Conclusion

In this study, we examined the soil bulk density, SOC density, VC density, soil water leakage and DOC leaching under grazing and 10 years of fencing in an alpine meadow, and the results showed a significant soil water percolation and DOC leaching phenomenon. From May to September, total soil water leakage and DOC leaching in the alpine meadow were 9.6 mm and 34.6 gC/m^2, respectively. Because long-term fencing decreased the soil bulk density in shallow soil, soil water infiltration was enhanced. Meanwhile, long-term fencing increased the density of SOC and VC, which increased the size of the carbon source that could be leached. Therefore, after 10 years of fencing, total soil water leakage and total DOC leaching in the alpine meadow were increased by 53.1 and 55.5%, respectively. Our results demonstrated that the DOC leached into the groundwater system with the leakage water and ultimately fed into the rivers and lakes is an important form of carbon emission from alpine meadows.

Acknowledgements We sincerely appreciate the invaluable comments of two anonymous reviewers. This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDB03030502) the Natural Science Foundation of Qinghai Province (No. 2014-ZJ-901, 2016-ZJ-943Q) and the National Natural Science Foundation of China (Nos. 31300385, 31270523).

References

Berendse F (1990) Organic matter accumulation and nitrogen mineralization during secondary succession in health land ecosystem. J Ecol 78:413–427

Berg WA, Bradford JA, Sims PL (1997) Long-term soil nitrogen and vegetation change on sandhill rangeland. J Range Manage 50:482–486

Binkley D, Singer F, Kaye M, Rochelle R (2003) Influence of elk grazing on soil properties in Rocky Mountain National Park. For Ecol Manag 185:239–247

Booth BBB, Jones CD, Collins M, Totterdell IJ, Cox PM, Sitch S, Huntingford C, Betts RA, Harris GR, Lloyd J (2012) High sensitivity of future global warming to land carbon cycle processes. Environ Res Lett 7:024002

Bu HY, Chen XL, Xu XL, Liu K, Jia P, Du GZ (2007) Seed mass and germination in an alpine meadow on the eastern Tsinghai-Tibet plateau. Plant Ecol 191:127–149

Cao GM, Tang YH, Mo WH, Wang YS, Li YN, Zhao XQ (2004) Grazing intensity alters soil respiration in an alpine meadow on the Tibetan Plateau. Soil Biol Biochem 36:237–243

Castellano MJ, Valone TJ (2007) Livestock, soil compaction and water infiltration rate: evaluating a potential desertification recovery mechanism. J Arid Environ 71:97–108

David CW, Jan S, Reimo K, Laura K, Klaus K, Matthew S, Martin K, Bruce AO (2011) Dissolved carbon leaching from an Irish cropland soil is increased by reduced tillage and cover cropping. Agric Ecosyst Environ 142:393–402

De JR, Bootsma A (1997) Estimates of water deficits and surpluses during the growing season in Ontario using the SWATRE model. Can J Soil Sci 77:285–294

Deng L, Zhang ZN, Shangguan ZP (2014) Long-term fencing effects on plant diversity and soil properties in China. Soil Till Res 137:7–15

Dong QM, Zhao XQ, Wu GL, Shi JJ, Ren GH (2013) A review of formation mechanism and restoration measures of "black-soil-type" degraded grassland in the Qinghai-Tibetan Plateau. Environ Earth Sci 70:2359–2370

Du YX, Wu CJ, Zhou SX, Huang L, Han SM, Xu XF, Ding Y (2011) Forest soil organic carbon density and its distribution characteristics along an altitudinal gradient in Lushan mountains of China. Chin J Appl Ecol 7:1675–1681 **(in Chinese with English abstract)**

Estavillo JM, Merino P, Pinto M, Yamulki S, Gebauer G, Corré W (2002) Short term effect of ploughing a permanent pasture on N_2O production from nitrification and denitrification. Plant Soil 239:253–265

Fan JW, Zhong HP, Harris W, Yu GR, Wang SQ, Hu ZM, Yue YZ (2008) Carbon storage in the grasslands of China based on field measurements of above- and below-ground biomass. Clim Change 86:375–396

Feng ZZ, Wang XK, Feng ZW (2005) Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao irrigation district, China. Agric Water Manage 71:131–143

Forrester DI, Pares A, O'Hara C (2013) Soil organic carbon is increased in mixed-species plantations of Eucalyptus and nitrogen-fixing Acacia. Ecosystems 16:123–132

Guo DL, Yang MX, Wang HJ (2011) Sensible and latent heat flux response to diurnal variation in soil surface temperature and moisture under different freeze/thaw soil conditions in the seasonal frozen soil region of the central Tibetan Plateau. Environ Earth Sci 63:97–107

Han DR, Cao GM, Guo XW, Zhang FW, Li YK, Lin L, Li J, Tang YH, Gu S (2011) The potential of carbon sink in alpine meadow ecosystem on the Qinghai-Tibetan Plateau. Acta Ecol Sin 31:7408–7417 **(in Chinese with English abstract)**

Hannu N, Jukka A, Kristiina L, Jouko S, Pertti JM (1995) Emissions of CH_4, N_2O and CO_2 from a Virgin Fen and a Fen Drained for Grassland in Finland. J Biogeogr 22:351–357

Heng LK, White RE, Helyar KR, Chen D (2001) Seasonal differences in the soil water balance under perennial and annual pastures on an acid Sodosol in southeastern Australia. Eur J Soil Sci 52:227–236

Hiernaux P, Bielders CL, Valentin C, Bationo A, Fernández-Rivera S (1999) Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. J Arid Environ 41:231–245

Holt JA (1997) Grazing pressure and soil carbon, microbial biomass and enzyme actives in semi-arid northeastern Australia. Appl Soil Ecol 5:143–149

Jette BC, Dorthe LJ, Thomas HC (1996) Effect of dissolved organic carbon on the mobility of cadmium, nickel and zinc in leachate polluted groundwater. Water Res 30:3037–3049

Ji JJ, Huang M, Li KR (2008) Prediction research on the carbon exchange between atmosphere and terrestrial ecosystem in China during 21st century. Sci China Earth Sci 38:211–223 **(in Chinese with English abstract)**

Li XJ, Zhang XZ, Wu JS, Shen ZX, Zhang YJ, Xu XL, Fan YZ, Zhao YP, Yan W (2011) Root biomass distribution in alpine ecosystems of the northern Tibetan Plateau. Environ Earth Sci 64:1911–1919

Li YY, Dong SK, Wen L, Wang XX, Wu Y (2013) The effects of fencing on carbon stocks in the degraded alpine grass lands of the Qinghai-Tibet an Plateau. J Environ Manage 128:393–399

Li EH, Mu XM, Zhao GJ (2014) Temporal changes in annual runoff and influential factors in the upper and middle reaches of Yellow River from 1919 to 2010. Adv Water Sci 25:155–163 **(in Chinese with English abstract)**

Mack UD, Feger KH, Gong Y, Stahr K (2005) Soil water balance and nitrate leaching in winter wheat summer maize double cropping systems with different irrigation and N fertilization in the North China Plain. J Plant Nutr Soil Sci 168:454–460

Marios S (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J 10:52–67

Naeth MA, Rothwell RL, Chanasyk DS, Bailey AW (1990) Grazing impacts on infiltration in mixed prairie and fescue grassland ecosystems of Alberat. Can J Soil Sci 70:593–605

Ni J (2002) Carbon storage in grasslands of China. J Arid Environ 50:205–218

Reeder JD, Schuman GE (2002) Influence of livestock grazing on sequestration in semi-arid mixed-grass and short-grass rangelands. Environ Pollut 116:457–463

Reeder JD, Schuman GE, Morgen JA, LeCain DR (2004) Response of organic and inorganic carbon and nitrogen to long-term grazing of the short grass steppe. Environ Manage 33:485–495

Reimo K, Jan S, Klaus K, David CW, Christian B, Nina B, Pierre C, Werner E, Gerd G, Thomas G, Alexander H, Anderas I, Stephanie KJ, Mike J, Katja K, Wener K, Klaus SL, Simon L, Benjamin L, Rebecca M, Eddy M, Bruce O, Kim P, Corinna R, Matthew S, Michael WIS, Marion S, Janine S, Ute S, Jean-francois S, Mark AS, Cindy T, Bernhard V, Matthias JZ, Martin K (2011) Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. Glob Change Biol 17:1167–1185

Risser PG, Birney EC, Blocker HD (1981) The true prairie ecosystem. Hutchinson Ross Pub. Co, New York

Robert GQ, Bruce LH (1990) Geochemistry of dissolved organic nutrients in water percolating through a forest ecosystem. Soil Sci Soc Am J 55:1112–1123

Sala OE, Oesterheld M, León RJC, Soriano A (1986) Grazing effects upon plant community structure in subhumid grasslands of Argentina. Vegetatio 67:27–32

Scholes B (1999) Will the terrestrial carbon sink saturate soon? IGBP Glob Change Newsl 37:2–3

Song MH, Jiang J, Cao GM, Xu XL (2010) Effects of temperature, glucose and inorganic nitrogen inputs on carbon mineralization in a Tibetan alpine meadow soil. Eur J Soil Biol 46:375–380

Tao Z, Sheng CD, Gao QZ, Sun YM, Yi WX, Li YN (2007) Soil organic carbon storage and CO_2 flux in alpine meadow. Sci China Earth Sci 37:553–563 **(in Chinese with English abstract)**

Wang GX, Qian J, Cheng GD, Lai YM (2002) Soil organic carbon pool of grassland soils on the Qinghai-Tibetan Plateau and its global implication. Sci Total Environ 291:207–217

Wang GX, Cheng GD, Shen YP, Qian J (2003) Influence of land cover changes on the physical and chemical properties of alpine meadow soil. Chin Sci Bull 48:118–124

Wang CT, Long RJ, Wang QJ (2007) Effects of altitude on plant-species diversity and productivity in an alpine meadow, Qinghai-Tibetan Plateau. Aust J Bot 55:110–117

Wang WJ, Qiu L, Zu YG, Su DX, An J, Wang HY, Zheng GY, Sun W, Chen XQ (2011) Changes in soil organic carbon, nitrogen, pH and bulk density with the development of larch (Larixg-melinii) plantations in China. Global Change Biol 17:2657–2676

Wang GX, Liu GS, Li CJ (2012) Effects of changes in alpine grassland vegetation cover on hillslope hydrological processes in a permafrost watershed. J Hydrol 444–445:22–33

Wu HB, Guo ZT, Peng CH (2003) Distribution and storage of soil organic carbon in China. Glob Biogeochem Cycles 17:1–11

Wu GL, Du GZ, Liu ZH, Simon T (2009) Effect of fencing and grazing on a Kobresia-dominated meadow in the Qinghai-Tibetan Plateau. Plant Soil 319:115–126

Wu GL, Liu ZH, Zhang L, Chen JM, Hu TM (2010) Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China. Plant Soil 332:331–337

Xiong DP, Shi PL, Sun YL, Wu JS, Zhang XZ (2014a) Effects of grazing exclusion on plant productivity and soil carbon, nitrogen storage in alpine meadows in northern Tibet, China. Chin Geogr 24:488–498

Xiong DP, Shi PL, Sun YL, Wu JS, Zhang XZ (2014b) Effects of grazing exclusion on plant productivity and soil carbon, nitrogen storage in alpine meadows in northern Tibet, China. Chin Geogr 24:488–498

Yang YH, Fang JY, Ji CJ, Han WX (2009) Above- and below ground biomass allocation in Tibetan grasslands. J Veg Sci 20:177–184

Yang WB, Tang JN, Liang HR, Dang HZ, Li W (2014) Deep soil water infiltration and its dynamic variation in the shifting sandy land of typical deserts in China. Sci China Earth Sci 57:1816–1824

Yi XS, Li GS, Yin YY (2012) The impacts of grassland vegetation degradation on soil hydrological and ecological effects in the source region of the Yellow River—a case study in Junmuchang region of Maqin country. Proced Environ Sci 13:967–981

Zeng CX, Wu JS, Zhang XZ (2015) Effects of grazing on above- vs. below-ground biomass allocation of alpine grasslands on the northern Tibetan Plateau. PLoS One. doi:10.1371/journal.pone.0135173

Zhang JX, Cao GM, Zhou DW, Hu QW, Zhao XQ (2003) The carbon storage and carbon cycle among the atmosphere, soil, vegetation and animal in the Kobresia humilis alpine meadow ecosystem. Acta Ecol Sin 23:627–634 **(in Chinese with English abstract)**

Zou JR, Zhao L, Xu S, Xu XL, Chen DD, Li Q (2013) Livestock exclosure with consequent vegetation changes alters photo-assimilated carbon cycling in a Kobresia meadow. Biogeosci Discuss 10:17633–17661