Effects of grazing on the soil properties and C and N storage in relation to biomass allocation in an alpine meadow

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Abstract

Livestock grazing is one of the most important factors influencing the above-ground community composition and structure in a natural grassland ecosystem. Different grazing intensities also have the potential to alter soil C and N storage substantially in grasslands. We conducted a field community study and soil analyses to determine the effects of different grazing intensities on the above-ground community and soil properties in an alpine meadow on the Tibetan Plateau. Our results showed the following: (i) the vegetation height, coverage, and above-ground biomass significantly declined with increased grazing intensity, but the species richness reached the highest level in a moderate grazing intensity meadow; (ii) grazing had a significant positive effect on soil properties in that the soil moisture content, soil organic carbon concentration, soil total nitrogen concentration, soil available nitrogen, soil total phosphorus, and soil available phosphorus significantly increased with increased grazing pressure; and (iii) soil C and N storage also significantly increased with increased grazing pressure; altogether, these increases had a significant positive correlation with the increase of below-ground biomass allocation. Our results indicated that higher grazing intensity might have a potentially positive effect to increase the soil C and N storage in alpine meadows. However, from a long-term perspective, moderate grazing may help to achieve a balance between species diversity protection, livestock production and soil C and N management.

Keywords: above-ground community, alpine grassland, biomass allocation, carbon, grazing intensity, nitrogen, soil properties.

1. Introduction

Grasslands of various types occupy approximately one-third of the earth's terrestrial surface (Gitay *et al.*, 2001), and 90% of China's grasslands (3.99 billion ha) are subject to varying degrees of degradation. Livestock overgrazing is one of the most important factors that results in grassland degradation, which is commonly assessed based on soil and vegetation conditions. Generally, vegetation biomass, height and coverage are reduced as grazing intensity increases (Milchunas *et al.*, 1998), but light or moderate grazing intensity can maintain species diversity and community productivity of grasslands compared with heavily grazed grasslands (Frank *et al.*, 2003). In addition, livestock grazing alters the cycles of soil carbon, nitrogen and other nutrients in grassland ecosystems by the interactions between plants and the soil (Stavi *et al.*, 2009; Wu *et al.*, 2009). However, Milchunas and Lauenroth (1993) reported that the soil organic C and N had positive, negative or no responses to grazing. Therefore, the biogeochemical effects of grazing intensity, and particularly their impact on the soil C and N storage, remain controversial (Milchunas and Lauenroth, 1993).

Intensive livestock grazing may destroy vegetation, resulting in decreased incorporation of plant residues into the soil (Bilotta *et al.*, 2007). However, other studies suggested that grazing can promote nutrient cycling because livestock faeces and urine provide large amounts of soluble nitrogen that is readily available to plants for growth (McNaughton, 1997), and livestock excretions can promote soil organic matter (SOM) mineralisation rates (McNaughton *et al.*, 1997). Among the reported studies, differences in the response of C and N to grazing are the result of differences in climate, soil properties, community composition, and grazing management practices. Thus, livestock grazing can affect the soil C and N dynamics and storage (Chaneton *et al.*, 1996; Gao *et al.*, 2009). Although inconsisten-

cies in grassland C and N responses to grazing have been reported, several general impacts of grazing on grassland C and N can be identified. Effective grazing management techniques can increase the above-ground biomass and have the potential to increase the C and N storage (Conant *et al.*, 2001). However, increases in the C and N storage as SOM have been reported, even when grazing management results in decreased above-ground biomass. This can be due to grazing-induced changes in the species composition causing a lower above-ground biomass but a greater below-ground biomass or root : shoot ratio (R : S) and, therefore, an increase in the allocation of C and N below-ground (Schuman *et al.*, 1999). Soil C and N storage also could increase if the decreased above-ground biomass inputs to the soil are offset by manure inputs (Conant *et al.*, 2001). Lastly, grazing can influence the plant photosynthetic rate and C and N allocation patterns among species (Painter and Detling, 1981). Overall, grazing management has different effects on the magnitude, distribution and cycling of C and N in different grassland ecosystems (Piñeiro *et al.*, 2010).

The soil on the Tibetan Plateau, similar to those in high-latitude grassland ecosystems, may be a major carbon sink because of the cold and relatively humid climate. However, the soil may also become an important carbon source if grazing intensity increases. In Tibetan alpine meadows, grazing leads to dramatic changes in the vegetation, such as decreased plant biomass, increased plant diversity and altered species composition (Wu *et al.*, 2009). However, whether these changes increase or reduce soil C and N storage remains unclear. The aim of this study was to quantify the impacts of different grazing intensities on vegetation and on the soil C, N, and P properties in an alpine meadow on the Tibetan Plateau. Specifically, we examined the impact of grazing intensity on (i) the

above-ground plant biomass, species richness and the allocation pattern of above- and below-ground biomass, (ii) the below-ground storage of C and N, and (iii) the relationship between soil C and N storage and the grazing-induced variation in plant biomass allocation patterns.

2. Materials and Methods

2.1. Study area

This experiment was conducted in an alpine meadow at 3,500 m above sea level in Maqu County, Gansu Province, PR China (N33°42'21", E102°07'02"), located on the eastern region of the Tibetan Plateau

(Figure 1). The yearly average temperature is 1.2 °C, ranging from -10 °C in January to 11.7 °C in July, with approximately 270 days of frost. The annual precipitation, as measured over the last 35 years, is 620 mm, occurring mainly during the short, cool summer. The annual cloud-free solar radiation is approximately 2580 h. The growing season ranges between April and September. The main soil type is sub-alpine meadow soil, with a soil depth of 80 cm (Chen and Wang, 1999). The vegetation, typical of Tibetan alpine meadows, is dominated by perennial sedges (e.g., *Kobresia capillifolia*), grasses (e.g., *Festuca* spp., *Elymus* spp.), Compositae species (e.g., *Saussurea* spp.), and other broad-leaved species (e.g., *Anemone* spp.) (Wu *et al.*, 2009).

Figure 1. The location of Gansu province in China and the location of the study site in Maqu county.

The three experimental sites were similar before the treatments, and these sites had undergone different grazing pressures during a 10-year nomadic grazing period with different densities of Tibetan sheep and

yaks. This grassland has traditionally been used as a summer pasture, with grazing occurring mainly from May to September (Wu *et al.*, 2009) and with three grazing regimes, light grazing (LG) intensity meadow,

moderate grazing (MG) intensity meadow and heavy grazing (HG) intensity meadow, based on the livestock density (livestock density = livestock (yak) numbers / pasture area). The LG intensity meadow supported 10 yaks and 15 Tibetan sheep (three Tibetan sheep were approximately equivalent to one yak, as based on their feed intake) within a 12.0-ha area, and its livestock density was 1.2 heads of yaks per ha, resulting in a 20% forage utilisation. The vegetation was dominated by *Kobresia capillifolia*, *Elymus nutans*, *Koeleria cristata*, *Poa poophagorum*, *Anemone rivularis*, and *Taraxacum maurocarpum*. The MG intensity meadow supported 21 yaks and 120 Tibet sheep within a 33.3-ha area, and its livestock density was 1.8 heads of yaks per ha, resulting in a 50% forage utilisation. The vegetation was dominated by *Scirpus pumilus*, *E. nutans*, *Potentilla fragarioides* and *Oxytropis ochrocephala*. The HG intensity meadow supported 72 yaks and 178 Tibet sheep within a 41.2-ha area, and its livestock density was 3.2 heads of yaks per ha, resulting in a 70% forage utilisation. The vegetation was dominated by *Potentilla ansrinalis*, *Stipa aliena*, *Saussurea hieracioides*, *O. ochrocephala* and *Ligularia virgaurea*.

2.2. Experimental design and soil sampling

Three sampling plots (10 m × 10 m) were selected in each grazing-intensity meadow. In each plot, three sampling quadrates (50 cm × 50 cm) were arranged, and each quadrate location was randomly selected with the constraint that it was at least 0.5 m from the margin to avoid any edge effects. Vegetation samples were taken in early September of 2010, when the biomass had reached its maximum height, from nine 50 cm × 50 cm quadrates in each grazing-intensity meadow. The mean vegetation height, cover, above-ground biomass and species richness of the studied meadows under different grazing densities were measured. The experiment comprised a total of 27 quadrates. All of

the samples were dried in an oven for 48 h at 80 °C and weighed on a balance with an accuracy of 10⁻² g.

Soil samples (0–15 cm depth) were collected from the three quadrates in each sampling plot of each grazing-intensity meadow after the above-ground material was harvested. In each quadrate, soil was randomly collected from three points (3.8 cm in diameter) using a bucket auger and mixed into a single soil sample. In addition, three soil samples of 15 cm in depth were collected from each sampling plot to estimate the root biomass, which was distributed mainly in the upper 15 cm of the soils (Chen *et al.*, 2010). All of the soil samples were brought into the laboratory in airtight plastic bags. For the root biomass, the soil samples were rinsed in water to remove the soil and debris, and the root samples were then dried at 80 °C for 48 h and weighed on a balance with an accuracy of 10⁻² g. The soil bulk density was determined using the core method and calculated as the mass of oven-dried soil (105 °C) divided by its volume (Chen *et al.*, 2010). All of the soil samples were air-dried and then filtered through a 0.2-mm sieve, discarding the visible roots or plant debris. The soil total C was determined by wet oxidation with potassium dichromate (K₂Cr₂O₇), both dichromate oxidation and dry combustion, using a carbon analyser with a Mebius method for the Walkley-Black acid digestion (Kalembasa and Jenkinson, 1973). The soil total nitrogen, available nitrogen, total phosphorus and available phosphorus were measured by the methods of Miller and Keeney (1982). The gravimetric soil moisture content before air drying was obtained by the oven-drying method. We calculated the total soil C and N storage (0–15 cm depth) from the examination of their concentrations and soil bulk densities.

2.3. Data analysis

One-way ANOVA analyses were conducted for the vegetation and soil characteristics among the three

grazing-intensity meadows. Linear regression analyses were used to examine the relationship of the soil C and N storage with the grazing-induced variations in the plant biomass allocation patterns. Post-hoc comparisons were performed using Tukey's HSD (Honest Significant Difference). All of the variables met the statistical assumptions (residuals normality, homogeneity of variance and data linearity) when tested using the Shapiro-Wilk's test and Levene's test. Significant differences for all of the statistical tests were evaluated at the level of $p \leq 0.05$. All of the statistical analyses were performed using the SPSS software program, ver.13.0 (SPSS Inc., Chicago, IL, USA).

3. Results and Discussion

3.1. Vegetation response

Grazing can play a key role in the dynamics of grassland ecosystems and lead to an alteration of the community structure and function as well as the loss of species diversity. Our study demonstrated that the grassland above-ground biomass, vegetation cover and height significantly decreased with increased

grazing intensity (Table 1), which was consistent with other studies (e.g., Gao *et al.*, 2009). Species richness reached its highest level in the MG intensity meadow (Table 1), and this result was consistent with the intermediate disturbance hypothesis (Grime, 1973). Livestock grazing can influence the composition and structure of the community mainly by modifying the competitive interactions (via selective feeding by livestock) between plants (Olofsson *et al.*, 2001). Our results suggested that the graminoid species, which are dominant in alpine communities and palatable for livestock, showed a decreased abundance in the HG intensity meadow (data not shown). Therefore, HG intensity meadows can experience the replacement of palatable graminoids by unpalatable forbs and legumes (e.g., *O. ochrocephala*) because yaks and sheep prefer graminoids species (e.g., *K. capillifolia*, *E. nutans*) over forbs species (e.g., *S. hieracioides*, *L. virgaurea*) (please see Appendix 1). Other studies demonstrated that grazing creates canopy gaps, relaxes intra- and inter-specific competition for light, and ultimately favours the establishment of short-stature, less-palatable forb species (Pavlů *et al.*, 2007).

Table 1. ANOVA results for the mean values ($\pm$ S.E.) of vegetation height, coverage, richness, above-ground biomass, below-ground biomass and R : S of meadow communities according to three grazing intensities. LG, light grazing; MG, moderate grazing; HG, heavy grazing.

	LG	MG	HG
Vegetation height (cm)	21.3 $\pm$ 3.2 ^a	15.6 $\pm$ 2.1 ^b	9.4 $\pm$ 2.2 ^c
Coverage (%)	84.5 $\pm$ 6 ^a	70.3 $\pm$ 4.4 ^b	56.1 $\pm$ 3.7 ^c
Richness (species m ⁻²)	19.1 $\pm$ 1.3 ^b	25.9 $\pm$ 2.2 ^a	11.7 $\pm$ 2.5 ^c
Above-ground biomass (g m ⁻²)	299.7 $\pm$ 6.1 ^a	231.5 $\pm$ 7.1 ^b	114.2 $\pm$ 4.0 ^c
Below-ground biomass (g m ⁻²)	715.5 $\pm$ 33.8 ^a	1478.3 $\pm$ 42.4 ^b	1899.4 $\pm$ 9.1 ^c
R : S	2.4 $\pm$ 0.1 ^a	6.4 $\pm$ 0.2 ^b	16.7 $\pm$ 0.7 ^c
Soil moisture content (%)	25.8 $\pm$ 0.3 ^b	28.7 $\pm$ 0.5 ^b	31.4 $\pm$ 0.2 ^a
Soil bulk density (g cm ⁻³)	0.9 $\pm$ 0.1 ^a	0.9 $\pm$ 0.2 ^a	1.0 $\pm$ 0.1 ^a

Note: The means in the same line followed by different letters are significantly different at $p=0.05$, as tested with ANOVA and Tukey's test for post-hoc comparisons.

Livestock foraging also significantly alters the above-ground community structure, whereas their trampling and excretions can also affect the below-ground conditions (e.g., soil properties and root biomass), although the root biomass responses to livestock grazing can be ambiguous (no changes, increases or is a function of grazing intensity) (Milchunas and Lauenroth, 1993; Turner *et al.*, 1993; Frank, 2002). Our results suggested that the below-ground biomass and R : S ratio significantly increased with increasing grazing pressure (Table 1). The increasing biomass allocation to the roots is an important adaptive response of plants to grazing and is favourable for grassland ecosystem restoration. However, previous studies indicated that livestock grazing decreased the allocation of below-ground biomass (De Deyn *et al.*, 2008).

3.2. Responses in soil C and N storage

Our study indicated that livestock grazing significantly increases the soil moisture content (Table 1); however, the soil bulk density did not change significantly (Table 1). This was because evaporation and the transpiration rate of the plants markedly decreased in the MG or HG intensity meadow (Wan *et al.*, 2002) as a result of the reductions in vegetation height, coverage and biomass with the increased grazing intensity. There was a significant positive effect of grazing on the soil chemical properties. The soil organic carbon concentration ($F=14.70$, $P<0.001$), soil total nitrogen concentration ($F=38.067$, $P<0.001$), soil available nitrogen

($F=12.03$, $P<0.001$), soil total phosphorus ($F=74.29$, $p<0.001$), and soil available phosphorus ($F=14.36$, $p<0.001$) significantly increased in the HG intensity meadow (Figure 2), which could be due to several potential mechanisms. Firstly, soil compaction (increased bulk density) reduces the oxygen content and slows decomposition. Secondly, differences in species composition (R : S ratio) might affect the rooting biomass contribution to the soil organic matter pool (Reeder *et al.*, 2004). Increased root allocation increases soil carbon inputs and also increases nitrogen retention within the soil (Stewart and Frank, 2008). The deposition of nitrogen in root tissues and closed cycling within the root zone have been suggested as mechanisms that increase nitrogen storage (Stewart and Frank, 2008). Additionally, the soil temperatures increase as grazing decreases the litter cover and the extent of the plant canopy, thereby, accelerating the decomposition rate of litter (Vermeire *et al.*, 2005). The increases in carbon and nitrogen may contribute to the grazing-induced increases in root biomass and plant residues because the roots and plant residues are important carbon and nitrogen sinks in grasslands (Gao *et al.*, 2009). Lastly, the urine and dung of livestock may accelerate nitrogen cycling in grassland ecosystems (McNaughton *et al.*, 1997). Furthermore, Hui and Jackson (2005) demonstrated that livestock grazing can increase carbon and nitrogen allocation to the below-ground biomass, enhancing the carbon input to the soil and nitrogen conservation and leading to the accumulation of soil organic carbon.

Figure 2. Means (± S.E., n=9) of soil organic carbon (A), soil total nitrogen (B), soil available nitrogen (C), soil total phosphorus (D) and soil available phosphorus (E) for a 0-15 cm soil depth and according to different grazing intensities. LG, light grazing; MG, moderate grazing; HG, heavy grazing. Different letters inside the histogram indicate significant differences ($p < 0.05$).

Soil carbon storage in the upper 0–15 cm of the soil significantly increased with increased grazing pressure ($F=18.83$, $p<0.001$). The soil carbon storage in the HG intensity meadow was 47% and 27% higher when compared with the LG intensity meadow and MG intensity meadow, respectively. The soil nitrogen storage in the upper 0–15 cm of the soil significantly increased with increased grazing pressure ($F=37.40$, $p<0.001$); the soil nitrogen storage in the HG intensity meadow was 46% and 44% higher when compared with the LG intensity meadow and MG intensity meadow, respectively (Figure 3). These results indicated that heavy grazing has a better potential for soil C and N storage in alpine meadow communities. This is consistent with the similar study of Gao *et al.* (2009), which found that the soil C and N concentrations were significantly higher in an HG site than in LG and MG sites. Linear regression analyses showed that there

was a significant negative correlation between the soil C and N storage and above-ground biomass (Figure 4a;d). However, both the below-ground biomass and R : S had significantly positive correlations with the soil C (Figure 4b;c) and N storage (Figure 4e;f). Our results demonstrated that a major contributor to the higher soil C and N storage in higher grazing intensity sites was the grazing-induced increase in the R : S, which is a reflection of the transfer of more below-ground C. Generally, less than 1% of grassland C is in above-ground biomass (Burke *et al.*, 1997), whereas the majority of plant C is in below-ground roots (Hui and Jackson, 2005). Schuman *et al.* (1999) also reported that larger root biomass can contribute more C and N to the soil in northern mixed-grass rangeland. Therefore, future research should continue to investigate which species have higher R : S values and species plasticity response to grazing.

Figure 3. Means ($\pm$ S.E., $n=9$) of soil carbon storage (A) and soil nitrogen storage (B) for the 0–15 cm soil depth and according to different grazing intensities. LG, light grazing; MG, moderate grazing; HG, heavy grazing. Different letters inside the histogram indicate significant differences ($p < 0.05$).

Figure 4. The relationship of the Log soil C storage (kg m^{-2}) with the Log above-ground biomass (g m^{-2}) (a), Log below-ground biomass (g m^{-2}) (b) and Log R : S (c); the relationship of the Log soil N storage (kg m^{-2}) with the Log above-ground biomass (g m^{-2}) (d), Log below-ground biomass (g m^{-2}) (e) and Log R : S (f).

Livestock grazing may influence the balance of soil C and N storage by altering the carbon and nitrogen inputs to and outputs from the soil. However, there is little information about the effect of grazing intensity on the C and N budget of alpine grassland ecosystems on the Tibetan plateau. Therefore, future research should encompass the processes of carbon and nitrogen outputs (e.g., soil organic matter mineralisation rates, soil nitrogen leaching and anti-nitrification, and soil respiration) to better understand the change of soil C and N storage under different grazing pressures.

4. Conclusions

Higher grazing intensity can lead to the increase of soil C and N storage through changes in the species composition and biomass allocation pattern. Nonetheless, heavy grazing intensity significantly decreased the vegetation height, coverage, diversity and above-ground biomass, which are harmful for livestock production and sustainable grassland development. Therefore, from a long-term perspective, moderate grazing may help to achieve a balance among species diversity protection, livestock production and soil C and N management.

Appendix 1. Species, family, functional group (FG), and palatability of the taxa in the alpine meadow used in our study. F, forb; L, legume; G, graminoid.

Species	Family	FG	Palatability
<i>Leontopodium nanum</i>	Compositae	F	Palatable
<i>Veronica eriogyne</i>	Scrophulariaceae	F	Palatable
<i>Gentianopsis paludosa</i>	Gentianaceae	F	Palatable
<i>Euphrasia regelii</i>	Scrophulariaceae	F	Palatable
<i>Agrostis gigantea</i>	Poaceae	G	Palatable
<i>Potentilla fragarioides</i>	Rosaceae	F	Palatable
<i>Poa poophagorum</i>	Poaceae	G	Palatable
<i>Potentilla anserina</i>	Rosaceae	F	Palatable
<i>Koeleria cristata</i>	Poaceae	G	Palatable
<i>Festuca ovina</i>	Poaceae	G	Palatable
<i>Aster alpinus</i>	Compositae	F	Palatable
<i>Ranunculus tanguticus</i>	Ranunculaceae	F	Palatable
<i>Taraxacum maurocarpum</i>	Compositae	F	Unpalatable
<i>Trollius farreri</i>	Ranunculaceae	F	Unpalatable
<i>Stipa aliena</i>	Poaceae	G	palatable
<i>Swertia tetraptera</i>	Gentianaceae	F	Palatable
<i>Kobresia capillifolia</i>	Cyperaceae	G	Palatable
<i>Pedicularis szetschuanica</i>	Scrophulariaceae	F	Palatable
<i>Delphinium kamaonense</i>	Ranunculaceae	F	Unpalatable
<i>Scirpus pumilus</i>	Cyperaceae	G	Palatable
<i>Carex kansuensis</i>	Cyperaceae	G	Palatable
<i>Polygonum viviparum</i>	Polygonaceae	F	Palatable
<i>Ligularia virgaurea</i>	Compositae	F	Unpalatable
<i>Halenia elliptica</i>	Gentianaceae	F	Palatable
<i>Allium sikkimense</i>	Liliaceae	F	Palatable
<i>Astragalus polycladus</i>	Leguminosae	L	Palatable
<i>Oxytropis ochrocephala</i>	Leguminosae	L	Unpalatable
<i>Anemone obtusiloba</i>	Ranunculaceae	F	Unpalatable

Continued...

Species	Family	FG	Palatability
<i>Tibetia himalaica</i>	Leguminosae	L	Palatable
<i>Anemone trullifolia</i>	Ranunculaceae	F	Unpalatable
<i>Elymus nutans</i>	Poaceae	G	Palatable
<i>Geranium pylzowianum</i>	Geraniaceae	F	Palatable
<i>Anemone rivularis</i>	Ranunculaceae	F	Unpalatable
<i>Thermopsis lanceolata</i>	Leguminosae	L	Palatable

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