The Journal of Animal & Plant Sciences, 25 (3 Suppl. 1) 2015 Special Issue Page: 165-171
ISSN: 1018-7081

MODERATE GRAZING PROMOTES ECOSYSTEM CARBON SEQUESTRATION IN AN ALPINE MEADOW ON THE QINGHAI-TIBETAN PLATEAU

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ABSTRACT

Grazing could alter plant primary production and carbon (C) storage in Alpine meadow ecosystems. The grazing optimization hypothesis (GOH) suggests that aboveground net primary production increases at a moderate grazing intensity. In this study, GOH was tested by investigating the responses of plant production and ecosystem C storage to grazing intensity. The results indicated that both the root biomass and total biomass reached the highest values in moderate grazing (MG), and the species richness, root to shoot ratio (R:S ratio) increased in MG, suggesting that more assimilates allocated from aboveground to belowground under MG. Similar plant material carbon concentrations were observed for all of the grazing intensities (i.e., 40-50%), and the soil organic carbon (SOC) storage depended on the root biomass. The soil organic C storage and ecosystem C storage both peaked with MG, which supported GOH. Thus, moderate grazing promoted ecosystem C sequestration by altering the plant community structure, plant production and R:S ratio in the Alpine grassland.

Key words: alpine meadow, grazing intensity, grazing optimization hypothesis

INTRODUCTION

Carbon(C) can be sequestrated in organic forms by soil through biomass production (Niu *et al.* 2011) and released into the atmosphere through soil respiration (Li *et al.* 2010). Soil can act as a C sink, or source. The global soil C pool (2500 Gt) is 3.3 times greater than the atmospheric pool (760 Gt) and 4.5 times greater than the biotic pool (560 Gt) (Lal 2004); consequently, small changes in soil carbon can affect global C cycle and balance.

The Qinghai-Tibetan plateau grassland accounts for approximately 55.6% of China's grassland SOC storage (Jian 2002). Grazing is the predominant type of land-use in this area. Several studies have shown that grazing could significantly impact ecosystem function by influencing species composition, productivity, and biomass quality (Frank *et al.* 2002; Kleinebecker *et al*. 2011), which could subsequently affect SOC accumulation (Wu *et al*. 2010).

The grazing optimization hypothesis (GOH) is based on the theory that, with a proper grazing intensity, herbivores can evoke growth compensation mechanisms and, therefore, enhance plant primary production (Hilbert *et al.*, 1981; de Mazancourt *et al.*, 1999; Hayashi *et al.*, 2007). According to these authors, improved photosynthetic ability, recycling of nitrogen in a nitrogen-limited system, high relative growth rates in plant by moderate grazing intensity could benefit grazing-induced overcompensation in plant production. This suggestion has been supported by aboveground biomass investigations (Leriche *et al.* 2003; Patton *et al.* 2007), but few studies have evaluated belowground responses to grazing (Rodríguez *et al.* 2007). Because the amount of C stored in the ecosystem in organic forms are through biological inputs mainly from plant biomass (Mishra *et al*.2013), so changes in SOC and ecosystem C storage have been associated with plant biomass affected by grazing intensities. The relationship between SOC and grazing intensity has been extensively studied (Review by Piñeiro *et al.* 2010), yielding varying results. Grazing has been reported to increase(Wright *et al.*, 2004), decrease (Derner *et al.*, 2006), or not effect(Cui *et al.*, 2005) on SOC. The effects of grazing intensity on soil carbon storage and ecosystem C storage are still controversial, and little information concerning these effects in the alpine meadows of the Qinghai–Tibetan Plateau is available. Thus, the grazing optimization hypothesis was evaluated for productivity and C storage within the plant-soil system by examining their responses to different grazing intensities in an alpine meadow on the eastern edge of the Qinghai–Tibetan Plateau.

MATERIALS AND METHODS

Study site: This study was conducted at the Alpine Meadow and Wetland Ecosystem Research Orientation Station of Lanzhou University (33°40′ N, 101°46′ E) in Maqu County of Gansu Province, China. This area has an average elevation of 3560 m and a typical continental climate. The average annual precipitation is 620 mm, The average annual temperature is 1.2 ºC, and ranges from -10 ºC in January to 11.7 ºC in July. The annual cloud-free solar radiation is 2,580 (Wu *et al.* 2010). Soil in this region is classified as inceptisols according to the soil classification system of the Food and Agriculture Organization (IUSS, 2014).

Experimental design: The study was conducted in the pastures of three adjacent family ranches. The maximum distance between these pastures is 2 km. The livestock on these ranches are yak (*Bos grunniens*). Stable light (LG,0.94 yak ha^{-1}), moderate (MG,1.55 yak ha^{-1}), and heavy (HG,2.86 yak ha^{-1}) grazing rates were used independently by the three families for over 20 years. The average of the yaks was 4.5 years. All three ranches belong to the local government, and were once used as horse ranches under the same management. The dominant vegetation species at that time was *Kobresia capillifolia*. The SOC concentrations in the 0-10-cm and 10-20-cm soil layers were 73.96 g/kg^{-1} and 27.01 g/kg^{-1}, respectively. These pastures were only grazed during the non-growing season (November 1st to April 1st). Five approximately 1 ha plots were established in each pasture. In each plot, two 100-m-long transects spaced a minimum of 20 m apart were designated for plant and soil parameter measurements.

Sampling and measurements: In 2010, soil and plant samples were collected from 0.5 m × 0.5 m quadrats in 10 m intervals along each 100 m transect at the peak standing biomass. The values from all of the sampling points within each plot were averaged as one replication. Within each quadrat, the vegetation was clipped and the underlying litter was collected. The root and soil cores were also collected from the clipped quadrats with an iron drill (10 cm and 3.5 cm diameters for root and soil sampling, respectively) then sorted into four soil depths (0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm). The roots were separated through flotation and hand washed through a 0.5 mm sieve. All of the plant biomass samples were dried in an oven at 65ºC for 72 hours and weighed in order to calculate the total dry biomass.

Soil samples obtained from the same depth in each plot were homogenized to form one composite sampler. Soil bulk density was determined with the core method. The air dried soil sample was used for measurements of soil physicochemical properties. SOC content was analyzed using the dichromate oxidation method (ISSCAS 1978).The plant C concentration (percent of dry mass) was analyzed using a Thermo CHNS/O analyzer (FlashEA1112, USA). The total C storage of the plant-soil system included the sum of all of the plants and SOC pools in the 60-cm soil profile.

Table1. Grazing intensities and vegetation characteristics of the study sites

Grazing intensity	Pasture area (ha)	Yak number (head)	Total cover (%)	Stocking density ($head.ha^{-1}$)	Dominant species	Weed percentage (%)	Average height (cm)	Plant species richness
LG	16	15	85	0.94	*Elymus nutans Griseb* *Kobresia capillifolia*	7.10^{c}	18.53^{a}	11.8^{c}
MG	22	34	65	1.55	*Kobresia capillifolia* *Anemone rivularis var. flore-minore*	15.20^{b}	13.85^{b}	21.5^{a}
HG	35	100	40	2.86	*Kobresia humilis* *Ligularia virgaurea*	22.00^{a}	3.28^{c}	14.6^{b}

The lower case letters indicate significant grazing effects ($P \leq 0.05$). LG: light grazing, MG: moderate grazing, HG: heavy grazing), the same in below

Data analyses: Total plant C is approximately equal to the sum of the aboveground and belowground biomass C pools, and is calculated by multiplying the C content of plant tissue by the corresponding plant biomass. Total SOC storage density (TSOC, kg m^{-2}) is estimated using a depth weighted average of total soil organic C (He *et al*. 2011):

Total organic carbon (TSOC)(kgC.m^{-2}*)* $=\sum D_i \times P_i \times C_i \times 10^{-2}$ (1)

where TSOC represents the total organic carbon and D_i, P_i, C_i, and i represent the soil thickness (cm), bulk density ($g.cm^{-3}$), organic carbon concentration ($g.kg^{-1}$), and soil layer (1-4), respectively.

All of the statistical analyses were performed using SPSS (v. 13.0, Chicago, USA). One-way ANOVA analyses were conducted in order to compare all of the parameters among the three grazing intensities. The significance of a linear relation between various parameters was expressed with the Pearson's correlation coefficient.

RESULTS

The responses of plant biomass and species richness: The grazing intensities influenced the plant biomass and plant species richness significantly (Tables 1 and 2) (*P*<0.05). LG resulted in the maximum aboveground live biomass; however, the species richness significantly decreased with LG. HG yielded the minimum litter biomass of the three grazing intensities. The total root biomass was greatest in the MG group but lowest in the HG group. Similarly, the total plant biomass was greatest in the MG group (4173.93 g m^{-2}) but lowest in the HG group (2770.83 g m^{-2}). However, the R:S ratio increased as the grazing intensity increased.

The root biomass distribution of the soil profile also differed significantly with grazing intensity (Table 2). The root biomass decreased significantly as the soil depth decreased for each of the three treatments (*P*<0.05). However, more roots were distributed near the surface as the grazing intensity increased. The root biomass in the top 10-cm soil layer accounted for 80.19 % of the HG total root biomass, while only 45.09% and 49.79% of the total root biomass was located in the LG and MG topsoil, respectively. The total root biomass of the 0-60-cm soil layer was, in descending order, MG > LG > HG (*P*<0.05).

Table2. Plant biomass as affected by grazing intensity (standard errors in parentheses)

Treatment	LG	MG	HG
Aboveground biomass(g·m^{-2})			
Live	356.32(18.3)^{a}	255.07(23.79)^{b}	79.80(7.0)^{c}
Litter	42.60(2.74)^{a}	43.70(3.16)^{a}	8.10(1.3)^{b}
Total aboveground	398.91(18.3)^{a}	298.77(23.6)^{b}	87.9(6.9)^{c}
Root biomass (by depth, g·m^{-2})			
0-10 cm	1366.87(81.8)^{c}	1929.55(56.93)^{b}	2151.46(37.5)^{a}
10-20 cm	698.85（19.11)^{b}	971.59(36.58)^{a}	260.76(22.67)^{c}
20-40 cm	577.07(31.76)^{b}	702.93(51.53)^{a}	181.27(12.27)^{c}
40-60 cm	388.53(25.01)^{a}	271.08(44.69)^{b}	89.43(8.60)^{c}
Total root	3031.34(80.71)^{b}	3875.16(62.32)^{a}	2682.93(42.15)^{c}
Total plant biomass (g·m^{-2})	3430.25(74.19)^{b}	4173.93(55.85)^{a}	2770.83(41.64)^{c}
R:S ratio	8.79(0.69)^{c}	16.42(1.55)^{b}	36.10(3.22)^{a}

The response of carbon concentration and storage: The grazing intensity significantly affected the ecosystem carbon concentration. The SOC concentration of the 0-10-cm soil layer in the HG group was higher than that of the LG and MG groups (Fig. 1a), but significantly decreased below 10 cm. The SOC concentration of the 10-20-cm soil layer was highest in the MG group, but no differences were found between the LG and MG groups in the 0-10-cm and 20-60-cm soil layers. The results indicated significant differences in soil C storage among the three grazing intensities (Fig. 1b). The soil carbon storage in the MG group was greater than that in LG group for the 10-20- and 40-60-cm soil layers, and the soil carbon storage in the MG and LG groups were greater than that in the HG group below 10 cm. The root C concentration did not change among the three grazing treatments (Fig. 2a). However, the root C storage of the soil layers beneath 10 cm in the HG group was significantly lower than that in the LG and MG groups; no significant differences between the LG and MG groups were observed in the 10-40-cm (Fig. 2b).

The aboveground plant C storage decreased significantly as the grazing intensity increased (Table 3); the highest value, 0.20 kg m^{-2}, was observed in the LG group. The total carbon storage of the plant-soil ecosystem in the HG group decreased by 23.35 % compared to that in the LG group (Table 4). In addition, the total C storage in the MG group increased by 11% compared to that in the LG group. The soil C storage accounted for 92.97%, 93.13%, and 92.52% of the total C storage in the LG, MG, and HG groups, respectively. The correlation analyses indicated that the soil carbon storage was positively related to the belowground biomass (R=0.775, *P*<0.01). In addition, the root organic carbon storage was positively related to the belowground biomass (R=0.765, *P*<0.01).

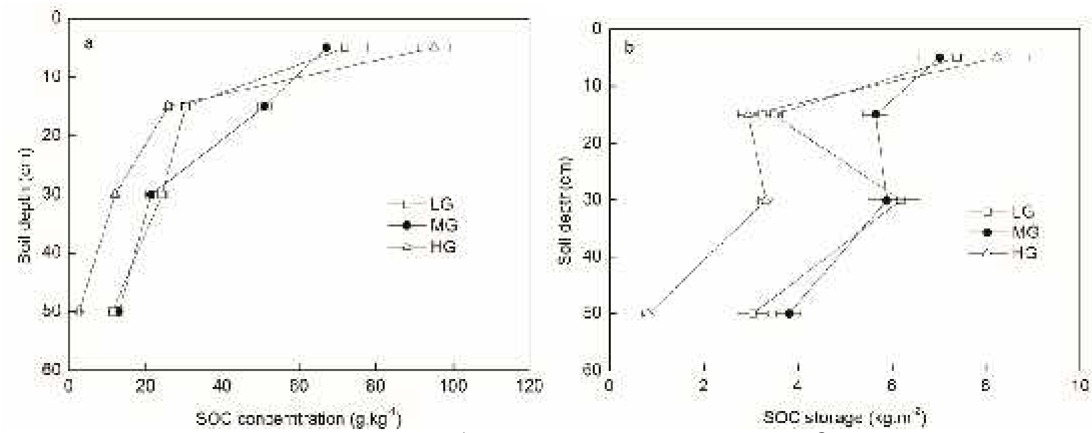

Figure 1. Soil organic C concentration (a, g.kg^{-1}) and soil C storage (b, kg.m^{-2}) up to 60 cm belowground for different grazing intensities.

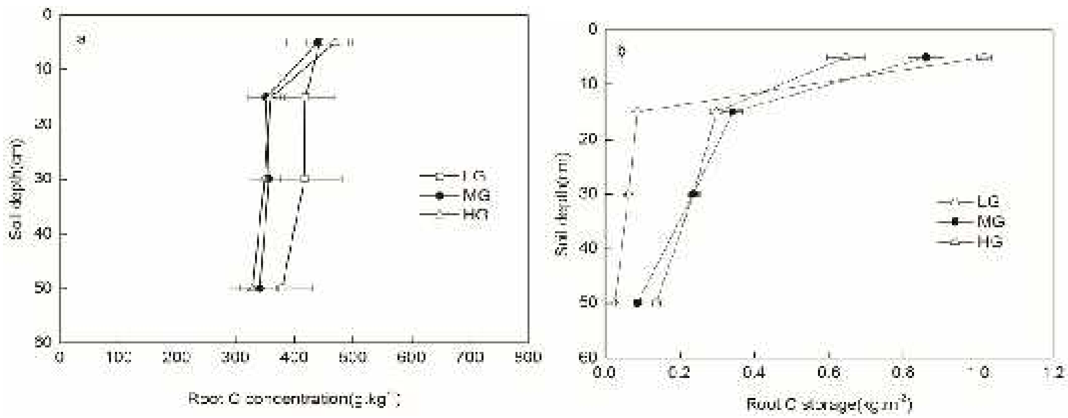

Figure 2. Root C concentration (a, g.kg^{-1}) and root C storage (b, kg.m^{-2}) up to 60 cm belowground for different grazing intensities.

Table 3. Total C pools in the plant-soil system (0-60-cm depth) for different grazing intensities

Treatment	Biomass carbon (kg m^{-2})			Soil C (kg m^{-2})	Total C(kg m^{-2})
	Aboveground	Belowground	Total		
LG	0.20(0.012) ^{a}	1.32(0.044) ^{b}	1.52(0.029)^{b}	20.11(0.436) ^{b}	21.63(0.290) ^{b}
MG	0.13(0.017) ^{b}	1.52(0.049) ^{a}	1.65(0.051)^{a}	22.36(0.403) ^{a}	24.01(0.811) ^{a}
HG	0.04(0.004) ^{c}	1.19(0.018) ^{b}	1.23(0.019)^{c}	15.34(0.668) ^{c}	16.58(0.703) ^{c}

DISCUSSION

The effect of grazing intensity on plant biomass: Grazing modifies the structure and function of ecosystems, especially the productivity, according to the GOH, plant primary production is uni-modally related to grazing intensity (Hilbert *et al.* 1981)., For this study, since there was no grazing during the growing season, the aboveground biomass at the peak standing biomass should represent the aboveground net primary productivity (ANPP). The aboveground biomass decreased as the grazing intensity increased (Table 2), thus, did not support GOH. Ferraro and Oesterheld (2002) conducted a review of 105 studies involving grazed and ungrazed sites around the world and found that 28% of them reported an increase and 72% reported a decrease in ANPP due to grazing. Variations in grazing history and grassland conditions could contribute to the contradictory effects of grazing on ANPP (Piñeiro *et al.*, 2010; Niu *et al.*, 2011).

In this study, both total root biomass and total biomass of the MG group were significantly greater than that of the LG and HG groups, which agreed with the uni-modal pattern described in GOH (Table 2). Similar results found in Pampa de Achala (Pucheta *et al.*, 2004). Moderate grazing could result in positive plant-animal interactions (Mulder *et al.* 2001). The moderate grazing changed the source utilization process in that, as an environmental disturbance, herbivory improves the photosynthetic ability of individual plants (Hayashi *et al*., 2007) , However, heavy grazing significantly decreased the aboveground biomass and species richness, which precluded the photosynthesis and photosynthate transport from aboveground to belowground, thereby, less belowground biomass. In addition, the belowground biomass was positively correlated with species richness (r=0.682). This result indicated that grazing could lead to niche complementarity in plant communities as a result of interspecific resource demand differences and spatial and temporal resource and habitat utilization (Mulder *et al.* 2001). Thus, the highest plant species richness in MG also contributed to the highest values of root biomass and total biomass.

More root biomass was distributed in the surface layers (Table 1). Shallow root distribution is caused by grazing via two main mechanisms In one of these mechanisms, soil trampling leads to low infiltration rates in the deep soil layers (He *et al*. 2011), resulting in oxygen deficiency and, therefore, decreased plant root activity. Thus, high R:S ratios and increased biomass allocation to the surface roots could benefit plant growth by enlarging the nutrient absorption area and enhancing the oxygen supply. In the other mechanism, the plant species composition shifts and unsown species are allowed to invade each year (Bonin *et al.* 2013). The weed percentages of the MG and HG groups were 15.2% and 22%, respectively (Table 1). The average height of the grass in the HG group was 5.65 times less than that of the LG group. Typically, tall species have deeper roots than short species; thus, the shift from tall native grass species to short invasive weeds in the HG group of this study could explain the effects of grazing on root distribution.

The effect of grazing intensity on carbon storage in plant-soil ecosystems: The characteristics of the aboveground and belowground biomass C storage differed among the grazing intensities. The MG exhibited 35% less aboveground plant biomass carbon storage and 15.15% more belowground biomass C storage than that of calculated for LG. However, the highest total biomass C storage was observed in the MG, which supported GOH. Because the carbon concentration of the aboveground (LG 50.9%±1.68, MG 43.6%±2.41, HG 48.5%±1.98) and belowground plant materials (Fig. 2a) was similar for all of the grazing intensities (i.e., 40-50 %), the biomass C storage was primarily determined by the biomass, which was the highest in the MG group.

Because plant root residues are primary source of SOC, the mass and distribution of SOC depend heavily on the root distribution and above- and belowground biomass allocation patterns (Reeder *et al.* 2004). In this study, the total soil carbon storage was the highest in the MG group, which corresponded to the uni-modal pattern. In the soil profile, the aboveground litter and fine roots that were distributed in the surface layers were the main sources of topsoil SOC. In this study, 80.19 % of the root biomass concentrated at 0-10 cm soil layer in the HG, 45.09 % and 49.79 % of root biomass was found in LG and MG in the same layer, respectively. Mass of SOC, however, was 2.4% and 17.2% higher in the 0 to 10cm depth increment of HG compared to LG and MG. The contribution of the roots to the SOC could be due to the high number of plant species and highly complementary functional group compositions. Furthermore, root-derived C is more stable than shoot-derived C (Rasse *et al.* 2005). In addition, in a study by Hafner *et al* (2012), less C was lost by shoot respiration (17% vs. 42%) and more C was translocated belowground (40% vs. 20%) in grazed plots than in un-grazed plots. The results obtained in this study were consistent with these studies.

In this study, the pattern of total carbon storage in the plant-soil ecosystem under different grazing intensities supported GOH. The total carbon storage of the MG increased by 11% compared to that of the LG, which was 44.81% higher than that of calculated for the HG. Thus, the GOH would not only be valid for plant primary productivity, but also for soil C storage and ecosystem C storage in Alpine meadows. The same results found in shortgrass communities in the North American Great Plains, the grazed site had 24% more ecosystem carbon storage compared to ungrazed site (Derner *et al*., 2006). Piñeiro *et al.* (2010) proposed three mechanisms for controlling SOC with grazing that could operate simultaneously: changing net primary production (NPP pathway), changing nutrition stocks (nutrition pathway), and changing organic matter decomposition (decomposition pathway). Our results suggested that net primary production change was the main pathway of carbon sequestration in Alpine meadows since the low temperatures exhibited in these regions could slow the degradation of dead roots and litter and, thereby, hinder the nutrient cycling process. The results also indicated that grassland total biomass and soil carbon sequestration can be increased simultaneously through management practices, such as maintain moderate grazing, proper reseeding, fertilizer applying and so on.

Conclusion: Land degradation and desertification are spreading in Alpine grassland ecosystems due to overgrazing, often resulting in increased CO_2 emissions. Certain management practices, such as changes in grazing intensity, could assist in restoring C storage in these ecosystems. In this study, MG changed the species composition and increased the R:S ratio, resulting in a modification of the assimilate distribution from aboveground to belowground. The main soil carbon sequestration pathway in the Alpine meadow was through a change in net primary production. In this study, the soil C storage accounted for 92.97%, 93.13%, and 92.52% of the total C storage in the LG, MG, and HG groups, respectively. The total C storage and soil C storage were far higher than that in temperate grasslands and deserts. This indicated that Alpine grasslands play a significant role in maintaining the local C balance. Therefore, further efforts should be made in maintaining the SOC and productivity of fragile alpine grassland ecosystems.

Acknowledgments: This study was supported by a special fund for agroscientific research in public interest （201203041）, the National Basic Research Program of China (2014CB138703), the Natural Science Foundation of China (31201837) and the Program for Changjiang Scholars and Innovative Research Team in University (IRT13019).Thanks to Jennifer K. Learned (Arizona State University, USA) for help in revising the manuscript.

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