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Comprehensive analysis of grazing intensity impacts soil organic carbon: A case study in typical steppe of Inner Mongolia, China

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ABSTRACT

Overgrazing is a primary cause of grassland degradation, including the loss of soil carbon, but comprehensive analysis of the mechanism by which grazing affects soil organic carbon (SOC) is limited. To investigate this mechanism, we measured the contents of total soil organic carbon (*TSOC*) and active SOC fractions in grazed and ungrazed soil, and we examined the influence of grazing on soil microenvironments, soil carbon input, transformation and utilization, and soil respiration. The experiment was conducted in typical steppe in Inner Mongolia, China, under light, moderate, and heavy grazing plus a no-grazing control. Grazing changed the contents and stocks of the *TSOC* and active SOC fractions as well as the composition of the SOC. After three years, light and moderate grazing increased *TSOC* content by 3.44% and 5.43%, respectively, while heavy grazing decreased it by 4.30%. The changes in active SOC fractions were not uniform under different grazing intensities. All grazing intensities increased the stocks of microbial biomass carbon (*MBC*) and dissolved organic carbon (*DOC*) compared with the control, but their magnitudes did not rise with increased grazing intensity. Moderate grazing increased the stocks of potentially mineralizable carbon (*PMC*) and particulate organic carbon (*POC*), whereas light and heavy grazing decreased them; this may indicate likely long-term changes in SOC following changes in grazing intensity. Light grazing resulted in a larger C input to soil and faster transformation, more emission, and less accumulation of SOC. Moderate grazing led to a smaller C input to soil, and its transformation, utilization and emission rates were between those associated with light grazing and heavy grazing, and there was more accumulation. Heavy grazing resulted in the smallest C input, faster transformation and utilization, less change in emission, and less accumulation. Based on these results, moderate grazing is likely the most practical grazing intensity for the sustainable utilization of this grassland ecosystem to feed livestock. However, because this was a short-term study, the results did not reach significance, and long-term studies are needed.

1. Introduction

Grassland ecosystems cover about 30% of the global land surface (Jia et al., 2006) and store 28%–37% of the carbon in terrestrial ecosystems (Lal, 2004; IPCC, 2007). Thus, these ecosystems play a key role in the global carbon cycle (Monkany et al., 2006). However, excessive utilization of grasslands (and especially overgrazing) has led to degradation of large areas, accompanied by decreased soil quality. Soil organic carbon (SOC) is an important indicator of soil quality (Wiesmeier et al., 2015; Liu et al., 2017). Worldwide, Dlamini et al. (2016) summarize 55 studies with 628 soil profiles, of which grassland degradation significantly reduced SOC stocks by 16% in dry climates (< 600 mm) compared to 8% in wet climates (> 1000 mm), and Asia was the most affected continent (–23.7%). Therefore, SOC content in grasslands needs to be increased or maintained in order to sustain these ecosystems.

Several studies have shown that grazing intensity can significantly affect the magnitude and even the direction of changes in belowground C pools (Mcsherry and Ritchie, 2013; Zhou et al., 2017). However, published studies on the effects of grazing intensity have shown inconsistent results. Some researchers have found that as the grazing intensity increases, the SOC content decreases (Su et al., 2005; Pei et al., 2008; Zuo et al., 2008; Golluscio et al., 2009) or does not change significantly (Nosetto et al., 2006; Raiesi and Asadi, 2006; Shrestha and

Abbreviations: ρ, soil bulk density; *AGB*, aboveground biomass; *DOC*, dissolved organic carbon; *MBC*, microbial biomass carbon; *PMC*, potentially mineralizable carbon; *POC*, particulate organic carbon; R_{sa}, soil autotrophic respiration; R_{sh}, soil heterotrophic respiration; R_{ts}, total soil respiration; *SP*, soil porosity; *ST*, soil temperature; *SWC*, soil water content; *TSOC*, total soil organic carbon; *VC*, vegetation coverage

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Stahl, 2008; Steffens et al., 2008). Other studies have shown that under certain grazing intensities, SOC content can increase (Wienhold et al., 2001; Reeder and Schuman, 2002). Milchunas and Lauenroth (1993) summarized 34 studies on grazed vs. ungrazed sites, of which 40% showed decreases in soil carbon storage under grazing and 60% showed increases.

In the course of soil degradation, active SOC fractions are preferentially lost (Wiesmeier et al., 2015). Grazing intensity, too, can change the content of active SOC fractions, but published studies have shown inconsistent results on the magnitude and direction of these changes. Previous studies on active SOC fractions have mainly focused on microbial biomass carbon (*MBC*) and particulate organic carbon (*POC*). In most of these studies, grazing reduced *MBC* by more than 20% (Ma, 2006; Zhou et al., 2017). However, in some cases, grazing had no significant effects on *MBC* (Teague et al., 2011). Published research has shown that grazing can lead to increases (Leifeld and Fuhrer, 2009), decreases (Wiesmeier et al., 2015), or slight or no significant changes (Herfurth et al., 2015; Martinsen et al., 2011) in *POC* content. Other research teams have focused on potentially mineralizable carbon (*PMC*) and dissolved organic carbon (*DOC*) and have not found significant effects from grazing on these measures (Martinsen et al., 2011; Fu et al., 2014).

Thus, the effects of grazing on *TSOC* and the active SOC fractions have differed among studies, likely due to the complexity of SOC dynamics. No good overall explanation of the potential mechanisms has been published (Mcsherry and Ritchie, 2013; Zhou et al., 2017). Therefore, in the present study, we examined SOC in plots with different grazing intensities in a typical steppe of Inner Mongolia, China, and examined the effects of grazing on soil microenvironments and on the input, transformation, utilization, and emission (soil respiration) of carbon in soil. We hypothesized that grazing at an appropriate intensity would increase SOC in this grassland. Our goals were to: (1) explore the potential mechanisms by which grazing affects SOC and identify predictors of long-term changes in SOC following changes in grazing; (2) determine the relationship between grazing intensity and the levels of *TSOC* and the active SOC fractions in soil; and (3) determine the optimal intensity for sustainable grazing in order to support grassland management.

2. Materials and methods

2.1. Study site

The study was carried out at the experimental grazing plots of the Institute of Grassland Research of the Chinese Academy of Agricultural Sciences. These plots are located in the Chaokewula Sumu region (ca. 44°15′N and 116°32′E, 1111 to 1121 m a.s.L.), in the Xilin Gol League of China's Inner Mongolia Autonomous Region. The area is situated in a semiarid steppe ecosystem and has a typical continental monsoon climate, with annual precipitation of 350 to 450 mm and an annual mean temperature of -0.1 °C, ranging from an average of –22.0 °C in January to 18.3 °C in July. The plant community is dominated by *Leymus chinensis*, *Stipa krylovii*, and *Stipa grandis*. The soils are classified as Calcic Chernozems (IUSS Working Group WRB 2006) and with similar physiochemical properties of chestnuts and calcic chernozems (Hoffmann et al., 2008).

The entire Chaokewula Sumu region is grazed by herds consisting of 70%–90% sheep and 10%–30% goats (Steffens et al., 2008), and the carrying capacity is around 0.50–0.75 standard sheep units (SSU) ha^{-1} yr^{-1}. From 2007 to 2014, grazing was prevented in the experimental plots, and the plots were mowed to provide fodder; the vegetation grew well under this regimen. At the start of the grazing experiment, plots were chosen so that vegetation cover, species composition, and soil properties were similar in all plots (data not shown).

The grazing study began in 2014. Each year, livestock were grazed in the grazing areas for a period of 90 days beginning on 10 June. The livestock were 2-year-old Ujumqin sheep wethers (castrated males) with an average weight of 31.5 kg. Four grazing intensities were applied to the study plots: control (no sheep), light, moderate, and heavy. The grazing intensities are equivalent to 0, 0.47, 0.93, and 1.40 standard sheep units (SSU) ha^{-1} yr^{-1}. The experiment had a completely randomized block design with three replications per grazing intensity. All means reported in this paper represent the mean of these three replicates per treatment.

2.2. Data acquisition

All samples were obtained at the same time during the plants' most vigorous growth period (in late July) in 2016.

2.2.1. Biomass and litter samples

We established three 1 m × 1 m subplots in each plot for a total of 36 subplots. We collected all aboveground biomass (*AGB*) and litter in the subplots, then oven-dried the samples at 65 °C for 24 h to constant weight. We used soil cores to measure the root biomass. The upper 30–40 cm of soil has the highest concentration of soil organic matter and contains approximately 80% of root biomass (Shrestha and Stahl, 2008). Hence, studies of SOM dynamics in grazing lands have most commonly sampled at this range of depth (Povirk et al., 2001). Samples were taken at depths of 0–10 cm, 10–20 cm, and 20–30 cm using a root drill (10 cm in diameter) at three locations in each subplot (i.e., a total of nine samples per plot). We separated the roots from the soil using a 1-mm sieve, washed the roots to remove any soil, then oven-dried the samples at 65 °C for 24 h to constant weight.

2.2.2. Soil sampling and measurements

In each subplot, we obtained an additional three soil cores (10 cm in depth and 8 cm in diameter) to obtain a mixed sample of fresh soil. We removed roots and stones with a 2 mm sieve and immediately stored the samples in iceboxes until they could be returned to the laboratory for microbial analysis, soil enzyme analysis, and measurement of two active SOC fractions: potentially mineralizable carbon (*PMC*) and dissolved organic carbon (*DOC*). Subsamples of each soil sample were air-dried and passed through a 2 mm sieve, then *TSOC*, *POC*, and pH were measured. Soil pH was measured using a Fisher Accumet probe (Thermo Fisher Scientific, Asheville, NC, USA) inserted into a 2:1 w/v mixture of soil to deionized water.

TSOC was measured using an Elementar Liqui TOCα analyzer (Elementar Co., Hanau, Germany). We used the method of Liu et al. (2009) to determine *MBC*. Briefly, aliquots of the fresh soil (15 g dry weight equivalent) were fumigated for 24 h with ethanol-free $CHCl_3$. Additional aliquots of fresh soil were used as unfumigated controls. Both the fumigated and unfumigated samples were then extracted with 60 mL of 0.5 M K_2SO_4 for 30 min on a shaker at 25 °C. The K_2SO_4 extracts were filtered through 0.45-μm filters and frozen at -20 °C before determining extractable C with the Elementar analyzer. *MBC* was calculated as the difference between the extractable C contents in the fumigated and unfumigated samples using conversion factors of $k_{EC} = k_{EN} = 0.45$. We used the method of Xu et al. (2011) to determine *DOC*. Briefly, we extracted 20 g of fresh soil with 100 mL of ultrapure water and filtered the extracts through a 0.45 μm membrane filter. We analyzed the extractable SOC using the Elementar analyzer. We measured *PMC* by placing 30 g of moist soil (adjusted to 60% of field water-holding capacity) in a 50 mL beaker and incubating the sample for 30 days in the dark at 25 °C in a 1 L airtight jar along with 10 mL of 1 M NaOH. We measured CO_2 evolution at 5-day intervals by titration with a standard HCl solution (Xu et al., 2011). We measured *POC* by dispersing 25 g of soil in 250 mL of $(NaPO_3)_6$ (at 5 g L^{-1}) and shaking for 18 h. We then passed the dispersed sample through a 53-μm filter. The material collected on the filter was dried to constant weight in a forced-air oven at 60 °C, then weighed. We ground the dried samples to pass through a 0.25-mm sieve, then analyzed the C concentration using the