509

Large ungulate grazing effects on soil carbon sequestration: evidence from a field-simulated grazing experiment

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Abstract

Grasslands store 10–30% of the world's soil organic carbon (SOC) and have the potential to partially mitigate rising atmospheric CO_2 concentrations. Large ungulate grazing plays a crucial role in regulating SOC storage in grassland ecosystems. However, a more detailed mechanistic understanding of how grazing influences SOC dynamics is still needed. We investigated soil C formation among different C pools, including particulate organic carbon (POC) and mineral-associated soil organic carbon (MAOC)in a multiyear field experiment by quantifying litter-derived C inputs, in response to mowing, trampling, and dung and urine return (and combinations), treatments. We found that mowing significantly enhanced litter-derived SOC and POC formation. Trampling increased SOC, POC and MAOC pool, possibly by enhancing mixing of litter and soil, and increasing C accessibility for soil microorganisms. Our results elucidated the specific mechanisms of large ungulate grazing by quantifying the C inputs and formation processes. Accurately quantifying the contribution of plant C input to SOC pool under various management practices in grasslands is the next critical step toward improving predictions of SOC dynamics.

Introduction

Ninety percent of the terrestrial carbon stocks are stored underground in the form of root biomass and soil organic carbon (SOC) (Bai & Cotrufo, 2022), is highly sensitive to small fluctuations. The C balance of grassland soils is affected by carbon inputs that affect long-term carbon sequestration, especially litter C inputs. For analysis, soil carbon was divided into two distinct carbon pools: mineral-associated soil organic carbon (MAOC, <53 µm) and particulate organic carbon (POC, >53 µm). The MAOC pool is stable over long timescales and is considered to cycle more slowly than the POC pool. Because of the large extent of grasslands globally, it is important to have a quantitative understanding of the dynamics of soil C to make a credible estimate of the possible impacts of grazing management on the global C cycle.

Grazing is a complex interaction of livestock and grasslands, involving three potentially important mechanisms: defoliation, dung and urine deposition, and trampling, each of which may strongly influence processes of soil C storage. Defoliation reduces plant biomass, height, and coverage (Zhu et al., 2012), which in turn increases UV exposure and affects soil parameters such as moisture (Li et al., 2022). Soil moisture is crucial for litter decomposition in semi-arid grasslands, and grazing limits litter decomposition by reducing soil moisture (Wang et al., 2020). Besides, trampling alters soil physical properties. For instance, it increases bulk density (Liu et al., 2015) but decreases aeration and moisture (Wang et al., 2018), thus limiting microbial activity and litter decomposition. Trampling also breaks up litter and incorporates it into the soil, making it more accessible to microbes, which promotes the formation of SOC or POC (Wei et al., 2021). Furthermore, dung and urine return increasing nitrogen availability (Liu et al., 2015), which accelerates litter decomposition by enhancing soil microbial biomass, and increasing MAOC formation. Overall, grazing can promotechang soil organic carbon formation through litter decomposition. However, evidence for this mechanism remains limited. This study investigated the effects of grazing on organic carbon formation from litter carbon, ^{13}C-labeled litter was used to trace the fate of carbon in the different C pools.

Methods

Study site and experimental design

We conducted the study in a semiarid steppe at the Duolun Restoration Ecology Station of the Institute of Botany, the Chinese Academy of Sciences (42° 02′ N,116° 17′ E, mean annual temperature is 2.1 ◦C, mean annual precipitation is 378 mm), Inner Mongolia, China.

In May 2015, we applied a factorial combination of mowing (M+ or M-, adding a liquid mixture of dung and urine (D+ or D-), and trampling (T+ or T-), which resulted in eight different treatment combinations (Liu et al., 2015). Eight replicant blocks were established, resulting in 64 plots total. Please refer to Wei et al. (2023) for specific experimental design.

In early June 2018, decomposition collars were placed in each plot (Wei et al., 2023). Soil samples from the 0-5 cm depth were extracted using a homemade auger (diameter = 11 cm, height = 5 cm), sieved (5 mm), and roots and residual plant material were removed. PVC collars (diameter = 10 cm, height = 6 cm) were inserted into the core holes, and the sieved root-free soil was refilled. PVC rings (diameter = 10 cm, height = 1 cm) with a 1 mm mesh were placed over the collars to prevent fresh litter from entering. The 1 mm nylon mesh provided limited protection against solar radiation. Two decomposition PVC collars were set up in each subplot, with the PVC collars matching the treatment of the subplot. At the end of September, one PVC collar received marked litter (2.5 g per collar, spread on the soil surface), while the other collar served as a control (bare soil). The litter was collected from 3-month-old *Stipa kilovii* plants, labeled with ^{13}C-CO$_2$, with a carbon content of 461.5 g kg^{-1}, nitrogen content of 16.2 g kg^{-1}, and a C:N ratio of 28.5. Prior to application, the litter was cut into 1-2 cm pieces and applied evenly. Each year (i.e., 2019 and 2020), soil and remaining litter samples were collected from the four collars in each plot. Soil samples from the corresponding bare soil controls were also taken.

Soil carbon was fractionated into POC and MAOC pools. A physical fractionation method was used to separate organic carbon into these two pools. Soil samples (10 g air-dried soil) were shaken with 30 mL of a chemical dispersant (sodium hexametaphosphate: NaHMP, 50 g L^{-1}) at 200 rpm for 18 hours. After shaking, the sample was passed through a 53 μm sieve under water using a vibrating sieve (AS 200 Control, Retsch, Germany) to ensure that all MAOC was thoroughly washed. The two fractions were dried at 65°C and weighed.

All analyses were performed using R 4.1.2. We firstly performed linear mixed models (LMMs) that included ‘treatments’ as a fixed effect and ‘block’ as a random effect to test the effects of mowing, trampling, and dung and urine on litter-derived SOC, POC and MAOC using the lmer function in the package lme4.

Results

Mowing significantly enhanced litter-derived SOC formation after two years of decomposition ($p < 0.05$), with increases of 15% and 34% in newly formed SOC, respectively (Fig. 1 a, d). Both mowing and trampling promoted POC formation after two years of decomposition, but only trampling enhanced MAOC formation (Fig. e, f). However, no effect of grazing treatments on litter-derived POC was observed during the first year of decomposition (Fig. 1b). The return of dung and urine had a limited impact on SOC formation in both years, but promoted the formation of MAOC after one year decomposition (Fig. 1c).

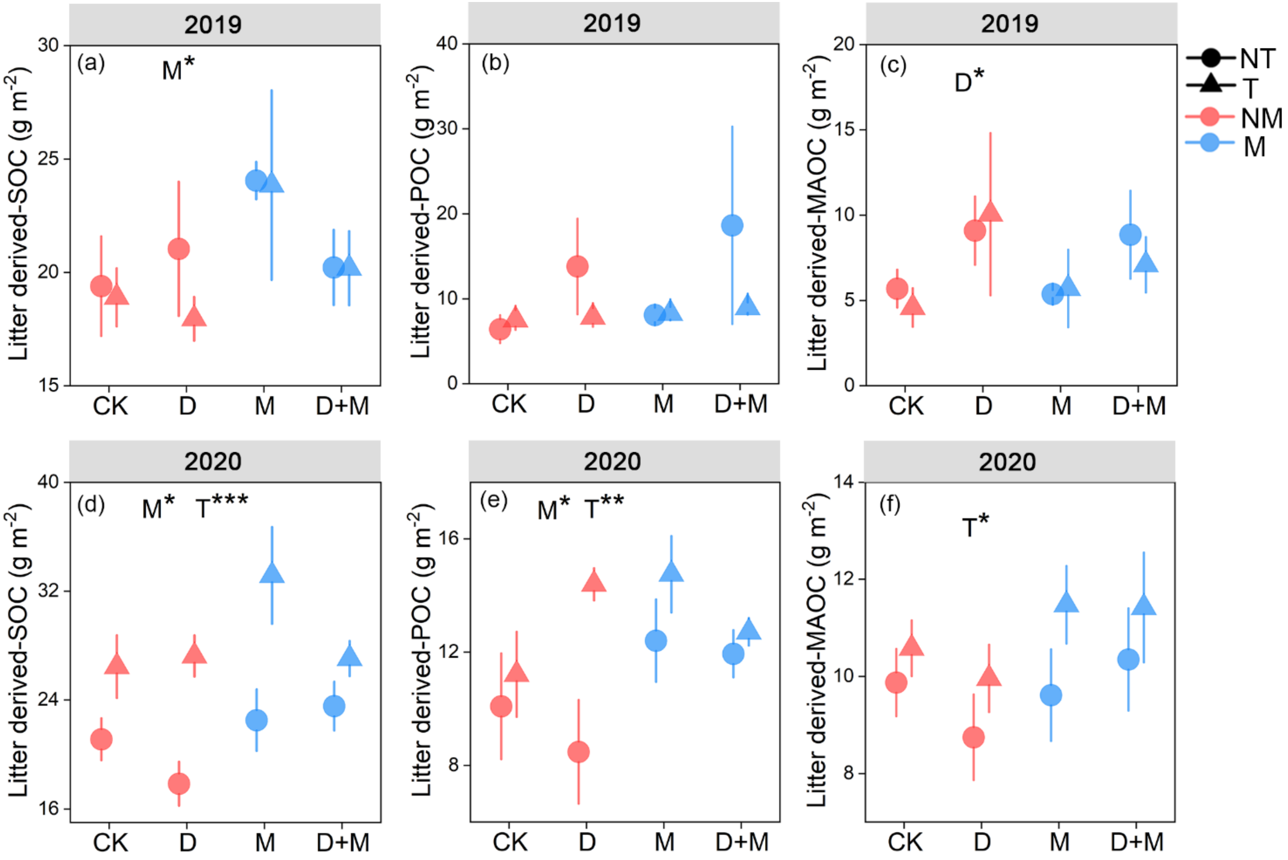

Fig. 1 The effects of simulated livestock grazing treatments on litter-derived SOC, POC, MAOC in 2019 (a, b, c) and 2020 (d, e, f). Note: CK: control, M: mowing, D: dung and urine return, T: trampling.

Discussion

Previous studies have demonstrated the impact of livestock grazing on changes in plant carbon inputs to the soil and the decomposition of litter inputs (Zhou et al., 2017). In this study, we used a ^{13}C isotope tracing method to quantify the effects of plant carbon inputs on SOC and the contribution of decomposed litter carbon to the SOC pool under grazing.

Mowing reduced aboveground biomass, plant height, and plant coverage, thereby increasing canopy light transmittance and UV exposure at the soil surface. In arid and semi-arid ecosystems, UV-induced litter decomposition plays a critical role in the decomposition of aboveground litter (Wang et al., 2017). Studies have shown that UV-induced increases in litter biodegradation, such as the decomposition of complex compounds, are more important than direct UV-driven abiotic degradation (Jiang et al., 2022). Changes in the physicochemical properties of litter compounds can accelerate subsequent microbial decomposition, a process known as the photodegradation effect (Wang et al., 2017). Therefore, the increased UV intensity in mowed areas promotes microbial involvement in organic carbon formation. However, it is undeniable that the increase in UV radiation, which leads to reduced soil moisture, may also somewhat limit the transfer of litter decomposition to the soil carbon pool.

Trampling causes soil compaction, increasing the proximity of soil microbes to litter, making it easier for microbes to decompose the litter and promoting the formation of POC (Helgason et al., 2014). Furthermore, trampling mixes litter with soil, increasing the proximity of litter to microbial communities and enhancing litter decomposition (Liu et al., 2018). Previous laboratory incubation experiments have found that trampling facilitates the incorporation of litter into the soil, promoting microbial utilization of litter carbon and the physicochemical stabilization of decomposed litter carbon (Wei et al., 2021).

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