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Conventional grazing decreases soil organic carbon by destroying physical and mineral protections

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Abstract

Conventional grazing, with high grazing pressure imposed during the plant growing season, destroys soil structure and carbon (C) protection mechanisms. Soil C is protected from decomposition by encapsulation in soil aggregates or adsorption with metal oxide mineral fractions. However, the processes by which conventional grazing affects soil C protection and the level of soil organic carbon (SOC) remain unclear. We sampled 15 pairs of sites (180 plots) contrasting grazing exclusion inside the fence and conventional grazing outside the fence, in the temperate steppe of Inner Mongolia, China, to elucidate processes affecting soil C protection and to assess the relative contribution of physical versus mineral protection to SOC. We characterized the physical and mineral protection of C by soil aggregate stability (mean weight diameter, MWD) and soil Fe/Al associated organic C, respectively. Our results showed that conventional grazing decreased SOC content (-14.83%) and weakened SOC physical (-4.88%) and mineral (-10.88%) protection, mainly due to increased soil bulk density and pH, and decreased microbial biomass C, compared with grazing exclusion. In addition, conventional grazing-induced reductions in plant inputs (root biomass) could indirectly weaken the physical and mineral protection of C. Declined root-derived C inputs will limit microbial biomass C, thus hindering microbial contribution to soil aggregation and the formation of mineral C fractions. More importantly, we found that destroying physical (57.90%) and mineral (36.76%) protection combined governed the loss of SOC in conventionally grazed grassland. These results imply a need to manage rangelands in a way that retains more litter or root-rich plant species to ensure more plant inputs, promoting physical and mineral protection of soil C.

Introduction

Grassland ecosystems, account for 20% of the world's land area (Yang et al. 2021) and store 10-30% of the global soil organic carbon (SOC) (Ward et al. 2016). As the most widespread land use, livestock grazing profoundly affects SOC by altering plant inputs and soil environment, resulting in a solid potential to regulate SOC dynamics (Lai & Kumar 2020). Conventional grazing is a high-intensity grazing pattern at the peak of the plant growing season. However, previous research has not clarified the mechanism of conventional grazing affecting soil carbon (C) sequestration.

Physical and mineral protection are two fundamental mechanisms for stabilizing SOC (Bai et al. 2020; Chen et al. 2021). Soil aggregates, as the physical protection, are formed by aggregating mineral particles and organic matter (Blanco-Canqui & Lal 2004). While soil metal mineral ions and their oxides (mainly iron, aluminum, and calcium) can interact with organic material through covalent bonds and chelation, limiting SOC mobilization and degradation to act as mineral protection (Ye et al. 2018). Little attention is paid to their relative contribution to SOC in previous research.

Biotic factors ("litter effect" and "root effect") and soil abiotic factors may alter SOC protection in grazing grassland ecosystems (Witzgall et al. 2021; Ye et al. 2018). Increasing litter mass enhanced the input of litter-derived C to soil organic matter by promoting microbial metabolism (Wang et al. 2021), facilitating the bonding and formation of soil aggregation and mineral-associated C. Researchers have generally considered that plant roots might play a dominant role in the protection compared to aboveground plants (or litter) (Sokol & Bradford 2018). Importantly, as a potential soil C pool to maintain SOC stability, root biomass seems to suffer less under grazing disturbance than the changes in litter mass (Yang et al. 2021). Soil abiotic factors could also directly or indirectly influence SOC protection. Grazing might induce extreme trampling to increase soil compaction, directly destroying soil aggregates (Wiesmeier et al. 2012); simultaneously, soil compaction may inhibit root growth and soil microbial activity, especially mycelial extension, thus restricting polymerization of soil aggregates and organo-mineral complexes (Poirier et al. 2018). However, few studies have elucidated the relative contribution of biotic and abiotic factors to the physical and mineral protection in grazed grasslands.

Here, we investigated SOC under conventional grazing and grazing exclusion at 15 sites in a semiarid grassland of northeast China. We tried to elucidate the drivers of physical and mineral protection and the relative contributions of physical and mineral protection to SOC in conventional grazing systems.

Methods

The study site is located in the Hulunbuir Grassland, Inner Mongolia (48.38-50.17°N, 116.73-120.19°E, and 524-780 m altitude). The dominant plant species were *Leymus chinensis* Tzvel. and *Stipa capillata* L. A regional (including 15 sites) field survey was conducted in August 2021. The grassland was fenced into two natural treatments: inside the fence for grazing exclusion and outside the fence for conventional grazing. Grazing was excluded for 2 ~ 35 years in theses 15 sampling grassland.The conventional grazing sites in our study were judged to be heavy grazing based on grazing intensities response ratios for the different intensities of aboveground biomass, SOC content, and soil bulk density in a Chinese grassland meta-analysis (Jiang et al. 2020). Each site was sampled in pairs inside and outside the fence (six pairs of 1m × 1m plots), with a distance of 30m between each pair of sample plots (Song et al. 2018). The soil types were consistent between each pair of sampling plots.

Plant litter was collected in each sample plot and then dried at 65 °C for 48 h. Root biomass was obtained by taking three cores mixed with a root drill in each sample plot, removing stones and soil to retain roots, washing plant roots and then drying them at 65°C for 48h and weighing them. Soil bulk density (BD) was determined using the cutting ring method. After three soil cores were taken by soil drill within each sample plot, they were mixed and passed through a 2 mm sieve to remove stones and roots, and the resulting soil samples were divided into two parts (air-dried and frozen). Frozen soil was used for the determination of soil microbial biomass carbon (MBC), which was fumigated with chloroform and extracted with 0.25 M K_2SO_4 and determined on a TOC analyzer (Multi N/C 3100) (Ding et al. 2016). Air-dried soil was used to determine other soil properties. Soil pH (soil: water of 1: 2.5) was determined using a pH meter. Soil total nitrogen (TN) content was determined using an elemental analyzer (Vario Macro, Germany), and SOC content was determined using an elemental analyzer for soil samples after hydrochloric acid fumigation. The physical protection of soil C was represented by the soil aggregates stability (mean weight diameter, MWD), which was determined by the wet sieving method using a soil aggregates wet apparatus (081301, Eijkekamp, Netherlands) to sieve the soil into macroaggregates (0.25 mm), microaggregates (0.053-0.25 mm), and silt and clay (<0.053 mm) (Kemper & Rosenau 1986). MWD is the sum of the product of the particle size of each aggregate and the weight percent of each fraction (Xu et al. 2021). Mineral protection of soil C was represented as soil Fe/Al associated organic C (Fe/Al-OC), which was extracted from the soil using the CBD method and determined by a TOC analyzer (Fang et al. 2019).

The grazing response ratio of each index was $Ln\ (Index_{conventional\ grazing} / Index_{grazing\ exclusion})$. A mixed linear model was used to test the effect of grazing on each variable, with the site as a random factor. Structural equation modeling (SEM) was used to analyze the pathways by which conventional grazing reduces physical and mineral protection of soil C, and multiple regression analysis was used to analyze the relative contribution of physical and mineral protection to SOC.

Results

SOC content in conventional grazing grassland was 14.84% lower than in grazing exclusion ($p < 0.01$, Fig 1a). For physical protection, the MWD was significantly lower in grazed than grazing exclusion grassland ($p < 0.01$, -4.88%, Fig 1a), resulting from the decrease in weight percentage of macroaggregates and increase in microaggregates ($p < 0.05$, Fig 1a). For mineral protection, soil Fe/Al-OC content was significantly lower in the grazed area than in the grazing exclusion area, reduced by 10.88% ($p < 0.05$, Fig 1a). In addition, Grazing reduced litter mass, root biomass, and MBC ($p < 0.01$, Fig 1b). Regarding soil abiotic factors, grazed grasslands had lower soil BD and pH than the grazing exclusion grasslands ($p < 0.05$, Fig 1b).

Concerning physical protection, grazing affected soil properties by decreasing root biomass (Fig 1c). Grazing-induced changes in MBC were determined by soil properties (Fig 1c). The changes in MWD were indirectly affected by grazing and jointly determined by MBC, root biomass, and soil properties (Fig 1c). For mineral protection, grazing-induced change in litter mass reduced soil Fe/Al-OC (Fig 1c). Additionally, changes in soil Fe/Al-OC resulted from reduced MBC and increased soil BD and pH by grazing (Fig 1c). Multiple regression analysis indicated that soil physical protection and mineral protection governed SOC content ($p < 0.001$, Fig 1d).

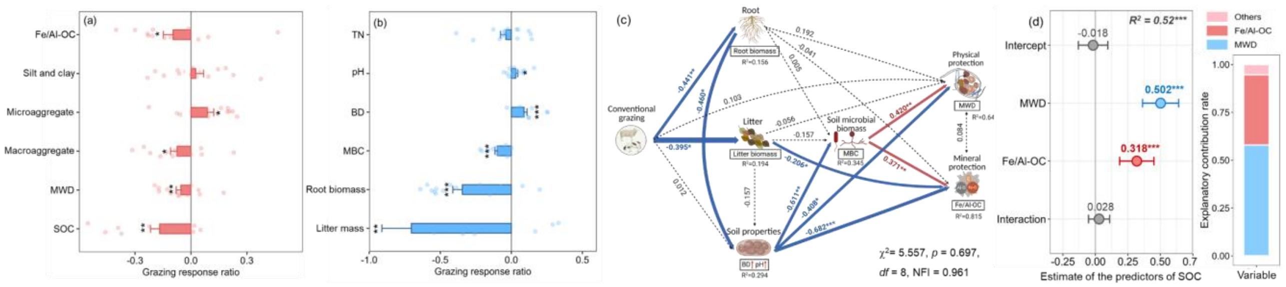

Figure 1 Grazing response ratios for each variable (a, b) with mechanisms by which grazing reduces soil organic carbon and its physical and mineral protection (c, d). The thickness of the arrows in the structural equation model represents the magnitude of the path coefficients, with red arrows representing positive relationships and blue arrows representing negative relationships. "*", "**", and "***" indicate that the result was significant at p <0.1, <0.05, <0.01, and <0.001, respectively. SOC: soil organic carbon; MWD:

mean weight diameter of soil aggregate; Fe/Al-OC: Fe/Al associated organic carbon; MBC: microbial biomass carbon; BD: soil bulk density; TN: soil total nitrogen.

Discussion

Plant roots and soil conditions are the main factors influencing SOC physical protection in grazing grasslands. In our study, grazing-induced decreases in root biomass may affect the formation of soil aggregates and alter root-derived C, driving SOC destabilization (Dijkstra et al. 2021). Previous studies found that continuous livestock grazing might inhibit root growth, and lower the input amount of root-derived C into the soil. That might aggravate the negative effects of physical entanglement in the aggregate and root exudates production (Poirier et al. 2018). We found that soil abiotic factors can mediate microbial pathways under grazing, indirectly affecting SOC physical protection. Soil microbial activity and biomass could be inhibited by soil abiotic factors such as soil pH and BD by filtering out some acidophilic microorganisms and reducing oxygen in grazed grasslands. Meanwhile, soil microorganisms decomposed the small molecular organic matter, mycelium, and other binding substances released as a result of the crushing soil aggregates (Fig 1a), thus destroying the physical protection of the SOC (See et al. 2022; Witzgall et al. 2021). All these processes may contribute to SOC destabilization, and the role of soil microorganisms should be considered more in the future.

In particular, grazing-induced reduction in litter mass and root biomass might decrease the potential input amount of plant-derived C, resulting in less production of soil mineral-associated organic C (Yang et al. 2021). Nevertheless, some organic acids (e.g., oxalic acid) in root deposits disrupt covalent metal bonds and mineral adsorption with mineral-associated organic C and increase soil hydrogen ions (Keiluweit et al. 2015). Previous research illustrated that soil microbial biomass and activity were significantly affected by below-ground input (Sokol & Bradford 2018). Then, the lack of microbial-derived C was associated with the decline in vivo turnover of soil microorganisms and the ability of microbial residues to interact with minerals (Lavallee et al. 2020). Our results also suggested that MBC was essential in regulating SOC chemical protection in grazing grasslands.

The multiple regression analysis suggested that SOC physical and chemical protection interact with each other and jointly benefit the retention of SOC. The involvement of soil metallic minerals in forming soil aggregation was like forming stable metal bonds and metal bridges (Bronick & Lal 2005). The adsorption of metal oxides to small molecules of organic matter enhanced the stability of the physical aggregation structure, especially iron and aluminum oxides (Regelink et al. 2015). Grazing negatively affects SOC physicochemical protection and thus promotes SOC loss.

Conventional grazing decreased physical and mineral protection of soil C and SOC compared with grazing exclusion in semiarid temperate grasslands. We highlighted that plant roots were key to maintaining SOC protection and SOC. However, litter mass and soil abiotic factors had a crucial effect on mineral protection. Targeting to improve the physicochemical protection of SOC in grasslands is essential to mitigate the decline in soil C sequestration induced by livestock grazing.

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