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Impact of grassland degradation on soil phytolith carbon sequestration in Inner Mongolian steppe of China

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ABSTRACT

Grasslands play an important role in the terrestrial biogeochemical carbon (C) cycle and partly mitigate climate change through C occlusion within phytoliths. Grassland degradation has a significant influence on the coupled biogeochemical cycles of C and silicon in the Inner Mongolian steppe of China, but there are few reports about the impact of grassland degradation on phytolith C sequestration in the steppe, the main grassland in northern China. Twelve sampling sites were chosen in the Xilingol League. Soil samples (0–50 cm) were collected from grasslands of four different degradation degrees to investigate the impact of grassland degradation on the soil phytolith and phytolith-occluded C (PhytOC) accumulation using a mass-balance approach. Soil phytolith storages were 12.97 ± 2.15, 15.90 ± 0.65, 14.35 ± 0.79 and 13.22 ± 1.07 t ha^{-1} in non-degraded, lightly degraded, moderately degraded and seriously degraded grasslands, respectively. The corresponding storages of soil PhytOC were 0.11 ± 0.02, 0.16 ± 0.02, 0.12 ± 0.01 and 0.07 ± 0.01 t ha^{-1}, respectively. The observed significant differences in soil phytoliths and PhytOC among grasslands of different degradation degrees indicate that grassland degradation influenced the phytolith and PhytOC accumulation in grassland soils. Grazing and harvesting are likely the major factors affecting soil phytolith and PhytOC storages through reducing the litterfall returning fluxes. Our preliminary findings imply that grassland restoration could be a promising way to increase long-term phytolith C sequestration through maximizing plant PhytOC production fluxes and soil PhytOC accumulation in degraded grasslands.

1. Introduction

Bioavailable silicon (Si) is absorbed by plant roots from soil solution and deposited as phytoliths in cell wall and cell lumen of the plants (Parr and Sullivan, 2005; Ma and Yamaji, 2006; Song et al., 2012a) or as other siliceous forms in intercellular spaces or in an extracellular (cuticular) layer (Sangster et al., 2001; Ma and Yamaji, 2006). A small amount (about 0.2–5.8%) of organic carbon (C) is occluded within phytoliths during their formation (Wilding, 1967; Parr et al., 2010). Phytolith-occluded C (PhytOC) can be preserved in soils or sediments for hundreds to thousands of years due to silica (SiO_2) protection (Parr and Sullivan, 2005; Zuo et al., 2014) and phytolith C sequestration is well-known as an important mechanism for long-term terrestrial biogeochemical C sequestration (Parr and Sullivan, 2005; Song et al., 2012b; Song et al., 2016). For example, Parr et al. (2010) estimated that the annual worldwide median PhytOC production flux of bamboo forests is 98.18 kg ha^{-1}. Soil PhytOC storage in soils to a depth of 100 cm under bamboo can reach 3.91 t ha^{-1} (X. Zhang et al., 2016). Previous studies highlighted that fertilizer applications could enhance PhytOC production flux through increased phytolith accumulation and aboveground net primary productivity (ANPP) rates (Song et al., 2012a, 2013a; Li et al., 2013; Song et al., 2016). These results have been verified in crop (Guo et al., 2015) and grassland ecosystems (Zhao et al., 2016).

Grassland ecosystems play an important role in phytolith production because of their large distribution area, high ANPP and high Si concentration of plants (Poaceae as Si accumulators) (Carnelli et al., 2001; Blecker et al., 2006; Song et al., 2012a). Grassland degradation is

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an urgent ecological and economic problem in the entire world, but particularly in China (Le Houérou, 1996; J. Zhang et al., 2016). Grassland degradation commonly occurs in the steppe driven by wind erosion, drought, pest damage and human disturbances in the semi-arid region of China (Zhao et al., 2005). In Inner Mongolia, China, nearly 90% of the grasslands are suffering from degradation with varying degrees (Jiang et al., 2009). The steppe ecosystems are fragile and easily affected by human disturbance. For example, human disturbance may significantly reduce vegetation cover, biodiversity and underground biomass, damage the soil macro-arthropod community (Zhou et al., 2008; Zhao et al., 2014) and significantly alter soil physical and chemical properties (Li et al., 2005; Jin et al., 2013; Xiong et al., 2017).

In grassland ecosystems, studies about phytolith C sequestration mainly focused on plant parts. Song et al. (2012a) estimated that aboveground phytolith and PhytOC production rates of global grasslands were 7.52×10^8 and 1.13×10^7 t a^{-1}, respectively, and reported that phytolith and PhytOC production rates of grasslands could be significantly influenced by their ANPP. Recently, Qi et al. (2017) reported that PhytOC accumulation in underground roots was higher than those in aboveground plant parts, and suggested that the belowground productivity of plants may play a dominant role in PhytOC production in grassland ecosystems. Although the accumulations of soil phytoliths and PhytOC in different grasslands have also been studied in eastern Inner Mongolia, China (Pan et al., 2017), the impact of grassland degradation on soil phytolith and PhytOC storages remains unclear. Therefore, this study aims to (1) investigate distribution and accumulation of soil phytoliths and PhytOC in grasslands of different degradation degrees, (2) explore the factors influencing soil phytolith and PhytOC storage, and (3) evaluate the significance of grassland restoration for phytolith C sequestration. These results will provide scientific evidence for developing management practices for grasslands with the focus on long-term biogeochemical C sequestration.

2. Materials and methods

2.1. Study area

The study area (42–46°N, 115–118°E) is located in Xilingol League in northern China and has a temperate continental climate. The mean annual temperature is 1.5 °C and the mean annual precipitation is 295 mm. The average elevation of the sampling sites is about 1300 m. The soils are mainly Arenosols based on the FAO soil classification system (IUSS Working Group WRB, 2007). Light yellow or light brown fine sand particles are the dominant particles in all soils (Fig. 1).

It is very difficult to develop a unified degradation index system because the scope of grassland degradation is very broad, and reasons causing degradation can vary and be complex. According to the National Standards of "Parameters for degradation, sandification and salification of rangelands" (GB19377-2003) and previous studies (Li, 1997), we choose plant community structure to quantify the grassland degradation degrees because it can indicate the status of grassland degradation better than other features in our study area.

Precipitation data from 1980 to 2010 were collected firstly from National Meteorological Information Center of China (http://data.cma.cn). We systematically sampled 120 plots along a rainfall gradient in July and August of 2014. Every plot had a size of 2 m × 2 m. Plant species richness and vegetation coverage were investigated and recorded for each plot. According to our field ecological survey data, grasslands in our study area were divided into four degradation gradients, namely non-degraded grasslands, lightly degraded grasslands, moderately degraded grasslands and seriously degraded grasslands. The information on vegetation status and soil profiles among non-degraded grasslands, lightly degraded grasslands, moderately degraded grasslands and seriously degraded grasslands is shown in Table 1 and Fig. 1. The non-degraded grasslands are dominated by *Leymus chinensis*, *Stipa baicalensis* and *Filifolium sibiricum*. The dominant species of grassland communities in lightly degraded grasslands are *Agropyron cristatum* and *Cleistogenes squarosa*. In moderately degraded grasslands *Artemisia desertorum* is dominant, and in seriously degraded grasslands *Psammochloa villosa* becomes dominant.

2.2. Field sampling

Three experimental sites were randomly chosen for each degradation gradient, non-degraded, lightly degraded, moderately degraded and seriously degraded. In order to address the spatial heterogeneity of soil properties, we randomly selected three plots (2 m × 2 m) at each site. We collected a soil sample of about 500 g from 0 to 10, 10–30, and 30–50 cm depth of each plot. The samples collected from the same layer of the three plots were mixed thoroughly into a composite sample, which was air-dried, ground and sieved (< 2 mm). Soil bulk density was determined on undisturbed soil samples from each layer using bulk density rings with a volume of 200 cm^3, and three repetitions were done for every degradation degree.

2.3. Sample analysis

Soil pH was determined in a mass ratio of soil to water of 1:5, and soil organic C (SOC) was measured using the potassium dichromate method (Lu, 1999). As primary source of plant Si, the total soil SiO_2 content was determined by inductively coupled plasma-optical emission spectroscopy (ICP-OES, Optima 2000, PerkinElmer Co., USA) after the soil samples were fused with lithium metaborate and dissolved in dilute nitric acid (4%) (Lu, 1999). Additionally, the soil bioavailable Si was extracted according to Song et al. (2013b).

In order to extract phytoliths, soil samples were treated by a wet oxidation method followed by a heavy liquid suspension method ($ZnBr_2$, 2.36 g cm^{-3}) (Zuo et al., 2014). All extracted phytoliths were dried at 65 °C for 24 h before weight determination. The potassium dichromate method was applied to determine the organic C content of phytoliths after phytolith dissolution with hydrofluoric acid (1 mol L^{-1}) (Li et al., 2013). All organic C content determinations were monitored using GBW07405 standard soil reference samples. The precision was better than 5%.

2.4. Calculations and statistics

The storages (t ha^{-1}) of soil phytoliths and PhytOC in grasslands of different degradation degree were estimated using the following equations:

$$\text{Soil phytolith storage} = \sum_{i=1}^{n} T_i \times BD_i \times (\text{phytolith content in soils})_i \quad (1)$$

$$\text{Soil phytolith storage} = \sum_{i=1}^{n} T_i \times BD_i \times (\text{PhytOC content in soils})_i \quad (2)$$

where i (i = 1, 2 and 3) is the soil profile layer (0–10, 10–30, and 30–50 cm from upper to lower, respectively), T_i is the thickness of each soil layer in different soil profiles (cm) and BD_i represents soil bulk density for each layer (g cm^{-3}). The equations were multiplied by 0.1 to transform results from mg cm^{-2} to t ha^{-1}.

All data presented are the average of three replicates. One-way analysis of variance (ANOVA) and Duncan's test were carried out using SPSS 20.0 statistical package program (SPSS Inc., USA).

3. Results

3.1. Soil physico-chemical characteristics

Soil bulk density was in the range of 1.41–1.55 g cm^{-3} and increased with depth at all grassland sites (Table 2). Soil pH was