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Effects of freeze-thaw cycles on aggregate-associated organic carbon and glomalin-related soil protein in natural-succession grassland and Chinese pine forest on the Loess Plateau

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ABSTRACT

Glomalin-related soil protein (GRSP) is a hydrophobic glycoprotein that can protect soil organic carbon (SOC) from decomposition by promoting the formation of soil aggregates. Few studies, however, have evaluated the response of aggregate-associated SOC and GRSP to freeze-thaw cycles (FTs) under different patterns of vegetation restoration. Soil samples were collected from three typical natural-succession grasslands (dominated by *Artemisia capillaris*, *A. sacrorum*, and *Bothriochloa ischaemum*) and a Chinese pine (*Pinus tabuliformis*) forest before and after natural FTs during a winter-spring season on the Loess Plateau in China. The soil aggregate stability and concentrations of SOC, easily extractable GRSP (EE-GRSP) and total GRSP (T-GRSP) in different aggregate fractions were measured. The FTs decreased the proportion of > 5.0 mm wet-sieved fractions, increased the proportion of < 0.25 mm wet-sieved fractions, and decreased the mean weight diameters by 8.7, 9.5, 2.9, and 9.4% in the soils of *A. capillaris*, *A. sacrorum*, *B. ischaemum*, and *P. tabuliformis*, respectively. The SOC, T-GRSP, and EE-GRSP concentrations in each aggregate fraction generally decreased after FTs in the four vegetation types. The SOC, T-GRSP, and EE-GRSP concentrations did not differ significantly in the larger aggregate fractions before the FTs in the soils for *B. ischaemum* and *P. tabuliformis*, but their concentrations were significantly higher for *B. ischaemum* than *P. tabuliformis* after FTs. The SOC and GRSP concentrations were significantly and linearly correlated in most aggregate fractions both before and after the FTs. These results indicated that the FTs decreased SOC by decreasing the GRSP concentration in each aggregate fraction and that SOC was more sensitive to FTs in forest than in natural-succession grassland.

1. Introduction

Soil organic carbon (SOC) in terrestrial ecosystems is the main component of the global carbon cycle (Post and Kwon, 2000). Restoring SOC is thus indispensable for improving soil quality, sustaining food production, and moderating increases in atmospheric CO_2 (Lal, 2004; Chang et al., 2011). Vegetation restoration can significantly increase terrestrial ecosystemic productivity and SOC sequestration (Gong et al., 2017). Grassland rehabilitation has increased SOC stocks by 0.12–0.33 t C ha^{-1} y^{-1} in South Africa (Chaplot et al., 2016), 0.32–0.57 t C ha^{-1} y^{-1} in New Zealand (Parfitt et al., 2014), and 0.27 t C ha^{-1} y^{-1} in China (Deng et al., 2017). Soils in ecosystems at mid-high latitudes or high altitudes experience freeze-thaw cycles (FTs) during winter as the air temperature fluctuates above and below 0 °C (Groffman et al., 2011; Wei et al., 2016). FTs can significantly disturb biogeochemical processes by influencing soil moisture, structure, and microorganisms, thus leading to changes in SOC sequestration in terrestrial ecosystems (Tan et al., 2014; J. Tang et al., 2016). Further study of the SOC dynamics during FTs would contribute to a better understanding of winter ecological processes in the restoration of degraded ecosystems.

Numerous studies have evaluated the responses of SOC fractions to FTs based either on laboratory or field studies (Yu et al., 2011; Makarov et al., 2015; Wu et al., 2017). Laboratory studies can provide valuable information about the effects of cycle amplitude and freezing rate on SOC fractions, but they cannot always determine what actually occurs in the field (Henry, 2007). Furthermore, small soil-sample cores and different sampling dates are major drawbacks in laboratory-based studies (Wei et al., 2016). W.B Wang et al. (2015) and J. Tang et al. (2016) reported that FTs in field studies decreased the SOC concentration in

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biological soil crusts in cold deserts and saline-alkali paddy soil, respectively. Dissolved organic carbon (DOC), an active and important component of SOC, is more sensitive to FTs (Song et al., 2017a; 2017b). The dynamics of DOC during FTs are inconsistent due to differences in freeze-thaw characteristics (such as the frequency and intensity of freezing and thawing) and soil properties (Tan et al., 2011; Fan et al., 2012). A meta-analysis indicated that freezing and thawing increased DOC concentrations by 27.5% (Song et al., 2017b). An increase in FTs can improve the desorption capacity of DOC (Yu et al., 2010), thereby decreasing SOC concentration. The physical protection of SOC in soil aggregates is the most important mechanism for conserving SOC (Liu et al., 2014; F.K. Tang et al., 2016). The dynamics of soil C during freezing and thawing have been significantly correlated with the formation, stabilization, transformation, and destruction of aggregates (Dagesse, 2013; Urakawa et al., 2014). Aggregates protect SOC from decomposition by physical disconnection (Six et al., 2002; Chaplot and Cooper, 2015). The SOC concentration in each aggregate fraction during FTs has rarely been evaluated, which has hindered a deeper understanding of the soil C dynamics in areas with seasonal FTs.

Soil aggregates are the basic units of soil structure (Jastrow, 1996). A variety of aggregate-binding agents contribute to the formation and stability of aggregates (Spohn and Giani, 2011). The heat-stable protein glomalin produced by arbuscular mycorrhiza is one of the most important aggregate-binding agents (Wright and Upadhyaya, 1998; Bedini et al., 2009). Glomalin has been operationally defined and extracted from soils as glomalin-related soil protein (GRSP). The GRSP concentration has been significantly positively correlated with aggregate stability and C accumulation (Rillig, 2004; Zhang et al., 2012). The formation and stabilization of aggregates by the redistribution of GRSP in various aggregate classes contribute to the dynamics of SOC (Xie et al., 2015). Little is known, however, about the effects of vegetation restoration on the concentration and allocation of GRSP in the aggregate fractions, especially during periods of FTs. A comprehensive study of the allocation of GRSP in various fractions and the distribution of aggregates would contribute to a better understanding of the underlying mechanisms of SOC dynamics during winter FTs.

Long-term agricultural exploitation on the Loess Plateau in China has led to soil degradation and SOC losses. The Chinese Government launched the "Grain-for-Green" program to control soil erosion and enhance ecological rehabilitation. A large amount of sloped farmland was converted to grassland and forest or was abandoned for natural recovery. Conversions of croplands to forest or abandonment for natural-succession grassland are two typical patterns of vegetation restoration on the Loess Plateau (Zhu et al., 2017). Studies have found that vegetation restoration on the plateau significantly increased SOC storage (Deng et al., 2014). Forests had a larger effect than grasslands on the capacity of SOC sequestration, especially in the central and southern regions of the plateau (Chang et al., 2011). All of these studies, however, were conducted during the growing season (May to October). The Loess Plateau is located in the mid-latitude zone and has distinct seasonal cycles of freezing and thawing during winter (Li et al., 2013). Few studies, however, have investigated the effect of freezing and thawing on SOC concentrations associated with soil aggregates and on aggregate stability. The objectives of our study were to examine the effects of FTs on the size distribution of soil aggregates and aggregate-associated SOC and GRSP concentrations under a chronosequence of natural-succession grassland and a Chinese pine forest on the Loess Plateau. We hypothesized that (1) FTs would decrease the SOC concentration by decreasing the GRSP concentration in each aggregate class, and (2) SOC would be more sensitive to FTs in forest than in natural-succession grassland.

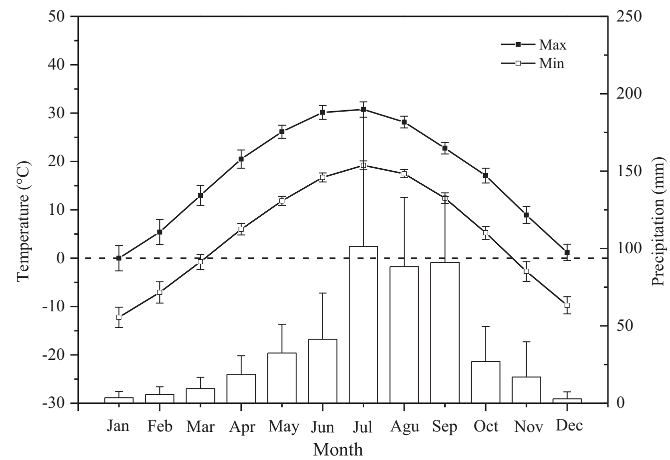

Fig. 1. Mean monthly maximum and minimum air temperatures (lines) and monthly precipitation (bars) for 2000–2015 at the study site. The error bars indicate standard errors.

2. Materials and methods

2.1. Site description and soil sampling

This study was conducted in the Wangmaogou watershed on the Loess Plateau (37°34′13″–37°36′03″N,110°20′26″–110°22′46″E), 5 km north of Suide County, Shaanxi Province, China. The watershed has an area of 5.97 km^2 and a continental monsoon climate with a mean annual precipitation of 513 mm, most of which falls between July and September. The altitude of the watershed is 940–1200 m a.s.l. The area has a mean annual temperature of 10.2 °C, with the highest recorded temperature of 39 °C (July) and lowest recorded temperature of −27 °C (January). The area has distinct seasonal freezes and thaws. The seasonal FTs on the plateau extend from October to April of the next year (Li et al., 2013). FTs in the Wangmaogou watershed can occur every month from November to March of the next year, especially in November, February, and March (Fig. 1). The soil type is mainly loessial (Calcaric Cambisols, FAO), which is extremely susceptible to erosion.

The study area suffers serious soil and water loss in the rainy season. Sloped farmland has been abandoned for natural recovery or planted with Chinese pine (*Pinus tabuliformis*) since the 1960s to reduce erosion and improve soil quality. The dominant grassland vegetation changed from *Artemisia capillaris* to *A. sacrorum* and then to *Bothriochloa ischaemum* after sloped farmland was abandoned for natural-succession recovery (Chang et al., 2016). We selected one of these three communities to represent the various stages of succession as research subjects to study the response of aggregate-associated SOC and GRSP to FTs during natural vegetation succession. A Chinese pine forest was also selected to determine whether grass or forest was more efficient for vegetation restoration in this loessial area. A total of four vegetation types were thus selected. The ages of the four vegetation types were determined by interviewing local farmers and village elders and by reviewing rental contracts between farmers and the government. The four sites had similar altitudes, slopes, aspects, and previous farming practices. Detailed information about the sample sites is presented in Table 1. The basic physical and chemical properties of the soil of the four vegetation types are shown in Table 2.

Soil samples were collected in late October 2016 and early April 2017 to represent samples before and after FTs, respectively. We randomly set up three 20 m × 20 m plots for each vegetation type. In each plot, five soil samples were collected in the 0–20 cm soil layer and mixed to form a bulk sample. The samples were air-dried, ground and sieved through 0.15- and 2.0-mm sieves for bulk-soil SOC and GRSP determinations, respectively. In addition, three undisturbed soil cores