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Fine-root distribution, production, decomposition, and effect on soil organic carbon of three revegetation shrub species in northwest China ☆

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ABSTRACT

Revegetation with xerophilous shrubs is an effective approach to combat desertification in northwestern China; however, evaluation studies on fine-root properties of shrubs and soil organic carbon are limited. To gain a better understanding of revegetation practices, we investigated the vertical distribution of fine-root biomass, necromass, production, and effect on soil organic carbon (SOC) content in three shrub species (*Salix psammophila*, *Hedysarum mongolicum*, and *Artemisia ordosica*). In addition, we also estimated the fine root decomposition rate with litterbag techniques. The results showed that revegetation practices resulted in a significant increase in SOC content. Over a 10 year period of revegetation, the SOC content in *S. psammophila*, *H. mongolicum*, and *A. ordosica* plots increased by 0.87, 1.07, and 1.82 times, respectively, more than that in bare-land plot. Increase in total SOC content was mainly due to increase in light-fraction SOC, except for the *A. ordosica* plot. Variations in the short-term increase of SOC content after revegetations with the three shrubs on sand land might be explained by fine root decomposition rates, at least in part. *A. ordosica* may be a better species for SOC accumulation and sequestration in the study site. Additionally, fine-root biomass and production were not associated with more SOC content increase in shrub plots. The results suggest the mechanism of SOC accumulation and sequestration differed among shrub plots and highlight the effectiveness of different shrub species as revegetation materials in terms of SOC accumulation and sequestration.

1. Introduction

China has been severely impacted by desertification, which is widely recognized as a significant environmental problem that increasingly threatens human survival and development (Gao et al., 2012). Revegetation that has been used extensively in northwestern China since the 1980's, is one of the most effective and sustainable means to control desertification and rehabilitate degraded land (Zhang et al., 2009). *Salix psammophila*, *Hedysarum mongolicum*, and *Artemisia ordosica* are considered as excellent fixed-dune species due to their high adaptability to arid and infertile areas affected by wind erosion. Currently, these three shrub species are dominant in desert plant communities of northwestern China, particularly in the Mu Us Desert. Although their distribution patterns (Chen et al., 2002), water-use efficiency (Yang et al., 2008), effects on soil nutrients, and other environmental benefits (Gao et al., 2014) have been studied extensively, information on their root properties and effects on soil carbon (C) is limited.

Root systems fulfill important functions in nutrient uptake and C exchange in terrestrial ecosystems, thus they play an important role in biogeochemical cycling (Trumbore and Gaudinski, 2003). The belowground part of plants is considered to be a major C pathway to soil and significantly contributes to belowground C cycle (Chapin III and Ruess, 2001). In addition, it is known that the root system influences soil microbial activity and decomposition processes (Janssens et al., 2002).

Fine roots (<2 mm) are an ephemeral part of the root system and have faster turnovers, as well as higher metabolic activity compared to lower-order roots (Pregitzer et al., 2002; McCormack et al., 2013). Although fine roots constitute a small proportion (<5%) of total standing root biomass in many terrestrial ecosystems (Gill and Jackson, 2000), it is estimated that 33% of global net primary production is consumed for fine-root growth, respiration, and turnover (Jackson et al., 1997). Fine roots are also the major sites of infection by mycorrhizal fungi, which affect a wide

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range of soil physicochemical and biological properties, including soil structure and nutrient content (Strand et al., 2008). Although mycorrhizal colonization, root exudation, and soil properties significantly affect soil organic carbon (SOC) content (Matamala et al., 2003), fine roots are the dominant pathways through which C enters the soil organic matter (SOM) pool (Jackson et al., 1997), and their structure and functional processes have an impact on SOC stocks and dynamics (Ferguson and Nowak, 2011). Therefore, information on the properties and dynamics of fine roots is essential for understanding the biogeochemical processes in terrestrial ecosystems (Pregitzer et al., 2002; Strand et al., 2008; Upson and Burgess, 2013).

Fine-root properties and dynamics may play a key role in nutrient cycle and soil C sequestration (Chang et al., 2012; Upson and Burgess, 2013) in forest ecosystems (Matamala et al., 2003); for instance, fine-root biomass and vertical distribution potentially influence long-term changes in SOC content (Ferguson and Nowak, 2011; Asaye and Zewdie, 2013), while higher rates of fine-root production lead to higher C inputs to soil (Stover et al., 2010). Recent studies showed that spatial heterogeneity of SOC was positively correlated with the vertical distribution of fine roots (Beniston et al., 2014) and also soil C with fine-root biomass and C across all depth intervals (Liao et al., 2014). In addition, it is known that fine-root production and turnover directly impact biogeochemical cycle of C in terrestrial ecosystems (Matamala et al., 2003), while fine-root productivity may be similar in magnitude to foliar productivity (Norby et al., 2004). The presence of root scars indicates that fine roots are ephemeral root modules, which shed like leaves and serve as source of C for soil (Pregitzer et al., 2002). Previous studies showed that approximately 30–80% of SOC content is provided through the rapid turnover and decomposition of fine roots (Ruess et al., 2003) and variation in SOC stocks mainly depends on fine-root decomposition rates influenced by genetic and environmental factors (Lemma et al., 2007; Hobbie et al., 2010). Therefore, a study of fine-root properties is essential for a detailed understanding of their role as a source of litter and C storage in soil.

Compared to the moist ecosystems, fine roots comprise a higher proportion of total plant biomass in the drylands (Jackson et al., 1997; Zhang et al., 2009), probably because of the increased allocation of C to root system due to relatively low nutrient availability in soil (Clark et al., 2010). Fine roots, which act as a conduit for the transport of C into the SOM pool (Strand et al., 2008), may play a key role in the accumulation of SOC in the drylands (Nosetto et al., 2006); therefore, additional information on fine-root properties is critical for a better understanding of the belowground C cycle.

Previous studies focused either on fine roots (Huang et al., 2008; Cheng et al., 2009) or on SOC content (Li et al., 2012) in revegetation areas of northwest China; however, few studies have assessed the fine-root properties and dynamics, total SOC content and its fractions following revegetation. In this study, we investigated the vertical distribution of the fine root biomass, necromass, production, and SOC content in three shrub species (*A. ordosica*, *H. mongolicum*, and *S. psammophila*) in order to gain a better understanding of revegetation practices. Our specific objectives were to (1) estimate fine-root properties, including fine root biomass, distribution, production and decomposition; and (2) detect the effect of fine roots on SOC content; and (3) elucidate the variation in SOC stocks based on fine-root properties rate in three revegetation shrub species.

2. Materials and methods

2.1. Study site description

The study was conducted at the Yanchi Research Station (37°6 8′N–37°73′N, 107°20′E–107°26′E; 1530 m a.s.l), in Ningxia Province, northwestern China. The study site is located at the south edge of the Mu Us Desert and has a semiarid continental monsoon climate. The average annual temperature is 8.1 °C (1954–2014) and the frost-free period lasts from April to November and is 156 days on average (Feng et al., 2013). Rainfall occurs mainly from July through September with average annual precipitation being approximately 287 mm (Jia et al., 2014). The soil texture of the study area is sandy in the 0–1-m profile and average soil bulk density is 1.5 g m^{-3}. In 2001, *H. mongolicum* and *A. ordosica* were randomly established with aerial seeding and *S. psammophila* was planted using cuttage (row spacing of 4 m) on stabilized sand dunes. After revegetation, shrub plots were fenced, grazing was prohibited, and no fertilizer was applied since then. Although *S. psammophila* was planted using cuttage, disturbances were limited to plot preparation. Overall, human and wild-animal disturbances in shrub plots were rare. Soil type and micro-physiographic conditions were similar among shrub plots (Table 1). Plots were relatively flat with a slope of 1.0–3.0°.

2.2. Fine-root biomass and necromass determination

Fine roots were sampled with a steel bucket-type soil auger (8.5-cm-diam. bucket auger with 25 cm height) with T-handle in September 2011. Three plots of 30 m × 30 m were established at the research area, one for each species (*S. psammophila*, *H. mongolicum*, and *A. ordosica*). Each plot of *A. ordosica* and *H. mongolicum* was divided into 36 subplots of 5 m × 5 m and a total of 72 randomly selected soil cores (36 subplots × 2 shrub species) were collected. The distance between cores and shrubs ranged approximately from 0.1 to 0.5 m and 0.05 to 0.2 m, respectively, in *A. ordosica* and *H. mongolicum* plots, and were 0.5, 1.0, 1.5 and 2.0 m from shrubs in *S. psammophila* plots. Fine-root samples were collected at depth intervals of 0–20, 20–40, 40–60 and 60–80 cm. The uppermost 0–20 cm layer consisted of humus in all cases and the thickness of organic layers ranged from 0 to 0.5 cm. Four soil cores collected at the same depth were mixed in order to ensure a good representation of fine roots in each sample. In total 52 soil cores were collected to create 13 soil samples for the determination of fine-root biomass.

All soil samples were sieved through a three metal-sieve stack with different pore sizes (2, 1, and 0.5 mm from top to bottom) and all roots and root nodules were manually collected. All sieved soil samples were stored based on depth interval for measuring fine-root production with ingrowth cores. Roots were stored in zip polythene bags and transported to laboratory within 30 min from collection, where they were stored in a freezer at 10 °C. Dead fine roots (fine-root necromass) were separated from live (fine-root biomass) based on their color and lustre, elasticity, toughness, smell, and the appearance of phloem (Brassard et al., 2013). To determine fine-root biomass, all root samples were sorted. Roots with a diameter more than 2 mm and grass roots were discarded. Both live and dead fine-root samples were washed with distilled water and then dried at 70 °C until a constant weight for determine root dry weight.

2.3. Measurement of SOC content

Approximately 100 g of sieved soil was collected from each of four depth intervals (0–20, 20–40, 40–60, and 60–80 cm) in three shrub plots. Soil samples were collected with a 10-cm bucket-type auger at depth intervals of 0–20, 20–40, 40–60, and 60–80 cm in each subplot. To have a good representation of SOC in each sample, 3 soil cores collected at the same depth were mixed in order to ensure a good representation of three shrub plots. To identify the effect of shrub planting on SOC content, we chose a bare land plot (30 m × 30 m), in which 12 soil cores were