



Introducing a shrub species in a degraded steppe shifts fine root dynamics and soil organic carbon accumulations, in northwest China



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ABSTRACT

In the semiarid and arid regions of China, the introduction of shrubs into degraded steppe is generally considered a crucial tool to facilitate vegetation restoration and reduce desertification. However, the resultant changes in root dynamics, plant composition and soil carbon have not been completely evaluated, casting doubt on the ecological viability of this method. In this study, the fine root dynamics and soil organic carbon (SOC) of two land-use types, *Caragana microphylla* shrubland (CM-shrubland) and a natural restoration steppe (NR-steppe) in northwest China were compared. Fine root biomass and production of CM-shrubland were lower by 65.7% and 43.9%, respectively, than those in the NR-steppe, in soil depths down to 80 cm. Herbaceous fine roots in the CM-shrubland had the fastest turnover and decomposition rates, followed by herbaceous plants in the NR-steppe, and then by *C. microphylla*. Differences in SOC stocks between land-use types (including a decrease in the shrubland compared to the steppe) were reflected in the heavy fraction of SOC storage in the subsoil layer (60–80 cm), rather than in total and heavy fraction of SOC in the top soil layer (0–60 cm). Surprisingly, the light fraction of SOC increased slightly (8.7%) after *C. microphylla* introduction. Thus, changes in fine root dynamics contributed to differences in SOC and its fractions between the CM-shrubland and NR-steppe. These patterns suggest that, in terms of soil C sequestration, shrub restoration might not be an effective choice for land degradation control. Instead, a moderately protected steppe is a better approach for ecological restoration.

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1. Introduction

Despite efforts to control land desertification and degradation, 27.2% of land area of China still suffered from desertification. In northwest China, desertified steppes are the most common landscape (Wang et al., 2014; Zhang et al., 2014), constituting the regional vegetation of arid and semiarid regions (Niu et al., 2008). Introducing trees or shrubs into these degraded steppes is the primary approach currently used to reverse this trend of land degradation. The introduction of some leguminous shrubs has been favoured due to their adaptability to harsh environments and ability to fix nitrogen (N) (Lal, 2004). *Caragana microphylla*, for example,

has been widely planted (approximately 1.33×10^6 hm²) in northwest China during the past few decades, to prevent wind erosion and restore the degraded steppe (Cao et al., 2008; Zhang et al., 2006). However, it is unclear if this type of land conversion is the most ecologically appropriate option for vegetation restoration in these areas.

Introducing woody plants usually changes herbaceous species composition (Buscardo et al., 2008). In grasslands, shrub introduction increases interspecific competition (Ludwig et al., 2004; Schenk, 2006), which then influences the patterns of plant litter and the amounts of carbon (C) added to the soil (Peichl et al., 2012). As the litter of herbaceous plants differs from that of shrubs in quantity and chemistry (Liao et al., 2014), the introduction of one group or the other affects nutrient cycling (Chapin et al., 2000) and soil microbial properties, such as biomass and activity (Zhou et al., 2012).

Fine roots (<2 mm) are an ephemeral part of root systems and have a high turnover rate (Jackson et al., 1997; Leppälammikujansuu et al., 2014; Yuan and Chen, 2012; Wang et al., 2016), which makes them vulnerable to land-use changes (Upson and

Abbreviations: CM-shrubland, *Caragana microphylla* shrubland; NR-steppe, natural restoration steppe; SOC, soil organic carbon; HF-SOC, heavy fraction of soil organic carbon; LF-SOC, light fraction of soil organic carbon.

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Burgess, 2013). The development of shrub root systems can lead to changes in fine root biomass and distribution, influencing the belowground competition between shrubs and herbaceous plants. Several studies have shown that fine roots are strongly affected by grassland afforestation (Peichl et al., 2012; Upson and Burgess, 2013; Zhou et al., 2012). In a mixed ecosystem, the shallow-root systems of herbaceous plants absorb the erratic and discontinuous water from upper soil profiles, whereas the deep-root systems of shrubs use the stable water resources located in deeper soil profiles (Ward et al., 2013). Studies evaluating belowground competition showed that mixed systems contain more herbaceous plants with fine roots in surface soil layers than pure grasslands (Ludwig et al., 2004; Schenk, 2006). Root biomass input via the extensive fine root systems of herbaceous plants is considered a major contributor of organic matter and nutrients in mixed ecosystems (Peichl et al., 2012).

A meta-analysis on 70 litter-manipulation experiments showed that aboveground litter affected soil organic C (SOC) accumulation in the top 10 cm of soil, and that dry ecosystems might show lower sensitivity to changes in litter inputs than other ecosystems (Xu et al., 2013). Limited soil resources in dryland ecosystems may cause plants to allocate more C toward root systems (Clark et al., 2010), producing a denser fine root network (Loiola et al., 2016). Although this increased fine root network could explain the low sensitivity to litter input changes observed in semiarid and arid regions, data on the effects of root systems on SOC are still scarce.

Land conversion also influences the cycles and stocks of soil C (Peichl et al., 2012; Wang et al., 2016). In semi-arid steppes, grassland afforestation is often accompanied by increased rates of C cycling (Zhou et al., 2012), and dryland soils have also shown great potential for SOC sequestration associated to changes in land-use and management (Lal, 2004). Tree or shrub plantations biomasses can accumulate considerable amounts of C (Strand et al., 2008), and some studies documented SOC increments in the top soil layers when grasslands or pastures were replaced by shrublands (Wheeler et al., 2007). In contrast, other studies showed that converting grasslands or steppes to woody plantations failed to change or decreased SOC storage (Wei et al., 2009; Zhou et al., 2012).

Overall, several studies have independently evaluated changes in the ecological and biochemical characteristics of fine roots or in SOC change due to shrub introduction (Guo et al., 2007; Lai et al., 2014). However, studies considering only fine root dynamics and their effects on SOC are not sufficient to completely evaluate the ecological effects of such changes in dry ecosystems. In order to approach such an evaluation, based on steppe and shrubland converted sites, the present study examined (1) fine root biomass distribution, lifetime, turnover rate, and decomposition following the conversion from steppe to shrubland; (2) changes in SOC stock and fraction after this land-use change; and (3) the effects of shrub and herbaceous fine root dynamics on SOC accumulation.

2. Methods and materials

2.1. Study site

The study site was located on the southern edge of the Mu Us desert, northwest China (37°04' N–38°10' N, 106°30' E–107°41' E; 1400–1800 m above sea level). This region experiences a semiarid continental climate, with an average annual temperature of 8.1 °C and an average frost-free period of 156 days (Jia et al., 2014). The mean annual precipitation is 287 mm, and 62% of the rainfall occurs between July and September (Liu et al., 2015). The potential mean annual evaporation exceeds 2000 mm. Soils in this region are classified as calciorthids, and the site is relatively flat with a slope of 1.2–2.0°. Since the 1980s, *C. microphylla* has been widely planted in

degraded steppes of northwest China to prevent soil erosion, using an alley cropping system (Lai et al., 2014; Zhang et al., 2006). The *C. microphylla* plantation (CM-shrubland) and neighbouring degraded steppe (natural restoration steppe, or NR-steppe) evaluated in the present study were fenced to exclude grazing and enable ecological restoration after planting. The physicochemical properties of the different soil layers in the NR-steppe and the CM-shrubland are shown in Table A.1. The dominant native grasses and forbs in the NR-steppe were *Pennisetum centrasiticum*, *Thermopsis shischkinii*, *Sophora alopecuroides*, and *Astragalus melilotoides*, whereas CM-shrubland was co-dominated by *Lespedeza davurica*, *Setaria viridis*, and *Artemisia scoparia* (Table A.2). In the NR-steppe, the average plant height and cover were about 23.4 cm and 80%, respectively. In the CM-shrubland, *C. microphylla* mean density, height, and ground cover were 334 clusters ha⁻¹, 158.4 cm, and 8.4%, respectively; the average plant height and cover between *C. microphylla* belts were 12.4 cm and 40% (Table A.3).

The *C. microphylla* plantation and neighbouring NR-steppe had the same soil type and were both unfertilized. The two plots (50 × 50 m), one from each land-use type, selected for the present assessment had similar micro-physiographic features to enable comparisons of fine root dynamics and SOC accumulation.

2.2. Fine root distribution and production

To determine fine root biomass, soils were sampled during September 2011, after the wet season (July–September), using a cylindrical metal corer with a sharpened edge (diameter: 8.5 cm; height: 20 cm). In the CM-shrubland, four soil cores were taken at four perpendicular distances from the shrub row (1, 2, 3, and 4 m), and pooled into a composite sample (for method details, see Lai et al., 2014). Each 80-cm soil sample consisted of four soil cores taken at: 0–20, 20–40, 40–60, and 60–80 cm. Eighty-eight soil cores were collected in the CM-shrubland, providing 22 composite root samples per sampling depth. In the NR-steppe plot, 88 soil cores were randomly obtained (separated by 4–5 m) at the same depth ranges as CM-shrubland samples, and pooled into 22 composite samples per depth. All composite soil samples were sieved three times using 2-, 1-, and 0.5-mm meshes. After sieving, roots and root fragments were extracted with forceps and placed in a ziplock bag, which was kept on ice and immediately transported to laboratory for further analysis. In the lab, debris and attached soil particles were removed from the roots, which were cleaned with deionized water. Roots larger than 2 mm in diameter were discarded. In CM-shrubland root samples, roots of herbaceous plants and *C. microphylla* were separated based on their colour. To determine the biomass of dead fine roots, living and dead *C. microphylla* fine roots were separated based on colour, consistency, and smell (Brassard et al., 2011; Gwenzi et al., 2011). To distinguish the roots of different herbaceous plants, specimens of all herbaceous plants present in the plots were collected, classified, and labelled. In the lab, annual and perennial herbaceous plant roots were classified based on these root specimens.

After removing the roots, sieved soils were immediately transferred to nylon mesh bags (length: 80 cm; diameter: 8.5 cm; pore size: 0.5 mm), which were placed back at their corresponding sampling site and depth level. In September 2012, these 176 ingrowth cores (4 × 22 in CM-shrubland + 4 × 22 in NR-steppe) were collected and divided according to their soil depth: 0–20, 20–40, 40–60, and 60–80 cm. The subsequent handling and processing of the soil cores and roots were identical to that described for the original samples taken in September 2011.

To determine fine root dry mass, all fine roots were washed with deionized water, packed in paper bags, oven-dried for 72 h at 70 °C (Sariyildiz, 2015; Zewdie et al., 2008), and weighed. Fine root biomass density (FRBD, g m⁻²) and fine root production

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