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Co-variation of fine-root distribution with vegetation and soil properties along a revegetation chronosequence in a desert area in northwestern China

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ABSTRACT

This study investigated the changes in the distributions of fine roots and explored their responses to changes in vegetation and soil properties along a 46-year revegetation chronosequence in a desert area in northwestern China. Fine roots and soil samples at depths of 0–3.0 m soil profile were obtained from revegetated sand-binding areas and compared with those from moving sand dunes, natural undisturbed vegetated dunes, and a desert steppe. The soil physicochemical properties in the top 0.8 m layer were analyzed, and the soil water contents at depths of 0–3.0 m soil profile were measured. Redundancy and regression analyses were conducted to explore the relationships between fine roots, vegetation and soil properties. Both the cumulative fine-root length and mass in the 0–0.4 m layer and throughout the 0–3.0 m profile increased along the revegetation chronosequence, and those of the 1.0–3.0 m layer increased up to 29 years and then decreased. Additionally, the proportion of fine roots in the 0–0.4 m layer increased and the proportion of fine roots from 1.0–3.0 m decreased along the revegetation chronosequence. The fine-root length in 0–0.4 m layer was mainly influenced by herbaceous cover, while the fine-root mass at depth of 0–3.0 m was affected by shrub cover and biomass. The amounts of fine soil particles, soil organic carbon, and total nitrogen were the main edaphic factors that influenced the distribution of fine roots. The fine-root length and mass in the 0–0.4 m layer were weakly and positively correlated with soil water contents, while those in the 1.0–3.0 m layer had strong negative relations with the soil water contents in corresponding layers. Our results demonstrated that the fine-root distribution in revegetated sand dunes was regulated by the succession of the vegetation-soil system after revegetation.

1. Introduction

Fine roots play a crucial role in the exchange of materials and energy flow between plants and soil (Casper and Jackson, 1997; Waisel et al., 2002), and the distribution of fine roots with depth is among the most relevant aspects that influence water, carbon, and nutrient fluxes (Jackson et al., 1997; Norby and Jackson, 2000; Schenk and Jackson, 2002). Generally, the distribution of fine roots in a certain area results from the combined influences of climate, vegetation and soil (Schenk and Jackson, 2005). For instance, plants in water-limited ecosystems often present deep rooting and have relatively large root systems (Canadell et al., 1996; Chapin et al., 1993; Schenk and Jackson, 2002), particularly in coarse-textured soils in which soil water and nutrients are regularly scarce (Collins and Bras, 2007; Wilcox et al., 2004). Currently, changes in vegetation are mainly characterized by shifts between woody and herbaceous species, and associated soil changes are ongoing in water-limited ecosystems (Sala and Maestre, 2014). Studies of the potential consequences of such changes under certain climate conditions on root distributions are urgently needed.

Changes in plant life forms typically alter the rooting depth and biomass of fine roots (Canadell et al., 1996; Jackson et al., 1996,

Abbreviations: BSCs, Biological soil crusts; MSD, Moving sand dunes; R20, Sand-binding dunes revegetated in 1990 (20 years old); R29, Sand-binding dunes revegetated in 1981 (29 years old); R46, Sand-binding dunes revegetated in 1964 (46 years old); Ref, Undisturbed naturally vegetated sand dunes; Ste, Desert steppe; SWC, Soil water content; FRLD, Fine-root length density per cubic meter ($m\ m^{-3}$); FRMD, Fine-root mass density per cubic meter ($kg\ m^{-3}$); FRL, Fine-root length per square meter ($m\ m^{-2}$); FRM, Fine-root mass per square meter ($m\ m^{-2}$).

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2000). A study by Jackson et al. (2002) indicated that the rooting depths increased by at least 2 m from the initial depth following the invasion of woody plants into a grassland. Other studies have also shown that fine-root biomass in shallow soil layers after woody encroachments exceeded (Hibbard et al., 2001) or was no different than (Bai et al., 2009) the fine-root biomass in the shallow soil layers of semiarid grasslands. Consequently, limited available data has led to unclear and sometimes controversial depictions of the responses of fine-root distributions to changes in vegetation (Barger et al., 2011).

Modifications in the distribution of fine roots are closely linked to the vertical changes of soil conditions in soil profiles (Schenk, 2005). The soil texture (Cable et al., 2008) and soil water content (SWC) (Cheng et al., 2009) have frequently been identified as important factors that regulate fine-root distribution patterns. Fine-textured soils favor fine-root distributions due to their greater water holding capacity (Peng et al., 2015; Sperry and Hacke, 2002). Additionally, fine-textured soils tend to increase soil nutrient availability and create nutrient-rich patches of soil (Ettema and Wardle, 2002), which further stimulates the accumulation of fine roots (Hodge, 2006). The positive responses of fine roots to soil nitrogen have been reported in numerous studies and are intensified when soil nutrients are limiting (Burton et al., 2000; February and Higgins, 2010; Imada et al., 2013; West et al., 2004). Wilcox et al. (2004) showed both positive and negative relationships between fine roots and soil moisture at the same site. In addition, Zhou and Shangguan (2007) reported a poor relationship between soil nitrogen and fine roots. Overall, the optimal fine-root distribution profile was shaped by the soil texture and soil nutrient availability.

In the arid and semi-arid regions of China, revegetation is an effective method for controlling desert encroachment and desertification. For example, revegetation has been consistently implemented since the 1950s to stabilize moving sand dunes (MSD) and avoid sand burial of the Baotou-Lanzhou Railway, which lies along the southeastern fringe of the Tengger Desert. According to long-term monitoring data, significant changes in vegetation and soil properties occurred in our study area after revegetation of MSD (Li et al., 2007b). Ten initially planted shrub species grew rapidly and reached a peak cover of 33% after 15 years, but only three of the ten shrub species maintained a cover of 9% after 40 years. The number of naturally inhabited herbaceous species increased to 14 after 40 years, and their cover fluctuated and depended closely on precipitation. In addition, pedogenic processes occurred on the dune surface with the changes in revegetation. These processes were characterized by the accumulation of fine-textured aeolian deposits with high nutrient concentrations as well as the formation and development of biological soil crusts (BSCs) (Duan et al., 2004; Li et al., 2007a). Because of its high water-holding capacity, the topsoil intercepted most of the rainfall, which results in a lack of rainwater infiltration into the deep soil layers below a depth of 0.4 m (Wang et al., 2008). Similarly, the nutrient concentrations in the upper soil layers mainly resulted from nutrient-rich dustfall and nitrogen fixation by BSCs (Duan et al., 2004). Notably, the SWC in the deep layer gradually decreased because of the high rate of evapotranspiration by deep rooting shrubs and the low rainwater infiltration rate (Li et al., 2004a, 2014). Thus, the succession of the soil system increases soil water and nutrient availability in the shallow soil layer and decreases the soil water availability in the deep layers (Li et al., 2014). The revegetation chronosequence offers an opportunity to explore the responses of fine-root distributions to changes in vegetation and soil during revegetation.

The objectives of this study are to characterize the vertical distribution of fine roots along the revegetation chronosequence and to investigate the relationships between fine-root distributions and vegetation and soil properties. Three revegetation sites (established in 1964, 1981, and 1990) were selected to conduct a rigorous investigation of fine roots relative to vegetation and soil properties, and one undisturbed naturally vegetated sand dune was considered as a reference site. One site on MSD was selected to represent the initial stage before revegetation, and one site on an adjacent desert steppe was considered to represent a future stage of revegetation. Previous studies indicated that the population of common shallow-rooted herbaceous species increased, the population of deeply rooted shrub species decreased, the topsoil conditions improved, and the availability of soil water in the shallow and deep soil layers was reversed following revegetation (Duan et al., 2004; Li et al., 2004b, 2007b, 2014; Wang et al., 2006). Based on these knowledge of the revegetation changes in our study area, we hypothesized that 1) the vertical fine-root distribution would generally shift toward shallow rooting along the 46-year revegetation chronosequence and that 2) the fine-root distribution would be closely linked to variations in the vegetation and soil properties.

2. Materials and methods

2.1. Site description

This study was conducted along the southeastern fringe of the Tengger Desert in northwestern China, which is characterized as a zone of transition from a sandy desert to a steppe. Within this transition zone, six study sites were set up from the east to the west (Fig. 1). Because of the great depth of groundwater (>80 m) and its unavailability to vegetation, precipitation is the sole source of soil water in the study area (Li et al., 2004a).

Four sites are located near the Shapotou Desert Research and Experimental Station (here after abbreviated as SDRES) (Fig. 1). Three of these sites are located on sand-binding dunes that were revegetated in 1964, 1981 and 1990 (corresponding to revegetation ages of 46, 29 and 20 years and abbreviated as R46, R29, and R20, respectively, when the study was conducted in 2010.) Another site is located on a moving sand dune (hereafter abbreviated as MSD). SDRES (lat 37°32′ N, long 105°02′ E, at an elevation of 1300 m AMSL) is located in a typical temperate desert region. According to a 50-year (1956–2005) meteorological record, the annual mean temperature at SDRES is 10 °C, and the mean January and July temperatures are −6.9 and 24.3 °C, respectively. The annual mean wind velocity is 2.9 m s^{-1}, and the annual mean precipitation is 186 mm, with 80% of the precipitation falling between May and September. Large and dense reticulated barchans sand dune chains are typical of the landscape, and the soils are mainly aeolian sandy soils (FAO/UNESCO, 1974). MSD are dominated by the shrub species *Hedysarum scoparium* Fisch. & C. A. Mey. and the herbaceous species, *Agriophyllum squarrosum* (L.) Moq., which provide a cover less than 1%. In the 1950s, a 16-km-long, 500-m-wide rain-fed revegetation protective system was established along both sides of the Baotou-Lanzhou Railway to stabilize MSD and prevent desert encroachment. Xerophytic shrubs were planted following the establishment of the sand barrier. Subsequently, revegetation was further developed in 1964, 1981, and 1990. After long-term revegetation efforts, a diversified ecosystem composed of planted xerophytic shrubs (mainly *Artemisia ordosica* Krasch., *Caragana korshinskii* Kom., and *H. scoparium*), naturally inhabited herbaceous species (*Eragrosti spoaeoides* P. Beauv., *Bassia dasyphylla* (Fisch. & et Mey.) O. Kuntze, *Corispermum patelliforme* Iljin, *Salsola ruthenica* Iljin, and *Aristida adscensionis* L.), and BSCs evolved on the sand-binding dunes.

A control site (used as the reference and hereafter abbreviated as Ref) lies in the vegetated protective system of the railway (lat 37°27′ N, long 104°46′ E, at an elevation of 1570 m AMSL) and is characterized by undisturbed natural vegetation (Fig. 1). This site has the same landscape and soil type as the sites near SDRES, and the predominant plant species include the shrubs *Ceratoides lateens* (J. F. Gmel.) Reveal et Holmgren, *A. ordosica*, *C. korshinskii*, and *Oxytropis aciphylla* Ledeb. and the herbaceous plants *Artemisia capillaries* Thunb., *Allium mongolicum* Regel, *S. ruthenica*, *Stipa breviflora* Griseb., *Cleistogenes*