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Soil nutrients and water affect the age-related fine root biomass but not production in two plantation forests on the Loess Plateau, China

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ABSTRACT

Fine root production in forests heavily regulates belowground carbon allocation and nutrient cycling in terrestrial ecosystems. While the Grain for Green project substantially increased vegetation coverage on China's Loess Plateau, it remains unclear how this program altered fine root production in plantation forests. Here, we investigate fine root biomass, production, and turnover in relation to soil nutrient and water content in 10-, 25- and 40-year-old stands of coniferous (*Pinus tabulaeformis*) and broad-leafed (*Robinia pseudoacacia*) tree plantations on the Loess Plateau. Fine root biomass and production of *P. tabulaeformis* decreased with stand age, but fine root production of *R. pseudoacacia* increased with stand age. *P. tabulaeformis* had greater fine root biomass and production than *R. pseudoacacia* in only 10- and 25-year-old stands. Fine root biomass was more sensitive to soil water content in *R. pseudoacacia* than in *P. tabulaeformis*. Fine root turnover for both species was fastest in 10-year-old stands. Soil nitrogen was positively correlated to fine root biomass, but not fine root production. These results strongly support that fine root production and total biomass during vegetation recovery are not only species-specific, but also reliant on adequate soil nutrients and water.

1. Introduction

Fine roots (≤2 mm in diameter) represent a small component of total biomass, but fine root production (FRP) and turnover (FRT) are key players in belowground carbon (C) allocation and nutrient cycling (Hendrick and Pregitzer, 1996; Jackson et al., 1997; Malhi et al., 2011; Matamala et al., 2003; Roumet et al., 2016). Previous studies have demonstrated that annual input of C and other nutrients into soil from fine roots is often similar to or even greater than that from foliage (Norby et al., 2000). It has been estimated that, in some forest ecosystems, FRP accounts for more than 70% of net primary production (NPP) (Gower et al., 1996; Grier and Ballard, 1981). Therefore, more accurate estimates of FRP provide a better understanding of how forest ecosystems function (Børja et al., 2008; Claus and George, 2005).

Fine root biomass (FRB), in addition to FRP and FRT, fluctuates depending on stand age, tree species, and soil conditions (Finér et al., 2007; Nadelhoffer and Raich, 1992; Yang et al., 2004; Yuan and Chen, 2013). While stand age is a major driver of both total forest FRB and FRP (Guo and Ren, 2014), studies on FRP often show conflicting results with regards to different tree species: FRP was found to increase with stand age in Scots pine stands (Makkonen and Helmisaari, 2001) but decrease with stand age in mixed boreal conifer-broad-leafed forest stands (Finér et al., 1997).

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Additionally, in boreal forests, FRB and FRP are greater in coniferous species than in broad-leaved species, but FRT of coniferous species is lower when compared to broad-leaved species (Yuan and Chen, 2010). Moreover, soil properties such as soil nutrient content, bulk density, moisture, and temperature can also affect FRB and FRP (Chang et al., 2012; Leuschner et al., 2004; Yuan and Chen, 2010; Zhou and Shangguan, 2007), and these effects on FRB and FRP may be specific to stand site or species, particularly in arid regions (Imada et al., 2013). Most studies have found that FRP follows a curvilinear path over time (Bond-Lamberty et al., 2004; Yuan and Chen, 2012), though the dynamics of root senescence and/or accumulation are less well documented.

The Loess Plateau, located in Northwestern China with an area of 6.4×10^7 ha, is known in the world for its severe degree of soil erosion, making it as the main area for implementing China's Grain for Green (GFG) project (Deng et al., 2014; Zhou et al., 2009). The goal of the GFG project is to convert approximately 2.03×10^6 ha of cropland located on slopes greater than 15° into woodland or grassland (Chang et al., 2011). In the arid and semiarid regions of the Loess Plateau, *Pinus tabulaeformis* and *Robinia pseudoacacia* are two typical plantation species that thrive due to their high adaptability and environmental stress resistance (Jin et al., 2011; Zhou and Shangguan, 2007). Studies have found that *P. tabulaeformis* and *R. pseudoacacia* plantations have contributed greatly to NPP in this region (Xiao, 2014). Although both FRP and FRT are critical variables for predicting the function of an ecosystem (Norby and Jackson, 2000), little work has been done in the Loess Plateau region. Existing reports focusing on FRB are confined to stands of a single species or age (Chang et al., 2012; Zhou and Shangguan, 2007) and no study has addressed how FRP varies with stand age or has compared FRP between stands dominated by different tree species.

In this study, we investigated the FRB, FRP, and FRT of *P. tabulaeformis* and *R. pseudoacacia* plantation forests on the Loess Plateau in relation to stand age, and how these root variables changed in relation to soil nutrient content, bulk density, and water content. We hypothesized that FRB and FRP of both tree species would differ with stand age due to physiological differences in species traits such as coniferous *vs.* broad-leaved, and evergreen *vs.* deciduous. Given that our studied region is limited by the availability of soil nutrients, especially soil nitrogen (N), we hypothesized that FRB or FRP of both tree species are positively correlated with soil N availability. Furthermore, we expected the FRB of *R. pseudoacacia* to be more sensitive to soil water content since this species has higher water consumption and lower drought resistance than *P. tabulaeformis* in arid and semiarid regions.

2. Materials and methods

2.1. Study sites

The study was conducted in the southern region of Yan'an, Shaanxi Province, China (36°9′–36°29′ N, 109°16′–109°33′ E; 1059–1352 m.a.s.l.). This region is characterized by a semiarid continental climate, with a mean annual temperature of 9 °C. The mean annual precipitation is 560 mm, with most precipitation occurring from July to August (Jin et al., 2011). Soils are described as Calcaric Cambisols according to the FAO classification system. The study area is composed of forest steppe and temperate grassland. *P. tabulaeformis* and *R. pseudoacacia* were planted throughout this area from 1953 to 2003 for soil and water conservation. In *P. tabulaeformis* plantation forests, the dominant understory species included *Spiraea pubescens*, *Rosa xanthina*, *Viburnum schensianum*, *Artemisia sacrorum*, *Artemisia giraldii*, *Heteropappus altaicus*, *Rubia cordifolia*, *Thalictrum aquilegifolium*, *Anemone tomentosa*, *Carex lanceolata*, *Patrinia heterophylla*, and *Pulsatilla chinensis*. In *R. pseudoacacia* plantation forests, dominant understory species included *Periploca sepium*, *R. xanthina*, *Ostryopsis davidiana*, *Cotinus coggygria*, *Lonicera japonica*, *A. sacrorum*, *Artemisia capillaris*, *Artemisia scoparia*, *H. altaicus*, *Lespedeza davurica*, *Stipa bungeana*, and *Melica scabrosa*.

2.2. Study design and root sampling

Tree species (*P. tabulaeformis* or *R. pseudoacacia*) and stand age (10-, 25- and 40-year-old at the time of sampling) were each replicated three times, for a total of eighteen sampling stands. All selected stands had been planted on similar slopes and were long-term cultivated cropland before being converted for tree planting. The mean diameter at breast height (DBH), mean tree height, and tree density of each experimental stand are presented in Table 1. Sampling of fine roots was conducted in 2014 and 2015 from a randomly selected 10 m × 10 m plot within each sampling stand. FRB and FRP were respectively determined by soil cores and ingrowth cores at stand level. FRT was calculated dividing FRP by FRB.

Soil cores were collected in July 2014. Seven soil cores were randomly placed in each plot and each soil core was about 1.0 m away from the nearest tree. A total of 126 soil cores were obtained for the eighteen sampling stands. Soil cores were extracted with a soil corer (inner diameter 9 cm) at three depth intervals of 0–20 cm, 20–40 cm and 40–60 cm. Root ingrowth cores were established for seven random points in each sampling plot in July 2014. Root ingrowth cores, made by nylon net bags with 9 cm diameter and 60 cm depth, were placed after soil columns were removed. Ingrowth cores were gradually filled with root-free soils of local origin. All ingrowth cores were removed after one year by carefully removing the soil around the cylinder and collecting roots that had grown into the core. Ingrowth cores were separated into three layers in the same manner as soil cores.

Root samples were placed in plastic bags and stored in the laboratory at 4 °C until root separation. Samples were placed on a 0.15 mm mesh sieve to sort out both live and dead fine roots (≤2 mm in diameter). Fine roots were picked out from the soil by hand and any affixed soil residue was carefully removed with tweezers. After visible fine roots were collected, the remaining soil in the 0.15 mm mesh sieve was gently washed to collect fine root segments. After separation, fine roots were oven-dried at 65 °C to a constant mass and weighed. Roots of the understory vegetation were not separated from the total collected roots because of the intensive labor required and difficulty of separation. Fine roots reported actually referred to the fine roots of *P. tabulaeformis* and *R. pseudoacacia* communities.

2.3. Soil sampling and measurements

Soil samples were collected from three layers (0–20 cm, 20–40 cm, and 40–60 cm) in each soil profile near the root sampling stands in July of 2014 and 2015. Soil samples used to investigate the content of organic C, total N, and total phosphorus (P) were replicated three times. These samples were taken to the laboratory and air dried before determining soil organic C (potassium-dichromate oxidation method), total N (micro-Kjeldahl method) and total P (digestion with H_2SO_4-$HClO_4$ and molybdenum-antimony anti-spectrophotometric method). Soil samples used to determine bulk density and water content were collected from the 100 cm^3 cylindrical corers and were replicated five times. Soil samples were oven-dried at 105 °C to a constant mass and weighed.