Analysis of Fine Root Characteristics under Community Structure Adjustment in Degraded Plantation Forests in Semi-arid Loess Hilly Regions (Postprint)

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Date: 2021-02-13T15:55:21+00:00

Abstract

Roots, especially fine roots, play a crucial role in plant growth and development. This study examined fine root length density, root surface area density, root biomass density, specific root length, and specific root area at different soil depths and diameter classes in mixed forests (poplar + 5-year-old Chinese pine, poplar + 10-year-old Chinese pine, apricot + spruce, and apricot + Mongolian pine) formed after adjusting artificial forest community structure, compared with pure monocultures, in two typical degraded artificial forests (poplar and apricot) in the Longtan watershed of Chanikou Town, Dingxi City, Gansu Province, aiming to reveal fine root distribution characteristics under different artificial forest restoration patterns. The results showed that: (1) The mixed restoration pattern exerted certain positive effects; most mixed forests exhibited increased fine root length density, root surface area density, and root biomass density in the surface soil layer compared with pure forests. The proportion of fine roots in the shallow layer of mixed forests was enhanced and increased with restoration age. (2) Significant positive correlations existed between fine root length density, root surface area density, and root biomass density and soil total carbon, total nitrogen, water content, and organic carbon, as well as between specific root length and specific root area and soil total carbon, total nitrogen, and organic carbon.

Full Text

Fine Root Characteristics of Degraded Artificial Forests Under Community Structure Adjustment in Semi-arid Loess Hilly Regions

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Abstract

Roots, particularly fine roots, play a crucial role in plant growth and development. This study investigated fine root characteristics in the Longtan watershed of Chankou Town, Dingxi City, Gansu Province, China, focusing on two typical degraded artificial plantations: *Populus tomentosa* and *Armeniaca sibirica*. We examined how community structure adjustment through the establishment of mixed forests—*Populus tomentosa* with 5-year-old and 10-year-old *Pinus tabuliformis*, and *Armeniaca sibirica* with *Picea asperata* and *Pinus sylvestris*—affected fine root distribution compared to pure stands. Fine root metrics including root length density (RLD), root area density (RAD), root biomass density (RBD), specific root length (SRL), and specific root area (SRA) were analyzed across different soil depths and diameter classes.

Our results demonstrate that mixed restoration modes exerted positive effects on fine root development. Most mixed forests exhibited higher RLD, RAD, and RBD in the surface soil layer compared to pure stands. The proportion of fine roots in shallow layers increased under mixed forest configurations and rose with restoration age. Correlation analysis revealed significant positive relationships between fine root metrics (RLD, RAD, RBD) and soil total carbon, total nitrogen, water content, and organic carbon. Similarly, SRL and SRA showed significant positive correlations with soil total carbon, total nitrogen, and organic carbon.

Keywords: loess hilly region; mixed forest; fine root; restoration pattern

1 Introduction

Roots serve as vital functional organs in plants, with their development and distribution profoundly influencing plant growth. Fine roots (diameter $\leq$ 2 mm) exhibit short lifespans and rapid turnover rates. Despite comprising a small proportion of total biomass, they possess extensive length and surface area, serving as the primary pathway for carbon and nutrient transport between plants and soil. Fine roots facilitate both upward water and nutrient transport and downward carbon allocation, representing major contributors to belowground carbon input and playing essential roles in tree physiology and forest ecology.

Analysis of root distribution characteristics, particularly fine roots, provides scientific foundations for evaluating tree species adaptability in challenging sites and understanding patterns of water and nutrient acquisition and consumption. The Loess Plateau represents one of the world' s most severely eroded regions, with extremely fragile ecosystems. Since the large-scale implementation of the Grain for Green Program in the 1990s, vegetation restoration has progressed steadily, improving soil and water conservation. However, with increasing restoration duration, ecological problems have emerged, including excessive species homogeneity and severe degradation of artificial vegetation.

Species diversity significantly influences soil structure and function. Long-term monoculture plantations may lead to nutrient depletion, specific element deficiencies, and soil fertility decline, whereas mixed restoration modes can mitigate these issues. Since the 12th Five-Year Plan period, the Loess Plateau has adjusted vegetation community structures in degraded pure plantations by introducing new species to establish mixed forests. While previous research has examined how these adjustments affect soil components, studies on impacts to tree root systems remain limited, and conclusions regarding mixed restoration effects on roots are inconsistent. Some studies indicate that mixing promotes root growth and development, while others suggest no promotion or even reduced fine root biomass. Furthermore, previous root research has primarily focused on biomass across different restoration ages, vegetation types, and soil depths, with less attention to root length density and root area density—which reflect soil resource availability—or specific root length and specific root area, which indicate root physiological function.

This study addresses these research gaps by investigating fine root characteristics in typical degraded pure *Populus tomentosa* and *Armeniaca sibirica* plantations in the Longtan watershed of Dingxi, Gansu, and comparing them with mixed forests established through community structure adjustment. Our objective is to reveal fine root distribution patterns under different restoration modes and provide scientific guidance for vegetation restoration and appropriate species selection in the Loess Plateau.

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2 Materials and Methods

2.1 Study Area The study area is located in the Longtan watershed of Anding District, Dingxi City, Gansu Province (35°43 ~35°46 N, 104°27 ~104°32 E), covering approximately 16 km^2 at an average elevation of 1,900 m. The region experiences a typical temperate continental monsoon climate with an average annual temperature of 6.8°C, January average of -7.9°C, extreme minimum of -27.1°C, and maximum of 34.9°C. Mean annual precipitation is 386 mm, concentrated in June-September. The dominant soil type is loessal soil, characterized by loose structure and high erodibility. Major planted species include *Armeniaca sibirica*, *Populus tomentosa*, *Pinus tabuliformis*, *Platycladus orientalis*, *Caragana korshinskii*, and *Medicago sativa*, with natural vegetation dominated by *Stipa bungeana* and *Heteropappus altaicus*.

2.2 Root Sampling and Analysis Root samples were collected in July 2018 using the root drilling method. Sample plots (20 m × 20 m) were established in pure *Populus tomentosa* stands, pure *Armeniaca sibirica* stands, and their corresponding mixed forests with similar slope, aspect, elevation, and other environmental conditions. Five standard trees were selected per plot as replicates. Basic plot characteristics are presented in .

For each standard tree, five sampling points were established at approximately equal distances within a 1 m radius circle centered on the tree. After removing litter and surface vegetation, soil cores were extracted using a 10 cm diameter root drill to depths of 0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm. Samples from the same standard tree were mixed, bagged, and transported to the laboratory, yielding 420 total samples.

In the laboratory, soil was sieved and roots were carefully extracted and rinsed with deionized water to remove attached soil and impurities. Herbaceous roots were removed based on morphological characteristics, and living roots were distinguished from dead roots by appearance, color, and elasticity. Roots were scanned using an EPSON scanner and analyzed with WinRHIZO software, classifying fine roots into three diameter classes: 0-0.5 mm, 0.5-1 mm, and 1-2 mm. Root length and surface area were obtained for each class. Fine roots ≤ 2 mm were measured with calipers, placed in paper envelopes, oven-dried at 65°C to constant weight, and weighed to determine biomass.

Simultaneously, soil samples were collected by layer for physicochemical analysis. Average soil total carbon, total nitrogen, total phosphorus, organic carbon, and water content in the 0-100 cm profile for each plot type were: *Populus tomentosa* pure stand (21.69, 0.41, 0.83, 3.63 $g \cdot kg^{-1}$, 11.04%); *Populus tomentosa* with 5-year-old *Pinus tabuliformis* (24.20, 0.51, 0.83, 5.11 $g \cdot kg^{-1}$, 14.20%); *Populus tomentosa* with 10-year-old *Pinus tabuliformis* (26.60, 0.49, 0.88, 6.45 $g \cdot kg^{-1}$, 14.35%); *Armeniaca sibirica* pure stand (22.80, 0.51, 0.88, 5.42 $g \cdot kg^{-1}$, 12.46%); *Armeniaca sibirica* with *Picea asperata* (26.65, 0.52, 0.83, 6.50 $g \cdot kg^{-1}$, 13.44%); and *Armeniaca sibirica* with *Pinus sylvestris* (28.81, 0.48, 0.84, 7.41 $g \cdot kg^{-1}$, 18.37%).

2.3 Data Analysis Five indices were calculated:

$$\text{RLD} = L_r/V \quad (\text{cm} \cdot \text{cm}^{-3})$$
$$\text{RAD} = A_r/V \quad (\text{cm}^2 \cdot \text{cm}^{-3})$$
$$\text{RBD} = W_r/V \quad (\text{mg} \cdot \text{cm}^{-3})$$
$$\text{SRL} = L_r/W_r \quad (\text{cm} \cdot \text{mg}^{-1})$$
$$\text{SRA} = A_r/W_r \quad (\text{cm}^2 \cdot \text{mg}^{-1})$$

where L_r is root length (cm), A_r is root surface area (cm^2), W_r is root dry weight (mg), and V is soil volume (cm^3).

Excel 2003 and SPSS 24 software were used for data processing and statistical analysis. One-way ANOVA and least significant difference (LSD) tests compared differences in indicators among vegetation restoration patterns and soil layers. Significance was set at $P < 0.05$.

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3 Results

3.1 Fine Root Length Density (RLD) As shown in [Figure 1: see original paper], the *Populus tomentosa* mixed forest with 10-year-old *Pinus tabuliformis* exhibited higher RLD than the pure stand across all soil layers, particularly in the 0–20 cm layer. The *Populus tomentosa* mixed forest with 5-year-old *Pinus tabuliformis* showed higher RLD than the pure stand in surface and deep layers, demonstrating an increasing trend with restoration age. In *Armeniaca sibirica* stands, the mixed forest with *Pinus sylvestris* had higher RLD than the pure stand across all layers, while the mixed forest with *Picea asperata* showed higher RLD only in the 0–10 cm and 10–20 cm layers, with lower values in deeper layers compared to the pure stand.

Significant differences ($P < 0.05$) were observed between *Populus tomentosa* pure stand and its mixed forest with 10-year-old *Pinus tabuliformis* in the 0–20 cm layer, and between *Armeniaca sibirica* pure stand and its mixed forests in the 10–20 cm layer. Vertically, RLD and its distribution proportion decreased significantly with soil depth across all restoration patterns ([Figure 2: see original paper]), with over 60% of fine root length concentrated in the 0–30 cm layer. The proportion of fine root length in shallow layers was higher in mixed forests than in pure stands for both species groups and increased with restoration age.

Diameter class analysis revealed that absorptive roots (diameter ≤ 0.5 mm) dominated, comprising 60.53–64.37% of total fine root length. In *Populus tomentosa* mixed forests, the proportion of absorptive root length decreased compared to pure stands and declined with increasing restoration age. In contrast, *Armeniaca sibirica* mixed forests showed increased proportions of absorptive roots (62.17–64.37%) compared to the pure stand.

3.2 Fine Root Area Density (RAD) As illustrated in [Figure 4: see original paper], the *Populus tomentosa* mixed forest with 10-year-old *Pinus tabuliformis* showed higher RAD than the pure stand across all layers, with significant differences ($P < 0.05$) in the surface layer (0–10 cm). The 5-year-old mixed forest exhibited higher RAD than the pure stand above 30 cm depth, while below 30 cm, the pure stand showed the highest values. Significant differences ($P < 0.05$) between the pure stand and 5-year-old mixed forest occurred in the 30–60 cm layer.

For *Armeniaca sibirica*, the mixed forest with *Pinus sylvestris* had higher RAD than the pure stand across all layers, while the mixed forest with *Picea asperata* showed higher RAD only in the surface layer. Vertically, RAD decreased significantly with depth ([Figure 5: see original paper]), with distribution proportions in shallow layers higher in mixed forests than in pure stands. The pure stands showed lower RAD proportions in surface layers compared to their mixed forest counterparts.

Diameter class analysis ([Figure 6: see original paper]) indicated that in *Populus tomentosa* mixed forests, the proportion of root area contributed by 0–0.5 mm diameter roots was lower than in pure stands and decreased with restoration age. In *Armeniaca sibirica* mixed forests, the 0.5–1 mm diameter class contributed higher proportions of total root area compared to the pure stand.

3.3 Fine Root Biomass Density (RBD) As shown in [Figure 7: see original paper], the *Populus tomentosa* mixed forest with 10-year-old *Pinus tabuliformis* exhibited higher RBD than the pure stand across all layers, with significant differences ($P < 0.05$) in the 10–20 cm layer. The average RBD values for the pure stand, 5-year-old mixed forest, and 10-year-old mixed forest were 0.58, 0.66, and 0.82 $mg \cdot cm^{-3}$, respectively, demonstrating an increasing trend with restoration age.

For *Armeniaca sibirica*, surface layer and 80–100 cm layer RBD showed the pattern: *Pinus sylvestris* mixed forest > *Picea asperata* mixed forest > pure stand. The 10–30 cm and 60–80 cm layers showed highest RBD in the *Picea asperata* mixed forest. Vertically, RBD distribution proportions exhibited clear surface aggregation ([Figure 8: see original paper]), with significant differences between surface (0–30 cm) and deeper layers. The proportion of fine root biomass in shallow layers increased in mixed forests compared to pure stands, with *Populus tomentosa* mixed forests showing age-dependent increases.

3.4 Specific Root Length (SRL) and Specific Root Area (SRA) SRL and SRA represent the ratio of root length and area to biomass, indicating root activity and nutrient absorption capacity per unit weight. In surface soil, *Populus tomentosa* mixed forests showed higher SRA than pure stands, while in other layers, pure stands exceeded mixed forests. Pure *Populus tomentosa* stands had higher SRL than their mixed counterparts across all layers ([Figure 10: see original paper]), with significant differences in the 30–40 cm layer.

In contrast, *Armeniaca sibirica* mixed forests, particularly the *Pinus sylvestris* mixture, showed higher SRL and SRA than the pure stand in most layers, especially in the 10–20 cm layer where SRL was significantly higher. The *Picea asperata* mixed forest showed minimal differences from the pure stand ([Figure 9: see original paper]).

3.5 Relationships Between Fine Roots and Soil Properties Correlation analysis () revealed that RLD, RAD, and RBD were extremely significantly positively correlated with soil total nitrogen, total carbon, organic carbon, and water content ($P < 0.01$). SRL and SRA showed extremely significant positive correlations with soil organic carbon ($P < 0.01$) and significant positive correlations with total carbon and total nitrogen ($P < 0.05$), but no significant relationships with total phosphorus or water content.

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4 Discussion

Root length density and root area density reflect plant capacity for water and nutrient absorption, while specific root length and specific root area indicate the balance between nutrient acquisition and root construction/maintenance costs. Larger SRL and SRA values suggest greater soil contact area per unit weight, implying higher activity and absorption capacity.

Our findings demonstrate that mixed restoration increased fine root density in surface soil layers for most forest combinations. The *Populus tomentosa* mixed forests showed age-dependent increases in RLD, RAD, and RBD, consistent with previous research indicating that increasing tree age elevates nutrient and water demands, thereby stimulating fine root proliferation. Additionally, soil carbon is a crucial component, and vegetation restoration can enhance soil carbon content. Our results show that soil total carbon and organic carbon increase with mixed forest restoration age, and the extremely significant positive correlations between soil nutrients and fine root metrics indicate that improved soil fertility contributes to fine root enhancement.

The inconsistent outcomes between different mixed forest types underscore that species interactions are dynamic and can shift between complementary and competitive roles depending on resource availability and environmental conditions. The divergent results between *Populus tomentosa* and *Armeniaca sibirica* mixed forests may relate to different species combinations and their varying effects on soil properties. The *Populus tomentosa* mixed forests showed decreased proportions of absorptive roots ($ $0.5 mm) with increasing restoration age, while *Armeniaca sibirica* mixed forests exhibited increased absorptive root proportions. This suggests that *Populus tomentosa* mixtures favored coarser root development, whereas *Armeniaca sibirica* mixtures enhanced absorptive root production.

Fine root distribution is strongly correlated with soil nutrients and moisture, which typically decrease with depth. All studied plantations showed decreasing RLD, RAD, and RBD with increasing soil depth, with over 60% of fine roots concentrated in the 0–30 cm layer—a pattern consistent with previous studies demonstrating root surface aggregation. This concentration facilitates efficient water utilization, enhances soil anti-scourability, and prevents erosion. Mixed restoration altered vertical distribution patterns, increasing the proportion of fine roots in shallow layers. The abundant litter input in mixed forests likely contributes to nutrient-rich surface layers, promoting fine root proliferation near the soil surface.

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5 Conclusions

Based on our investigation of fine root distribution patterns in pure *Populus tomentosa* and *Armeniaca sibirica* stands and their mixed forests with *Pinus tabuliformis*, *Picea asperata*, and *Pinus sylvestris*, we conclude:

1) Mixed restoration modes differentially affect root growth and distribution. Compared to pure stands, most mixed forests exhibited increased RLD, RAD, and RBD in shallow soil layers, with absorptive roots (diameter $\leq$ 0.5 mm) dominating across all diameter classes. *Populus tomentosa* pure stands generally showed higher SRL and SRA than their mixed forests, whereas *Armeniaca sibirica* pure stands showed lower values than their mixed counterparts.

2) With increasing restoration age, the *Populus tomentosa* mixed forests demonstrated elevated RLD, RAD, RBD, and the proportion of fine root biomass in shallow soil layers.

3) Vertically, all plantations exhibited significant decreases in RLD, RAD, and RBD with increasing soil depth, demonstrating clear surface aggregation. Pure stands had lower proportions of fine root length and area density in shallow layers compared to mixed forests, while mixed restoration increased the proportion of fine root biomass in shallow layers for the *Populus* group.

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Note: Figure translations are in progress. See original paper for figures.