Fine Root Distribution in Vegetation of Different Restoration Types and Its Coupling with Soil Physicochemical Properties: Postprint

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Abstract

Focusing on major artificial afforestation and natural enclosure vegetation restoration types in Wuqi County, a typical loess hilly region of northern Shaanxi, sample plots of sea buckthorn, apricot, and naturally restored grassland under restoration durations of 5, 15, and 40 years were established for profile sampling. Fine root biomass and soil physicochemical properties were analyzed to investigate temporal variation patterns and coupling relationships between fine root biomass and soil properties across different restoration types and durations. The results showed that: (1) Overall, fine root biomass of both main afforestation species and naturally enclosed grassland on abandoned farmland increased with stand age and restoration duration. Fine root biomass of artificially planted species exceeded that of naturally restored grassland at the same restoration duration, and fine root biomass of all vegetation communities exhibited an exponential decrease with soil depth. (2) Soil water content in naturally enclosed grassland ecosystems was higher than in artificial apricot and sea buckthorn forests. Under both artificial afforestation and natural enclosure restoration, soil aggregate stability increased with restoration duration, while soil organic matter, total nitrogen, and total phosphorus contents also increased, and average soil water content decreased. (3) Fine root biomass was significantly correlated with soil bulk density and aggregate stability, indicating that plant fine roots play an important role in improving soil structure.

Full Text

Preamble

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Fine Root Biomass Distribution and Coupling to Soil Physicochemical Properties Under Different Restored Vegetation Types

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Abstract

This study investigated fine root biomass distribution and its coupling relationships with soil physicochemical properties under different vegetation restoration types in Wuqi County, a typical loess hilly region of northern Shaanxi. Sample plots were established for major artificial afforestation species (*Prunus armeniaca* and *Hippophae rhamnoides*) and naturally restored grassland at 5, 15, and 40 years after cropland abandonment, with soil profile sampling conducted to analyze vertical distribution patterns.

The results showed:
(1) Fine root biomass in both abandoned grassland and *P. armeniaca* forests increased with stand age and abandonment duration. Artificial forest species exhibited significantly greater fine root biomass than naturally restored grasslands, with all vegetation types showing an exponential decrease in biomass with soil depth.
(2) Soil water content in the grassland ecosystem was significantly higher than in artificial *H. rhamnoides* and *P. armeniaca* forests. With increasing restoration age, soil aggregate stability improved under both artificial afforestation and natural enclosure, while organic matter, total nitrogen, and total phosphorus contents increased. However, the average soil water content decreased with abandonment years.
(3) Fine root biomass was significantly correlated with soil bulk density and aggregate stability, indicating that plant fine roots play a crucial role in soil structural improvement.

Keywords: Loess Plateau; abandonment years; fine root; vegetation recovery and restoration; soil aggregate stability; soil physicochemical properties

Introduction

The Loess Plateau is characterized by fragmented terrain, low and concentrated precipitation, severe soil erosion, and dysfunctional ecosystems. To combat these issues, large-scale “Grain for Green”programs were implemented after 1999, significantly increasing vegetation coverage [1-2]. Sediment discharge from the middle Yellow River (Toudaoguai to Huayuankou stations) decreased by approximately 80.4% between 2000–2012, with ecological construction and vegetation restoration playing a vital role in this reduction [4-5]. Sustainable, functionally coordinated ecosystems will be key to maintaining stable sediment transport in the Yellow River [6].

Organic carbon from plant roots constitutes a major input to soil carbon pools. Studies on forest ecosystems demonstrate that root production is an important source of soil nutrients [8]. Fine roots (2 mm) are particularly significant for material cycling and energy flow, often more so than aboveground components [9]. Previous research has examined factors influencing root biomass, especially management practices. Mixed forests generally exhibit higher root biomass than pure stands [10], and continuous planting promotes root development [11]. Regarding root biomass dynamics, some studies suggest it increases with stand age, peaking before gradually declining [12]. The relationship between plant roots and soil properties has been extensively investigated across different climates and vegetation types, showing that roots significantly influence soil conditions [13-18]. However, most research has focused on aboveground community succession characteristics and soil property changes during succession [19]. Comparative analyses of root-soil coupling relationships under different restoration modes and vegetation types over time, particularly from a soil and water conservation perspective, remain limited. Understanding the temporal dynamics of vegetation root systems and soil hydrophysical properties, and their coupling with soil conservation functions, requires further investigation.

Wuqi County represents a typical area of "Grain for Green" implementation on the Loess Plateau. Previous studies have focused on land use and soil property changes during the restoration process, but research on fine root distribution and its relationship with soil physicochemical properties under different vegetation cover and successional stages remains insufficient. This study selected natural grassland, artificial *P. armeniaca* forests, and other major restoration vegetation types in Wuqi County to analyze vertical distribution characteristics of fine roots and changes in soil physicochemical properties across successional stages, exploring the intrinsic relationships between roots and soil properties and their potential for soil improvement. This research provides theoretical support for ecological restoration evaluation and rational land use planning on the Loess Plateau.

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1 Study Area Description

The study area is located in Wuqi County, Shaanxi Province (107°39 -108°32 E, 36°34 -37°24 N), in the agricultural-pastoral transition zone on the southern edge of the Mu Us Sandy Land. Situated in the upper reaches of the Beiluo River (a first-order tributary of the Wei River), the county covers 3,792 km^2.

The region has a temperate continental monsoon climate with mean annual temperature of 7.8°C, annual sunshine hours of 2,400 h, and mean annual precipitation of 478.3 mm, with 62.4% concentrated in July-September. The frost-free period is 146 days. The area belongs to semi-arid loess hilly-gully region with frequent natural disasters such as drought and rainstorms. The main soil type is loessal soil (Huangmian soil).

Since implementing the "Grain for Green" policy in 1999, Wuqi County has experienced dramatic land use/cover changes. Forest area reached 12.0×10 hm^2, accounting for 51.2% of the county area, with vegetation coverage in the upper Beiluo River basin increasing from 30.82% to 80.3%. Mean annual erosion sediment discharge decreased by 11.68% after restoration [22]. Major afforestation species include *H. rhamnoides* (pure stands accounting for 80.4% of restored area) and *P. armeniaca*, in addition to extensive naturally enclosed grassland.

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2 Methods

2.1 Sample Plot Establishment

Sample plots were selected for abandoned grassland, *H. rhamnoides*, and *P. armeniaca* at different restoration ages (5, 15, and 40 years). Under similar site conditions, representative plots with uniform population distribution and high homogeneity were chosen. Plot sizes were 1 m × 1 m for grassland, 5 m × 5 m for shrub communities, and 20 m × 20 m for forest communities. Detailed plot information is provided in . Field surveys were conducted on clear, rainless days in two periods (data showed minimal variation and were comparable).

** Status of different vegetation types**

Plot	Vegetation Type	Age (years)	Altitude (m)	Gradient (°)	Spacing (m)	Canopy Density (%)	Underground Coverage (%)	Main Herb Species
AL5	Abandoned grassland	5	1233	21	-	45	40	*Heteropappus hispidus*, *Artemisia scoparia*
AL15	Abandoned grassland	15	1450	18	-	65	60	*Artemisia giraldii*, *Glycyrrhiza uralensis*

Plot	Vegetation Type	Age (years)	Altitude (m)	Gradient (°)	Spacing (m)	Canopy Density (%)	Underground Coverage (%)	Main Herb Species
AL40	Abandoned grassland	40	1680	15	-	85	80	*Stipa bungeana*, *Lespedeza davurica*
H15	*H. rhamnoides*	15	1380	20	1×1.5	70	65	*Stipa bungeana*, *Agropyron cristatum*
P15	*P. armeniaca*	15	1420	17	2×3	60	55	*Potentilla chinensis*, *Heteropappus hispidus*
P40	*P. armeniaca*	40	1809	14	2×3	75	70	*Artemisia giraldii*, *Polygala tenuifolia*

2.2 Fine Root Collection and Processing

Fine roots are crucial for water and nutrient uptake [23]. Root sampling was conducted using a root corer (7 cm diameter) to 100 cm depth at 20 cm intervals, with 100 cm total depth sampled. For shrub and forest communities, coring locations were 10 cm from representative plants to minimize spatial heterogeneity. In the laboratory, roots 2 mm diameter were sorted, cleaned, oven-dried at 80°C to constant weight, and weighed. Fine root biomass was calculated as g/m².

2.3 Soil Physicochemical Property Measurements

Soil bulk density, natural water content, mean weight diameter of aggregates, organic matter, total nitrogen, and total phosphorus were analyzed. Soil cores (46 mm × 25 mm) were collected from profiles using the ring knife method. Water-stable aggregates were measured by wet sieving, and mean weight diameter (MWD) was calculated. Soil organic matter was determined by potassium dichromate external heating method, total nitrogen by semi-micro Kjeldahl method, and total phosphorus by molybdenum-antimony colorimetry. Detailed methods follow the Soil Agrochemical Analysis Handbook [24].

2.4 Data Processing

Data were organized using Excel 2010. SPSS 21 was used to test differences in fine root biomass and soil properties among land use types and soil layers, with significance tests for correlations. Origin 8.0 was used for bivariate correlation analysis (Spearman method) and regression analysis ($= 0.05$).

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3 Results

3.1 Vertical Distribution Characteristics of Fine Root Biomass

Fine root biomass varied significantly among vegetation types and restoration ages, following the order: 40-year *P. armeniaca* (2203 g/m^2) > 15-year *P. armeniaca* (1847 g/m^2) > 15-year *H. rhamnoides* (907 g/m^2) > 40-year grassland (821 g/m^2) > 15-year grassland (545 g/m^2) > 5-year grassland (343 g/m^2). Artificial forests had significantly greater fine root biomass than naturally restored grasslands ($P < 0.05$). For grassland and *P. armeniaca* communities, fine root biomass increased with restoration age.

All vegetation types showed decreasing fine root biomass with soil depth, primarily concentrated in the surface 0-20 cm layer (52%-81% of total profile biomass), except 15-year *P. armeniaca* where biomass peaked at 20–40 cm (accounting for 45% of total). Regression analysis revealed an exponential decay pattern for all vegetation types [Figure 1: see original paper], consistent with previous studies [25-26]. The exponential model fit was weaker for 15-year *P. armeniaca*, possibly due to its arboreal biology causing deeper root distribution [27].

[Figure 1: see original paper] The vertical root biomass distribution diagram of different vegetation types

** Exponential fitting of vertical fine root biomass distribution of different vegetation types**

Stand	Exponential Fitting	Correlation Coefficient
AL5	y = 544.5e^(-0.048x)	0.92
AL15	y = 1240.6e^(-0.054x)	0.95
AL40	y = 444.5e^(-0.020x)	0.88
H15	y = 3275.3e^(-0.053x)	0.91
P15	y = 455.5e^(-0.025x)	0.73
P40	y = 1650.6e^(-0.033x)	0.89

Note: y = fine root biomass (g/m²), x = soil depth (cm)

3.2 Soil Bulk Density and Water Content Characteristics

Soil bulk density, a comprehensive indicator of soil physicochemical properties, generally increased with depth while decreasing with restoration age [29-30]. In the 0–100 cm profile, surface bulk density was lower than subsurface layers. However, patterns varied among vegetation types. The 5-year and 15-year grasslands showed significantly lower surface bulk density than deeper layers ($P < 0.05$), likely due to historical tillage effects. The 40-year grassland showed no significant depth trend, while *P. armeniaca* stands exhibited fluctuating increases with depth, possibly due to human trampling as an economic tree species. The 15-year *H. rhamnoides* stand showed significantly lower surface bulk density (1.0 g/cm^3) than deeper layers (1.38 g/cm^3), attributable to minimal human disturbance and abundant litter accumulation [31].

Soil natural water content showed consistent patterns across plots: increasing with depth to 20–40 cm, then decreasing [Figure 2: see original paper]. Mean water content decreased with restoration age due to increased transpiration and reduced infiltration from surface litter, consistent with findings from Yan'anguou in Yan' an [32]. Grassland water content was significantly higher than forest stands ($P < 0.05$).

[Figure 2: see original paper] Soil bulk density and water properties in the profile of different vegetation types

3.3 Soil Aggregate Stability Characteristics

Aggregate stability is a key indicator of soil erosion resistance. Mean weight diameter (MWD) of water-stable aggregates reflects stability, with higher values indicating stronger aggregates. All vegetation types showed decreasing MWD with depth [Figure 3: see original paper]. With restoration progression, aggregate stability significantly increased in most soil layers, particularly in the 0–40 cm layer of grassland and *P. armeniaca* stands ($P < 0.05$). The 40-year *P. armeniaca* stand had significantly greater surface MWD than 15-year stands, while *H. rhamnoides* and grassland showed no significant age difference.

Fine roots significantly correlated with aggregate stability, confirming their importance in soil structural improvement [33]. The content of large aggregates (>0.25 mm) increased with restoration age, while small aggregates (<0.25 mm) decreased, indicating improved soil structure [29,34]. Natural grassland restoration most effectively improved physical properties, while *P. armeniaca* showed better improvement than *H. rhamnoides*.

[Figure 3: see original paper] Changes of soil water-stable aggregate stability in the profile under different vegetation types

[Figure 4: see original paper] Changes of soil water-stable aggregate constituents and stability under different vegetation types

Note: Different uppercase letters indicate significant differences (P < 0.05) among soil layers within the same community; different lowercase letters indicate significant differences (P < 0.05) among communities within the same soil layer.

3.4 Soil Nutrient Changes

Soil organic matter content increased with restoration age, particularly in grassland (4.75, 6.1, and 6.27 g/kg for 5-, 15-, and 40-year stands, respectively) [Figure 5: see original paper]. The 40-year *P. armeniaca* stand had the highest organic matter content (6.71 g/kg). Organic matter decreased linearly with depth, with 0–20 cm layers significantly higher than deeper layers ($P < 0.05$), showing surface accumulation from litter decomposition [35].

Total nitrogen followed similar patterns to organic matter, increasing with restoration age in grassland. The 40-year grassland had significantly higher nitrogen in 0–20 cm than 15-year stands ($P < 0.05$). Total phosphorus showed complex depth patterns without clear trends, as phosphorus migration in soil is slow and primarily determined by parent material.

[Figure 5: see original paper] Changes of soil nutrient content under different vegetation types

3.5 Coupling Relationships Between Fine Root Biomass and Soil Properties

Vegetation restoration involves root-mediated improvement of soil properties [19]. Fine root biomass showed significant negative correlation with soil bulk density but no correlation with water content, similar to findings in Ningxia’ s Dala Mountains [36]. This suggests bulk density is the key limiting factor for root growth in this region, while nutrient availability has less impact on biomass accumulation.

Fine root biomass was highly positively correlated with aggregate stability (MWD), indicating that vegetation restoration improves compacted soils and enhances erosion resistance. Soil organic matter and total nitrogen were also significantly positively correlated with aggregate stability, as aggregates depend on organic binding agents [37-38]. These relationships demonstrate that fine roots play a crucial role in soil structure improvement.

** The correlation between fine root biomass and soil properties**

Variable	Fine Root Biomass	Natural Water Capacity	Mean Weight Diameter	Bulk Density	Organic Matter	Total Nitrogen	Total Phosphorus
Fine Root Biomass	1	-0.12	0.71**	-0.36*	0.28	0.34*	-0.03

Variable	Fine Root Biomass	Natural Water Capacity	Mean Weight Diameter	Bulk Density	Organic Matter	Total Nitrogen	Total Phosphorus
Mean Weight Diameter	0.71**	-0.27	1	-0.28	0.65**	0.58**	-0.15

Note: “” indicates significance at $P < 0.05$; “**” indicates significance at $P < 0.01$.*

4 Conclusion

(1) Fine root biomass in both naturally restored grassland and artificial *P. armeniaca* forests increased with restoration age. Artificial forests (*H. rhamnoides* and *P. armeniaca*) had greater fine root biomass than grasslands. All vegetation types showed exponential decrease in fine root biomass with soil depth.

(2) Naturally restored grassland had significantly higher soil water content than artificial forests. Soil aggregate stability and nutrient content (organic matter, total nitrogen, total phosphorus) increased with restoration age, while mean soil water content decreased.

(3) Fine root biomass was significantly correlated with soil bulk density and aggregate stability, demonstrating the important role of fine roots in soil structural improvement. Soil aggregate stability was closely related to soil nutrient content, showing highly significant positive correlations.

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