Characteristics of Soil Phosphorus Fractions in Robinia pseudoacacia Plantations of Different Stand Ages in the Western Shanxi Loess Region (Postprint)

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Abstract

Taking Robinia pseudoacacia plantations of different stand ages (18 a, 22 a, 26 a, 30 a, 33 a, 40 a) in the Caijiachuan watershed of Ji County in the Western Shanxi Loess Region as the research object, the Hedley phosphorus fractionation method was used to investigate the distribution patterns of soil phosphorus fractions (H2O-P, NaHCO3-P, NaOH-P, D.HCl-P, C.HCl-P, Residual-P) in the 0–100 cm soil layer, clarify the changes in soil phosphorus fractions across different stand ages, and explore the influence of soil physicochemical properties on these changes. The results showed that: (1) The average total soil phosphorus content in the 0–100 cm soil depth of Robinia pseudoacacia plantations of different stand ages followed the order: 30 a (590.44 mg · kg-1) > 26 a (571.68 mg · kg-1) > 22 a (527.05 mg · kg-1) > 18 a (517.83 mg · kg-1) > 33 a (490.71 mg · kg-1) > 40 a (464.49 mg · kg-1); the proportion of soil phosphorus fractions across the six stand ages was: stable phosphorus > residual phosphorus > moderately labile phosphorus > labile phosphorus. (2) Each soil phosphorus fraction exhibited a trend of initially increasing and then decreasing, with the 30 a Robinia pseudoacacia plantation having the highest content of each fraction. With increasing soil depth, the contents of both total soil phosphorus and soil phosphorus fractions decreased. (3) Redundancy analysis revealed that total soil nitrogen content and soil pH were the primary factors influencing changes in soil phosphorus fractions. Soil phosphorus fractions gradually accumulated during the early afforestation stage, peaked at middle age, and as stand age increased, phosphorus limitation effects gradually intensified, with soil phosphorus fractions declining after maturity. Therefore, from the perspective of phosphorus content limitation, appropriate phosphorus fertilizer application at 30 a could ameliorate phosphorus deficiency in Robinia pseudoacacia plantations in the Western Shanxi Loess Region during later growth stages.

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Full Text

Characteristics of Soil Phosphorus Fractions in Robinia pseudoacacia Plantations of Different Stand Ages in the Loess Region of Western Shanxi Province

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Abstract

This study examined Robinia pseudoacacia plantations of different stand ages (18, 22, 26, 30, 33, and 40 years) in the Caijiachuan watershed of Jixian County, located in the Loess Plateau region of western Shanxi. Using the Hedley phosphorus fractionation method, we investigated the distribution patterns of soil phosphorus fractions (H_2O-P, $NaHCO_3$-P, NaOH-P, D.HCl-P, C.HCl-P, and Residual-P) in the 0–100 cm soil layer across different stand ages. The study aimed to clarify how soil phosphorus fractions change with stand age and to explore the influence of soil physicochemical properties on these changes.

The results showed that the average total phosphorus content at 0–100 cm soil depth followed this trend: 30 a ($590.44\ mg \cdot kg^{-1}$) > 26 a ($571.68\ mg \cdot kg^{-1}$) > 22 a ($527.05\ mg \cdot kg^{-1}$) > 18 a ($517.83\ mg \cdot kg^{-1}$) > 33 a ($490.71\ mg \cdot kg^{-1}$) > 40 a ($464.49\ mg \cdot kg^{-1}$). The distribution of phosphorus fractions in the soil followed the order: stable phosphorus > residual phosphorus > moderately active phosphorus > active phosphorus. Each phosphorus fraction initially increased and then decreased with stand age, peaking in the 30-year-old plantation. Additionally, as soil depth increased, both total phosphorus and phosphorus fractions decreased. Redundancy analysis revealed that soil total nitrogen content and soil pH were the primary factors influencing phosphorus fraction variations. These findings suggest that in the early stages of afforestation, soil phosphorus fractions gradually accumulate in R. pseudoacacia plantations, peaking at middle stand ages. However, as stand age increases, phosphorus limitation becomes more pronounced, leading to a gradual decline in phosphorus fractions after maturation. Therefore, from the perspective of phosphorus limitation, appropriate phosphorus fertilization at around 30 years of age can effectively mitigate phos-

phorus deficiency in mature R. pseudoacacia plantations in the Loess Plateau region of western Shanxi Province.

Keywords: soil phosphorus fractions; forest soil; Robinia pseudoacacia; loess region of western Shanxi Province

1. Introduction

The Loess Plateau is located in the transitional zone from semi-humid to semi-arid and arid climates, where severe soil erosion leads to substantial phosphorus loss. To alleviate the ecological degradation in this region, large-scale afforestation programs such as the Three-North Shelter Forest Program and the Grain for Green Project were initiated in 1999, significantly increasing the area of artificial forests. However, while vegetation restoration improves soil structure, it also alters microfaunal communities and the quantity and quality of litter inputs, causing changes in soil phosphorus fractions and creating differences in phosphorus cycling processes across regional ecosystems.

Phosphorus is an essential nutrient for plant growth, and forest soil phosphorus availability directly affects forest productivity. Soil phosphorus comprises multiple forms, and previous studies have shown that phosphorus fraction availability is largely influenced by plant growth and soil physicochemical properties. However, long-term observations indicate that phosphorus has gradually become a key limiting nutrient for R. pseudoacacia growth in the Loess Plateau region. Current research on R. pseudoacacia plantations in this region has primarily focused on soil physicochemical properties, vegetation community structure, and limited measurements of phosphorus forms, but lacks in-depth exploration of the transformation mechanisms among different phosphorus fractions and their relationships with soil physicochemical factors. The active phosphorus fraction is highly responsive to plant availability, yet its dynamic patterns during R. pseudoacacia forest development remain unclear. Stable phosphorus constitutes a high proportion of total soil phosphorus, but whether its transformation potential is regulated by stand age is still unknown. Furthermore, how key soil physicochemical factors affect the dynamics of different phosphorus fractions requires quantitative analysis.

Therefore, this study examined R. pseudoacacia plantations of different stand ages (18, 22, 26, 30, 33, and 40 years) in the Loess Plateau region of western Shanxi. By measuring soil phosphorus fractions and physicochemical properties, we aimed to reveal the evolution of soil phosphorus fractions during forest development, analyze the key soil physicochemical factors influencing phosphorus fraction dynamics, and provide a scientific basis for the management of R. pseudoacacia plantations.

1.1 Study Area Description

The study area is located in the Caijiachuan watershed of Jixian County, Linfen City, Shanxi Province (36.08°–36.10°N, 110.23°–110.28°E), covering an area of

34.23 km^2. This typical Loess residual tableland gully region has a main gully length of 14 km and an elevation range of 800-1600 m. The region has a warm temperate continental monsoon climate with an average annual temperature of 10 °C, average annual precipitation of 533.5 mm, and average annual evaporation of 1724 mm. Precipitation is concentrated from June to September, accounting for approximately 70% of the annual total. The soil type is primarily cinnamon soil with loess parent material. The watershed forest coverage rate is 65.3%. The study area selected typical artificially planted R. pseudoacacia pure forests with a complete stand age sequence and similar natural conditions and management history. Understory vegetation includes Rosa xanthina, Amygdalus davidiana, Periploca sepium, Artemisia gmelinii, Artemisia selengensis, and Syringa oblata.

1.2 Sample Plot Establishment

We determined the actual stand age of R. pseudoacacia plantations using an increment borer. Following principles of consistency and representativeness, we established standard 20 m × 20 m sample plots in plantations with similar soil, terrain, and stand density conditions but different stand ages. Sample plots were established for six stand ages (18, 22, 26, 30, 33, and 40 years), with three replicate plots per age class, totaling 18 plots. Stand surveys were conducted in each plot, including basic location information and tree measurements. Basic plot information is presented in .

1.3 Soil Sampling and Laboratory Analysis

In August 2023, we conducted soil sampling in each of the three replicate plots per stand age, selecting areas with similar density and site conditions. At each sampling point, we excavated a soil profile to 100 cm depth and divided it vertically into five layers (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm). Soil samples were collected from each layer using ring knives and aluminum boxes for different analyses. The collected soil samples were transported to the laboratory, where intact soil from ring knives was used to determine soil water content and bulk density, while aluminum box samples were preprocessed for determination of total phosphorus, soil organic carbon, pH, and phosphorus fractions.

1.3.1 Soil Physicochemical Property Determination Soil samples were air-dried after removing foreign matter. A portion was ground and sieved for nutrient content determination. Soil organic carbon (SOC) was measured using the potassium dichromate volumetric method. After appropriate pretreatment, total nitrogen (TN) was determined using an automated chemical analyzer (SmartChem-200). Soil pH was measured using the potentiometric method. Soil bulk density (BD) was determined using the ring knife method, and soil water content (SWC) was measured using the aluminum box drying method.

1.3.2 Soil Phosphorus Fraction Determination Based on the Hedley fractionation method, soil phosphorus can be divided into active (H_2O-P, $NaHCO_3$-P), moderately active (NaOH-P), stable (D.HCl-P, C.HCl-P), and residual fractions. We used the sequential phosphorus extraction method on 0.5 g of sieved soil (0.149 mm), extracting sequentially with deionized water, 0.5 $mol \cdot L^{-1}$ $NaHCO_3$, 0.1 $mol \cdot L^{-1}$ NaOH, 1 $mol \cdot L^{-1}$ D.HCl, and concentrated HCl (C.HCl). The residual soil after extraction was digested with concentrated H_2SO_4 and H_2O_2. All extracts and digests were analyzed using the phosphomolybdate blue colorimetric method in a spectrophotometer to determine inorganic and total phosphorus contents. Organic phosphorus content in each fraction was calculated as the difference between total and inorganic phosphorus.

1.4 Data Processing

Data statistics and graphing were performed using Excel 2016 and Origin 2021 software. One-way ANOVA with Duncan' s test was used for significance testing of differences among stand ages and soil depths. Two-way ANOVA was used to analyze the interaction effects of stand age and soil depth on phosphorus fractions. Redundancy analysis (RDA) was conducted using Canoco 5.0 software to examine relationships between soil phosphorus fractions and physicochemical properties.

2. Results

2.1 Soil Total Phosphorus Variation Characteristics

The total phosphorus content in the 0–100 cm soil layer of R. pseudoacacia forests varied across stand ages, ranging from 455.70 to 602.08 $mg \cdot kg^{-1}$. Total phosphorus content showed a pattern of initial increase followed by decrease with stand age, following the order: 30 a (590.44 $mg \cdot kg^{-1}$) > 26 a (571.68 $mg \cdot kg^{-1}$) > 22 a (527.05 $mg \cdot kg^{-1}$) > 18 a (517.83 $mg \cdot kg^{-1}$) > 33 a (490.71 $mg \cdot kg^{-1}$) > 40 a (464.49 $mg \cdot kg^{-1}$). As soil depth increased, total phosphorus content decreased across all stand ages, with the highest values in the 0–10 cm layer. However, ANOVA results indicated no significant differences among soil layers ($P < 0.05$).

2.2 Soil Phosphorus Fraction Variation and Distribution with Stand Age

Stand age significantly affected all soil phosphorus fractions ($P < 0.05$). With increasing stand age, phosphorus fractions generally showed an initial increase followed by decrease, peaking in the 30-year-old plantation. The distribution of phosphorus fractions followed the order: Residual-P (40.15%-43.08%) > C.HCl-Pi (18.31%-18.38%) > C.HCl-Po (16.38%-17.27%) > NaOH-Po (15.39%-16.27%) > NaOH-Pi (2.75%-3.97%) > D.HCl-Pi (1.77%-2.85%) > H_2O-Pi (0.45%-0.85%) > $NaHCO_3$-Po (0.44%-0.97%) > $NaHCO_3$-Pi (0.15%-0.31%).

D.HCl-Pi content was significantly higher than other inorganic phosphorus fractions, making it the dominant inorganic phosphorus form in R. pseudoacacia plantations. Among organic phosphorus fractions, C.HCl-Po had the highest content and was the main organic phosphorus form.

2.3 Soil Phosphorus Fraction Variation with Soil Depth

All phosphorus fractions in R. pseudoacacia forests of different ages showed consistent vertical distribution patterns, decreasing with soil depth but showing no significant differences among soil layers ($P < 0.05$). Surface soil (0–20 cm) generally had higher phosphorus fraction contents than deeper layers, particularly for H_2O-Pi, $NaHCO_3$-Pi, and $NaHCO_3$-Po. The NaOH-P fraction showed relatively stable distribution with soil depth changes.

2.4 Effects of Soil Physicochemical Properties on Phosphorus Fractions

To further explore factors influencing phosphorus fractions, we selected major soil physicochemical factors for redundancy analysis. At different stand ages, soil total nitrogen (TN) was the dominant factor affecting phosphorus fraction variation, showing positive correlations with all phosphorus fractions. Soil pH was also an important influencing factor, with different physicochemical factors affecting phosphorus fractions differently across stand ages. Soil pH showed negative correlations with phosphorus fractions, while soil organic carbon (SOC) showed positive correlations. At different soil depths, soil pH significantly affected phosphorus fraction changes, with other factors having weaker effects, indicating that the influence of different soil physicochemical factors on phosphorus fractions varied significantly among soil layers.

3. Discussion

Soil total phosphorus content reflects the long-term phosphorus supply potential to plants. When total phosphorus content falls below 0.8–1.0 $g \cdot kg^{-1}$, phosphorus deficiency occurs. This study showed that total phosphorus content in R. pseudoacacia plantations in the Loess Plateau region of western Shanxi ranged from 0.46–0.6 $g \cdot kg^{-1}$, indicating potential phosphorus supply deficiency. Total phosphorus content increased initially then decreased with stand age, but showed no significant correlation with stand age. Similar patterns have been observed in other studies in the Loess Plateau gully region, likely because increased vegetation cover reduces light penetration, affecting water, heat, and nutrient conditions and consequently influencing microbial and enzyme activities, thereby reducing the rate of phosphorus return from litter decomposition. This fails to meet the phosphorus demand of R. pseudoacacia plantations during mid-to-late development stages, leading to increasingly pronounced phosphorus limitation.

The content and proportion of readily available active phosphorus fractions

(H_2O-Pi, $NaHCO_3$-Pi, $NaHCO_3$-Po) that plants can easily absorb showed an initial increase followed by decrease with stand age. This may occur because as R. pseudoacacia forests grow, aboveground biomass and litter production increase, along with root exudates. Soil microbial and phosphatase activities increase during the 18–30 a growth stage, maintaining litter decomposition at an optimal level and effectively replenishing active phosphorus fractions in soil. The 26-year-old plantation showed significantly lower active phosphorus fractions than other ages, possibly because this stage represents rapid growth with increased phosphorus demand, leading to absorption and depletion of active phosphorus fractions.

The moderately active phosphorus fractions (NaOH-Pi, NaOH-Po) showed an initial increase followed by decrease with stand age, peaking at 30 years. This result aligns with previous research. The NaOH-Pi content and proportion were relatively high, likely because NaOH-Po undergoes long-term mineralization and decomposition, converting to active phosphorus to meet plant growth needs, with a smaller portion being adsorbed by soil and converted to moderately active inorganic phosphorus. This indicates that moderately active organic phosphorus plays an important phosphorus buffering role in forest ecosystem development and serves as a crucial source of active phosphorus fractions. The NaOH-Po/NaOH-Pi ratio initially increased then decreased with stand age. The proportion of D.HCl-Pi in total phosphorus initially decreased then increased with stand age, differing from some previous studies. This may be due to increased soil organic acid accumulation with stand age, causing soil acidification and promoting D.HCl-Pi activation, thereby reducing its proportion in total phosphorus.

The proportion of more recalcitrant C.HCl-Pi in total phosphorus remained relatively stable with stand age, differing from studies showing decreasing trends. This may be because stable phosphorus fractions maintain a relatively stable dynamic balance in soil, serving as phosphorus reserves and buffers to help maintain soil phosphorus solution equilibrium when readily available phosphorus is insufficient for plant growth. The content of stable phosphorus fractions (D.HCl-Pi, C.HCl-Pi, C.HCl-Po, Residual-P) initially increased then decreased with stand age, possibly because after readily available phosphorus is absorbed by plants, stable phosphorus fractions mineralize and decompose to compensate.

Soil total phosphorus content was relatively uniformly distributed in the 0–100 cm profile, similar to findings by Zhao et al. This may be because soil phosphorus cycling is a sedimentary cycle with minimal exchange with the external environment except for small losses through leaching. Additionally, mineral weathering is extremely slow. Over short timescales, soil phosphorus input mainly comes from plant residue decomposition and external fertilizer application. Wei et al. found that soil microbial community content in R. pseudoacacia plantations was higher in the 0–20 cm layer, facilitating litter decomposition and replenishing soil phosphorus fractions in this layer.

Soil phosphorus exists in dynamic equilibrium, with transformation among different fractions influenced by vegetation, litter, soil organisms, and physicochemical properties. Redundancy analysis showed that at different stand ages, soil total nitrogen significantly affected phosphorus fraction variation, showing positive correlations. Research indicates that nitrogen deposition increases soil nitrogen content, stimulating proton (H^+) production and increasing iron-aluminum mineral content, leading to significant increases in NaOH-P. Soil pH showed strong negative correlations with phosphorus fractions, possibly affecting soil microbial activity and thus influencing phosphorus migration within soil. Residual-P, as the most stable phosphorus fraction, was less affected by pH.

At different soil depths, soil pH significantly affected phosphorus fraction variation, while other factors had weaker effects. In R. pseudoacacia plantations, soil pH gradually increased with depth. Under alkaline conditions, organic matter and iron-aluminum minerals have difficulty binding with phosphorus, making it harder for stable phosphorus to transform into active forms. Residual-P, as the most stable phosphorus fraction, was similarly less affected by pH.

This study was limited by experimental conditions and could not explore other potential factors affecting soil phosphorus fractions, such as soil fauna, which regulate phosphorus biogeochemical cycling through feeding on microorganisms and litter, or precipitation, which alters soil surface mechanical composition through erosion, changing soil physicochemical properties and phosphorus cycling. Future research should integrate soil fauna community structure, microbial functional genes, and precipitation monitoring to further reveal the multi-factor coupling mechanisms of phosphorus fraction transformation, providing more comprehensive theoretical support for precise management and ecological restoration of R. pseudoacacia plantations on the Loess Plateau.

4. Conclusion

Using the Hedley phosphorus fractionation method, variance analysis, and redundancy analysis, this study systematically revealed the dynamic variation characteristics and driving mechanisms of soil phosphorus fractions with stand age and soil depth in R. pseudoacacia plantations in the Caijiachuan watershed of the Loess Plateau region in western Shanxi. The main conclusions are:

1) Both soil total phosphorus and nine phosphorus fraction contents showed a "single-peak" trend with stand age, peaking at 30 years (total phosphorus content of 590.44 $mg \cdot kg^{-1}$), indicating this stage is a critical period for phosphorus accumulation. After 30 years, total phosphorus and active phosphorus fractions (H_2O-Pi, $NaHCO_3$-Pi) significantly decreased, reflecting that the transformation rate of phosphorus to active fractions was lower than the absorption rate by mature R. pseudoacacia plantations.

2) Soil total phosphorus and phosphorus fraction contents decreased with soil depth, but the differences were not significant. Surface soil (0–20 cm) had significantly higher active phosphorus fractions (H_2O-Pi, $NaHCO_3$-Pi) than deeper layers, indicating that litter input and root activity are

the main drivers of phosphorus cycling in the surface layer.

3) At the stand age scale, soil total nitrogen (TN) was the dominant factor affecting phosphorus fraction dynamics (explanatory power of 42.2%), showing significant positive correlations with all phosphorus fractions, reflecting that nitrogen accumulation indirectly regulates phosphorus form transformation by promoting organic matter mineralization. At the soil depth scale, soil pH was the dominant factor (explanatory power of 68.9%), showing positive correlations with active phosphorus fractions (H_2O-Pi, $NaHCO_3$-Pi) but negative correlations with residual phosphorus (Residual-P), reflecting that alkaline conditions inhibit phosphorus fixation while enhancing the potential availability of active phosphorus.

To enable R. pseudoacacia plantations to better perform their ecological functions at all stages, we recommend applying external calcium-magnesium phosphate fertilizer to supplement the active phosphorus pool when plantations reach approximately 30 years of age, combined with autumn litter cover measures to reduce phosphorus leaching. For plantations over 30 years old, thinning can adjust the forest microenvironment to promote litter decomposition and phosphorus recycling.

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