Postprint: Soil Ecological Stoichiometric Characteristics of Typical Restored Vegetation Following Farmland Abandonment in the Loess Hilly Region

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Abstract

To investigate the stoichiometric characteristics of soil carbon (C), nitrogen (N), and phosphorus (P) and their influencing factors under different vegetation types, soils at 0–100 cm depth under four typical restored vegetation types following farmland abandonment in the loess hilly region—Pinus tabuliformis, Robinia pseudoacacia, Hippophae rhamnoides, and grassland—were studied to analyze soil organic carbon (SOC), total nitrogen (STN), total phosphorus (STP) contents and their stoichiometric characteristics. The results showed that: (1) Different restored vegetation types had significant effects on soil nutrient contents, with Robinia pseudoacacia having the highest SOC and STN, Pinus tabuliformis having the lowest SOC and STN, and STP showing the pattern of grassland > Robinia pseudoacacia > Pinus tabuliformis > Hippophae rhamnoides. (2) Soil nutrients in different restored vegetation types exhibited "surface accumulation", with SOC and STN contents decreasing as soil depth increased, while STP showed weaker variability. Notably, SOC and STN under Robinia pseudoacacia showed an increasing trend in the 60–100 cm layer. (3) Differences in soil SOC:STN (C:N) and SOC:STP (C:P) among different restored vegetation types were not significant ($P>0.05$), while soil STN:STP (N:P) under Robinia pseudoacacia was significantly higher than other vegetation types ($P<0.05$). Soil C:N, C:P, and N:P ratios were all lower than global and national averages, indicating rapid decomposition of organic matter, high P availability, and that vegetation growth was primarily limited by N element. (4) Soil C:N, C:P, and N:P ratios in the study area were mainly influenced by SOC and STN; soil nutrients were negatively correlated with soil water content (SWC) and bulk density (BD), and positively correlated with soil slit and clay contents, with STP showing a stronger response to fine soil particles than SOC and STN. Soil stoichiometry in the study area differed significantly among different restored

vegetation types following farmland abandonment, with Robinia pseudoacacia exhibiting better soil nutrient status than other vegetation types, which can provide a reference for further vegetation restoration efforts in this region.

Full Text

Ecological Stoichiometric Characteristics of Soil in Typical Fallow-Restored Vegetation in the Loess Hilly Region

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Abstract

The hilly and gully areas of China' s Loess Plateau are characterized by fragile ecosystems and harsh climates in arid and semi-arid regions. A series of ecological restoration projects, such as the "Grain for Green Project," have significantly improved local environmental conditions. Understanding nutrient cycling following vegetation restoration requires investigation of soil carbon (C), nitrogen (N), and phosphorus (P) content and their ecological stoichiometry across different vegetation types, as well as identification of the underlying driving factors. This study analyzed soil organic carbon (SOC), total nitrogen (STN), and total phosphorus (STP) content and stoichiometric characteristics in 0–100 cm soil profiles under *Pinus tabulaeformis*, *Robinia pseudoacacia*, *Hippophae rhamnoides*, and grassland in the loess hilly region. The effects of soil water content (SWC), bulk density (BD), and soil texture on these stoichiometric characteristics were also examined. The results revealed four key findings: (1) Vegetation type significantly influenced soil nutrient content, with *R. pseudoacacia* exhibiting the highest SOC and STN contents, while *P. tabulaeformis* showed the lowest. STP content followed the order: grassland > *R. pseudoacacia* > *P. tabulaeformis* > *H. rhamnoides*. (2) Soil nutrients exhibited pronounced surface accumulation across all vegetation types. SOC and STN decreased with soil depth, whereas STP showed relatively weak vertical variability. Notably, SOC and STN in *R. pseudoacacia* increased in the 60–100 cm depth interval. (3) Variations in soil C:N and C:P ratios among vegetation types were not statistically significant, though *R. pseudoacacia* had significantly higher N:P ratios than the other three vegetation types. All three stoichiometric ratios were lower than global and national averages, indicating rapid organic matter decomposition, high phosphorus availability, and predominant nitrogen limitation for vegetation growth. (4) C:N ratio was primarily influenced by SOC, while C:P and N:P ratios were mainly affected by both SOC and STN. Overall, soil nutrients were negatively correlated with SWC and BD but positively correlated with silt and clay content, with STP showing stronger responses to fine soil particles than SOC and STN. Significant differences in soil stoichiometric characteristics were observed among the four fallow-restored vegetation types in the 0–100 cm profile, with *R. pseudoacacia* demonstrating superior soil nutrient status. These findings provide valuable guidance for future vegetation restoration efforts in loess hilly regions.

Keywords: loess hilly region; fallow-restored vegetation; soil nutrients; ecological stoichiometry; soil physical and chemical properties

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1.1 Study Area Overview

The study area is located in Wuqi County, Shaanxi Province (36°33.5 -37°24.5 N, 107°39 -108°33 E), at an elevation of 1,233–1,809 m. The region experiences a temperate continental monsoon climate and represents a typical loess hilly-gullied area. Annual precipitation averages 483.4 mm, concentrated primarily in summer as heavy rainfall events. The soils are characterized by poor fertility and water retention capacity, with severe soil erosion. Since implementing the "Grain for Green" program, extensive vegetation restoration has been conducted on sloping croplands and barren hills, establishing forests dominated by artificial stands of *Armeniaca sibirica*, *Robinia pseudoacacia*, *Ulmus pumila*, *Pinus tabulaeformis*, and *Platycladus orientalis*, shrubs including *Hippophae rhamnoides* and *Caragana korshinskii*, and naturally restored grasslands.

1.2 Soil Sample Collection and Nutrient Measurement

Soil sampling was conducted in August 2020. Based on field surveys and local vegetation restoration records, we selected representative 20 m × 20 m plots for *P. tabulaeformis*, *R. pseudoacacia*, *H. rhamnoides*, and grassland, all with similar restoration ages. Basic plot information is provided in . Within each plot, surface litter and humus layers were removed before collecting soil samples at 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm depth intervals using a 5-cm diameter soil auger. Five replicate samples were collected from each layer and combined into one composite sample. Concurrently, undisturbed soil cores were taken using cutting rings to determine bulk density, and fresh soil samples were collected in aluminum boxes for gravimetric water content determination.

SOC content was measured using the potassium dichromate oxidation method, STN by the semi-micro Kjeldahl method, and STP by molybdenum-antimony colorimetry following perchloric acid digestion. Soil particle size distribution was analyzed using a laser particle size analyzer (Mastersizer 3000).

1.3 Data Processing

SPSS 26.0 software was used for one-way ANOVA to examine differences in soil stoichiometric ratios among vegetation types, with least significant difference (LSD) tests for multiple comparisons. Pearson correlation analysis was performed to assess relationships between soil nutrients and stoichiometric ratios. Redundancy analysis (RDA) and multiple regression analysis were conducted using the Vegan package in R 3.6.3, with results visualized using ggplot2.

2.1 Distribution Characteristics of Soil Carbon, Nitrogen, and Phosphorus Nutrient Content

Across the 0-100 cm profile, SOC content ranged from 0.557-0.631 $g \cdot kg^{-1}$, STN from 0.232-0.367 $g \cdot kg^{-1}$, and STP from 0.034-0.056 $g \cdot kg^{-1}$. SOC and STN showed the highest values in grassland, followed by *R. pseudoacacia* and *H. rhamnoides*, with *P. tabulaeformis* having the lowest values. Coefficients of variation across soil layers were 0.45–0.80 for SOC, 0.26–0.47 for STN, and 0.04–0.05 for STP, indicating moderate variation for SOC and STN and weak variation for STP.

In the surface 0-10 cm layer, *R. pseudoacacia* had significantly higher SOC and STN contents than *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). The STP content in *R. pseudoacacia* was significantly higher than in *H. rhamnoides* and grassland ($P < 0.05$). In the 10–20 cm layer, *R. pseudoacacia* maintained significantly higher SOC and STN than the other three vegetation types ($P < 0.05$). In the 20–40 cm layer, SOC and STN in *R. pseudoacacia* were significantly higher than in *H. rhamnoides* and grassland ($P < 0.05$). In the 40-60 cm layer, SOC and STN in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). In the 60–80 cm layer, SOC and STN in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis* and grassland ($P < 0.05$). In the deepest 80-100 cm layer, SOC and STN in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). Detailed nutrient contents for each vegetation type and soil layer are presented in .

2.2 Distribution Characteristics of Soil Carbon, Nitrogen, and Phosphorus Stoichiometric Ratios

Soil C:N ratios in the 0–100 cm profile ranged from 6.284–7.516, C:P ratios from 0.395–0.588, and N:P ratios from 0.058–0.090. C:N ratios were highest in grassland, followed by *H. rhamnoides* and *P. tabulaeformis*, with *R. pseudoacacia* showing the lowest values. Coefficients of variation across soil layers were 0.23-0.36 for C:N, 0.46–0.81 for C:P, and 0.20–0.47 for N:P, all indicating moderate variation.

Variations in C:N and C:P ratios among vegetation types were not statistically significant ($P > 0.05$), except in the 60–80 cm layer. The N:P ratio in *R. pseudoacacia* was significantly higher than in the other three vegetation types across all soil layers ($P < 0.05$). In the surface 0-10 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). In the 10-20 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis* and grassland ($P < 0.05$). In the 20-40 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). In the 40-60 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis* and grassland ($P < 0.05$). In the 60-80 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis*, *H. rhamnoides*, and grassland ($P < 0.05$). In the 80-100 cm layer, C:P and N:P ratios in *R. pseudoacacia* were significantly higher than in *P. tabulaeformis* and grassland ($P < 0.05$). Stoichiometric ratios for each vegetation type and soil layer are summarized in , with distribution patterns illustrated in [Figure 2: see original paper].

2.3 Correlation Analysis of Soil Physical and Chemical Properties

SOC, STN, and STP were all significantly positively correlated with each other ($P < 0.01$). SOC and STN showed stronger correlations with each other than with STP. Both SOC and STN were significantly positively correlated with soil water content ($P < 0.05$), while STP was negatively correlated with soil water content ($P < 0.05$). SOC and STN were significantly positively correlated with soil silt and clay content ($P < 0.01$) and significantly negatively correlated with soil bulk density ($P < 0.01$). STP was positively correlated with silt content ($P < 0.05$) and negatively correlated with sand content ($P < 0.05$).

Redundancy analysis revealed that the first two ordination axes explained 83.0% and 12.9% of the variation in soil stoichiometric characteristics, respectively. SOC and STN were negatively correlated with soil water content, bulk density, and sand content, but positively correlated with silt and clay content. STP was positively correlated with silt content and negatively correlated with sand content, bulk density, and soil water content. The correlation matrix of soil physical and chemical properties is shown in [Figure 3: see original paper].

Stepwise regression analysis was performed to determine the relative importance of soil physical properties on stoichiometric characteristics. The results indicated that soil bulk density and clay content were the main factors influencing SOC ($r^2 = 0.62$, $P < 0.01$). Soil bulk density and silt content were the primary factors affecting STN ($r^2 = 0.58$, $P < 0.01$). Soil bulk density, silt content, and soil water content collectively influenced STP ($r^2 = 0.31$, $P < 0.01$). Soil bulk density and silt content were the main factors for C:N ratio ($r^2 = 0.21$, $P < 0.01$). Soil bulk density, silt content, and soil water content were the primary determinants of C:P ratio ($r^2 = 0.61$, $P < 0.01$). Soil bulk density and soil water content were the main factors influencing N:P ratio ($r^2 = 0.60$, $P < 0.01$). Detailed regression equations are provided in .

3.1 Effects of Different Vegetation Types on Soil Nutrients

Our results demonstrate that soil nutrients in different vegetation types exhibit pronounced surface accumulation, gradually decreasing with soil depth, consistent with previous research. This pattern occurs because nutrient sources, including aboveground litter and root exudates, are concentrated in the surface layer and are subject to leaching by precipitation. Soil phosphorus content is primarily influenced by parent material, climate, and biological factors, resulting in relatively weak vertical variation.

SOC and STN contents varied significantly among vegetation types, with *R. pseudoacacia* showing the highest values. This species is a nitrogen-fixing broadleaf tree that develops a complex community structure with abundant understory vegetation, thick litter layers, and high species diversity, all contributing to increased organic matter input. Additionally, its extensive root biomass enhances carbon sequestration in deeper soil layers. The increase in SOC and STN in *R. pseudoacacia* at 60-100 cm depth aligns with findings from other studies, likely due to deep root distribution and decomposition.

In contrast, *P. tabulaeformis* had the lowest SOC and STN contents, particularly in the 0-10 cm layer. This can be attributed to its nature as a coniferous species with slow litter decomposition rates and limited nutrient input to the surface layer. Furthermore, high surface C:N ratios in *P. tabulaeformis* stands may accelerate nitrogen leaching to deeper layers. However, *P. tabulaeformis* showed higher SOC and STN contents than *H. rhamnoides* and grassland in deeper layers (60-100 cm), reflecting its deeper root distribution and associated root exudates and dead root decomposition.

Hippophae rhamnoides and grassland exhibited higher surface soil nutrient contents than *P. tabulaeformis* due to their understory composition (*Lespedeza daurica*, *Leymus secalinus*, *Artemisia vestita*) and associated litter and root inputs. However, their shallower root systems resulted in lower nutrient contents in deeper layers compared to the coniferous species.

3.2 Effects of Different Vegetation Types on Soil C:N:P Stoichiometric Ratios

The soil C:N ratio reflects nitrogen mineralization capacity, with lower values indicating higher mineralization potential. Our measured C:N ratios (6.284-7.516) were substantially lower than global (14.3) and national (11.9) averages, suggesting high nitrogen mineralization capacity in the study area. The relatively stable C:N ratios across vegetation types indicate that carbon and nitrogen accumulation and consumption processes remain balanced during vegetation growth.

Soil C:P ratio represents the potential for organic matter decomposition and phosphorus release. Our C:P ratios (0.395-0.588) were significantly lower than the national average (52), indicating strong potential for organic matter decomposition and high phosphorus availability. The N:P ratio is a critical indicator of nutrient limitation, with values below 14 suggesting nitrogen limitation. Our N:P ratios (0.058–0.090) were far below both global (6.6) and national (3.9) averages, confirming that vegetation growth in the study area is primarily limited by nitrogen, though *R. pseudoacacia* showed better soil fertility conditions with significantly higher N:P ratios.

The lower stoichiometric ratios in our study compared to previous research on the Loess Plateau may be attributed to differences in soil profile depth and the region' s unique soil parent material and climatic conditions, which influence selective nutrient absorption by plants during restoration.

3.3 Correlations Between Soil Physical Properties and Stoichiometric Characteristics

SOC and STN were significantly positively correlated with soil water content, silt content, and clay content, but negatively correlated with bulk density. These relationships indicate that soil texture and structure strongly influence organic matter accumulation and nitrogen retention. The positive correlation between STP and silt content suggests that fine particles enhance phosphorus adsorption and storage.

The contrasting relationship between soil water content and STP (negative correlation) versus SOC and STN (positive correlation) may reflect differences in nutrient cycling processes. Excessive or insufficient soil moisture can reduce phosphorus availability, while moderate water content promotes organic carbon and nitrogen accumulation through enhanced microbial activity and plant growth. The negative correlation between bulk density and nutrient contents confirms that soil compaction limits nutrient storage capacity.

Stepwise regression analysis revealed that soil bulk density and silt content were the most important factors influencing stoichiometric ratios, explaining 21–61% of the variation. Notably, no variables entered the regression equation for C:N ratio, likely due to the tight coupling between carbon and nitrogen cycles that makes this ratio less responsive to individual soil properties.

4 Conclusions

This study investigated soil nutrient content and stoichiometric characteristics in 0–100 cm profiles under *Pinus tabulaeformis*, *Robinia pseudoacacia*, *Hippophae rhamnoides*, and grassland in the loess hilly region. Four main conclusions were drawn:

1. Soil nutrient content varied significantly among vegetation types, with *R. pseudoacacia* exhibiting the highest nutrient levels and representing a suitable reference species for local vegetation restoration efforts.
2. Soil nutrients displayed pronounced surface accumulation, with SOC and STN decreasing with depth while STP showed weak vertical variation.

Notably, SOC and STN in *R. pseudoacacia* increased in the 60–100 cm layer.

3. Variations in C:N and C:P ratios among vegetation types were not significant, but *R. pseudoacacia* had significantly higher N:P ratios than other vegetation types. All stoichiometric ratios were lower than global and national averages, indicating rapid organic matter decomposition, high phosphorus availability, and predominant nitrogen limitation for vegetation growth.
4. Soil bulk density, silt content, and clay content were the primary physical properties influencing soil nutrient stoichiometry, with soil fine particles showing stronger effects on STP than on SOC and STN.

These findings provide important theoretical guidance for optimizing vegetation restoration strategies and understanding soil nutrient cycling mechanisms in loess hilly regions.

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