Relationship between Herbaceous Diversity and Soil Nutrients in Pinus tabuliformis Forests of Different Restoration Ages in the Western Shanxi Loess Region (Postprint)

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Abstract

This study examined Pinus tabuliformis forests of different afforestation ages (11, 17, 22, and 26 years) in the Loess Hilly and Gully Region of western Shanxi, measuring soil nutrient factors at different soil depths (0–60 cm), and investigated the variations and interrelationships of understory herbaceous plant diversity and soil nutrients using redundancy analysis (RDA) and regression analysis. The results showed: A total of 8 plant species belonging to 6 families and 8 genera were observed under Pinus tabuliformis plantations of different afforestation ages; with increasing afforestation age, the species diversity indices (Margalef and Patrick indices), richness indices (Simpson and Shannon indices), and evenness index (Pielou index) of the herbaceous layer all decreased; among understory herbs, Artemisia gmelinii had the highest frequency of occurrence, with an importance value of 27; The average soil organic matter and total nitrogen in the 0–60 cm soil layer showed an increasing trend with afforestation age, exhibiting a surface enrichment effect, while soil ammonium nitrogen, pH, and total phosphorus decreased with increasing afforestation age; available potassium first decreased and then increased with afforestation age, whereas available phosphorus showed the opposite trend; organic matter, total nitrogen, pH, and available potassium decreased with increasing soil depth; Redundancy analysis indicated that understory herbaceous diversity was influenced by other environmental factors in addition to soil nutrients, with soil nutrient factors explaining only 41.42% of the variation in herbaceous diversity; the richness index, diversity index, and evenness index of the herbaceous layer under Pinus tabuliformis plantations were all negatively correlated with organic matter and total nitrogen, and positively correlated with pH, ammonium nitrogen, and total phosphorus; Regression analysis revealed that the Patrick index showed significant power relationships with organic matter, pH, and ammonium nitrogen (R^2

= 0.743, 0.708, $P < 0.01$), the Margalef index exhibited linear relationships with organic matter and total nitrogen (R^2 = 0.651, 0.719); the Shannon index had linear relationships with pH and ammonium nitrogen (R^2 = 0.539, 0.790); the Simpson index showed a linear relationship with organic matter (R^2 = 0.672); the Pilou index displayed exponential relationships with organic matter, pH, and total nitrogen (R^2 = 0.631, 0.515, 0.550). These results demonstrate that soil nutrients exert a certain influence on herbaceous diversity indices.

Full Text

Relationship Between Species Diversity at the Herbaceous Stratum and Soil Nutrients in *Pinus tabulaeformis* Plantations of Various Ages on the Loess Plateau of Western Shanxi Province, China

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Abstract

In *Pinus tabulaeformis* plantations of various ages (11, 17, 22, and 26 years), we assessed changes in nutrient contents at various soil layers (0–60 cm) and explored the relationship between species diversity at the herbaceous stratum and soil nutrients using redundancy and regression analyses. Eight understory species belonging to eight genera of six families were recorded. With increasing plantation age, species diversity (Margalef and Patrick indices), richness (Simpson and Shannon indices), and evenness (Pielou's index) at the herbaceous stratum decreased. *Artemisia gmelinii* showed the highest frequency of occurrence at the herbaceous stratum, with an importance value of 27. Moreover, average soil organic matter and total nitrogen contents increased with increasing rehabilitation time, with obvious surface effects. Conversely, ammonia nitrogen and total phosphorus contents and pH decreased with increasing rehabilitation time. With increasing plantation age, potassium available in the soil decreased at first and then increased, whereas phosphorus available in the soil showed the opposite trend. Organic matter, total nitrogen, and available potassium contents as well as pH decreased with increasing soil depth. According to redundancy analysis, species diversity was affected by soil nutrients and also by other environmental factors, explaining 41.42% of variation. Species richness, diversity, and evenness indices were negatively correlated with organic matter and total nitrogen contents and positively correlated with ammonia nitrogen and total phosphorus contents and pH. Regression analysis indicated that the Patrick index showed a significant power function relationship with organic matter content, pH, and ammonia nitrogen content (R^2 = 0.743, 0.708; P < 0.01). The Shannon index was linearly correlated with pH and ammonia nitrogen content (R^2 = 0.539 and 0.790, respectively). The Simpson index was linearly correlated with organic matter content (R^2 = 0.672); Pielou's index was exponentially correlated to pH and total nitrogen and organic matter contents (R^2 = 0.631, 0.515, and 0.550, respectively). In conclusion, soil nutrients affect species diversity at the herbaceous stratum.

Keywords: *Pinus tabulaeformis*; herbaceous diversity; soil nutrients; RDA; regression analysis; Shanxi Province

1. Introduction

The relationship between forest understory vegetation and soil nutrients is a critical component of ecosystem functioning. Previous studies have examined biodiversity patterns in *Pinus tabulaeformis* plantations [1–2], understory vegetation dynamics [3–6], and soil fertility changes with stand development [7–10]. However, comprehensive analyses linking herbaceous layer diversity to soil nutrient dynamics across plantation chronosequences remain limited, particularly on the Loess Plateau where vegetation restoration plays a crucial role in soil conservation.

2. Materials and Methods

2.1 Study Area and Sampling Design The study was conducted in *Pinus tabulaeformis* plantations established in 1990. Four stand ages were selected: 11, 17, 22, and 26 years. Soil samples were collected from 0–60 cm depth layers to analyze nutrient contents. Herbaceous layer diversity was assessed using standard ecological indices.

2.2 Data Analysis Statistical analyses were performed using Excel 2010, Origin 2017, and SPSS 22.0. One-way ANOVA and Kruskal-Wallis tests were used to compare differences in diversity indices and soil nutrients among stand ages. Redundancy analysis (RDA) was conducted using Canoco 4.5 to examine relationships between herbaceous diversity and soil nutrients. Spearman correlation analysis assessed pairwise relationships, and Monte Carlo permutation tests validated RDA results. Regression analysis established quantitative relationships between diversity indices and soil factors.

3. Results

3.1 Species Composition and Diversity Characteristics A total of eight understory species belonging to eight genera across six families were recorded (Table 2). *Artemisia gmelinii* was the most frequently occurring species, with an importance value of 27. Quantitative characteristics of diversity indices are presented in Table 3. With increasing plantation age, all diversity metrics—including Margalef and Patrick indices for species diversity, Simpson and Shannon indices for richness, and Pielou's index for evenness—showed decreasing trends.

3.2 Soil Nutrient Dynamics Soil organic matter and total nitrogen contents increased significantly with stand age ($P < 0.05$), with the 26-year stand showing 57.88% and 31.10% higher values respectively compared to the 11-year stand (Figures 1–2). Conversely, ammonia nitrogen and total phosphorus contents decreased with age, while pH showed a declining trend across the chronosequence. Available potassium content initially decreased then increased with stand age, whereas available phosphorus showed the opposite pattern (Figures 3–4). All nutrients exhibited significant surface enrichment effects, with higher concentrations in the 0–10 cm layer compared to deeper soils ($P < 0.05$).

3.3 Relationships Between Diversity and Soil Nutrients Redundancy analysis revealed that soil nutrient factors explained 41.42% of the variation in herbaceous diversity (Figure 5). The first two RDA axes showed strong correlations with soil organic matter ($r = -0.8608$), total nitrogen ($r = 0.8319$), and total phosphorus ($r = 0.6295$) (Table 4). Species diversity indices were negatively correlated with organic matter and total nitrogen, but positively correlated with ammonia nitrogen, total phosphorus, and pH.

Correlation analysis (Table 5) confirmed these patterns, with significant relationships ($P < 0.01$) between diversity indices and multiple soil nutrients. Regression models (Table 6) provided quantitative relationships:

- **Patrick index**: Power function with organic matter ($R^2 = 0.743$), pH ($R^2 = 0.708$), and ammonia nitrogen ($R^2 = 0.627$)
- **Margalef index**: Power function with organic matter ($R^2 = 0.651$) and total nitrogen ($R^2 = 0.719$)
- **Shannon index**: Linear with pH ($R^2 = 0.539$) and ammonia nitrogen ($R^2 = 0.790$)
- **Simpson index**: Linear with organic matter ($R^2 = 0.672$)
- **Pielou index**: Exponential with pH ($R^2 = 0.631$), total nitrogen ($R^2 = 0.515$), and organic matter ($R^2 = 0.550$)

All regression models were significant at $P < 0.01$ level.

4. Discussion

The decline in herbaceous diversity with increasing plantation age is consistent with previous research on forest succession [20–21]. *Artemisia gmelinii* dominance reflects its adaptation to the understory environment of *P. tabulaeformis* plantations. The observed soil nutrient patterns demonstrate significant temporal and spatial dynamics, with organic matter and nitrogen accumulation over time while phosphorus availability and pH decrease.

The RDA results indicate that soil nutrients are primary drivers of understory diversity, though other environmental factors account for nearly 60% of unexplained variation. The negative correlation between diversity and organic matter/total nitrogen may reflect competitive exclusion by dominant species in nutrient-rich conditions. Positive correlations with ammonia nitrogen and pH suggest these factors may limit species establishment when at low levels.

These findings have important implications for plantation management on the Loess Plateau. Maintaining understory diversity requires consideration of soil nutrient management, particularly phosphorus supplementation and pH regulation in older stands. The established regression equations provide quantitative tools for predicting diversity changes based on soil conditions.

5. Conclusion

Soil nutrients significantly influence herbaceous layer diversity in *Pinus tabulaeformis* plantations, explaining 41.42% of community variation. Diversity decreases with stand age, with distinct relationships to different nutrient parameters. Management practices should focus on nutrient regulation to maintain biodiversity and ecosystem stability in these plantations.

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