Effects of Close-to-Nature Transformation on Organic Phosphorus Fraction Contents in Soil Aggregates of Pinus massoniana Plantations (Postprint)

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Abstract

Organic phosphorus (Po) is an important component of the soil phosphorus pool. To explore the effects of near-natural transformation of Pinus massoniana plantations on the distribution characteristics of Po in soil aggregates, this study selected pure Pinus massoniana plantations (PP) and near-naturally transformed Pinus massoniana-broadleaf mixed forests (CP) in subtropical regions as research objects. After collecting 0-10 cm soil samples, they were sieved into three aggregate size fractions using the dry sieving method: >2 mm, 0.25-2 mm, and <0.25 mm. The various Po fractions, microbial biomass phosphorus (MBP), and acid phosphatase (ACP) activity were measured in the bulk soil and each aggregate size fraction. The results showed: (1) The soil Po fractions in CP changed compared with PP. Highly resistant organic phosphorus (HRO P) and moderately labile organic phosphorus (MLO P) in the bulk soil and all aggregate size fractions were significantly higher in CP than in PP ($P < 0.05$), while labile organic phosphorus (LO P) and moderately resistant organic phosphorus (MRO P) showed no significant differences between CP and PP. There was no obvious pattern of change for each Po fraction in the bulk soil and aggregate size fractions between PP and CP. (2) The proportion of each Po form in PP was HRO P > MRO P > MLO P > LO P, while in CP it was HRO P > MLO P > MRO P > LO P. (3) MBP and ACP activity in CP were significantly higher than in PP in the bulk soil and all aggregate size fractions, and ACP activity increased with decreasing aggregate size. (4) Redundancy analysis revealed that soil available phosphorus (AP), mean weight diameter of soil aggregates (MWD), MBP, and total nitrogen (TN) were the main driving factors of soil Po fractions. In conclusion, near-natural transformation is beneficial for phosphorus accumulation and transformation in Pinus massoniana plantation

soils. The results of this study provide a theoretical basis for improving soil quality and productivity in Pinus massoniana plantations.

Full Text

Effects of Close-to-Nature Forest Management on Content of Soil Organic Phosphorus Fractions in Soil Aggregates of *Pinus massoniana* Plantations

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Abstract: Organic phosphorus (Po) constitutes an important component of soil phosphorus pools. To investigate the effects of close-to-nature silvicultural transformation on the distribution characteristics of Po in soil aggregates of *Pinus massoniana* plantations, this study examined pure *P. massoniana* plantations (PP) and *P. massoniana*-broadleaf mixed plantations (CP) following close-to-nature transformation in southern subtropical China. Soil samples from the 0–10 cm layer were collected and separated into three aggregate size fractions (>2 mm, 0.25–2 mm, and <0.25 mm) using dry sieving. The Po fractions, microbial biomass phosphorus (MBP), and acid phosphatase (ACP) activity were measured in bulk soil and each aggregate fraction. The results showed: (1) Soil Po fractions in CP differed from PP, with highly recalcitrant organic phosphorus (HRO-P) and moderately labile organic phosphorus (MLO-P) significantly higher in both bulk soil and all aggregate fractions ($P < 0.05$), while labile organic phosphorus (LO-P) and moderately recalcitrant organic phosphorus (MRO-P) showed no significant differences between CP and PP. No consistent patterns of Po fraction distribution were observed across aggregate sizes in either plantation type. (2) The relative proportions of Po fractions in PP followed the order HRO-P > MRO-P > MLO-P > LO-P, whereas in CP the order was HRO-P > MLO-P > MRO-P > LO-P. (3) MBP and ACP activity in CP were significantly higher than in PP across all aggregate fractions, with ACP activity increasing as aggregate size decreased. (4) Redundancy analysis identified soil available phosphorus (AP), mean weight diameter (MWD), MBP, and total nitrogen (TN) as the primary drivers of soil Po fraction variation. In conclusion, close-to-nature transformation benefits phosphorus accumulation and transformation in *P. massoniana* plantation soils, providing a theoretical basis

for improving soil quality and productivity in these systems.

Keywords: *Pinus massoniana* plantations, soil aggregates, organic phosphorus fractions, close-to-nature silviculture, subtropical

Introduction

Soil phosphorus is a critical element for plant growth and soil development, playing a vital role in biogeochemical cycling processes [?, ?, ?]. Phosphorus availability is generally low in most terrestrial ecosystems, with many systems experiencing phosphorus limitation [?, ?]. In highly weathered tropical and subtropical soils, available phosphorus often binds tightly to soil particles, iron and aluminum oxides, making it difficult for plants to absorb [?, ?]. Additionally, the unique climate pattern of concurrent rainfall and heat in these regions increases phosphorus leaching, further exacerbating limitations on plant growth. Therefore, enhancing soil phosphorus retention capacity and availability is crucial for improving soil quality, increasing land productivity, and maximizing ecosystem services in forest plantations.

Soil phosphorus exists in both inorganic and organic forms, with bioavailability depending on the content of inorganic phosphorus that plants can absorb and organic phosphorus that constitutes the soluble phosphorus pool. Determination of phosphorus fractions is essential for assessing soil phosphorus availability [?, ?, ?]. In forest ecosystems, organic phosphorus originates from organic matter inputs (e.g., litterfall), microbial biomass, and soil organic phosphorus pools, accounting for 20%–80% of total phosphorus [?, ?]. Mineralized organic phosphorus can serve as an available phosphorus source for plants and microorganisms, particularly in highly weathered tropical and subtropical soils [?, ?]. However, direct quantification of soil organic phosphorus has been challenging due to analytical limitations, resulting in fewer studies on organic compared to inorganic phosphorus [?, ?]. Biologically mediated phosphorus transformations, particularly mineralization by extracellular phosphatases, are crucial for plant phosphorus acquisition [?, ?]. Microorganisms secrete phosphatases that hydrolyze certain organic phosphorus compounds into inorganic forms [?, ?], while also immobilizing phosphorus in their biomass, preventing adsorption by soil inorganic colloids [?, ?]. Upon microbial death, this phosphorus is released for plant utilization [?, ?]. Soil microorganisms and organic phosphorus transformation are thus primary factors influencing phosphorus bioavailability [?, ?]. Investigating soil organic phosphorus fractions and their distribution characteristics will deepen our understanding of soil phosphorus cycling and provide new insights for addressing phosphorus limitation in tropical and subtropical regions.

Soil aggregates are fundamental structural units that influence biogeochemical cycling processes and ecosystem functions [?, ?]. Aggregates are typically classified using 0.25 mm as the threshold, with >0.25 mm fractions considered macroaggregates and <0.25 mm fractions as microaggregates [?, ?]. Different aggregate sizes exhibit varying capacities for phosphorus adsorption, fixation, and release, leading to differences in soil phosphorus levels across fractions [?, ?, ?]. Studies in semi-arid regions have shown that both organic phosphorus and microbial biomass phosphorus are higher in macroaggregates than microaggregates, with organic phosphorus fractions showing distinct distribution patterns across aggregate sizes [?, ?]. Research on abandoned farmland converted to tea plantations revealed significant differences in the retention capacity of soil organic phosphorus fractions among aggregate sizes [?, ?]. However, [?, ?] found no significant differences in total, inorganic, or organic phosphorus contents across aggregate fractions in Chinese fir plantations of different ages. The distribution characteristics of soil organic phosphorus and its fractions within aggregates are influenced by regional and environmental factors, making it important to examine these patterns from an aggregate perspective.

Pinus massoniana is an important native tree species widely planted in subtropical China. However, long-term monoculture plantations of this species impede soil nutrient cycling and cause degradation of ecosystem structure and function [?, ?]. To improve soil quality and productivity in *P. massoniana* plantations, more sustainable management approaches are needed. Close-to-nature mixed transformation has gained widespread application as a management strategy involving thinning of coniferous plantations and interplanting with multiple broadleaf species to create uneven-aged, multi-layered mixed stands [?, ?]. This transformation alters species composition and diversity, triggering cascading effects on root exudates, litter properties, and soil microbial communities. Recent studies have demonstrated that close-to-nature transformation can optimize stand structure, improve soil quality, increase timber yield, and enhance ecosystem functioning [?, ?, ?]. However, the accumulation, transformation, and underlying mechanisms of soil organic phosphorus fractions in aggregates following transformation of coniferous monocultures remain unclear. Therefore, this study selected untransformed *P. massoniana* pure plantations and transformed *P. massoniana*-broadleaf mixed plantations to address: (1) the effects of close-to-nature transformation on soil organic phosphorus fractions, and (2) the primary influencing factors. The findings will provide theoretical support for enhancing phosphorus availability and sustainable soil utilization in *P. massoniana* plantations.

1.1 Study Site Description

The study was conducted at the Guangxi Youyiguan Forest Ecosystem National Observation and Research Station in Pingxiang City, Guangxi, China (106°39 50 –106°59 30 E, 21°57 47 –22°19 27 N). Located in a subtropical region with a monsoon climate, the area has a mean annual temperature of 21 °C and mean annual precipitation of approximately 1,400 mm, concentrated between April and September. Soils are acidic red soils derived from highly weathered granite, and the topography consists of low hills. The region features both pure and mixed plantations with diverse artificial forest types.

We selected a coniferous-broadleaf uneven-aged multi-layered mixed plantation (CP) created through close-to-nature transformation of *P. massoniana* and used an adjacent pure *P. massoniana* plantation (PP) with consistent stand management and site conditions as a control. The CP originated from a pure *P. massoniana* plantation established in 1993 at 2,500 plants $\cdot$ hm^{-2}, which underwent three thinning operations in 2000, 2004, and 2007, followed by interplanting with one-year-old seedlings of *Castanopsis hystrix* and *Michelia macclurei* in spring 2008. After transformation, the final stand density was 1,200 plants $\cdot$ hm^{-2}. An adjacent untransformed PP with the same density served as the control. A randomized block design was employed with four blocks, each containing one 400 m^2 (20 m $\times$ 20 m) plot for both PP and CP. In July 2020, vegetation surveys were conducted, and six 1 m $\times$ 1 m nylon mesh litter traps (1 mm mesh size) were randomly installed in each plot at 0.5 m above ground to collect litterfall for biomass determination. Basic stand information is presented in Table 1 .

Table 1 Basic information about the sample site

Forest type	Altitude (m)	Slope (°)	Pinus massoniana		Broad-leaf species		Canopy density
			TH (m)	DBH (cm)	TH (m)	DBH (cm)	
PP	20.04$±0.83	22.83±0.63	11.58±0.20	25.99±1.37	—	—	0.76±0.02b
CP	25.99±1.37	37.55±1.00	12.75				

Note: Values = mean ± SE, n = 4. PP: Pure plantation; CP: Mixed plantation; TH: Tree height; DBH: Diameter at breast height; BD: Soil bulk density; LF: Litterfall mass. Different lowercase letters in the same column indicate significant differences between PP and CP, P < 0.05. The same below.

1.2 Soil Sample Collection and Processing

Soil samples were collected in August 2020 using a systematic sampling approach. Each 20 m $\times$ 20 m plot was divided into 16 equal 5 m $\times$ 5 m grids, with sampling points located at grid intersections. Surface litter, humus, stones, and other debris were gently removed before collecting intact soil cores from the 0–10 cm layer, taking care to minimize structural disturbance. Intact cores were placed in rigid plastic boxes to prevent compression during transport and stored in insulated containers with ice packs before laboratory processing.

In the laboratory, roots and small stones were removed from samples, and soil blocks were gently broken along natural structural planes into fragments $ $5 mm diameter. To ensure sample representativeness, soils from nine sampling points within each plot were thoroughly mixed into a composite sample. Composite samples were air-dried under cool conditions and sieved at approximately

10% moisture content to separate >2 mm macroaggregates, 0.25–2 mm microaggregates, and <0.25 mm fine aggregates. Each sample was then divided: one portion was stored at -20 °C for determination of Po fractions, MBP, and ACP activity, while the other was air-dried for analysis of basic soil physicochemical properties.

1.3 Laboratory Analyses

1.3.1 Soil Physicochemical Properties Soil physicochemical properties were determined following methods described in *Soil Agrochemical Analysis* [?, ?]. Soil bulk density (BD) was measured using the core method. Soil organic carbon (SOC) was determined by $K_2Cr_2O_7$-H_2SO_4 oxidation, and total nitrogen (TN) by the Kjeldahl method. Soil inorganic nitrogen (NH_4^+ and NO_3^-) was extracted with 2 $mol \cdot L^{-1}$ KCl and measured using a continuous flow analyzer (SEAL AutoAnalyzer3). Total phosphorus (TP) was extracted using $HClO_4$-H_2SO_4, and available phosphorus (AP) by HCl-H_2SO_4 extraction, with both extracts analyzed by molybdenum-antimony colorimetry at 882 nm using a multimode microplate reader (Infinite M200 PRO). Soil pH was measured in a 1:2.5 soil/water suspension using a pH meter. Basic soil properties are shown in Table 2 .

Table 2 Basic soil physical and chemical properties of PP and CP

Sample	Forest type	SOC ($g \cdot kg^{-1}$)	TN ($g \cdot kg^{-1}$)	NH_4^+-N ($mg \cdot kg^{-1}$)	NO_3^--N ($mg \cdot kg^{-1}$)	TP ($g \cdot kg^{-1}$)	AP ($mg \cdot kg^{-1}$)	pH	BD ($g \cdot cm^{-3}$)	MWD (mm)
Bulk soil	PP	36.25$±2.31*b*	3.89±0.12*b*	45.60±3.39*b*	38.17±2.46*a*	0.25±0.02*a*	8.57±0.18*b*	4.13±0.04*a*	1.69±0.01	

Note: SOC: Soil organic carbon; TN: Total nitrogen; NH_4^+-N: Ammonium nitrogen; NO_3^--N: Nitrate nitrogen; TP: Total phosphorus; AP: Available phosphorus; pH: Soil pH value; MWD: Mean weight diameter.

1.3.2 Soil Organic Phosphorus (Po) Fractions Soil Po fractions were determined using the Bowman-Cole method [?, ?], which separates Po into four fractions: labile organic phosphorus (LO-P), moderately labile organic phosphorus (MLO-P), moderately recalcitrant organic phosphorus (MRO-P), and highly recalcitrant organic phosphorus (HRO-P). These fractions were sequentially extracted with 0.5 $mol \cdot L^{-1}$ $NaHCO_3$, 0.1 $mol \cdot L^{-1}$ NaOH, and 1.0 $mol \cdot L^{-1}$ H_2SO_4 solutions.

1.3.3 Soil Microbial Biomass Phosphorus (MBP) and Acid Phosphatase (ACP) Activity Soil MBP was extracted using the chloroform fumigation-extraction method [?, ?]. Samples were fumigated for 24 h, then extracted with 50 mL of 0.5 $mol \cdot L^{-1}$ $NaHCO_3$ (soil:extractant = 1:20) by shaking for 30 min. Extracts were filtered and analyzed by molybdenum blue colorimetry. MBP was calculated as:

$$\text{MBP} = \frac{E_{pt} \times K_p}{K_b}$$

where E_{pt} is the difference in phosphorus between fumigated and non-fumigated soils, K_p is the conversion coefficient (0.4), and K_b is the phosphorus recovery rate after KH_2PO_4 addition.

Soil ACP activity was determined following [?, ?]. Fresh soil (1.25 g) was mixed with 125 mL of 50 $mmol \cdot L^{-1}$ sodium acetate buffer (pH 4.5), homogenized for 1 min, and the suspension transferred to 96-well microplates. Using 4-methylumbelliferyl phosphate as substrate, samples were incubated at 25 °C in darkness for 3 h before reaction termination with 5 µL of 0.5 $mol \cdot L^{-1}$ NaOH. Activity was measured at 365–450 nm using a multimode microplate reader (Infinite M200 PRO) [?, ?] with eight replicates per sample, expressed as $nmol \cdot g^{-1} \cdot h^{-1}$.

1.4 Data Analysis

Mean weight diameter (MWD, mm) of soil aggregates was calculated as [?, ?]:

$$\text{MWD} = \sum_{i=1}^{n} X_i \times W_i$$

where X_i is the mean diameter of aggregates in size class i (mm) and W_i is the proportion of aggregates in that class (%).

Differences in soil physicochemical properties, Po fractions, MBP, and ACP activity between PP and CP were tested using independent sample t-tests. One-way ANOVA with least significant difference (LSD) tests compared differences among aggregate fractions within each plantation type. Pearson correlation analysis examined relationships among Po fractions and between Po fractions and MWD, MBP, and ACP. Statistical analyses were performed in SPSS 25.0 (IBM, Chicago, IL, USA) with significance at $P < 0.05$. Principal component analysis was conducted on soil Po fractions to determine if they differed between plantation types. Redundancy analysis (RDA) with Monte Carlo tests identified the importance of environmental factors ($P < 0.05$). Both analyses were performed in Canoco 5.0, and figures were created using Origin 2022.

Results

2.1 Characteristics of Soil Organic Phosphorus Fractions

Close-to-nature transformation altered soil Po fractions in *P. massoniana* plantations (Figure 1 [Figure 1: see original paper]). LO-P and MRO-P did not differ significantly between CP and PP ($P > 0.05$). LO-P concentrations ranged from 1.56–1.67 $mg \cdot kg^{-1}$ in PP and 1.61–1.91 $mg \cdot kg^{-1}$ in CP across bulk soil and all aggregate fractions. MRO-P concentrations were 3.44–4.24 $mg \cdot kg^{-1}$ in PP and 3.06–4.45 $mg \cdot kg^{-1}$ in CP. In contrast, MLO-P and HRO-P were significantly higher in CP than PP in both bulk soil and all aggregate fractions ($P < 0.05$). MLO-P increased by 96.70%, 99.55%, 84.64%, and 53.84% in bulk soil and >2 mm, 0.25–2 mm, and <0.25 mm aggregates, respectively, rising from 3.12–3.67 $mg \cdot kg^{-1}$ in PP to 5.64–6.46 $mg \cdot kg^{-1}$ in CP. HRO-P increased by 70.41%, 39.47%, 30.58%, and 46.79% in the corresponding fractions, from 12.22–16.63 $mg \cdot kg^{-1}$ in PP to 20.34–24.41 $mg \cdot kg^{-1}$ in CP.

The relative proportions of Po fractions differed between plantation types (Figure 2 [Figure 2: see original paper]). In PP, the order was HRO-P (62.53%) > MRO-P (16.56%) > MLO-P (14.05%) > LO-P (6.85%). In CP, the order shifted to HRO-P (65.28%) > MLO-P (18.35%) > MRO-P (10.97%) > LO-P (5.40%). HRO-P showed significant positive correlations with LO-P and MLO-P (Table 3).

Table 3 Correlation coefficients between soil organic phosphorus fractions

	MLO-P	MRO-P	HRO-P
MLO-P	1		
MRO-P	0.372*	1	
HRO-P	0.752**	0.421*	1

Note: indicates significant differences at $P < 0.05$; ** indicates significant differences at $P < 0.01$; *** indicates significant differences at $P < 0.001$.*

2.2 Soil Microbial Biomass Phosphorus and Acid Phosphatase Activity

Soil MBP in CP was significantly higher than in PP across all aggregate fractions ($P < 0.05$) (Figure 3 [Figure 3: see original paper]a). MBP ranged from 12.80–14.65 $mg \cdot kg^{-1}$ in PP and 18.96–19.70 $mg \cdot kg^{-1}$ in CP. ACP activity was also significantly higher in CP than PP ($P < 0.05$) (Figure 3b), with both plantation types showing increasing ACP activity as aggregate size decreased, though differences among fractions were not statistically significant. ACP activity ranged from 125.20–143.29 nmol $\cdot$ g^{-1} $\cdot$ h^{-1} in PP and 145.17–206.46 nmol $\cdot$ g^{-1} $\cdot$ h^{-1} in CP.

2.3 Influencing Factors of Soil Organic Phosphorus Fractions

MWD indicates soil physical structural stability. Relationships between Po fractions and MWD were similar across bulk soil and aggregate fractions (Figure 4 [Figure 4: see original paper]). LO-P and MRO-P showed no significant correlations with MWD (Figures 4a, c). MLO-P was significantly positively correlated with MWD in >2 mm and 0.25–2 mm fractions ($P < 0.05$) and highly significantly correlated in <0.25 mm fractions ($P < 0.01$) (Figure 4b). HRO-P was highly significantly positively correlated with MWD in bulk soil and >2 mm fractions ($P < 0.01$) and significantly correlated in <0.25 mm fractions ($P < 0.05$) (Figure 4d).

MBP was significantly positively correlated with LO-P, MLO-P, and HRO-P ($P < 0.05$) but not with MRO-P (Figure 5 [Figure 5: see original paper]). ACP activity was highly significantly positively correlated with MLO-P and HRO-P ($P < 0.01$) but not with LO-P or MRO-P (Figure 6 [Figure 6: see original paper]).

Redundancy analysis of soil Po fractions in PP and CP explained 65.60% of variation along the first two axes (60.47% by axis 1, 5.13% by axis 2). Environmental factor ranking identified AP, MWD, MBP, and TN as the four main drivers of soil Po fractions ($P < 0.05$), explaining 50.3%, 6.7%, 5.1%, and 3.8% of variation, respectively (Figure 7 [Figure 7: see original paper]).

Discussion

3.1 Effects of Close-to-Nature Transformation on Soil Organic Phosphorus Accumulation

In highly weathered tropical and subtropical soils, organic phosphorus turnover maintains phosphorus supply, with its distribution and transformation determining available phosphorus levels [?, ?]. Our study found significantly higher HRO-P and MLO-P in mixed plantations compared to pure plantations, consistent with previous research showing higher organic phosphorus contents in mixed stands [?, ?, ?]. This likely results from greater organic matter inputs (litterfall, fine root biomass) in mixed plantations [?, ?]. Litter quantity and quality are important factors affecting soil phosphorus forms and availability [?, ?, ?]. HRO-P was the dominant fraction, similar to findings by [?, ?], while LO-P was the least abundant. MRO-P and MLO-P showed intermediate levels. These patterns differ from other studies, likely due to variations in vegetation type, soil type, and environmental conditions [?, ?, ?]. The absence of consistent patterns across aggregate fractions contrasts with previous research [?, ?, ?], suggesting that regional and environmental factors strongly influence organic phosphorus distribution.

MLO-P has the highest bioavailability among organic phosphorus fractions [?, ?]. The significantly higher MLO-P and AP in mixed plantations indicate enhanced phosphorus availability, with MLO-P serving as a potential short-term source of labile phosphorus [?, ?]. The higher HRO-P in mixed plantations suggests nutrient accumulation, likely due to increased litter inputs. The shift in fraction proportions, with MLO-P exceeding MRO-P in CP but not PP, indicates that transformation may convert moderately stable to moderately labile organic phosphorus. The lack of significant difference in LO-P between plantation types may reflect more rapid utilization by the more developed root systems and microbial communities in mixed stands. In highly weathered soils, organic phosphorus mineralization is the primary process delivering phosphate to solution [?, ?], though changes in inorganic phosphorus fractions require further investigation to fully understand phosphorus dynamics.

3.2 Effects of Close-to-Nature Transformation on Soil Phosphorus Transformation

Soil microorganisms are sensitive indicators of nutrient changes in terrestrial ecosystems. Microbial biomass phosphorus represents 8%–11% of total phosphorus in surface soils (0–15 cm) [?, ?] and is the most active organic phosphorus fraction. Higher ratios of MBP to organic phosphorus indicate greater organic phosphorus activity and faster transformation [?, ?]. The significantly higher MBP in transformed plantations reflects improved soil nutrient conditions that promote microbial growth and influence different phosphorus forms [?, ?]. Our finding of significant positive correlations between MBP and LO-P, MLO-P, and HRO-P aligns with previous research. Long-term soil development results in most weathered phosphorus being utilized by microorganisms and plants [?, ?], so changes in microbial biomass affect phosphorus turnover and availability, particularly in tropical and subtropical soils [?, ?, ?].

Microorganisms produce soil enzymes to regulate resource limitation, with phosphatases playing a key role in phosphorus availability by hydrolyzing organic compounds into plant-available inorganic phosphorus [?, ?]. Phosphatase activity represents the potential capacity for phosphorus release [?, ?, ?] and is commonly used to evaluate phosphorus availability [?, ?]. The significantly higher phosphatase activity and AP content in transformed plantations suggest that mixed stands enhance phosphorus availability through increased phosphatase activity, indicating strengthened organic phosphorus mineralization [?, ?]. Changes in stand structure increase litter inputs and nutrient return, altering soil conditions to favor microbial proliferation and activity, leading to greater phosphatase secretion and mineralization of recalcitrant phosphorus fractions [?, ?]. The significant positive correlations between some organic phosphorus fractions and phosphatase activity contrast with findings of negative relationships [?, ?], possibly due to higher substrate concentrations in our mixed plantations stimulating microbial activity and phosphatase production [?, ?]. Previous studies have shown that phosphorus mineralization increases with organic phosphorus concentration [?, ?], with mineralization rates potentially more dependent on organic phosphorus supply than inorganic phosphorus demand. Regardless of whether phosphatase activity is demand- or supply-driven, it is linked to organic phosphorus fraction changes that affect phosphorus availability [?, ?], highlighting the complexity of soil phosphorus transformation under different environmental conditions.

Vegetation type influences phosphorus transformation and distribution in unfertilized soils [?, ?]. In our study, vegetation change likely affected organic phosphorus accumulation and transformation by altering both abiotic factors (pH, SOC, TN) and biotic factors (MBP, ACP). Redundancy analysis identified AP, MWD, MBP, and TN as the primary drivers of soil organic phosphorus fractions. The positive relationship between AP and phosphorus fractions indicates that higher AP results from conversion of organic phosphorus fractions, with different forms directly affecting phosphorus availability [?, ?]. The significant correlations between MWD and most organic phosphorus fractions, particularly MLO-P and HRO-P, demonstrate that close-to-nature transformation can increase soil organic phosphorus by improving aggregate structure. This aligns with findings that improved soil structure enhances organic phosphorus content by physically protecting organic compounds from degradation and erosion, thereby increasing organic matter storage and nutrient cycling [?, ?]. MBP was a major environmental factor influencing organic phosphorus fractions, consistent with previous research [?, ?]. The positive correlations between ACP and phosphorus fractions likely reflect improved stand structure creating favorable conditions for microbial activity, thereby increasing ACP activity and promoting organic phosphorus transformation [?, ?, ?, ?]. This contrasts with reports of negative correlations where increased ACP activity resulted from phosphorus limitation [?, ?]. Soil organic phosphorus content is related to organic matter content; when phosphorus is limiting or strongly sorbed, AP primarily originates from mineralization of organic phosphorus in soil organic matter [?, ?, ?, ?]. SOC provides adsorption sites for phosphorus and carbon sources for microorganisms, promoting mineralization of recalcitrant phosphorus and increasing AP [?, ?]. In our redundancy analysis, SOC explained only 0.6% of organic phosphorus variation, though its individual effect reached 45.9%, suggesting overlapping explanatory power with other factors (AP, MWD, MBP, TN). Additionally, pH was negatively correlated with most organic phosphorus fractions, consistent with previous findings that organic phosphorus solubility varies with pH and precipitation accelerates at lower pH [?, ?].

In summary, close-to-nature transformation of *P. massoniana* plantations increased litter inputs and soil organic matter, favoring organic phosphorus accumulation. The improved soil environment enhanced microbial activity and phosphatase production, promoting mineralization of organic phosphorus to inorganic available phosphorus. This maximized phosphorus utilization by plants and microorganisms, with microbial biomass phosphorus released upon microbial death contributing to the organic phosphorus pool (Figure 8 [Figure 8: see original paper]). Future research should examine inorganic phosphorus fractions to more directly assess phosphorus transformation, and further investigate the key mechanisms by which microorganisms regulate soil phosphorus fractions.

Conclusion

Close-to-nature transformation significantly altered soil organic phosphorus fractions in *P. massoniana* plantations. Soil available phosphorus, mean weight diameter, microbial biomass phosphorus, and total nitrogen were the primary drivers of these changes. The transformed plantations exhibited improved soil quality, enhanced microbial activity, and increased acid phosphatase secretion, which facilitated mineralization of organic phosphorus to inorganic forms and increased phosphorus availability, thereby alleviating phosphorus limitation in this subtropical plantation ecosystem. These findings have important practical significance for developing *P. massoniana* plantations with better soil quality, higher productivity, more stable ecosystem structure, and stronger ecological service functions.

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