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Effects of Long-Term Chemical and Organic Fertilizer Application on Soil Phosphorus Fractions in Lei Bamboo Plantations

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Abstract: Phosphorus (P) is a key nutrient in forest ecosystems in subtropical regions. However, the effects of the long-term application of organic amendments on P availability are poorly understood. Here, we compared the soil P fractions and associated soil properties in southern Chinese Lei bamboo plantations using both an intensive management system (IMS) and a traditional management system (TMS). The results show that the IMS significantly ($p < 0.05$) increased the soil total organic carbon (C), soil ammonium N (NH_4-N), total P, and available potassium content; microbial biomass C and P content; P activation coefficient, and soil C:P ratios, while significantly ($p < 0.05$) decreasing pH and microbial C:P. The labile-P-to-total-phosphorus-content ratio increased significantly in the IMS (46%) compared with that in the TMS (32%). The selected soil properties (except nitrate [NO_3-N]) were significantly related to soil P fractions (except for concentrated HCl-extracted organic P). The IMS had a higher C:P ratio and labile P content than the TMS, suggesting that the IMS could promote soil P transformation and availability. Overall, the IMS increased soil P availability and supply capacity, and the changes in P forms could be a risk factor for P loss.

Keywords: bamboo plantations; forest management; long-term fertilization; phosphorus loss; phosphorus availability

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1. Introduction

The bamboo forest, also known as "the second largest forest in the world," comprises more than 1200 species [1]. The 9th National Forest Resources Survey estimates that there are 6.01 million hectares of bamboo forests in China. Lei bamboo is a famous and excellent bamboo shoot species in China, with its tender, crispy, and refreshing shoots, as well as its high nutritional value and yield; given these characteristics, Lei bamboo has emerged as a high-quality agricultural and forestry product for export in China [2]. These objectives are attained via the utilization of intensive management techniques, such as overfertilization and mulching with organic amendments, with the purpose of improving soil moisture and temperature in the winter, thereby increasing bamboo shoot production and economic efficiency [3,4].

Furthermore, organic amendments have been used as exogenous fertilizers to increase the soil stability, biomass of soil microorganisms, and activity of some soil enzymes, improving the effectiveness of soil remediation [5–8]. Rice husk is one of the common organic amendments, which is high in C/P ratio (133.4) and produces phenolic acid substances, which have an allelopathic effect on the plant and are effective at inhibiting disease [9]. Long-term mulching with organic amendments, however, causes an imbalanced distribution of nutrients, including soil carbon and nitrogen, as well as excessive nutrient accumulation [10]. The impact of organic amendments on the cycle of phosphorus has been less well studied. In addition, there is a coupled relationship between soil carbon and phosphorus. This interaction is caused by soil microbes' mineralization of organic phosphorus to produce carbon [11–13]. To date, there are no effective measures to address the issues related to the long-term intensive management of bamboo forests, particularly as it pertains to P cycling, which is crucial for comprehending the coupling relationship between carbon and phosphorus in forest ecosystems.

P ranks second among the nutrients most required by plants for growth and productivity [14]. P deficiency causes an irregular roots structure by changing the number and density of lateral roots, decreasing enzyme activities related to C and N metabolism, and disrupting the structure and abundance of the soil microbial population [15–17]. Additionally, P deficiency also inhibits metabolic and biosynthetic processes such as photosynthesis and respiration in plants [18,19]. Soil P is a macronutrient with low mobilization, where only relatively small amounts can be taken up and used by plants [20]. Soil inorganic P (Pi) is the preferred source for plant uptake and is present in the soil solution. To release inorganic P for plants to absorb, soil organic P (Po) must be mineralized. The process of soil P turnover is influenced by a variety of biotic and abiotic variables, with turnover times ranging from a few weeks to several months [21,22]. However, different P fractions have different bioavailabilities for uptake by plants and microorganisms, which are crucial for the biogeochemical processes associated with the P cycling [23]. Therefore, changes in the P fractions within the soil of intensively managed bamboo forests can largely determine P availability in the soil, thereby affecting bamboo forest production. The dynamics of the P fraction depend on various factors, such as topography, climatic environment, microorganisms, and vegetation [24–26]. Ding et al. [27] found that applying organic matter amendments in arid and semiarid areas reduced soil salinity, increased organic matter content, and increased effective soil P levels. Verma et al. [28] discovered that organic fertilizers were more responsive to changes in NaOH-P within acidic soil. This information was used to demonstrate the effects of fertilizers on soil. Zhang et al. [29] found that after 10 years of long-term fertilization, phosphorus retention in black, brown, and purple soils in China differed, and the form of phosphorus changed markedly. The surface layer of black soil is rich in the organic form of P, whereas the deep layer is rich in P in its inorganic form. Brown tide and purple soil are both rich in the inorganic form of P. Therefore, studying the changes in soil properties and P fractions associated with the long-term application of chemical fertilizers and organic amendments contributes to a better understanding of biochemical cycling and P bioavailability in bamboo plantations.

It is still unknown how intensive management affects the soil P fractions in bamboo plantations, particularly how organic C buildup may affect soil P availability. This study investigated the effects of long-term intensive management (using organic amendments) and traditional management on the soil properties of Lei bamboo plantations. This study specifically aimed to: (a) investigate the effects of the long-term use of organic amendments on soil physical chemical properties and P fractions; (b) examine the relationships between soil C:P stoichiometry and P fractions during the long-term application of organic amendments; and (c) characterize the relationship between soil P availability and C sequestration.

2. Materials and Methods

2.1. Study Area Description and Soil Collection

The research region is located in Hangzhou, Zhejiang Province, southeast China, in the Fuyang District (119°72′ E, 30°05′ N). The study area's sample plots' climate details have already been described [10]. Briefly, the region has a mid-latitude subtropical monsoon climate, with a mean annual precipitation and temperature of 1452.0 mm and 16.2 °C, respectively. We established the experimental comparison plantations, namely, Lei bamboo plantation with an intensive management system (IMS) and a plantation with a traditional management system (TMS). The two comparison plantations had the same initial site conditions. During the experimental period (2005–2021), the annual input of chemical fertilizers (NPK15–15–15) was 600 kg·ha^{-1} in the TMS. In addition to applying the same amount of chemical fertilizer, the IMS used 40 t·ha^{-1} organic amendment mulch (rice husk) in November and December to raise the soil temperature and maintain soil moisture for the early bamboo shoots' emergence [4]. The IMS was performed over 16 years.

Five subplots (10 × 10 m^2) were randomly established in each selected plantation in October 2021. Soil samples were collected from a depth of 0–20 cm, with five different points being taken from each subplot, which were mixed to form a composite sample. Samples for the soil property analysis were sieved (<2 mm) to remove rough stones and roots. The soil samples were then divided into two parts. An aliquot of each fresh sample was frozen at 4 °C for further analysis, and the remaining samples were air-dried to measure soil properties and P fractions.

2.2. Soil Basic Properties

For each sample, the soil pH was recorded from a soil suspension of soil: water (1: 2.5; w·v^{-1}) using a pH meter (PHS-3E; REX, China). The total soil organic C (TOC) was analyzed using a total organic carbon analyzer (Multi N/C 3100; Analytik Jena, Germany). Soil nitrate and ammonium N (NO_3-N, NH_4-N) content was extracted using 2 M potassium chloride (KCl) and determined using UV spectrophotometry. The total phosphorus (TP) content was determined using $HClO_4$ and H_2SO_4. Available potassium (AK) content was determined using the novAA Atomic Absorption Spectrometer (Analytik Jena, Germany). Microbial biomass C (MBC) and P (MBP) were determined using the chloroform fumigation extraction method [30,31].

2.3. Fractionation Procedure for Soil P

The protocols for P fractionation extraction have been described by Tiessen and Moir [32] and Hedley et al. [33] (Figure 1). Briefly, air-dried soil (0.5 g) was collected and shaken with 30 mL 0.5 M $NaHCO_3$ (pH 8.5), 0.1 M NaOH, and 1 M HCl for 16 h each to extract the $NaHCO_3$-P, NaOH-P, and D.HCl-P fractions, respectively. The soil residue was extracted with 10 mL of concentrated HCl at 80 °C (conc. HCl-P). The final residue was boiled with 5 mL of concentrated H_2SO_4 and 10 drops of $HClO_4$ (residual P). Soil Pi was calculated as the sum of $NaHCO_3$ Pi-, NaOH-Pi, and HCl-Pi, and soil organic phosphorus (Po) was calculated as the difference between total P and Pi [34–36].

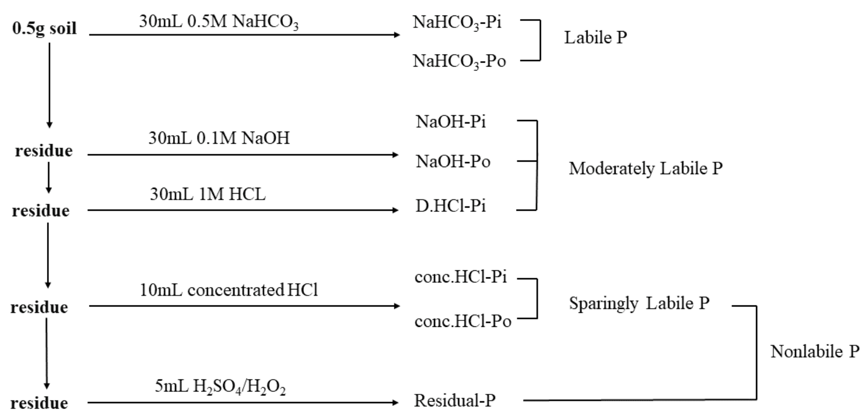

Figure 1. Flow diagram of the P fractionation method.

2.4. Statistical Analysis

To facilitate interpretation, P fractions were classified into three main groups according to their availability: labile P, moderately labile P, and non-available P (sparingly labile P and residual P) [37]. Labile P contained $NaHCO_3$-P; moderately labile P consisted of 0.5 M NaOH-P and D.HCl-Pi; similarly, non-available P was composed of concentrated HCl-P and residual P. All statistical analyses were performed using SPSS 19. Significant differences at $p < 0.05$ were assessed by analysis of variance (ANOVA) and the least significant difference (LSD) test. Visual analyses were performed using the vegan and ggplot 2 packages in R version 4.2.1. The correlation coefficient between soil physicochemical properties and soil phosphorus fractions was also determined. Using the Origin 2022b version, we investigated the relationship between changes in the soil phosphorus fractions and the soil C:P ratio.

3. Results

3.1. Soil Basic Properties

The soil properties differed significantly between the two management practices (Table 1). Compared with the TMS plots, the IMS plots had significantly ($p < 0.05$) lower pH values and ($p < 0.05$) higher levels of soil TOC, MBC, TP, AP, MBP, AK, NH_4-N, soil C:P, and P activation coefficient (PAC). However, no significant differences ($p > 0.05$) were observed between the two management practices for NO_3-N and microbial C:P.

Table 1. Soil basic properties under different management systems.

	TMS	IMS
pH	4.48 ± 0.03 a	3.90 ± 0.05 b
TOC ($g \cdot kg^{-1}$)	34.38 ± 0.20 b	83.07 ± 0.99 a
MBC ($mg \cdot kg^{-1}$)	356.67 ± 13.55 b	793.78 ± 16.36 a
NH_4-N ($mg \cdot kg^{-1}$)	21.37 ± 2.64 b	30.57 ± 0.75 a
NO_3-N ($mg \cdot kg^{-1}$)	10.74 ± 0.17 a	10.81 ± 0.32 a
TP ($g \cdot kg^{-1}$)	1.69 ± 0.00 b	2.81 ± 0.06 a
AP ($mg \cdot kg^{-1}$)	304.50 ± 5.42 b	789.06 ± 8.24 a
MBP ($mg \cdot kg^{-1}$)	43.26 ± 2.26 b	115.22 ± 5.48 a
AK ($mg \cdot kg^{-1}$)	68.24 ± 0.55 b	280.94 ± 1.48 a
Microbial C:P	8.35 ± 0.61 a	6.95 ± 0.33 a
Soil C:P	46.18 ± 1.85 b	63.31 ± 6.13 a
PAC	0.18 ± 0.00 b	0.28 ± 0.01 a

1Values are expressed as the mean (n = 5) ± SE. Values with different lowercase letters on the same row indicate a significant difference ($p \leq 0.05$) between to the two management practices (LSD test). TMS: traditional management system; IMS: intensive management system. TOC: Total organic carbon; MBC: Microbial biomass carbon; NH_4-N: Soil ammonium nitrogen; NO_3-N: Soil nitrate nitrogen; TP: Total Phosphorus; AP: Available phosphorus; MBP: Microbial biomass Phosphorus; AK: Available K; Soil C:P, TOC: TP; PAC, the ratio of AP: TP; Microbial C:P, MBC: MBP.

3.2. Soil P Fractions

Labile, moderately labile, and sparingly labile P increased significantly under the IMS (Table 2). Compared with the TMS, the content of $NaHCO_3$-Pi and $NaHCO_3$-Po in the fractions was elevated by 62% and 64%, respectively, in the IMS. Additionally, the $NaHCO_3$-Pi content was at its maximum compared with the other P fractions. In terms of moderately labile P, the P fractions extracted by NaOH, NaOH-Pi and NaOH-Po, increased by 32% and 42% in the IMS, respectively, whereas the D.HCl-Pi fractions underwent a significant decrease of 35%. As for sparingly labile P, the conc. HCl-Po trend was not consistent with that of conc. HCl-Pi; the concentration of conc. HCl-Pi did not change significantly in the IMS and was the lowest in the P fraction. Compared with the TMS, the content of residual P fractions in the IMS increased by 54%.

Our results show that the IMS significantly affected the relative content of each P fraction (Figure 2). The relative level of labile P was 46% of the total P, indicating an increase associated with the IMS treatment (Figure 2a). Furthermore, the relative contents of $NaHCO_3$-Pi and $NaHCO_3$-Po in relation to total P increased by 8% and 6%, respectively. Notably, $NaHCO_3$-Pi contributed the most to the total P in the IMS (28%) (Figure 2b). The IMS also altered the composition of moderately labile P. Following organic amendment application, the relative content of moderately labile P decreased from 52% to 42% (Figure 2a). The proportion of NaOH-extracted and 1 M HCl-extracted Pi in moderately labile P decreased with organic amendment application; however, the proportion of NaOH-Po was unchanged (Figure 2b). Compared with the TMS, applying organic amendments did not change the relative content of Nonlabile P; however, the composition varied within a limited range of 1–2% (the relative content of conc. HCl-P decreased) (Figure 2b).

Table 2. Mean content of soil P fractions ($g \cdot kg^{-1}$) under different management systems.

P Fraction	TMS	IMS
$NaHCO_3$-Pi	0.31 ± 0.04 b	0.77 ± 0.02 a
$NaHCO_3$-Po	0.18 ± 0.06 b	0.50 ± 0.03 a
ΣLabile P	0.49 ± 0.01 b	1.28 ± 0.04 a
NaOH-Pi	0.30 ± 0.00 b	0.44 ± 0.02 a
NaOH-Po	0.32 ± 0.02 b	0.55 ± 0.02 a
D.HCl-Pi	0.26 ± 0.01 a	0.17 ± 0.08 b
ΣModerately P	0.88 ± 0.43 b	1.16 ± 0.04 a
Conc.HCl-Pi	0.08 ± 0.00 b	0.11 ± 0.00 a
Conc.HCl-Po	0.06 ± 0.01 a	0.08 ± 0.00 a
ΣSparingly labile P	0.14 ± 0.02 a	0.19 ± 0.01 a
Residual P	0.06 ± 0.01 b	0.13 ± 0.01 a
ΣNonlabile P	0.20 ± 0.02 b	0.32 ± 0.04 a

1Values are expressed as the mean (n = 5) ± SE. Values with different lowercase letters on the same row indicate a significant difference ($p \leq 0.05$) between to the two management practices (LSD test). ΣLabile P ($NaHCO_3$-Pi, $NaHCO_3$-Po); ΣModerately labile P (NaOH-Pi, NaOH-Po, D.HCl-Pi); ΣSparingly labile P (Conc.HCl-Pi, Conc.HCl-Po); ΣNonlabile P (ΣSparingly labile P, Residual P).

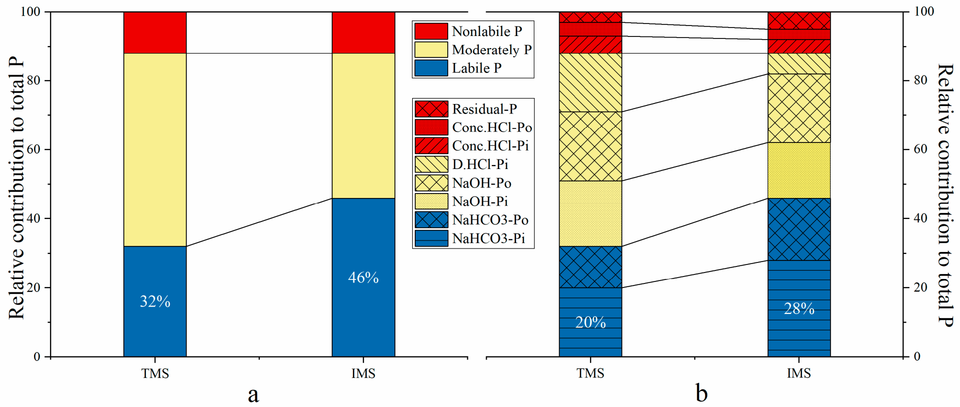

Figure 2. Percentage of each phosphorus (P) fraction under different management practices. (**a**) Percentage of Labile P, Moderately labile P, Nonlabile P. (**b**) Percentage of $NaHCO_3$-Pi, $NaHCO_3$-Po, NaOH-Pi, NaOH-Po, D.HCl-Pi, Conc.HCl-Pi, Conc.HCl-Po, and Residual P.

Compared with the TMS, the contents of Po and Pi increased significantly in the IMS (Figure 3). Specifically, in the IMS, the Pi content was 1.18 times greater than that of Po. However, with organic amendment application, the relative content of Pi decreased from 60% to 54%, whereas the relative content of Po increased from 40% to 46%.

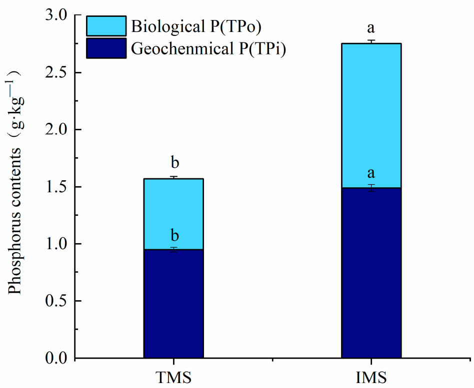

Figure 3. Biological P and geochemical P under different management practices. Different lowercase letters indicate significant differences $p \leq 0.05$ (LSD test) for different business practices. Biological phosphorus is total organic phosphorus (TPo); geochemical phosphorus is total inorganic phosphorus (TPi).

3.3. Correlation Analysis between P Fractions and Soil Properties

The correlation coefficients between the soil P fractions and soil properties are shown in Figure 4. NH_4-N content was significantly correlated with all extracted P fractions (except for conc. HCl-Po and residual P), whereas NO_3-N was not correlated with all the P fractions. TP, AP, and MBP were significantly positively correlated with $NaHCO_3$-Pi/Po, NaOH-Pi/Po, and conc. HCl-Pi, negatively correlated with D.HCl-Pi (R^2 = −0.89, 0.90, and 0.91), and showed no significant correlation with conc. HCl-Po ($p > 0.05$). AK was similar to AP, exhibiting a higher correlation with all P fractions. In contrast, soil pH was significantly negatively correlated with extracted P ($NaHCO_3$-Pi, R^2 = −0.94; $NaHCO_3$-Po, R^2 = −0.88; NaOH-Po, R^2 = −0.87; NaOH-Po, R^2 = −0.90; conc. HCl-Pi, R^2 = −0.88; residual P, R^2 = −0.88), and significantly positively correlated with D.HCl-Pi (R^2 = 0.81). TOC content was positively correlated with the soil $NaHCO_3$-Pi and NaOH-Pi contents (R^2 = 0.99, 0.92); conversely, it was negatively correlated with D.HCl-Pi fractions (R^2 = −0.91). No correlation was observed between conc. HCl-Pi/Po fraction and TOC. MBC exhibited similar relationships to that between the TOC and P fractions; MBC was highly correlated with $NaHCO_3$-Pi, NaOH-Pi, $NaHCO_3$-Po, and NaOH-Po fractions, and all of these correlations were positive. Furthermore, the linear regression results show that soil C:P ratios were positively correlated with labile and moderately labile P (Figure 5).

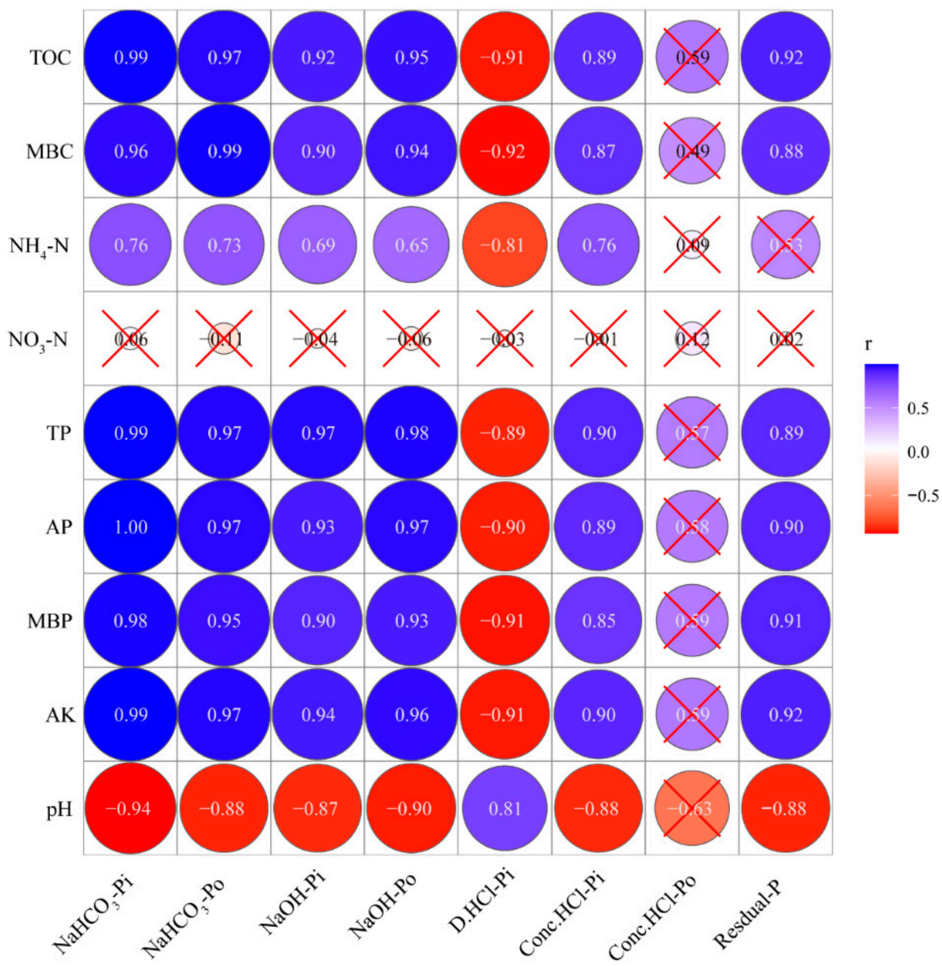

Figure 4. Pearson correlation analysis between soil P fractions and soil properties.

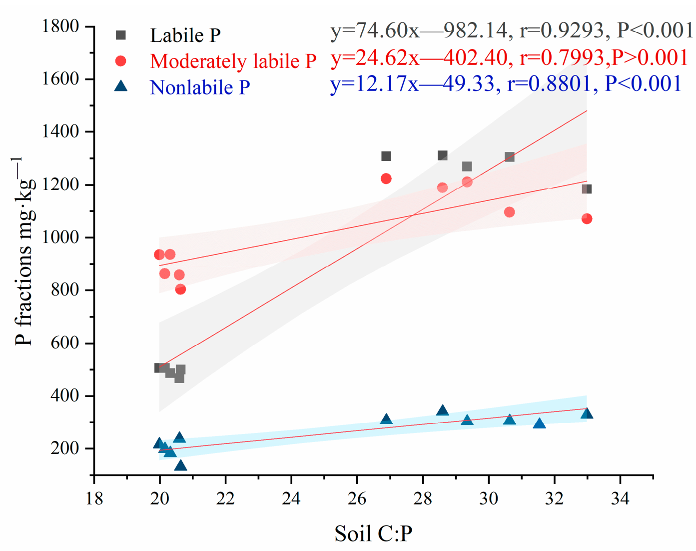

Figure 5. Linear regression indicating the relationship between soil C:P ratios and P pools. Labile P ($NaHCO_3$-Pi, $NaHCO_3$-Po), Moderately labile P (NaOH-Pi, NaOH-Po, D.HCl-Pi), Nonlabile P (conc.HCl-Pi, conc.HCl-Po, Residual P).

4. Discussion

4.1. Impacts of Long-Term Application of Organic Amendments on Soil Physicochemical Properties

This study shows that the IMS significantly increased soil TOC, MBC, NH_4-N, MBP, AP, and AK levels (Table 1). This is due to the ability of soil microbial activity and soil respiration to accelerate the rate of decomposition of nutrients (C/N, P, and K) in organic amendments [38–40]. Consequently, the nutrients in the organic matter were higher in concentration than the crop requirements, causing a significant buildup of AP, N, and K. In addition, organic amendments have direct and indirect effects on the TOC [40], with residues of recalcitrant C compounds, the coupling effect of trace metal ions, and changes in the microbial community effectively increasing soil organic C levels [38,41]. Moreover, organic amendments stimulated the overall fixation rate of NH_4-N and prevented NO_3-N accumulation in the soil upon fierce competition with nitrifying agents for available NH_4-N [42]. According to the results of this study, soil MBC was significantly negatively correlated with NH_4-N and significantly positively correlated with NO_3-N [43]. Thus, the IMS constraint on nitrification processes leads to NH_4-N accumulation in the soil. Increased P content indicates that the P added to the IMS is stored in the soil and not fully used by the plant, as it exceeds the P concentration required by the plant [42]. Furthermore, adding a lot of organic amendments lowers soil pH and generates large amounts of hydrogen ions (H^+), which may be triggered by an increase in organic acid secretion [44] and an increase in nitrification processes (leaching of NO_3-N) [45].

4.2. Impacts of Long-Term Application of Organic Amendments on the P Fractions and MBP

$NaHCO_3$-Pi and $NaHCO_3$-Po are the active fractions in plants and microbes [46]. The labile P (1.28 $g \cdot kg^{-1}$) content was highest in the soil under the IMS conditions; $NaHCO_3$-Pi and $NaHCO_3$-Po levels increased by 60% and 64%, respectively (Table 2), consistent with the findings of Ahmed et al. [47], who showed that the combined application of inorganic P fertilizers and manure enhanced labile P. That the IMS improves soil organic matter is one explanation. $NaHCO_3$-Pi, a transient P fraction that is accessible to plants, is abundant in soils high in organic matter [48,49]. Soil microorganisms functioning as sources and sinks for labile P is another factor [50]. Zhang et al. [10] showed that the IMS had a marked influence on the structure and diversity of soil bacterial communities, which include a large number of bacteria involved in the C and N cycles, stimulating the microbial demand for P, where $NaHCO_3$-Po acts as a rapid replenishment of available P sources [45]. In addition, this study discovered that the labile P fraction represents a large proportion of the TP (labile

P accounts for 61% of TP) (Figure 2). Thus, the prolonged use of organic amendments encourages the accumulation of labile P, particularly $NaHCO_3$-Pi, which poses a high risk for P loss.

The NaOH-Pi/Po content in the IMS plots increased significantly as a result of this investigation. This finding is consistent with the most relevant studies, including Yan et al.'s [51] study showing that the deposition of organic amendment lowered soil pH, increased the adsorption capacity for Fe-Al oxides, and promoted the formation of complexes with additional free P. Meanwhile, Fe and Al mineral concentrations are relatively high in acidic soils (pH < 5) [52,53]. Furthermore, in the current study, the content and ratio of D.HCl-Pi sharply declined with the long-term use of organic amendments (Table 2), which is consistent with Nan's finding [54]. Organic molecules released by microbial decomposition of organic matter have been shown to interfere with the binding of P and calcium (Ca) in soils. The D.HCl-Pi may be Ca-P, because Fe-P or Al-P remaining after NaOH extraction is insoluble in acid [52]; when the easily extractable P is depleted, it is then mobilized in the labile fraction. Soltangheisi et al. [55] speculated that cover crops should convert the D.HCl-Pi fraction to other available P fractions for plant uptake.

Moreover, the stability of HCl-extractable P strongly depends on the pH [37]. We found a significant positive correlation between D.HCl-Pi and pH (R^2 = 0.81, $p < 0.05$) (Figure 4). The study area included the subtropical region with acidic soils and poorly stabilized P fractions. Notably, organic amendments significantly lowered soil pH (Table 1), The combined use of organic amendments and fertilizers stimulates microbial demand for P, resulting in the secretion of more phosphatases or more H^+ to promote the dissolution of insoluble phosphates and increase protons (H^+) in the soil solution, leading to soil acidification [56]. Therefore, the D.HCl-P decreased, possibly because of a decreased soil pH, thereby causing Ca dissolution. Additionally, the long-term application of organic amendments significantly increased the moderately available P level (Table 2). This is consistent with Khan et al.'s [37] findings, who also noticed the presence of a large amount of moderately available P in the topsoil. Consequently, the long-term application of organic amendments transformed moderately labile P and enhanced the proportion of its fractions in the soil, facilitating P subsurface transport.

Non-available P is the most recalcitrant form of P. Notably, non-available P does not readily exchange with soil solutions and includes HCl-P and residual P fractions [57]. In this study, the residual P content in the IMS treatment was significantly elevated compared with the TMS treatment (Table 2), which was consistent with the results of Verma et al. [28], who showed that NPK treatment resulted in an increase in residual P, which was attributed to the participation of these phosphorus fractions in the long-term phosphorus cycle [47]. Residual P is a stereoisomer of inositol hexakis phosphate and is the most stable form of soil organic P synthesized by plants that enter the soil upon the direct deposition of plant material [42]. Therefore, residual P accumulation results from a long-term interaction between organic amendments and Lei bamboo roots.

Soil microorganisms are the most sensitive indicators that can rapidly and accurately sense detect changes in soil quality [41]. Excluding soil inorganic and organic P fractions, organic amendments also increased soil MBC and MBP (Table 2), consistent with the findings of Zeng [58] in torch pine and bamboo plantations. The availability of readily metabolizable C from organic amendments may be the main cause of the increase in MBC. This beneficial effect is caused by plant growth and microbial proliferation, both directly and indirectly [40]. Wang et al. [59] showed that microbial demand for carbon promotes MBP, and that soil MBP is highly dependent on the quantity and quality of organic matter returned to the soil, particularly volatile organic matter. In addition, degrading organic amendments stimulates soil phosphatase to synthesize aryl sulfate lyase, thereby promoting the degradation of organic matter [40]. In synthesis, the P fraction is influenced by organic amendments, explaining the positive effect on soil P supply induced by the increase in the labile and moderately labile P fractions in the IMS.

4.3. Impacts of Long-Term Application of Organic Amendments on Soil Stoichiometry and Its Ecological Implication

The long-term application of organic amendments can play an important role in soil P dynamic cycling [4,60]. This study revealed that organic amendment significantly increased the geochemical (Pi) and biochemical (Po) fractions (Figure 3), providing slow-release P sources for bamboo and soil microorganisms. The importance of geochemical (Pi) and biochemical (Po) factors in soil P dynamics has been supported by previous studies; Po is considered the ultimate source of soil AP, explaining why lignin in rice straw can increase the AP functional group via the competitive adsorption of phosphorus [61–63]. Thus, the long-term application of organic amendments effectively increased the relative Po content. Nevertheless, by adding ^{14}C or ^{33}P–labeled glucose-6-phosphate to soil, Christine et al. [64] found that microorganisms used more C than phosphorus derived from glucose-6-phosphate, suggesting that the microbial mineralization of Po is microbially driven by the need for C, rather than P. The coupling between carbon and phosphorus facilitates the accumulation of soil Po. Therefore, the long-term combined use of organic amendments and fertilizers in bamboo plantations results in a higher rate of Po accumulation than Po mineralization.

Furthermore, consistent with previous studies [65], the proportions of labile and moderately labile P fractions in this study were positively correlated with soil TOC and MBC (Figure 4), suggesting a possible role of TOC in accumulating labile and moderately labile P [37,47]. One explanation is that the long-term application of organic amendments raises the relative abundance of *Proteobacteria (Proteobacteria* primarily contribute to changes in soil C and N motion), effectively enhancing soil nutrient cycling [10,66]. This in turn stimulated the activity of soil labile and moderately labile P fractions. Another explanation is the increased number of negatively charged functional groups in the TOC, which interact with Fe and Al oxides to facilitate the desorption of P on the surfaces of the oxides [67,68]. In addition, Al oxides are insensitive to redox and have high affinities for P, which can significantly increase labile P. Therefore, the long-term application of organic amendments affects the soil C: P ratio and TOC content, increasing soil labile P and soil phosphorus availability.

Soil stoichiometry directly reflects soil fertility and assesses the soil's P status [69]. This study showed that the soil C:P ratio was significantly increased. In contrast, the microbial C:P ratio did not change significantly in the IMS compared to that in the TMS (Table 2), consistent with the findings of Zhang [70]. The soil C:P ratio is closely related to phosphatase activity and *phoD* gene abundance [54], and acid phosphatase and alkaline phosphatases are crucial in promoting the mineralization of Po via the enzymatic conversion of Po to inactive Pi [71]. Therefore, our data support previous findings that increasing soil C:P ratio destabilizes labile Pi accumulation. Contrary to Muhammad et al.'s [72] findings, which stated that a high soil C:P ratio was negatively correlated with labile P, this investigation revealed that the soil C:P ratio was positively correlated with labile P and moderately correlated with P (Figure 5). Different forest and agricultural soil types can explain these conflicting results [70]. As mentioned above, a higher soil C:P ratio would increase the amount of labile P, thereby encouraging soil P conversion and availability.

5. Conclusions

Our study's findings indicate that acidification and nutrient imbalance in bamboo forest soils after the long-term application of organic amendments severely altered the soil P fraction. The most evident increases in labile and moderately labile P facilitated the mobilization of soil P for plant availability, directly promoting P conversion and reducing its accumulation in the soil. In addition, organic C mineralization and high soil C:P ratios promoted the conversion of Po to labile P, regulating the soil P cycle. Taken together, these findings indicate that the long-term application of organic amendments can alleviate P deficiency in bamboo plantations and increase the soil P's supply capacity and potential, providing insights into the drivers of P dynamics and helping mitigate P loss.

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