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Effects of different mulching measures on soil physicochemical properties and phosphorus fractions in orchards in the southeast hilly region of China

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Abstract: Soil phosphorus plays an important role in the soil ecological environment and sustainable development of the fruit industry in the soil hilly region of southern China, but the impact of different mulching measures on soil available phosphorus and phosphorus fractions in orchards remains unclear. In this study, soil basic physicochemical properties, available phosphorus, inorganic phosphorus fractions and their interrelationships under natural grass cover (NG), film mulch (FM) and clean tillage (CK) in orchards were explored. Compared to CK treatment, both FM and NG treatments have been shown to increase the contents of soil organic carbon (SOC), total nitrogen (TN), and available nitrogen (AN). Additionally, compared with the FM treatment, the NG treatment increased total phosphorus (TP), total potassium (TK), available potassium (AK), and soil acid phosphatase (S-ACP), resulting in greater improvements in soil fertility. The NG treatment increased the contents of aluminium-bound phosphate (Al-P) and iron-bound phosphate (Fe-P) in the 0–40 cm soil layer, whereas the FM treatment decreased the contents of Fe-P and Al-P and increased the content of occluded phosphate (O-P). Compared with the CK treatment, the NG treatment significantly increased the available phosphorus in the 0–40 cm soil layer, whereas the FM treatment significantly decreased it. Redundancy analysis revealed that pH and S-ACP were the main factors affecting soil phosphorus components. Al-P, Fe-P, and S-ACP were the three factors with the highest correlations with available phosphorus. However, according to multiple stepwise analyses, only Al-P was directly related to available phosphorus. Overall, in the southeast hilly orchards, the NG treatment improved soil nutrient and enzyme activity and is considered an effective strategy to increase the biological effectiveness of phosphorus while reducing leaching losses.

Keywords: macronutrient; availability; soil quality; bray1-P; citrus; multiple stepwise regression analysis

Phosphorus is one of the essential elements for plant growth, accounting for approximately 0.2% of plant dry weight (Fan et al. 2019). Crop growth and development are influenced by soil phosphorus levels (Khan et al. 2018), affecting approximately 30–40% of global crop yields (Vance et al. 2003). Most soils have a high phosphorus fixation capacity and convert phosphorus into inorganic and organic forms that crops cannot absorb. The seasonal phosphorus use efficiency of most crops is approximately 10–15%, with excess phosphorus from fertilisers accumulating in the soil (Zhu et al. 2018), leading to soil degradation, phosphorus resource waste, and eutrophication of water bodies (Asghar and Kataoka 2021). Thus, the availability and accumulation of soil phosphorus significantly impacts plant growth and development, soil quality and fertility, and environmental safety.

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Over 99% of the total soil phosphorus consists of inorganic phosphorus, organic phosphorus, and microbial phosphorus, and inorganic phosphorus accounts for 50–75% of the total soil phosphorus (Hesterberg 2010, Maharjan et al. 2018). In tropical and subtropical regions, heavy rainfall and high temperatures increase desilication and ferrallitisation, resulting in low soil pH and high iron and aluminium contents, and inorganic phosphorus accounts for 58–82% of the total phosphorus in subtropical soils (Cui et al. 2015, Su et al. 2021). Chang and Jackson (1957) developed a classification system for inorganic phosphorus that is particularly applicable to neutral and acidic soils in tropical and subtropical regions. In this method, soil inorganic phosphorus is categorised into aluminium-bound phosphate (Al-P), iron-bound phosphate (Fe-P), calcium-bound phosphate (Ca-P), and occluded phosphate (O-P). The primary source of available phosphorus in soil is inorganic phosphorus, which serves as a crucial resource for plant availability in acidic soils. Plants' absorption and utilisation of phosphorus are closely related to the chemical forms of phosphorus present in the soil (Yang and Post 2011, Fan et al. 2019). In acidic red soil, the influence of inorganic phosphorus components on available phosphorus is mediated through Al-P and soluble phosphorus (Chen et al. 2022). Therefore, in tropical and subtropical soils, available and inorganic phosphorus components are closely related.

The inorganic phosphorus components in soil are influenced primarily by factors such as moisture, temperature, pH, microorganisms, and minerals. These influences subsequently affect the available phosphorus in the soil (Zhang et al. 2023). In the southeast hilly region, the reduction in phosphorus availability is attributed to the gradual transformation of loosely bound phosphates, which are accessible for plant uptake, into insoluble compounds through ligand exchange processes (Chen et al. 2022). Therefore, producers often apply large amounts of fertilisers to increase yield and maintain efficiency. For example, in Pinghe County, in the southeastern hilly region of China, from 1985 to 2015, the long-term application of phosphorus fertiliser in grapefruit orchards resulted in a 42-fold increase in the Olsen-P concentration of surface soil and a 25-fold increase in total phosphorus pools (Yan et al. 2022). This practice has led to an accumulation of phosphorus in the soil and heightened environmental risks (Yan et al. 2022, Ren et al. 2023). Therefore, analysing the components of inorganic phosphorus and the distribution of available phosphorus in orchard soils within the hilly region is crucial for increasing fertiliser utilisation efficiency and ensuring ecological safety in orchards. Furthermore, many orchards located in hilly areas worldwide are situated on slopes ranging from 5–20° (Umali et al. 2012, Hallman et al. 2023). Most orchard management practices are clean tillage, which poses risks of nutrient depletion and soil erosion (Ren et al. 2023). The erosion of soil by water in orchards, coupled with excessive fertilisation, can lead to an imbalance of soil nutrients and eutrophication in watersheds (Tu et al. 2021, Ren et al. 2023). In orchards, cover measures have been widely adopted because of their effectiveness in reducing soil erosion and nutrient loss. Additionally, these practices can alter soil moisture, temperature, and aeration, subsequently impacting various physicochemical properties of the soil, including pH, organic matter content, and texture (Kader et al. 2017, Scavo et al. 2022). However, the impacts of orchard cover measures on soil phosphorus components and their availability in southeast hilly regions remain unclear.

Therefore, our research focuses on typical terraced orchards in southern hill areas, and the orchard management measures included clean tillage, film mulch, and natural grass cover treatments. In this study, we hypothesised that (1) natural grass cover and film mulch improve soil physicochemical properties, leading to changes in soil phosphorus fractions, and (2) soil physicochemical properties and phosphorus fractions affect available phosphorus levels under natural grass cover and film mulch treatments. The findings provide valuable insights into the impact of different cover measures on phosphorus fractions and available phosphorus in southeast hilly regions.

MATERIAL AND METHODS

Overview of the study area. This experiment was conducted in Wanfengxiang Farm (25°70'N, 119°23'E; elevation 105 m a.s.l.), which is located in the eastern part of Fujian Province, China. Orchards account for approximately 5.66% of agricultural land, making them one of the primary agricultural land use types. This area has a subtropical maritime monsoon climate characterised by warm and humid conditions with an average annual temperature of 20.1 °C and 326 frost-free days. The average annual rainfall is 1 500 mm, with most precipitation occurring from March to May. The terrain mainly

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consists of low mountains and hills. The study area is located in a coastal seismic zone with a complex geological structure, predominantly consisting of granite and metamorphic rocks. The soil type in this area is classified as Ferralsols according to the FAO classification (FAO/ISRIC/ISSS 1998). According to the United States Department of Agriculture's soil texture classification, the soil in the experimental area contains 15.56% sand, 67.18% silt, and 17.19% clay.

Experimental design. This study selected an orchard with a planting age of five years as a study site. Before its establishment as orchards, the land was utilised as forested. Within the orchard, three different cover treatment methods were implemented: clean tillage (CK); film mulch (FM), and natural grass cover (NG). For the CK treatment, regular weeding and removal of plant debris were conducted monthly to maintain a tidy orchard floor. The FM treatment method covers the soil surrounding citrus trees within a 1-meter radius with plastic film. The plastic film is removed during the fertilisation process to facilitate fertiliser application, and it is subsequently replaced once the fertilisation procedure has been completed. The NG treatment signifies the predominant grass species that naturally thrive in orchard environments, and the grass variety in the citrus orchard was *Stachys arvensis* L. The study area utilised a base fertiliser application of 1 200 kg/ha in the orchard, with 50% organic fertiliser and 50% compound fertiliser. In March, May, and July, 960 kg/ha (with each application being 320 kg/ha) of supplementary compound fertiliser was conducted. The compound fertiliser contained N at a concentration of 15%, P_2O_5 at 15% (equivalent to P 6.5%), and K_2O at 15% (equivalent to K 12.5%).

On March 1–2, 2023, six representative trees were selected for each treatment within the sampling area, with a minimum distance of 30 m between each tree. Soil samples from the same depth at two trees were combined to form one replicate. At each tree, one point was chosen approximately 35 cm inside and outside the vertical drip line, and surface vegetation and gravel were removed. The soil samples were collected *via* a stainless steel auger at depths of 0–10, 10–20, 20–40, and 40–60 cm, resulting in a total of 36 samples. The collected soil samples were air-dried indoors, after which the gravel, roots, and weeds were removed. The air-dried soil was divided into two parts: one part was sieved through 2 mm and 0.149 mm meshes for the determination of physical and chemical properties and inorganic phosphorus fractions; the other part was sieved through a 0.3 mm mesh for measuring acid phosphatase activity.

The soil pH was measured *via* a pH meter (BPH-252, Guangdong, China) at a soil-to-water ratio of 1:2.5; the soil bulk density (El-Beltagi et al. 2022) was determined *via* the ring knife method (Wang et al. 2024a); the soil organic carbon (SOC) and total nitrogen (TN) were measured *via* an elemental analyser (Wang et al. 2024b); after the soil was digested *via* the NaOH method, the soil total phosphorus (TP) was measured *via* molybdenum-antimony colourimetric methods, and the soil total potassium (TK) was determined *via* a flame photometer (Wang et al. 2024b); the soil available nitrogen (AN) was determined *via* the alkali diffusion method (Chen et al. 2020); the soil available phosphorus (AP) was measured *via* the Bray1-P method and obtained extracts were measured using molybdenum-antimony colourimetric method (Bray and Kurtz 1945). The soil available potassium (AK) was determined *via* NH_4OAc extraction and a flame photometer (Li et al. 2019). A laser diffraction particle size analyser measured the soil particle size distribution distribution.

The Chang and Jackson (1957) method determined soil inorganic phosphorus content. A 0.5 g soil sample sieved through a 0.149 mm mesh was sequentially extracted with (1) NH_4F (pH 8.5) for Al-P; (2) NaOH for Fe-P; (3) $Na_3C_6H_5O_7$-$Na_2S_2O_4$ for O-P, and (4) H_2SO_4 for Ca-P. Soil organic phosphorus (Po) content was calculated as a difference between the results of soil samples extracted with 0.5 mol/L H_2SO_4 after ignition (550 °C, 2 h) and samples extracted using the same acid but without ignition (Tiecher et al. 2012). Soil acid phosphatase (S-ACP) was determined *via* phenyl disodium phosphate colourimetry; an acidic buffer was used to allocate phenyl disodium phosphate, and then S-ACP was determined at a wavelength of 660 nm (Fan et al. 2024).

Statistical analysis. A statistical analysis of the soil properties and enzyme activities was conducted using Microsoft Office Excel 2016 (Microsoft, Redmond, USA). SPSS software version 26.0 (IBM, Chicago, USA) was used for multiple linear stepwise regression analysis and variance analysis (Duncan's test, $P < 0.05$), which were used to evaluate the significance of differences in soil physicochemical properties, inorganic phosphorus fractions, and acid phosphatase activities between different treatments and soil layers. Redundancy analysis (RDA) was performed with Canoco v. 5.0 (Microcomputer Power, Ithaca, USA). Origin 2021 (Microcomputer Power, Ithaca, USA) was used to create bar charts,

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percentage composition charts, and heat maps. Linear regression analysis of available phosphorus concerning soil physicochemical properties and phosphorus components was carried out *via* GraphPad Prism 10.1.2 GraphPad Software, San Diego, USA).

RESULTS

Effects of natural grass cover and film mulch on soil properties. Compared with the CK treatment, the mulching treatments significantly improved soil fertility, with the NG treatment showing the greatest increment (Table 1). The soil pH followed a consistent pattern across the different soil layers: NG > CK > FM. The soil pH initially decreased with depth but then increased. Compared with the CK treatment, the NG and FM treatments significantly reduced the bulk density of surface soil (0–20 cm) by 8.68% and 5.37%, respectively. Across the entire soil profile, the NG treatment had the highest SOC content, with increases of 63.74% and 38.97% compared with those of the CK and FM treatments, respectively. The SOC content decreased with increasing soil depth in all the treatments. The TN content across the individual soil layers showed a pattern similar to that of the SOC content, with the highest TN content in the NG treatment at 1.79 mg/kg, with increases of 8.48% and 15.48% compared with those in the FM and CK treatments, respectively. The dynamic of the TP content across the soil profile was similar to that of the SOC content. Over the entire soil profile, the total potassium content in the NG and CK treatments was significantly greater than in the FM treatment, with increases of 63.56% and 53.02%, respectively. Compared with the CK treatment, the NG and FM treatments increased the AN content by 25.79% and 33.96%, respectively. The NG treatment significantly increased the S-ACP activity in the 0–40 cm soil layer, whereas the FM treatment decreased it.

Effects of natural grass cover and film mulch on soil phosphorus fractions. The Po contents over the entire soil profile for the NG, FM, and CK treatments were 208.92, 198.98 and 205.55 mg/kg, respectively (Figure 1). Compared with the FM treatment, the NG and CK treatments increased the Po content by 5.00% and 4.30%, respectively. The Po content decreased with increasing soil depth under all the treatments.

The NG and FM treatments had different effects on various inorganic phosphorus forms. The contents of soil Al-P, Fe-P, O-P, and Ca-P decreased with soil depth under all the treatments (Figure 2). Throughout the soil profile, the contents of Al-P and Fe-P followed the order NG > CK > FM. The highest Al-P content was detected in the NG treatment. The FM treatment significantly increased the soil O-P content across the entire soil profile, reaching 451.31 mg/kg,

Table 1. Soil available phosphorus (Olsen-P) content under clean tillage (CK), film mulch (FM) and natural grass cover (NG) treatments

Soil layer (cm)	Treatment	Olsen-P (mg/kg)
0–10	CK	90.2 ± 17.09^{Ab}
	FM	19.9 ± 5.45^{Ac}
	NG	141 ± 16.06^{Aa}
10–20	CK	67.2 ± 5.46^{Bb}
	FM	14.2 ± 2.34^{ABc}
	NG	114 ± 3.71^{Ba}
20–40	CK	21.9 ± 5.10^{Ca}
	FM	14.4 ± 2.07^{ABb}
	NG	26.9 ± 3.34^{Ca}
40–60	CK	13.6 ± 0.54^{Ca}
	FM	10.5 ± 0.12^{Bb}
	NG	7.11 ± 0.12^{Dc}

Different uppercase letters indicate significant differences between the soil layers within the same treatment at $P < 0.05$. Different lowercase letters indicate significant differences between treatments within the same soil layer at $P < 0.05$

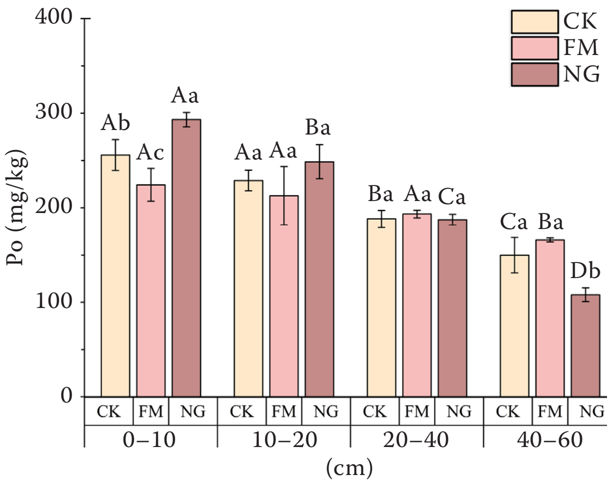

Figure 1. Organic phosphorus (Po) content in different soil layers under various treatments. CK – clean tillage; FM – film mulch; NG – natural grass cover. Different uppercase letters indicate significant differences between the soil layers within the same treatment at $P < 0.05$. Different lowercase letters indicate significant differences between treatments within the same soil layer at $P < 0.05$

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which was 2.11 and 2.18 times greater than the NG and CK treatments (Figure 2C). There was no significant difference in the soil Ca-P content on the surface among the three treatments (Figure 2D).

The NG treatment increased phosphorus activation, whereas the FM treatment promoted phosphorus fixation (Figure 3). Under the CK treatment, Al-P (28.5%) and Fe-P (37.5%) were the main inorganic phosphorus components, followed by O-P (28%) and Ca-P (6%). Compared with the CK treatment, the NG treatment increased the proportions of Al-P and O-P by 2% and 1.75%, respectively, while reducing the proportions of Fe-P and Ca-P by 1.5% and 2.25%, respectively. In the FM treatment, the proportion of O-P increased by 39.5%, whereas the Al-P, Fe-P, and Ca-P decreased by 24.75, 1.5, and 2.25%, respectively. Overall, the proportion of O-P increased with soil depth, whereas Al-P's decreased with soil depth under all the treatments.

Relationships between soil phosphorus fractions and soil physicochemical properties. Redundancy analysis (RDA) was conducted to examine correlations between soil phosphorus fractions and soil physicochemical properties in the 0–60 cm soil layer (Figure 4). The RDA revealed that soil physicochemical properties explained 93.85% of the variation in the soil phosphorus fractions in the 0–60 cm soil layer, with the first and second axes explaining 67.55% and 26.30% of the variation, respectively. Therefore, the first two axes adequately reflected the relationships between the soil phosphorus fractions and the soil physicochemical properties. The results suggest that S-ACP is the primary factor affecting phosphorus fractions, explaining 56.0% of the variation ($P < 0.01$), followed by pH (33.5%).

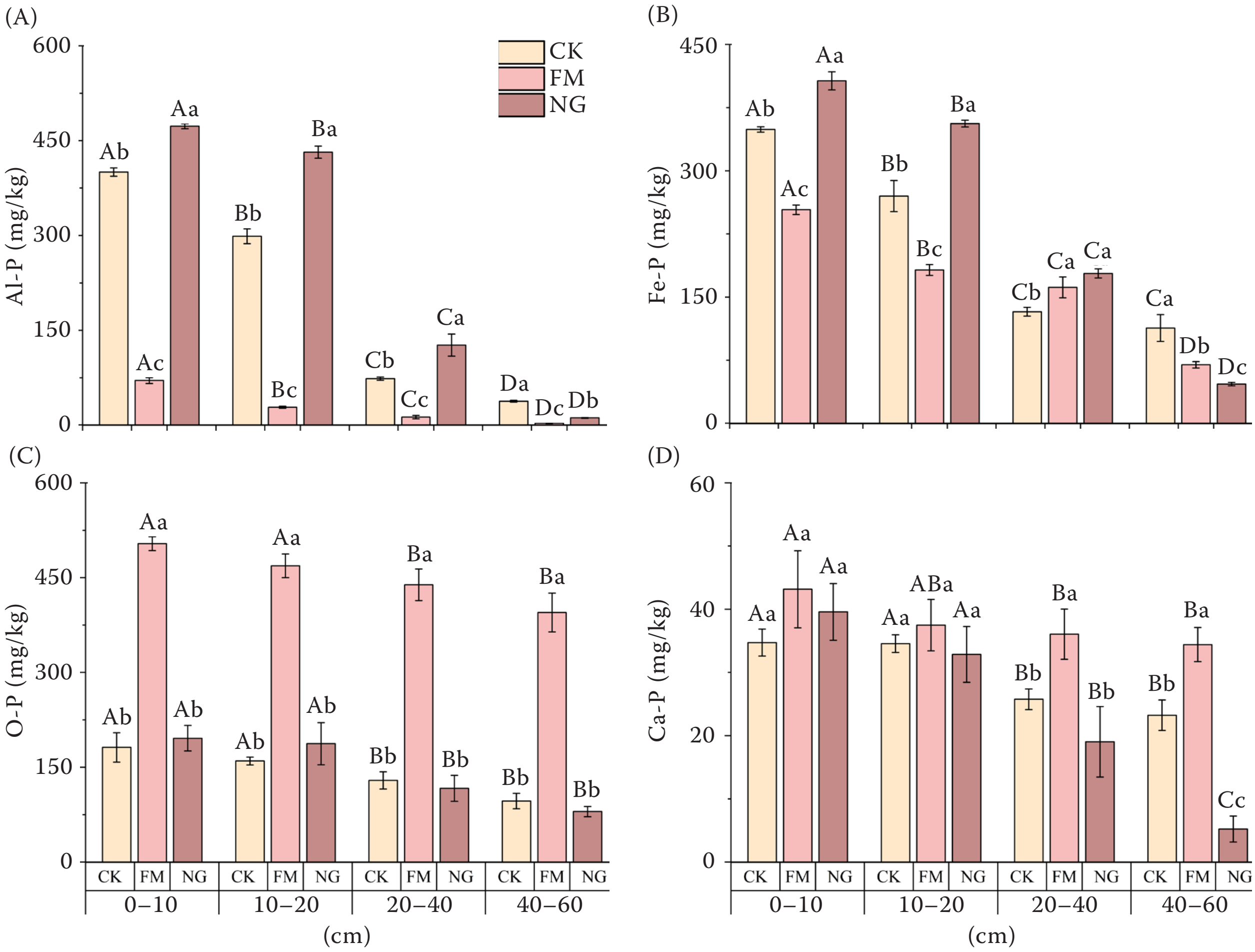

Figure 2. Inorganic phosphorus fractions in different soil layers under clean tillage (CK); film mulch (FM), and natural grass cover (NG) treatments. Different uppercase letters indicate significant differences between the soil layers within the same treatment at $P < 0.05$. Different lowercase letters indicate significant differences between treatments within the same soil layer at $P < 0.05$; Al-P – aluminium-bound phosphate; Fe-P – iron-bound phosphate; O-P – occluded phosphate; Ca-P – calcium-bound phosphate

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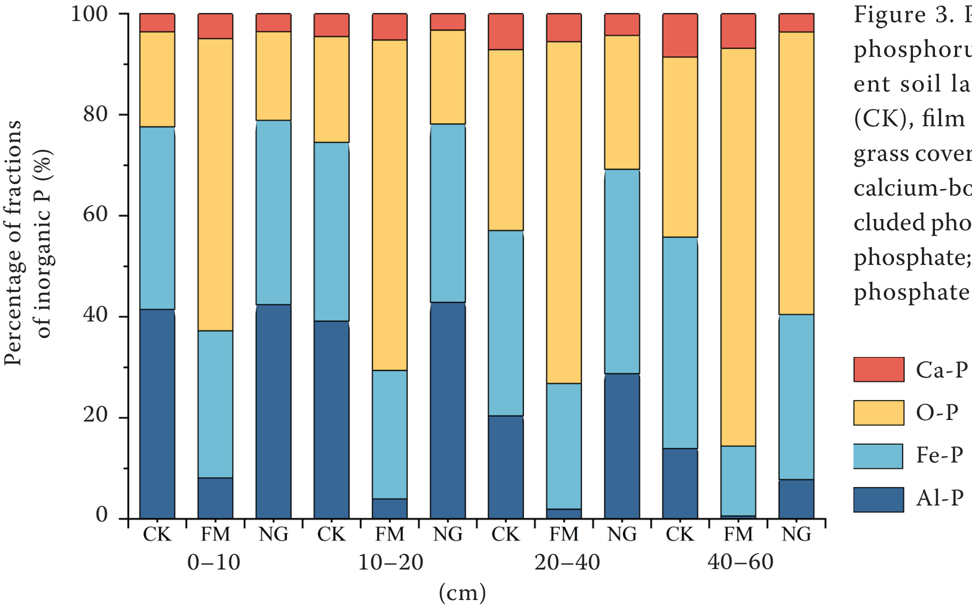

Figure 3. Proportions of inorganic phosphorus (P) fractions in different soil layers under clean tillage (CK), film mulch (FM), and natural grass cover (NG) treatments; Ca-P – calcium-bound phosphate; O-P – occluded phosphate; Fe-P – iron-bound phosphate; Al-P – aluminium-bound phosphate

The correlation analysis results indicated that TP and Po were highly significantly positively correlated with SOC, TN, AN, AK, S-ACP, Al-P, Fe-P, and Ca-P and highly significantly negatively correlated with BD. Po was also highly positively correlated with TP (Figure 5). Al-P and Fe-P were significantly positively correlated with SOC, TN, TK, AN, AK, S-ACP, and Ca-P and significantly negatively correlated with BD. Additionally, Al-P was significantly positively correlated with pH and Fe-P and significantly negatively correlated with O-P. O-P was highly significantly positively correlated with Ca-P and significantly positively correlated with AN but highly significantly negatively correlated with pH and TK. Ca-P was highly significantly positively

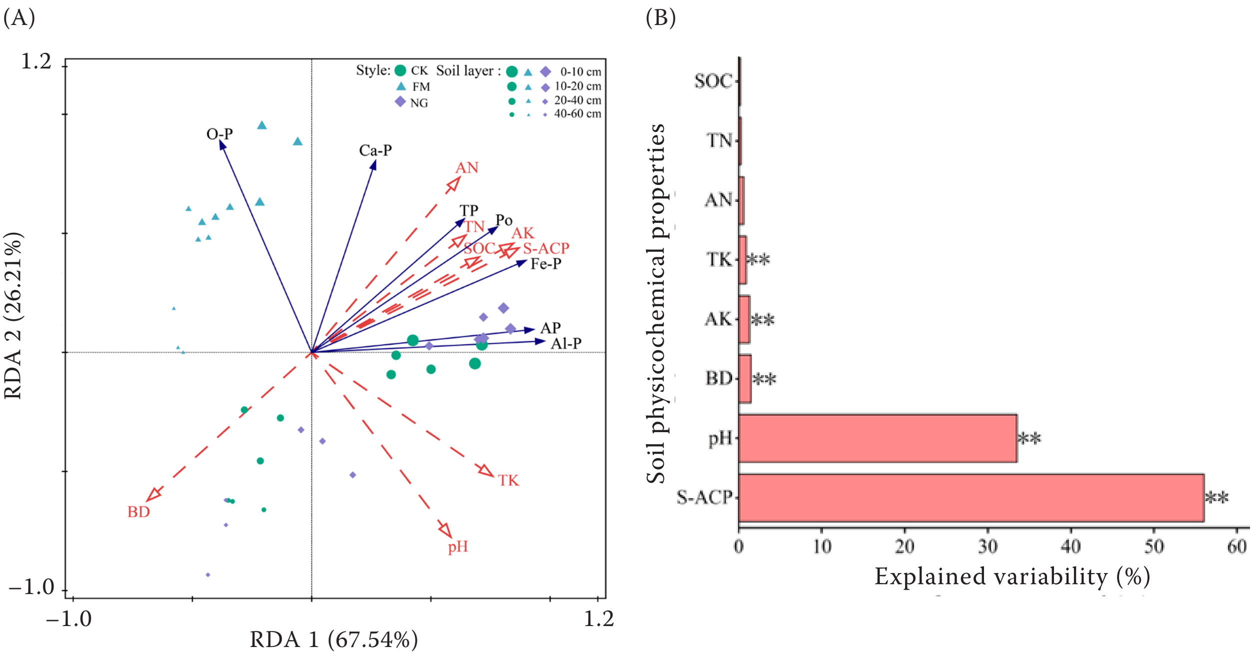

Figure 4. (A) Redundancy analysis of soil phosphorus fractions and soil physicochemical properties and (B) the contribution of soil physicochemical properties to the total variation in soil phosphorus fractions. $^{**}P < 0.01$; $^{*}P < 0.05$; Ca-P – calcium-bound phosphate; O-P – occluded phosphate; Fe-P – iron-bound phosphate; Al-P – aluminium-bound phosphate; TP – total phosphorus; AP – available phosphorus; Po – organic phosphorus; SOC – soil organic carbon; TN – total nitrogen; AN – available nitrogen; TK – total potassium; AK – available potassium; BD – bulk density; S-ACP – acid phosphatase

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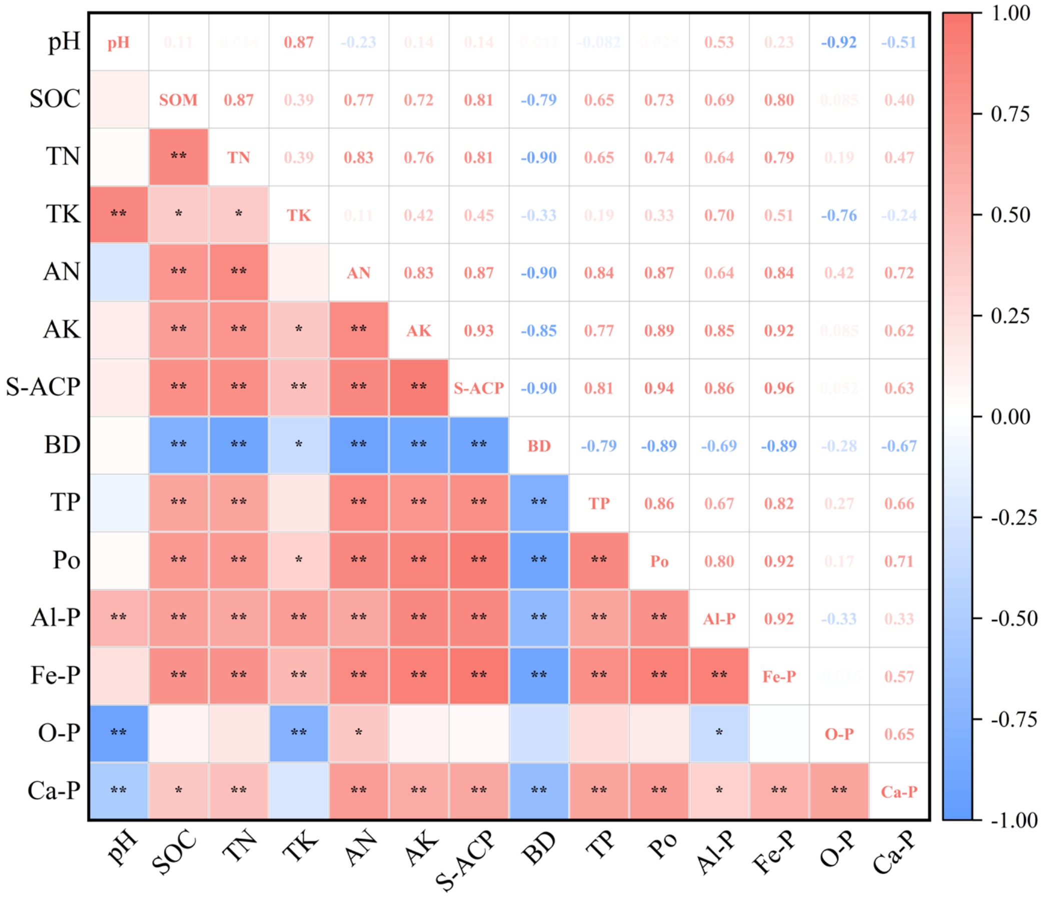

Figure 5. Correlation analysis between soil phosphorus fractions and soil physicochemical properties.***P* < 0.01; **P* < 0.05; SOC – soil organic carbon; TN – total nitrogen; TK – total potassium; AN – available nitrogen; AK – available potassium; S-ACP – acid phosphatase; BD – bulk density; TP – total phosphorus; Po – organic phosphorus; Al-P – aluminium-bound phosphate; Fe-P – iron-bound phosphate; O-P – occluded phosphate; Ca-P – calcium-bound phosphate

correlated with TN, AN, AK, and S-ACP, significantly positively correlated with SOC, and highly significantly negatively correlated with pH and BD.

The impact of natural grass cover and film mulch on available phosphorus. The AP content in the soil decreased with increasing soil depth. Across the entire soil profile, the NG treatment had the highest AP content at 159.04 mg/kg. The NG treatment significantly increased AP in the surface layer, whereas the FM treatment significantly reduced it.

Olsen-P is often used to categorise the levels of soil AP. In this study, we converted Bray1-P to Olsen-P *via* the following conversion formula: Olsen-P = 6.359 + 0.413 × Bray1-P (Song et al. 2024). According to the Olsen-P content classification for orchards in Fujian Province (Lei et al. 2019), the surface layer of the NG treatment had high phosphorus. In contrast, the FM and CK treatments had moderate phosphorus levels. In the 20–40 cm layer, the NG and CK treatments resulted in moderate phosphorus, and the FM treatment resulted in low phosphorus. All treatments presented low Olsen-P contents in the 40–60 cm layer. The critical level for the phosphorus leaching potential in surface soils of southern China is 78.2 mg/kg, with a recommended level of Olsen-P contents in the soil of 39.0 mg/kg (Li et al. 2015). Thus, the NG and CK treatments posed a phosphorus leaching risk in the surface layer, while the results of the NG treatment were closer to the recommended level in the 20–40 cm layer.

Figure 6 shows a significant correlation between AP and soil physicochemical properties and phosphorus fractions. AP was significantly negatively correlated with BD and positively correlated with pH, SOC, TN, TP, TK, AN, AK, Po, S-ACP, Al-P, Fe-P, and Ca-P. However, there was no correlation between AP and O-P. The three factors with the highest correlations with AP were Al-P (P < 0.0001;

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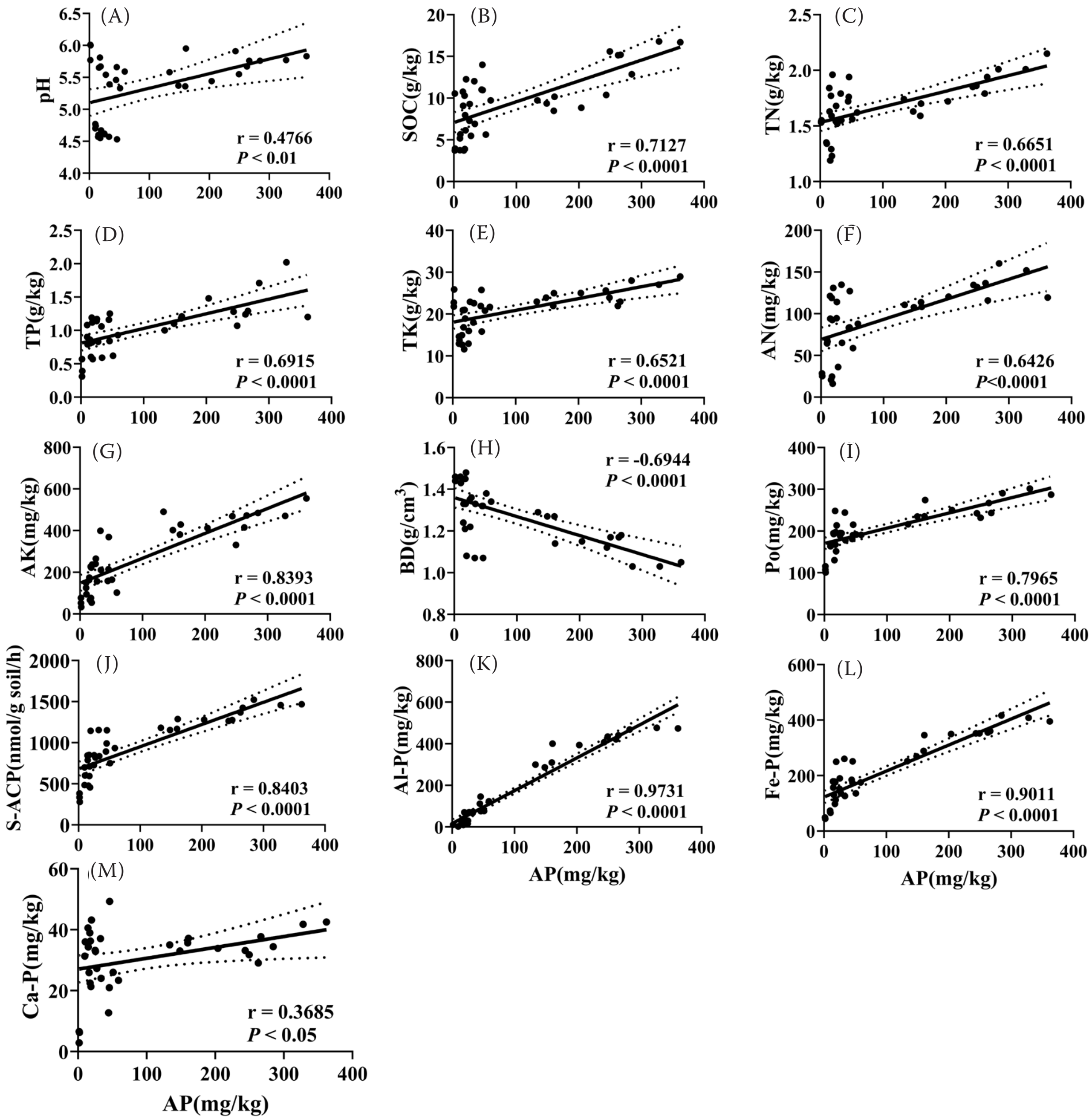

Figure 6. Relationships between available phosphorus and other phosphorus fractions and soil physicochemical properties. Linear regression was used, with the dashed lines around the regression line corresponding to the 95% confidence interval of the correlation. Only factors with $P < 0.05$ are shown in the figure. SOC – soil organic carbon; TN – total nitrogen; TP – total phosphorus; TK – total potassium; AN – available nitrogen; AK – available potassium; BD – bulk density; Po – organic phosphorus; S-ACP – acid phosphatase; Al-P – aluminium-bound phosphate; Fe-P – iron-bound phosphate; Ca-P – calcium-bound phosphate

Table 2. Multiple stepwise regression analysis parameters of the relationships between available phosphorus and other phosphorus fractions and between available phosphorus and soil physicochemical properties

Dependent variable	Explaining variables	Coefficient	*t*-value	*P*-value	VIF	Explained variability
Available P	constant	–4.808	–0.822	0.417		
	Al-P	0.600	24.606	0.000	1.000	94.50%

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Table 1. Soil physicochemical and biological properties under orchard clean tillage (CK); film mulch (FM), and natural grass cover (NG) treatments in the southeast hilly region of China

Soil layers (cm)	Treatment	pH	BD (g/cm^3)	SOC	TK	TN	TP	AN	AK	S-ACP (nmol/g soil/h)
				(g/kg)				(mg/kg)		
0–10	CK	5.77 ± 0.28^{Aa}	1.14 ± 0.02^{Da}	9.79 ± 0.83^{Ab}	25.2 ± 0.37^{Ab}	1.75 ± 0.08^{Ab}	1.32 ± 0.14^{Aa}	121 ± 13.05^{Aa}	437 ± 29.26^{Aab}	1 277 ± 11.75^{Ab}
	FM	4.59 ± 0.07^{Bb}	1.07 ± 0.01^{Db}	11.7 ± 0.69^{Ab}	17.6 ± 1.58^{Ac}	1.90 ± 0.10^{Aab}	1.15 ± 0.09^{Aa}	131 ± 3.85^{Aa}	335 ± 86.19^{Ab}	1 150 ± 4.98^{Ac}
	NG	5.78 ± 0.04^{ABa}	1.04 ± 0.01^{Dc}	15.4 ± 2.25^{Aa}	28.0 ± 0.98^{Aa}	2.06 ± 0.08^{Aa}	1.64 ± 0.41^{Aa}	144 ± 21.63^{Aa}	503 ± 45.00^{Aa}	1 483 ± 34.58^{Aa}
10–20	CK	5.44 ± 0.02^{ABb}	1.28 ± 0.01^{Ca}	9.19 ± 0.64^{Ab}	22.9 ± 0.99^{Ba}	1.65 ± 0.08^{ABb}	1.10 ± 0.09^{Aa}	111 ± 2.98^{Ab}	424 ± 57.83^{Aa}	1 168 ± 13.00^{Bb}
	FM	4.58 ± 0.02^{Bc}	1.22 ± 0.02^{Cb}	10.1 ± 0.75^{Bb}	15.9 ± 0.93^{Ab}	1.76 ± 0.08^{Bab}	1.07 ± 0.19^{Aa}	118 ± 3.66^{Bab}	218 ± 52.09^{Bb}	848 ± 3.59^{Bc}
	NG	5.66 ± 0.11^{BCa}	1.17 ± 0.01^{Cc}	15.3 ± 0.25^{Aa}	22.9 ± 0.99^{Ba}	1.87 ± 0.08^{Ba}	1.20 ± 0.12^{ABa}	128 ± 10.85^{Aa}	406 ± 70.93^{Aa}	1 356 ± 74.64^{Ba}
20–40	CK	5.42 ± 0.11^{Ba}	1.36 ± 0.03^{Ba}	6.00 ± 0.78^{Bb}	22.1 ± 1.13^{BCa}	1.54 ± 0.02^{Bb}	0.68 ± 0.13^{Bb}	53.3 ± 15.28^{Bb}	177 ± 29.72^{Ba}	802 ± 44.43^{Cb}
	FM	4.59 ± 0.04^{Bb}	1.34 ± 0.01^{Ba}	8.10 ± 0.90^{Cb}	12.4 ± 0.71^{Bb}	1.59 ± 0.04^{Cb}	1.02 ± 0.19^{Aa}	93.7 ± 1.13^{Ca}	212 ± 34.12^{Ba}	741 ± 40.32^{Bb}
	NG	5.57 ± 0.10^{Ca}	1.33 ± 0.01^{Ba}	11.6 ± 2.19^{Aa}	23.1 ± 2.30^{Ba}	1.70 ± 0.07^{Ca}	0.98 ± 0.17^{Bab}	84.9 ± 2.53^{Ba}	158 ± 56.00^{Ba}	940 ± 49.66^{Ca}
40–60	CK	5.71 ± 0.09^{ABb}	1.46 ± 0.02^{Aa}	4.59 ± 1.35^{Ba}	21.0 ± 0.03^{Ca}	1.24 ± 0.05^{Cc}	0.67 ± 0.14^{Bab}	20.5 ± 4.31^{Cc}	66.7 ± 11.06^{Cb}	509 ± 74.59^{Da}
	FM	4.74 ± 0.04^{Ac}	1.45 ± 0.02^{Aa}	4.86 ± 0.99^{Da}	13.8 ± 0.85^{Bb}	1.34 ± 0.07^{Db}	0.92 ± 0.15^{Aa}	66.6 ± 2.28^{Da}	123 ± 27.57^{Ba}	595 ± 107.91^{Ca}
	NG	5.46 ± 0.14^{Aa}	1.45 ± 0.01^{Aa}	6.07 ± 3.87^{Ba}	23.5 ± 2.14^{Ba}	1.54 ± 0.01^{Da}	0.42 ± 0.13^{Cb}	27.4 ± 1.93^{Cb}	54.0 ± 22.07^{Cb}	332 ± 51.61^{Db}

The data in the table are the means ± standard deviations. Different uppercase letters indicate significant differences between the soil layers within the same treatment at $P < 0.05$. Different lowercase letters indicate significant differences between treatments within the same soil layer at $P < 0.05$. BD – bulk density; SOC – soil organic carbon; TK – total potassium; TN – total nitrogen; TP – total phosphorus; AN – available nitrogen; AK – available potassium; S-ACP – acid phosphatase

$r = 0.9731$), Fe-P ($P < 0.0001$; $r = 0.9011$), and S-ACP ($P < 0.0001$; $r = 0.8403$). Multiple stepwise regression analysis indicated that soil Al-P was the only factor driving available phosphorus (Table 2). The multiple linear regression equation between the AP and Al-P content was: AP = –4.808 + 0.6 × Al-P.

DISCUSSION

Impact of natural grass cover and film mulch on soil physicochemical properties. Both natural grass cover and film mulch reduced the soil bulk density of the surface soil related to the CK treatment in the orchard in the southeast hilly region (Table 3). This reduction likely occurred because grass cover and film mulch can decrease soil disturbance, increase porosity, and increase the stability of soil aggregates and organic matter content (Kader et al. 2017). The NG and FM treatments improved soil fertility, effectively increasing SOC, TN and AN in the orchards. Additionally, NG increased soil TK and AK (Table 3). The phenomenon may be attributed to the following reasons: First, the use of grass cover and film mulch has demonstrated superior resistance to erosion and scouring, thereby reducing the loss of soil nutrients (such as SOC, TN, AN, etc.) (Kader et al. 2017). Secondly, film mulch increases the soil temperature and moisture levels while lowering the soil redox potential, thereby reducing the oxidation of SOC and the mineralisation of nitrogen (Hartman et al. 2017). Finally, compared with CK, live grass mulch may increase the input of plant residues, large quantities of

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which decompose and enter the soil (Daryanto et al. 2018). However, some studies have found that under Mediterranean climate conditions, the competition for soil nutrients between orchard grass and fruit trees becomes more pronounced after eight years, potentially affecting orchard yields (Castellano-Hinojosa et al. 2023). Therefore, comprehensive management strategies are crucial to mitigate nutrient competition between grass cover and fruit trees. These may include using low-nutrient-demanding grass species (such as *Trifolium repens* L. and *Lolium perenne* L.) and optimising water management (Wang et al. 2021, Castellano-Hinojosa et al. 2023, Dong et al. 2024). Under both the NG and FM treatments, the TP content in the entire soil layer did not differ significantly. Both mulch and orchard grasses reduce soil erosion, thereby reducing P runoff loss (El-Beltagi et al. 2022, Tang et al. 2022). The NG treatment significantly increased the S-ACP activity in the 0–40 cm soil layer, whereas the FM treatment decreased it. Soil phosphatases include alkaline phosphatase (S-ALP) and acid phosphatase (S-ACP). Studies have shown that S-ALP originates solely from soil microbes, whereas S-ACP can be produced by plants and soil microorganisms (Ma et al. 2021). The NG treatment increased root biomass, which may have increased S-ACP activity. There are two reasons for decreased acid phosphatase activity under the FM treatment. First, mulching film inhibited the growth and development of orchard grass. Another reason is that the oxygen content in the soil decreased, microorganisms needed more nutrients to produce enzymes, and microbial respiration increased, which resulted in an increase in carbonate ions in the soil and a decrease in soil pH. Carbonate ions and S-ACP are negatively correlated (El-Beltagi et al. 2022, Campdelacreu Rocabruna et al. 2024), which reduced S-ACP activity under the FM treatment. NG effectively increases the pH of acidic soils (Fu et al. 2023). However, the reduction in soil pH following FM treatment may be attributed to enhanced microbial respiration coupled with optimal moisture conditions that facilitate the leaching of alkaline ions from the soil (Gu et al. 2018). Undeniably, this study lacks information about soil pH and nutrient contents before the experiment establishment, so there is some risk that the differences in investigated properties were present even before the experiment started. It can be confirmed that the study area was all forest before being converted into orchards. This suggests that the difference in soil properties in different regions may not have been pronounced before the experiment started. Overall, the cover treatments effectively increased the soil SOC, TN, and AN contents, improving soil fertility, and the NG treatment also increased the TP, TK, AK, and S-ACP contents.

Natural grass cover and film mulch alter soil phosphorus fractions. Inorganic and organic phosphorus in soil significantly influences phosphorus transformation, with inorganic phosphorus being the primary form absorbed by plants (Parent et al. 2014). This study revealed that, compared with the CK treatment, the NG treatment increased the surface soil organic phosphorus content (Figure 1). This may have occurred due to the increase in SOC originating from roots and remnants after plant death and the increase in microbial diversity and abundance caused by natural grasses, which release Po when SOC decomposes (Wang et al. 2021, Xiang et al. 2023). In contrast, FM treatment inhibits orchard grass growth, reduces microbial diversity, and consequently lowers the organic phosphorus content (Wang et al. 2020).

Compared with the CK treatment, the NG treatment significantly increased the Fe-P and Al-P levels in the surface soil (Figure 2A, B). The FM treatment, on the other hand, increased the O-P content across all the soil layers (Figure 2C). Although the Ca-P levels were generally low, they were relatively high under the FM treatment. In acidic soils, phosphate ions react with iron and aluminium compounds, forming iron-aluminium phosphate complexes with Al^{3+} and Fe^{3+} (Weihrauch and Opp 2018). Long-term grass cover increases soil organic carbon and microbial activity, increasing phosphorus cycling and availability, which in turn increases the levels of Al-P and Fe-P (Wang et al. 2021). O-P refers to forming an oxide film on the surface of iron and aluminium phosphates or the encapsulation of phosphates by iron-aluminium oxides, isolating them from the external environment (Shao et al. 2019). Under the FM treatment, the soil pH significantly decreased. Studies have shown that in acidic soils, low pH increases the adsorption and fixation capacity of iron and aluminium phosphates, further trapping phosphorus within oxides and promoting O-P formation (Weihrauch and Opp 2018). However, film mulch could increase the soil temperature and moisture (Kader et al. 2017), and these two factors will accelerate the decomposition of soil organic carbon and release of calcium and phosphorus, promoting the formation of Ca-P.

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Soil S-ACP and pH are the key factors driving changes in soil phosphorus fractions in the orchard soils of the southeast hilly region (Figure 4). Phosphatase activity facilitates the conversion of organic phosphorus into inorganic phosphate, making it available for plant and microbial uptake (Cai et al. 2021). Therefore, S-ACP affects the Po and inorganic phosphorus fractions, indirectly influencing the TP content. Soil pH significantly impacts inorganic phosphorus fractions. In our study, the soil pH was consistently lower than 6.0. In acidic soils, phosphorus precipitates with Al and Fe, forming phosphates (Johan et al. 2021). Additionally, pH is a crucial determinant of microbial diversity, activity, and composition, indirectly affecting the mineralisation of organic phosphorus (Wan et al. 2020). Overall, the NG treatment increased soil organic phosphorus, Al-P, and Fe-P levels, effectively increasing soil phosphorus's bioavailability. In contrast, the FM treatment increased O-P levels, reducing the bioavailability of soil phosphorus. In acidic soils, S-ACP and pH play crucial roles in influencing soil phosphorus fractions.

Natural grass cover increases available phosphorus in orchard soils. In acidic soils, Bray1-P indicates soil phosphorus fertility, reflecting the soil phosphorus supply capacity and plant availability (Tchienkoua and Zech 2010, Lambers 2022). The NG treatment significantly increased the AP content in the 0–40 cm soil layer, whereas the FM treatment decreased it. This may be related to phosphorus storage in soil and plants: when fruit trees need phosphorus is met, excess phosphorus is stored in orchard grass and soil (Tang et al. 2022). After the death of orchard grass, some decompose into phosphorus-containing organic compounds. When the phosphorus content in the soil is relatively low, these phosphorus-containing organic compounds release P under phosphatase, thereby increasing the AP in the soil (Campdelacreu Rocabruna et al. 2024). In the 0–40 cm soil layer, the S-ACP content in the NG treatment was significantly greater than that in the CK treatment (Table 1), and the organic phosphorus content in the NG treatment was also greater than that in the CK treatment. Soil organic phosphorus exists in various forms, such as orthophosphate monoesters, diesters, and organic polyphosphates, which can be hydrolysed by phosphatases. When organic phosphorus is mineralised by these enzymes, it increases the available phosphorus content in the soil and enhances phosphorus cycling (Wang et al. 2021). Therefore, the increase in soil enzyme activity under the NG treatment enhances the mineralisation rate of organic phosphorus, leading to increased available phosphorus levels. In contrast, the FM treatment had the opposite effect, with inorganic phosphorus mainly in the form of O-P and lower levels of Al-P and Fe-P (Figure 3), reducing available phosphorus under the FM treatment. In addition, owing to the existence of adsorption interfaces for ions at the surface of the residual film, the adsorption of available phosphorus increased, and the availability of available phosphorus decreased (Pathan et al. 2020). AP can promote root growth and development, allowing plants to absorb other nutrients and water better. An adequate phosphorus supply can increase plant stress resistance (Bindraban et al. 2020, Wang et al. 2023). However, excessive accumulation of AP can pose environmental risks. In this study, as soil depth increased, AP under the NG treatment did not accumulate in the deeper 40–60 cm layer. In contrast, the available phosphorus content under the CK treatment was significantly higher than in the other two treatments at the 40–60 cm depth (Figure 7). With increasing years of fertilisation, the CK treatment may have resulted in the accumulation of phosphorus in the deep soil. Still, the NG treatment can reduce soil nutrient leaching to the bottom soil

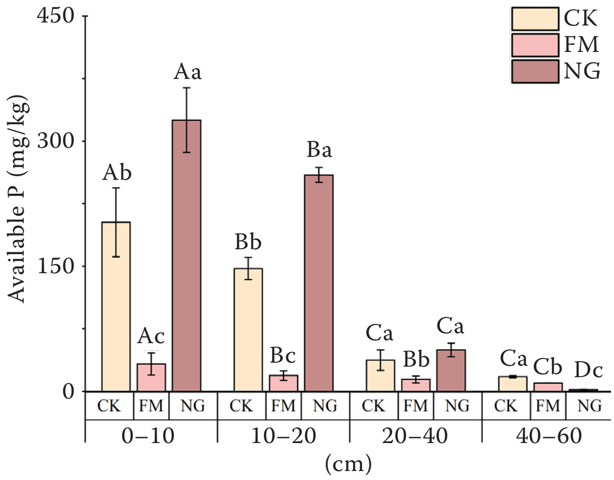

Figure 7. Available phosphorus (P) content in different soil layers under various treatments. CK – clean tillage; FM – film mulch; NG – natural grass cover. Different uppercase letters indicate significant differences between the soil layers within the same treatment at $P < 0.05$. Different lowercase letters indicate significant differences between treatments within the same soil layer at $P < 0.05$

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layer (Scavo et al. 2022, Ren et al. 2023). Clear tillage destroys the soil aggregate structure, which affects water infiltration and makes it easier for nutrients to be lost to deep soil. Moreover, bare soil surfaces can easily form crusts when it rains, which promotes surface runoff and leads to soil erosion and nutrient loss (Ramos et al. 2011). Therefore, in the hilly regions of southeast China, NG and FM treatments in orchards can help prevent groundwater pollution and eutrophication, with NG treatment being more effective.

Relationships between AP and P fractions and soil quality indicators help us better comprehend the potential supply of available phosphorus in soil (Zhu et al. 2021, Li et al. 2023). The three factors most strongly correlated with AP were Al-P ($P < 0.0001$; $r = 0.9731$), Fe-P ($P < 0.0001$; $r = 0.9011$), and S-ACP ($P < 0.0001$; $r = 0.8403$). Multiple regression analysis revealed that Al-P explained 94.5% of the variation in AP (Bray1-P) (Table 2). Maguire et al. (2000) and Chen et al. (2022) reported that in acidic red soils, the potential availability of phosphorus follows the order of soluble P > Al-P > Fe-P > Ca-P and O-P, with Al-P being the phosphorus fraction most related to AP. In highly weathered soils, plant roots increase AP by absorbing and mobilising Al-P and Fe-P (Almeida et al. 2018, Weihrauch and Opp 2018). Al-P is more available than Fe-P, primarily because of the greater stability and tighter structure of iron phosphate compounds, which have more phosphorus precipitation sites (Chen et al. 2022). Some bacteria and fungi produce organic acids and other compounds that help dissolve Al-P. Plant roots also secrete organic acids such as oxalic, citric, and malic acids, which chelate aluminium in the soil, releasing phosphorus from Al-P into the soil and increasing the amount of available phosphorus (Joshi et al. 2024).

The results of this study indicate that the application of plastic film can increase the total phosphorus content in soil; however, it simultaneously reduces the availability of phosphorus. This phenomenon may be attributed to the poor aeration of the plastic film, which leads to a decrease in pH and subsequently reduces the availability of phosphorus (Gu et al. 2018, Weihrauch and Opp 2018). The use of breathable membranes might reduce the fixation effect of phosphorus. The implementation of natural grass cover can enhance soil quality by increasing the total phosphorus and available phosphorus contents in the soil. Additionally, these measures effectively inhibit the accumulation of AP in deeper soil layers. Therefore, natural grass cover is an effective strategy for improving phosphorus management in orchards located in hilly red soil regions.

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