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Variations in Soil Phosphorus Levels in *Acacia* Hybrid Plantations Across Different Ages in Southern Vietnam

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ABSTRACT

Phosphorus (P) plays a crucial role in shaping nutrient cycles within terrestrial ecosystems. Understanding the fluctuations and factors influencing soil P in Acacia hybrid plantations in southern Vietnam is essential. The scarcity of comprehensive studies focusing on this specific ecosystem underscores the urgent need for further research to bridge this knowledge gap. This study aims to assess alterations in soil total phosphorus (TP) and available phosphorus (AP) levels and storage, as well as to identify the factors influencing soil TP and AP concentrations based on soil and forest stand characteristics across five different ages (2, 4, 6, 8, and 10 years old) of Acacia hybrid plantations within the Langa Forestry Company in southern Vietnam. Soil samples were collected at five different depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm). The results revealed that soil TP and AP concentrations in the five stands increased with stand age, showing a significant decrease with soil depth. Soil TP and AP stocks increased from 4.78-5.35 Mg ha^{-1} and from 0.12-0.50 Mg ha^{-1}, respectively, as the stand developed. Additionally, soil TP and AP stocks displayed noticeable aggregation in the topsoil, with over 40% of TP storage and over 50% of AP storage occurring within 0-40 cm depth. The structural equation model (SEM) suggested that both soil parameters (i.e., soil bulk density and pH) and forest stand characteristics (i.e., plant biomass) significantly influenced soil TP and AP concentrations. Mainly, soil properties parameters had a more substantial impact on soil P concentrations than forest stand features parameters. Our findings offer new insights into soil phosphorus dynamics, with significant implications for Acacia hybrid forests' protection and sustainable management.

Keywords: *Acacia* hybrid plantation, soil features, stand characteristics, structural equation modeling, stand age

INTRODUCTION

Phosphorus (P) is a crucial nutrient in forest soils. This nutrient availability significantly affects ecosystem functions by modulating soil properties such as physicochemical properties, soil microbial activity, plant growth, and competition in terrestrial ecosystems (Chi *et al*., 2022). Thus, when comparing P with other soil nutrients, P is an essential biomolecular component in all organisms and is considered an indispensable nutrient, significantly impacting soil productivity (Xu *et al*., 2022). P has also been demonstrated to be closely related to the cycles of soil organic carbon (C) (Fisk *et al*., 2015). As a result, soil P is linked to global climate change since its dynamics influence greenhouse gas emissions (Cuong *et al*., 2023b). Hence, understanding the dynamics of P accumulation in soil and its controlling factors is extremely important. This knowledge applies to assessing the dynamics of their contribution to nutrient cycling, their potential impacts on ecosystem function, and a better understanding of climate change and related P feedback to terrestrial ecosystems (Xu *et al*., 2022).

Acacia hybrid is a significant tree species in timber afforestation in Vietnam's southern provinces. Compared with other afforestation tree species, *A*. hybrid exhibits good wood quality, fast growth rate, high productivity, and strong adaptability, bringing high ecological, economic, environmental, and social values. According to the decision to announce the current state of forests nationwide in 2022, there were up to 1.5 million hectares (ha) of *A*. hybrid forests, amounting to 32.80% of Vietnam's total plantation forest area, and it plays an essential role in forestry production in the country (MARD, 2022). In the context of global climate change and multi-functional forest management, numerous researchers have studied biological characteristics and growth ability, morphological changes, physical and mechanical properties of wood, biomass and productivity, biomass and C sequestration potential, tissue culture propagation, soil features, degraded soil restoration, and biological nitrogen fixation capacity in *A*. hybrid forests (Ngo *et al*., 2006; Que *et al*., 2010; Dong *et al*., 2014; Trieu *et al*., 2014; Bon and Harwood 2016; Hung *et al*., 2017; Kha and Thinh 2017; Ha *et al*., 2021; Sunarti *et al*., 2021).

Nevertheless, during the development of *A*. hybrid forests, the dynamics of P in soil, particularly in the southern region of Vietnam, has yet to be documented. The present study aimed (1) to estimate the soil P content in *A*. hybrid forests across five different stand ages of *A*. hybrid forests, and (2) to explore the parameters affecting soil P concentrations in these forests. The results of the present study provide critical scientific knowledge to assist in formulating sustainable management measures and strategies for *A*. hybrid forests and to promote enhanced productivity of *A*. hybrid forests.

MATERIALS AND METHODS

Study area

This research was conducted at the Langa-Dongnai Forestry Company, Dinhquan district, Dongnai province, Vietnam (107°00′00″107°22′00″E; 11°00′00-11°23′00″N). The region is characterized by a tropical monsoon climate with an annual precipitation of approximately 3293 mm and an annual temperature of 25°C. The most dominant tree species in the region is the *A*. hybrid. The region also has woody plants, with the dominant species being *Dipterocarpus obtusifolius*, *Tectona grandis*, *Hopea odorata*, and *Sindora siamensis*. Of the entire forest area, 62.4% is made up of plantations. The area covered by *A*. hybrid plantations is 33.5% and the remaining area (*T. grandis, S. siamensis, H. odorata*, and *D. obtusifolius*) is 28.9%. The soil types in these regions are classified as yellowish-brown ferritic soil. Five stand ages of plantations with similar site conditions were chosen for this study, namely, 2, 4, 6, 8, and 10 year old *A*. hybrid plantations. Five different stand ages were located within a 2 km radius of each other (Fig. 1). Once a year for the first three years after planting, all stands were completely tilled prior to being provided with 60 g of NPK 16-16-8 fertilizer for each tree. The initially established planting density was 1667 trees ha^{-1} (3 m × 2 m), and thinning treatments were applied to the stands only after four years at an intensity not to exceed 30% of the standing volume.

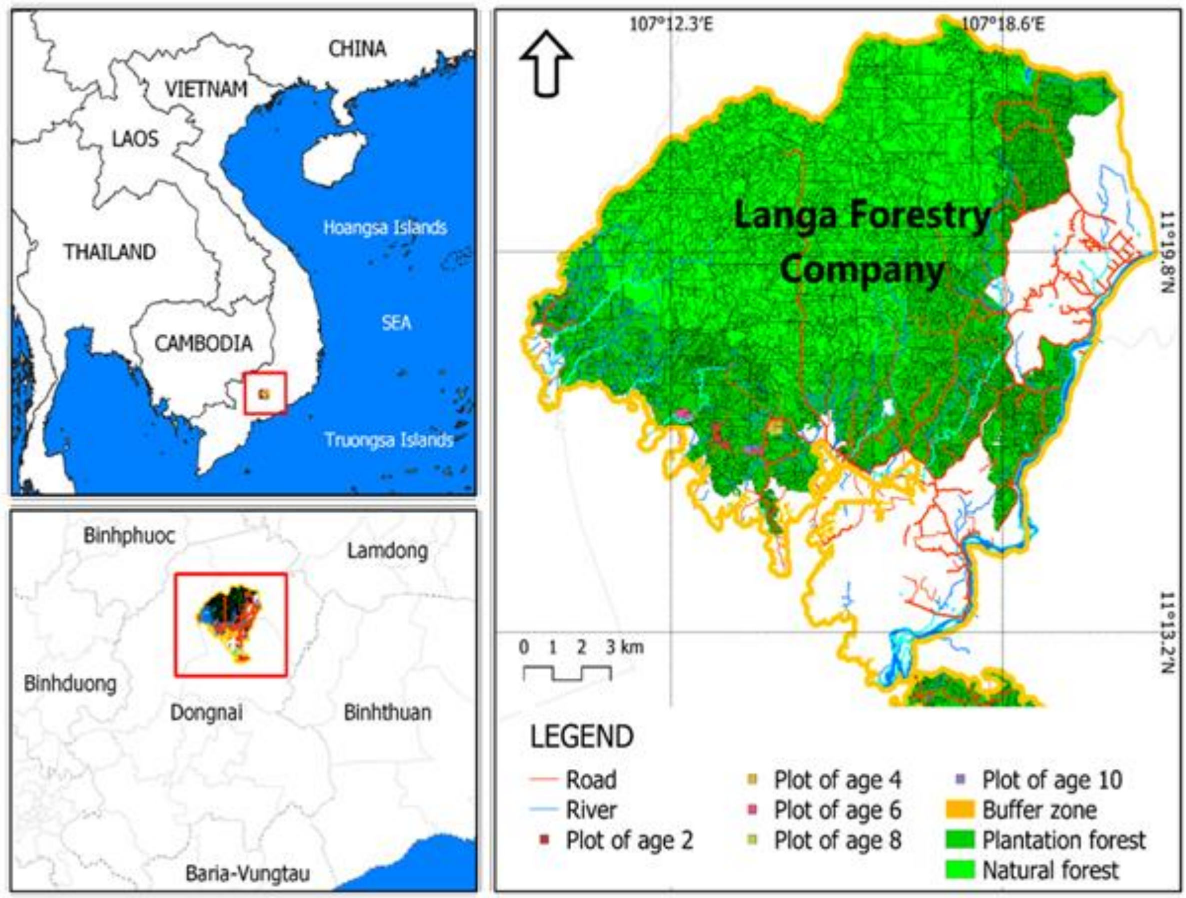

Figure 1. *Location of different-aged A. hybrid plantations in Langa Forestry Company, Southern Vietnam*

Experimental design and data dollection

Fifteen sample plots were established, with three plots measuring 25 m × 20 m in each stand. Field measurements and sampling were carried out between December 10th and January 30th, 2022. The trees' total height (H) and diameter at breast height (DBH) were measured simultaneously, while canopy closure was evaluated using a smartphone application, specifically the Gap Light Analysis Mobile Application software. Additionally, the biomass of understory plants, including shrubs and herbs, was estimated in each plot through destructive sampling conducted in five 2 m × 2 m quadrants. The biomass of forest litter contribution to the soil surface was quantified from five quadrants (1 m × 1 m) at the centre and four corners of the plot. Detailed information descriptions of the study sites and assessments of plant biomass were given by our previous study (Chau *et al*., 2023) and reproduced in Table 1, as follows:

Soil sampling and laboratory analysis

Five soil profile pits measuring 1 meter long, 1.5 meters wide, and 1 meter deep were excavated at the center and four corners of each plot. Soil samples were collected at five different depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm) using a soil drilling sampler with a 5 cm inside diameter. Approximately 500 grams of soil were collected from each depth of the soil profile, and samples from the same depth across all five sampling plots were thoroughly mixed. In total, 75 soil samples (representing 5 different stand ages, with 3 replicate sample plots for each age, and 5 soil depths) were gathered and transported to the laboratory for analysis.

TABLE 1
Basic characteristics of *A*. hybrid plantations at five different stand ages.

Measured factors	**Forest age (years)**				
	2	**4**	**6**	**8**	**10**
Slope (^{0})	2.67	3.33	5.00	3.67	7.33
Elevation (m a.s.l.)	83.33	86.00	85.00	94.67	93.33
Average DBH (cm)	1620±34^e	1247±43^d	980±21^c	807±13^b	620±21^a
Average tree Height (m)	6.30±0.36^a	12.40±0.40^b	16.13±0.32^c	17.80±0.26^d	19.93±0.40^e
Stand density (Plants· ha^{-1})	6.17±0.29^a	13.90±0.36^b	17.77±0.64^c	20.50±0.50^d	22.63±0.35^e
Canopy density	0.32±0.02^a	0.55±0.05^b	0.63±0.02^c	0.67±0.01^{cd}	0.69±0.01^d
Understory vegetation biomas (Mg· ha^{-1})	3.08±0.39^a	4.33±0.67^{ab}	5.64±0.56^b	7.33±0.94^c	8.53±1.21^c
Litter biomass (Mg· ha^{-1})	0.86±0.08^a	1.74±0.40^b	2.18±0.47^b	3.20±0.29^c	3.52±0.58^c
Main understorey plant species	*Mallotus apelta* (Lour.) Müll. Arg., *Lophatherum gracile* Brongn. (*L. gracile*), *Mimosa pudica var. tetrandra* (Willd.) DC., *Tetracera scandens* (L.) Merr., *Saccharum arundinaceum* (Retz.), *Chromolaena odorata* (L.) R.M. King & H. Rob., and (*Chrysopogon aciculatus* (Retz.) Trin.)				

Note: Values represent the mean ± Standard Deviation (SD). Within a row, distinct lowercase letters indicate significant differences at $p<0.05$. DBH stands for diameter at breast height (1.3 m), while H represents tree height.

Soil bulk density (BD, measured in g cm^{-3}) samples were collected using a cutting ring with a volume of 100 cm^3. Any small rocks, plant roots, and coarse debris in the samples were removed through a 0.25 mm mesh, and the samples were air-dried before analyzing the soil's physicochemical properties. Soil BD for each depth was determined by drying the core soil samples at 105°C for over 24 hours until a constant weight was achieved (Blake and Hartge 1986; Cuong *et al*., 2022a).

Soil chemical parameters, involving soil total phosphorus (TP), available phosphorus (AP), and pH were estimated based on methods described in our previously published research (Cuong *et al*., 2022b). Soil pH was measured using a pH meter (Sartorius PB-10) with a 1:2.5 soil-to-water ratio. The soil TP content (in g kg^{-1}) was determined using the colorimetric method after digestion with H_2SO_4 and $HClO_4$. Soil AP concentration (in mg kg^{-1}) was measured using the molybdenum antimony colorimetric method following leaching of the samples with $NaHCO_3$.

Calculation of soil phosphorus stocks

According to previous methods (Li *et al*., 2019), the soil TP and AP stocks (Mg ha^{-1}) were computed by the following equation:

$$TP_{iStock} = TP_i \times BD_i \times D_i \times 10^{-1} \quad \text{(eq. 1)}$$
$$AP_{iStock} = AP_i \times BD_i \times D_i \times 10^{-1} \quad \text{(eq. 2)}$$
$$P_{TA} = TA_i \times BD_i \times D_i \times 10^{-1} \quad \text{(eq. 3)}$$

In the equations 1-3, TP_i represents the concentration of soil total phosphorus in the i-th soil layer (measured in g kg^{-1}); AP_i signifies the concentration of available phosphorus in the i-th soil layer (measured in g kg^{-1}); BD_i denotes the bulk density of the i-th soil layer (measured in g cm^{-3}); D_i indicates the depth of the i-th soil layer (measured in cm); PTA denotes the stocks of TP and AP in the soil layer ranging from 0 to 100 cm (measured in Mg ha^{-1}); and TAi represents the concentrations of TP and AP in the i-th soil layer (measured in g kg^{-1}).

Statistical data analyses

Prior to conducting statistical analysis, all data underwent assessments for normality using the Kolmogorov-Smirnov test and for homogeneity of variance using Levene's test. One-way

ANOVA was employed to investigate variations in the physical and chemical properties as well as P stocks among *A.* hybrid plantations of different ages and soil layers. Pearson correlation analysis was conducted to elucidate the relationships between soil P concentrations and environmental parameters. The structural equation model (SEM), integrating path analysis and factor analysis, has been recognized as a method for causal inference in ecology, primarily employing maximum likelihood estimation (Shipley, 2016). Before commencing the SEM procedure, we utilized the variance inflation factor (VIF) threshold to address multicollinearity by excluding highly correlated variables, following the approach outlined by (Kock, 2015; Xing *et al*., 2023). Then, we established an a-prior model based on the known effects and relationships among the drivers of P concentrations. The path coefficients between variables were fitted by the maximum likelihood chi-square (χ^2) and standardized root means square residual (SRMR). The comparative fit index (CFI), nonsignificant chi-square test, and root-mean-square errors of approximation (RMSEA) were applied to assess the goodness of model fit. CFI $\geq$ 0.90, nonsignificant chi-square test ($p>0.05$), RMSEA < 0.06, and SRMR < 0.05 suggest a good fit (Zhu *et al*., 2016; Chi *et al*., 2022). The SEM analyses were conducted utilizing the 'lavaan' package in R software version 4.2.0 (R Core Team, 2022).

RESULTS

Content and storage of soil TP in *A*. hybrid plantations

Soil TP content and storage exhibited a temporal pattern across various layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm), showing a gradual increase coinciding with the growth of the Acacia hybrid forest (Figs. 2a-b), except for TP stocks in the 80–100 cm soil layer, which tended to remain stable (Fig. 2b). Soil TP content and stocks decreased in deeper soil layers at the same forest age. At all ages of plantations, total P content and stocks at the 0–20 cm soil depth were significantly higher than total P content and stock at the other soil depths (20–40, 40– 60, 60–80, and 80–100 cm) ($p<0.05$). Soil TP concentration and storage in each stand age decreased substantially in 0–40 cm soil depth ($p<0.05$) when soil depth was more than 40 cm but varied slightly with the increase of soil depth ($p>0.05$). Soil TP stocks ranged from 1.06–1.17 Mg ha^{-1} at the soil depth of 0–20 cm and 4.78–5.35 Mg ha^{-1} at the soil depth of 0–100 cm for all plantation forests (Fig. 2b). Over 40% of soil TP storage was stocked in 0–40 cm depth in each forest age.

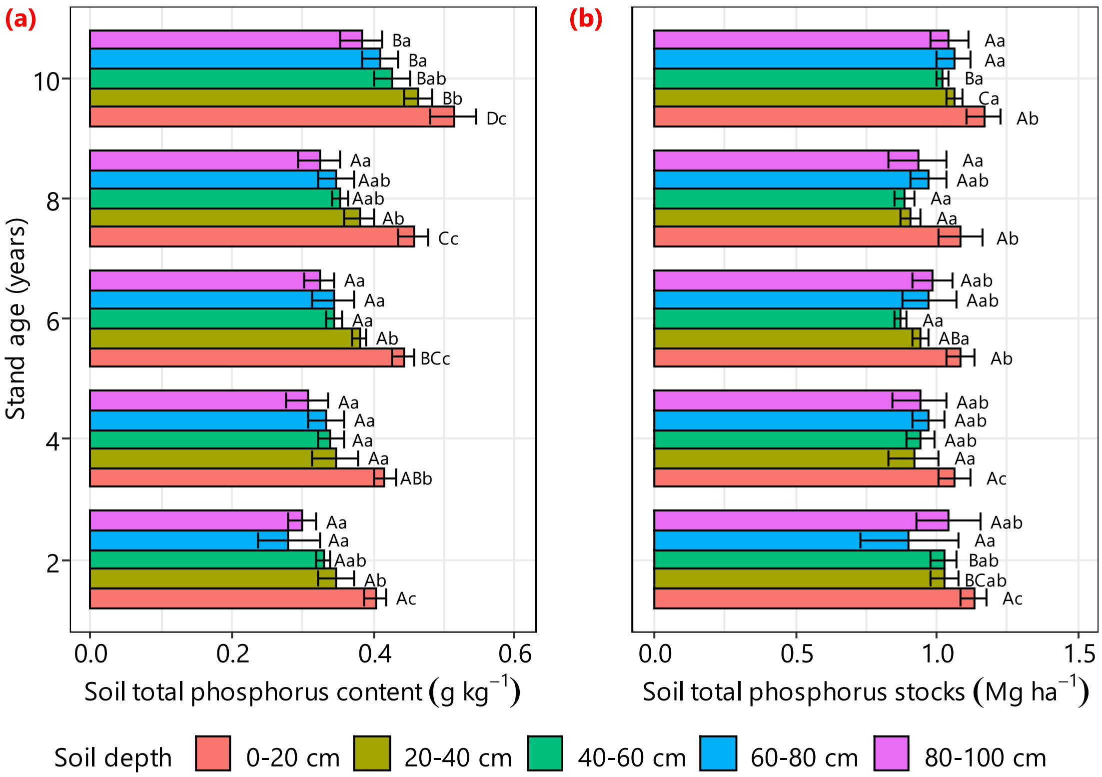

Figure 2. *Soil total phosphorus contents and stocks at different soil depths among different stand ages. Note: Distinct capital letters above the bars indicate significant differences between different stand ages within the same soil depth ($p<0.05$), while lowercase letters indicate significant differences between various soil depths within the same stand age ($p<0.05$). Values represent the mean ± standard deviation (n = 3).*

Content and storage of soil AP in *A.* hybrid plantations

The concentration and stocks of AP increased with forest age and significantly differed between different stand ages ($p<0.05$; Figs. 3a-b). The highest AP concentration and stocks of all forest ages were detected in the 0–20 cm soil layer, displaying a similar tendency to the soil TP ($p<0.05$). Soil AP concentration and stocks in different ages decreased with increasing depth in the 0–100 cm soil profile, and all of them decreased significantly in the 0–60 cm soil layer. Below 60 cm, the concentration and storage of soil AP demonstrated a tendency toward stabilization. Soil AP stocks observed at depths of 0–20 cm and 0–100 cm ranged from 0.03 Mg ha^{-1} to 0.14 Mg ha^{-1} and 0.12 Mg ha^{-1} to 0.50 Mg ha^{-1}, respectively. The soil AP stocks between the 0–40 cm were higher than that in deeper soil, comprising 50.08%, 47.52%, 51.98%, 55.22%, and 52.14% of the entire soil profile (0–100 cm) in the 2-, 4-, 6-, 8-, and 10- year- old plantations, respectively (Fig. 3b).

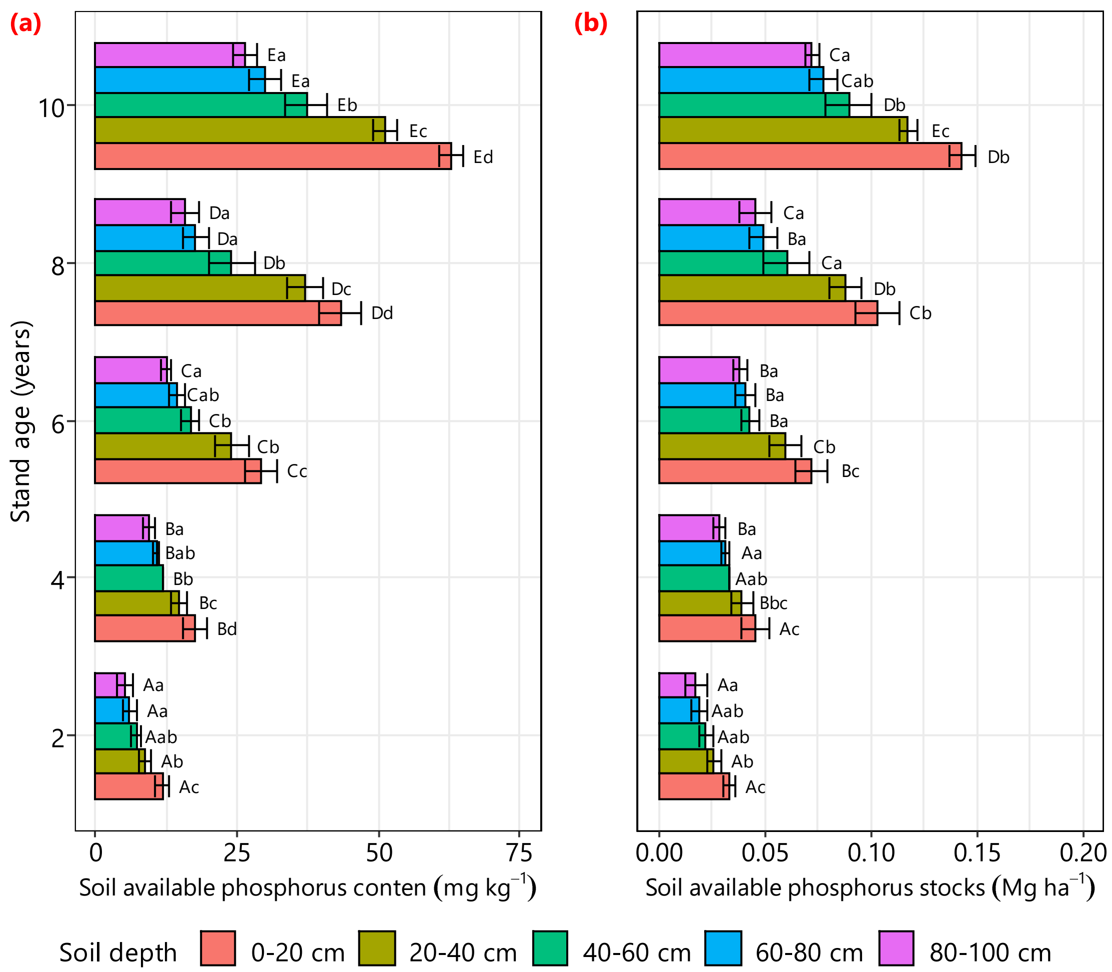

Figure 3. *Soil available phosphorus contents and stocks at different soil depths among different stand ages.*

Note: Different capital letters above the bars demonstrate significant differences between various stand ages within the same soil depth ($p<0.05$), and lowercase letters demonstrate significant differences between various soil depths within the same stand age ($p<0.05$). Values are the mean ± standard deviation (n = 3).

Soil physical and chemical characteristics in *A.* hybrid plantations

Figure 4 describes the physicochemical features of the soil layers of *A.* hybrid forest at different stand ages. Soil properties (soil BD and pH) varied among different forest ages. The soil BD value of the 10-year-old plantation was significantly more significant than the other forest ages ($p>0.05$). This trend was consistent at all five soil depths (Fig. 4a). Furthermore, soil BD decreased significantly with increasing depth in the 10-year-old plantation ($p>0.05$), which had similar soil BD as that of the other four stand ages (i.e. 8-, 6-, 4-, and 2-year-old plantations). Soil pH value decreased with forest age for all soil layers (Fig. 4b). However, statistical analysis revealed no significant variation in soil pH value between the five stands at the five soil depths ($p>0.05$). It exhibited an increasing tendency as soil depth increased in all five stands but was not significantly distinct among stand ages at all soil depths ($p>0.05$).

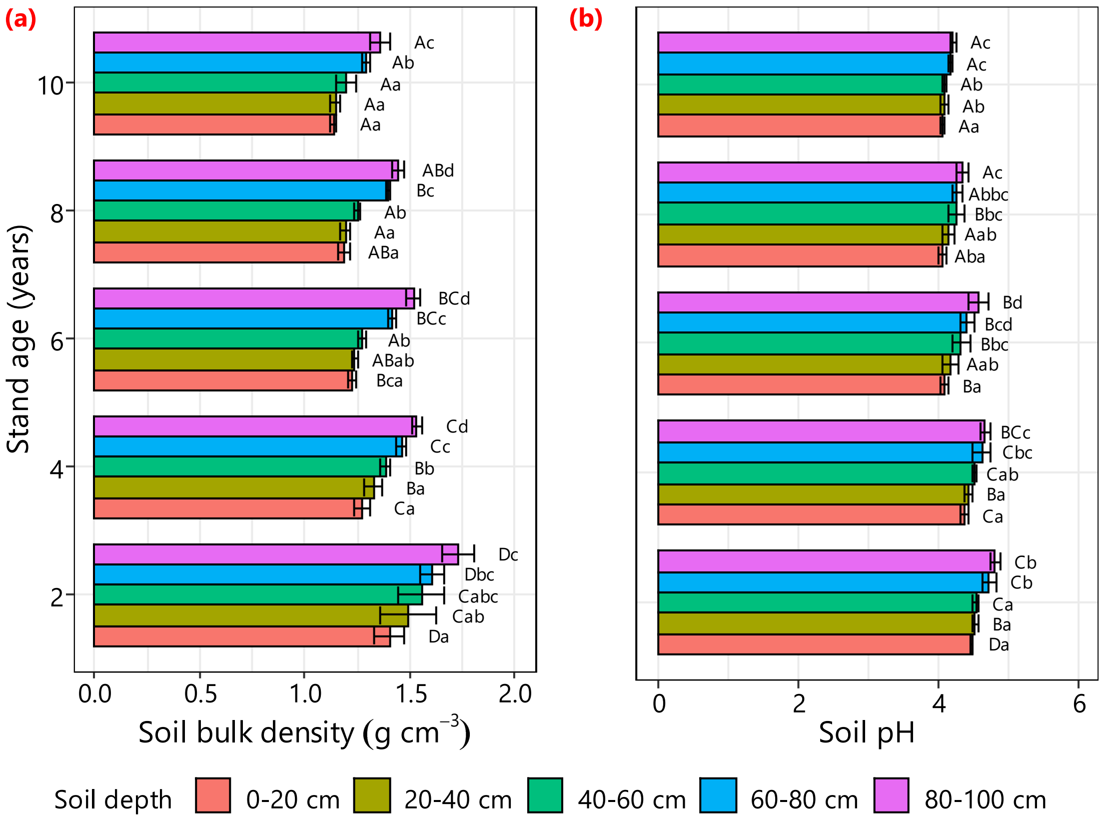

Figure 4. *Soil physicochemical features at different soil depths among different stand ages. Note: Different capital letters above the bars demonstrate significant differences between various stand ages within the same soil depth ($p<0.05$), and lowercase letters demonstrate significant differences between various soil depths within the same stand age ($p<0.05$). Values are the mean ± standard deviation (n = 3).*

Effects of soil and stand structure factors on soil P contents in *A.* hybrid plantations

The basic physical and chemical characteristics of the soil and forest structural features were considerably correlated with the soil P contents (Fig. 5). The TP and AP were strongly negatively correlated with the soil pH, BD, and SH (p<0.001). The soil TP and AP substantially negatively correlated with the SD (p<0.001), while they positively correlated with the SA, DBH, H, CA, LT, and UB (p<0.001).

The computed values of CFI and SRMR were 0.974 and 0.013, respectively, and an RMSEA value was 0.04 (Fig. 6). All figures were in the acceptable interval (CFI>0.95, SRMR<0.05, and RMSEA<0.06), further illustrating the appropriateness of the research model to the data. Therefore, the results revealed that the SEM model precisely depicts the relationship between environmental factors (involving stand structure and soil properties) and soil P contents in the study area.

As illustrated in Figure 6, standardized path coefficients (SPC) were identified to assess the strength of direct effect between the latent variables. The latent variable of soil features was substantially correlated with pH and BD, with corresponding SPC of 0.95 and 0.91, respectively. Contributions of pH and BD indexes to the latent variable of soil properties were similar. The latent variable of stand structural characteristics was strongly associated with UB and LT, and corresponding SPC values were 0.93 and 0.93, respectively. Contributions of both UB and LT to the latent variable of stand structural characteristics were identical. Finally, AP had the most excellent standardized path coefficient (0.97) concerning the latent parameter related to soil P concentrations.

As shown in Table 2, the study model revealed there was a positive association between stand structural factors and soil P contents and a negative association between soil factors and soil P contents. The standardized path coefficients for soil and stand structural features were -0.83 and 0.11, respectively. The findings suggested that soil characteristics are substantially more associated with soil P concentrations than stand structural properties. Consequently, soil P concentrations were significantly influenced by environmental parameters, with soil features having a more significant effect.

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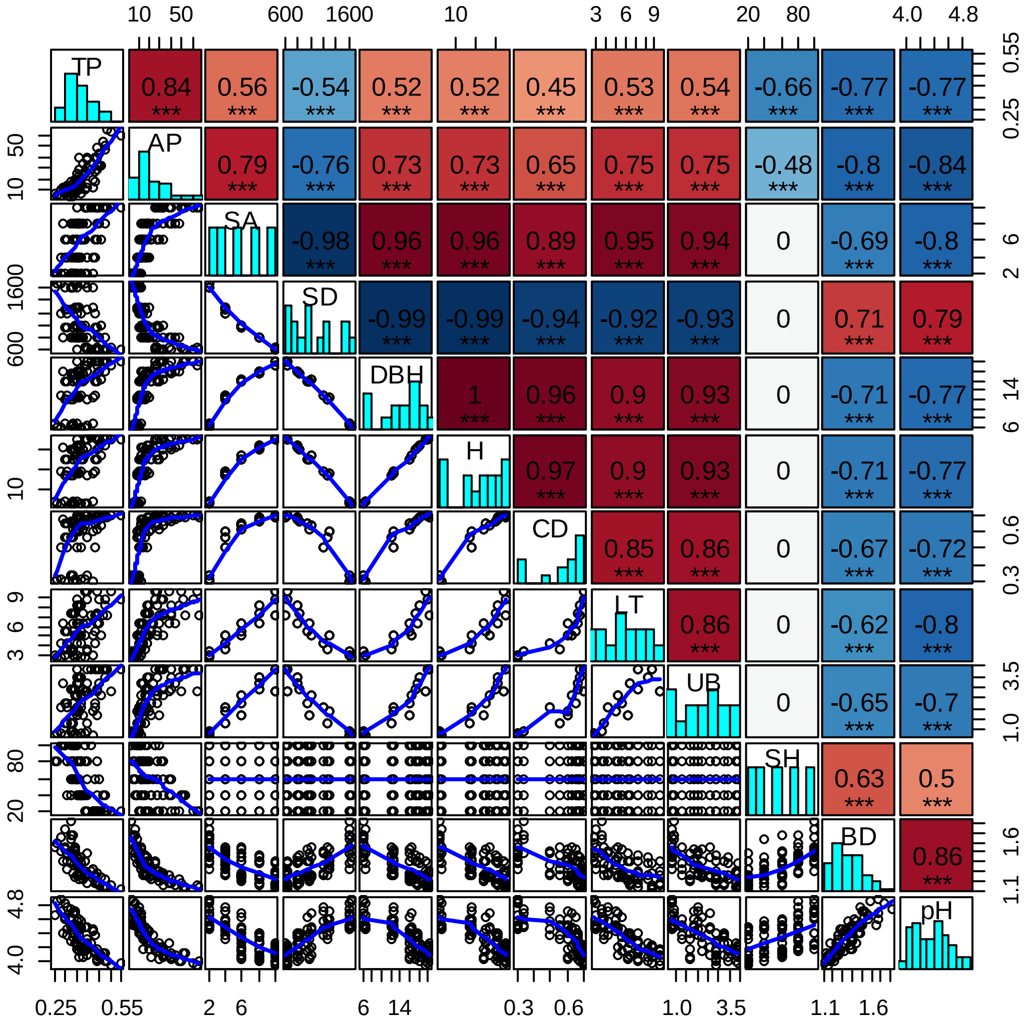

Figure 5. *Pearson correlation coefficients (r) between soil phosphorus contents and soil and stand structural features. Note: DBH (diameter at breast height, 1.3 m), H (tree height), SD (stand density), CD (canopy density), SA (stand age), UB (understory biomass), LT (litter biomass), BD (bulk density), SH (soil depth), TP (total phosphorus), and AP (available phosphorus). Significance levels: ***p<0.001; **p<0.01; *p<0.05.*

TABLE 2
Effects of soil, and stand structure factors on soil P contents.

Environmental factors	Path coefficients to PC	
SP	Total effect	-0.83**
SF	Total effect	0.11*

Note: PC refers to phosphorus concentrations, SF denotes stand structural features, and SP represents soil properties. Significance levels are indicated as follows: * p < 0.05, *** p < 0.001.

DISCUSSION

Soil phosphorus content and storage in *A*. hybrid plantations

This study found that stand age and soil depth strongly influenced the concentrations and stocks of phosphorus. The analysis results demonstrated that the soil TP and AP content and storage in the research area tended to decrease as the soil layer increased. The soil phosphorus was accumulated dominantly in the topsoil layer (0–20 cm) (Figs. 2-3). These trends are similar to previous research results (Selvaraj *et al*., 2018; Cuong *et al*., 2023b). As nutrients such as phosphorus typically store in the soil's top layer (Cuong *et al*., 2023a), microbially driven apoplast decomposition predominantly arises in the surface soil (0–20 cm) (Que *et al*., 2010), leading to an increase in the surface soil's phosphorus concentrations. Organic matter input decreases as soil depth rises because of decreased soil microbial decomposition activities, root residues, and secretions (Xu *et al*., 2019). Nonetheless, the trends distribution of soil TP and AP content and storage to decrease with increasing soil depth was less comparatively stable at depths below 40 cm for TP and at depths under 60 cm for AP in the current study since soil P is a sedimentary mineral with poor migration in soil, which is primarily impacted by soil parent material (Ma *et al*., 2020). Hence, the change in soil phosphorus in deep soils was relatively small. To date, numerous studies have been carried out to probe how afforestation affects alterations in soil TP (AP) stocks. Interestingly, there still exists some debates concerning the effects of stand age on the variability of soil TP (AP) stocks, involving increased (Zhang *et al*., 2019), decreased (Hu *et al*., 2018), or no significant change after afforestation (Zhou *et al*., 2022). The debate on soil TP (AP) stocks response to the stand age may be partly explained by variations in other contributing factors such as the choice of plant species applied for plantation, soil properties, forest type, climate, management practices, and prior land use, all of which may also overshadow the influence of stand age (Li *et al*., 2019). As shown in Table 1 and Figure 5, our data for an age sequence of *A*. hybrid plantations reveal a significant positive correlation (p<0.001) between soil TP (AP) storage and forest age. The observation could be explained, at least in part, by an essential accumulation of soil organic materials (plant roots and litter) with increasing stand age in *A*. hybrid plantations (Zhou *et al*., 2015). Additionally, a prior study has shown that with increasing stand age, soil microbial and enzymatic activities increase (García de León et al. 2016), thereby facilitating soil nutrient transformation and storage. Following afforestation, (Zhang *et al*., 2019; Cuong *et al*., 2023b) have also documented similar increases in soil TP (AP) storage. Besides, in the vertical distribution direction of soil phosphorus storage, over 40 % of soil TP stocks and more than 50 % of soil AP stocks were stored in the upper 40 cm in all five stands (Fig. 4), demonstrating that a significantly greater proportion of soil phosphorus storage was focused in the surface layer. This reveals that the topsoil in the study area is a large phosphorus pool despite being vulnerable to soil natural erosion and human disturbance. To promote phosphorus sequestration, it is therefore clearly necessary to implement good plantation management practices.

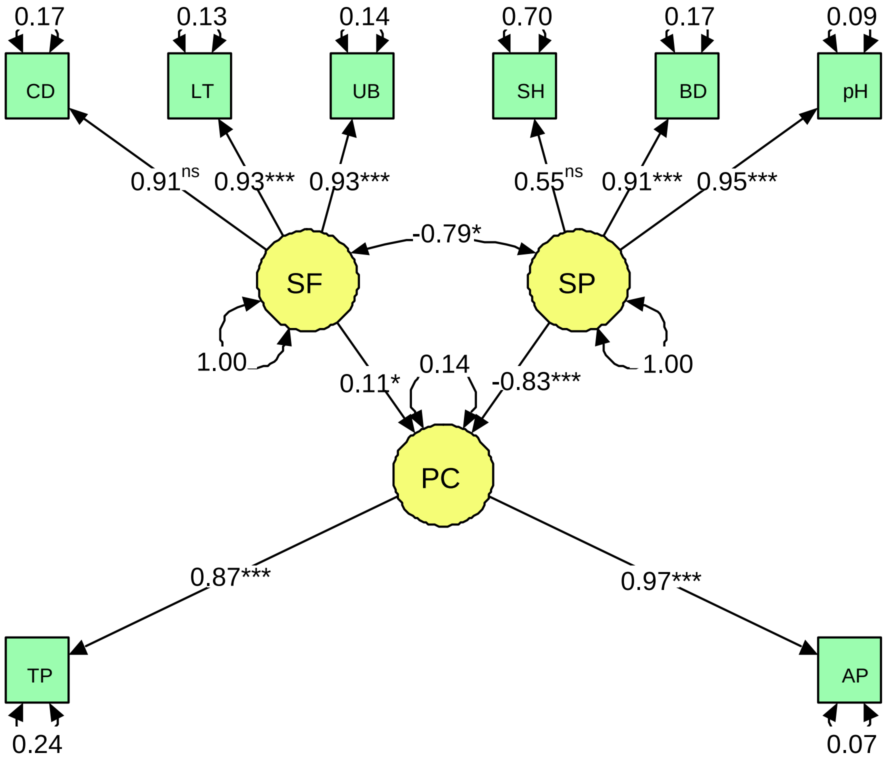

Figure 6. *Structural equation model (SEM) of the effect soil and stand structural properties on soil phosphorus contents.*

Note: The variables in the model include stand structural features (SF) and soil properties (SP), two exogenous latent variables representing stand structural and soil properties indices, respectively. Phosphorus concentrations (PC) is an endogenous latent variable that signifies phosphorus concentrations indices, whereas UB (understory biomass), LT (litter biomass), CD (canopy density) are observed variables associated with stand structure SF, and BD (bulk density), pH, and SH (soil depth) are observed variables associated with SP. TP (total phosphorus), and AP (available phosphorus) are observed variables linked to PC. Goodness-of-fit statistics for the model are as follows: χ^2 = 191.632, p = 0.585, CFI = 0.974, RMSEA = 0.04, SRMR= 0.013. The direction of the arrows reflects the interaction between the variables. A factor loading coefficient value of < 0 suggests a negative correlation, whilst a value of > 0 indicates a positive correlation. Significance level: *: p<0.05, ***: p<0.001, 'ns': non-significant.

Primarily factors modulating soil phosphorus contents in *A.* hybrid plantations

The SEM results illustrated that soil features, as reflected by the observed parameters of BD and pH, and stand structural properties, as identified by the observed parameters of LT and UB, strongly influenced the distribution of all the phosphorus concentrations in the *A.* hybrid plantation forest. Furthermore, the soil features exerted more effect on soil P contents than did stand structure properties (Fig. 6). According to previous studies, soil BD and pH are significant factors that impact soil functions such as soil microbial activity, microbial communities, and their diversity (Lei *et al.*, 2019), which are strongly connected to soil nutrient concentrations. Our data revealed a strong inverse relationship between soil BD and pH and soil TP and AP concentrations (Fig. 5), which is congruent with the recent finding of (Cuong *et al.*, 2023a). Studies have reported that lower soil pH inhibited the activities of soil microbial activities because the most suitable pH for soil microbe is typically in the neutral range of 6.5–7.5 (Que *et al.*, 2010), and thus will result in the accumulation of soil phosphorus concentrations. Additionally, the availability and distribution of soil phosphorus concentrations can be influenced by plant biomass parameters such as understory and litter biomass (Figs. 5-6) (Cuong *et al.*, 2023a). The effect strength of soil and stand structural properties con soil phosphorus contents were ranked as AP > TP according to the calculated standardized path coefficients (Fig. 6).

The current study illustrated the linkages between soil phosphorus concentrations and soil and stand structural features during forest stand development. However, soil phosphorus contents may be regulated by climate (e.g., temperature and precipitation), soil microorganisms, and other soil physicochemical characteristics (e.g., soil total organic carbon, total nitrogen, and texture) (Que *et al*., 2010; Li *et al*., 2019; Yang and Luo 2021; Wang *et al*., 2024). Thus, further studies are needed to explore the association of these parameters with soil phosphorus concentrations.

CONCLUSION

The present study explored the soil P dynamics of *A.* hybrid plantations at five stand ages in the Langa Forestry Company, Southern Vietnam. The effect of *A*. hybrid plantation age on soil TP and AP contents and stocks was significant. Soil TP and AP concentrations increased with stand age and reduced with increasing soil depth. The stocks of soil TP and AP increased from young to older. Soi TP and AP stocks illustrated apparent surface aggregation tendency, with over 40% TP storage and over 50% AP storage in 0–40 cm depth, respectively. The SEM analysis revealed the significant impact of soil (i.e., soil bulk density and pH) and forest stand properties parameters (i.e., plant biomass) on soil TP and AP concentrations. Notably, the soil properties parameters exerted a more pronounced effect on soil phosphorus concentrations than the stand features parameters. Overall, this study's findings offer important insights into the soil phosphorus dynamics and provide critical scientific data for the sustainable management of *A*. hybrid forests.

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