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# Variations in soil carbon, nitrogen, and phosphorus concentrations and stoichiometry with stand age in *Acacia* hybrid plantations in Southern Vietnam

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**Abstract.** *Chau M, Quy N, Xu X, Hung B, Cuong LV, Ngoan T, Nguyen T. 2024. Variations in soil carbon, nitrogen, and phosphorus concentrations and stoichiometry with stand age in Acacia hybrid plantations in Southern Vietnam. Biodiversitas 25: 565-573.* Soil Carbon (C), Nitrogen (N), and Phosphorus (P) contents are the three most critical soil nutrient elements required for plant growth and development, and their ecological stoichiometric ratios are significant indicators for understanding soil nutrient balance and cycling. This study was conducted to probe variations in the soil organic C (SC), total N (SN), and total P (SP) contents and stoichiometry at five soil depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm) in *Acacia* hybrid plantations of five different ages (2-, 4-, 6-, 8-, and 10-year-old plantations) in Langa-Dongnai Forestry Company, Southern Vietnam. The results showed that forest age and soil depth substantially impacted soil nutrient contents and their stoichiometric characteristics. The concentrations of SC, SN, and SP as well as C/N, C/P, and N/P ratios increased as the forest stand age increased. The contents of SC, SN, and SP reduced with soil depth, indicating an obvious soil "surface-aggregation" phenomenon. The nutrient restriction varied based on forest stand development, shifting from restricted nitrogen in the earlier growth periods of trees to restricted phosphorus in the later growth periods. The findings demonstrate that to resolve the issue of restricted availability of these nutrient indexes, additional nitrogen should be supplied during earlier growth periods and additional phosphorus during later growth periods. The results further emphasize the importance of understanding SC, SN, and SP interactions and nutritional limitations and provide relevant theoretical support for sustainable *Acacia* hybrid plantation management in the Southern region.

**Keywords:** *Acacia* hybrid plantation, ecological stoichiometry, soil depth, soil nutrients, stand age

## INTRODUCTION

Soil is a prominent constituent of terrestrial ecosystems and the primary source of nutrients to plants. Carbon (C), nitrogen (N), and phosphorus (P) in soil are the key nutrient elements for plants and are also the major restricting parameters in terrestrial ecosystems (Rahman et al. 2022). The concentrations of soil organic C, N, and P reflect the potential of the soil to supply nutrients for vegetation (Xu et al. 2019). Their synergistic impacts, to a certain extent, regulate ecological processes (e.g., cycling of biological elements and energy transformation) (Ma et al. 2020). The availability of soil N and P are key factors modulating the ecosystem C balance (Liu and Wang 2020). C/N/P stoichiometry is focused on the relationship and equilibrium among various nutritional components in ecological interactions (e.g., nutrient cycling and organic matter breakdown) and is a beneficial approach to understand the controlling mechanisms of nutrient distribution and restriction in the ecosystem (Jiang et al. 2019).

In recent times, immense advancements have been made on the understanding of C/N/P stoichiometric features in terrestrial ecosystems, such as plant tissue samples (Bai et al. 2019; Jia et al. 2023), forest stand ages (Yin et al. 2021; Ali et al. 2022), plant communities (Shuai et al. 2017; Zhao et al. 2017; Ma et al. 2020), plantations, and natural secondary forest ecosystems (Cao and Chen 2017). Jia et al. (2023) observed that the C/N/P stoichiometry in the plants-litter-soil system exhibited diverse patterns at various P addition levels. Ali et al. (2022) reported that as the stand age increased, the nutritional requirements of the plantations increased along with their soil N/P ratios. Yin et al. (2021) demonstrated that variations in plantation stand age considerably impacted soil nutrient concentrations and their stoichiometric value. Ma et al. (2020) showed that long-term vegetation restoration increased soil organic C and total N contents as well as soil C/P and N/P ratios. On the contrary, the contents of soil total P and C/N ratio were not considerably increased with vegetation restoration. Shuai et al. (2017) revealed that forest succession significantly affected soil organic C, total N, and total P contents and stoichiometry. Cao and Chen (2017) documented that C storage was lower in plantation forests than in natural forests. Although several studies have been conducted to explore the C/N/P stoichiometry in terrestrial ecosystems, little information is available on the soil C/N/P stoichiometry, particularly in Southern Vietnam. Hence, understanding the soil C/N/P stoichiometry is important for comprehending coupled nutrient cycling and maintaining sustainable management of forest ecosystems.

*Acacia* hybrid (*Acacia auriculiformis* A. Cunn. Ex Benth. × *A. mangium* Willd.) is a widely cultivated plantation tree species in Southern Vietnam. Owing to its traits of rapid growth, significant adaptability, and good timber quality, it contributes substantially to modulating the national economy and enhancing the ecological effectiveness and is presently cultivated across an area of 1.5 million ha in Vietnam, comprising 32.8% of total plantations in the country (MARD 2022). Several studies have been performed on *Acacia* hybrid plantations, including its biological growth traits (Ngoan and Bảo 2019), morphological variations (Sunarti et al. 2021), wood physical and mechanical features (Paiman et al. 2018; Duc Viet et al. 2020); biomass and productivity (Trieu et al. 2014), biomass and C sequestration potential (Hai et al. 2009), soil characteristics (Hung et al. 2017), and biological N fixation and restoration of degraded soils (Dong et al. 2014).

Nonetheless, information on soil C, N, and P contents and ecological stoichiometric characteristics in *Acacia* hybrid stands is relatively limited, which restricts the scientific understanding of the geochemical cycles of nutrient elements in these plantations. Hence, the contents and ecological stoichiometric traits of soil C, N, and P with regard to stand age (2-, 4-, 6, 8-, and 10-year-old stands) in *Acacia* hybrid plantation forests in the Southeast region of Vietnam should be comprehensively assessed. The following were the specific objectives of this study: (i) to examine the variations in soil C, N, and P contents in various stand ages; and (ii) to investigate soil C, N, and P ecological stoichiometric traits and nutrient limitations in *Acacia* hybrid forests. The findings of this study are expected to enrich our present knowledge on the ecological processes and nutrient status of *Acacia* hybrid plantations with stand age and serve as a providing valuable scientific data for formulating future sustainable forest management measures and strategies considering the benefits of soil quality improvement.

## MATERIALS AND METHODS

### Site characteristics

This study was performed in the Langa-Dongnai Forestry Company (11°00′00″-11°23′00″N and 107°00′00″-107°22′00″E), which is located in the Dinhquan Country, Dongnai Province, Vietnam (Figure 1). This region has a tropical monsoon climate, with an average annual precipitation of 3293 mm (occurs mainly from August to October) and an average annual temperature of 25°C (Ngoan et al. 2023). The elevation of the research area varies from 80 m to 93 m above sea level, and its slope angles range from 3° to 7°. The soil type in this area is yellowish-brown ferralitic soil derived from shale rocks, according to the FAO-UNESCO soil classification system.

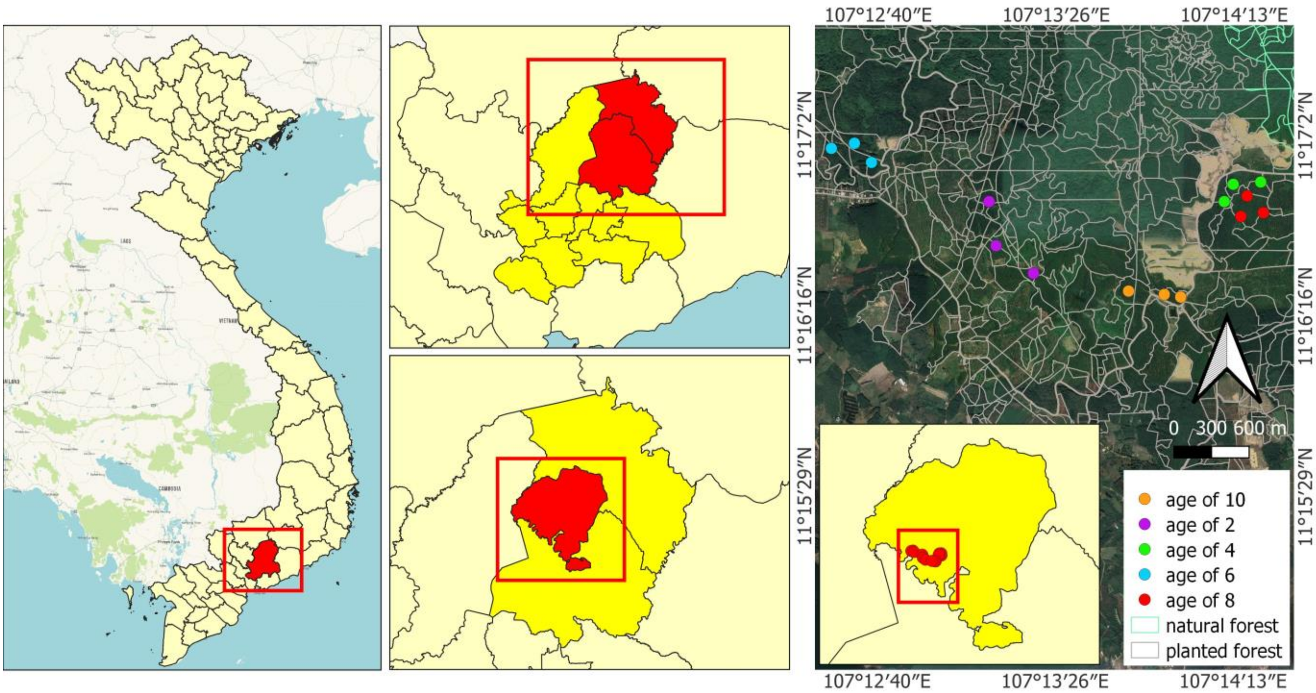


**Figure 1.** The experimental plots in Langa Forestry Company, Southern region, Vietnam

Multiple *Acacia* hybrid plantation stands of varying ages and densities are present in this region. Other woody plants include *Tectona grandis* L.f., *Sindora siamensis* Tejsm. Ex Miq. Var. *Siamensis*, *Dipterocarpus obtusifolius* Teijsm. Ex Miq., and *Hopea odorata* Roxb. Plantations constitute 62.4% of the total forest area. The area of *Acacia* hybrid plantations is 33.5%, and the rest (*Tectona grandis* L.f., *Sindora siamensis* Tejsm. Ex Miq. Var. *Siamensis*, *Dipterocarpus obtusifolius* Teijsm. ex Miq., and *Hopea odorata* Roxb) is 28.9%. *Acacia* hybrids are used extensively in the manufacture of pulp and timber. Five *Acacia* hybrid stands of various ages (2-, 4-, 6-, 8-, and 10-year-old stands) were selected in the research area. The twelve experimental plantations of various ages selected in the investigation were established on the same soil type and texture with a similar disturbance and topography after the first rotation was clear-cut and removed all tree stumps and branches. All stands were thoroughly tilled prior to planting and fertilized with 60 g of NPK 16-16-8 fertilizer per tree once a year for the first 3 years at planting. The initial planting density was 1667 trees$\cdot$ ha$^{-1}$ (3 m × 2 m), and thinning treatments were applied to the stands only after 4 years at an intensity not exceeding 30% of the standing volume (the thinning treatments were performed only once for the 4-, 6-, 8-, and 10-year-old plantations). Five stands of various ages were located within a 2 km radius of each other. Three plots (25 m × 20 min size) were established within each stand (i.e., a total of 15 plots). Field measurements and sampling were conducted from the 10$^{th}$ of December to the 30th of January 2022. Tree height (H) and Diameter at Breast Height (DBH) were recorded for all trees within these plots. Canopy closure was assessed using a smartphone application (Gap Light Analysis Mobile Application software), and 10 points were measured in each plot. The dominant understories in all sampling stands and certain basic information on the study area are presented in Table 1.

**Biomass measurements and soil sampling**

In each plot, the biomass of understory plants (involving shrubs and herbs) was quantified using destructive sampling in five 2 m × 2 m quadrants. The forest litter contribution to the soil surface was estimated from a set of five quadrants (1 m × 1 m) at the center and four corners of the plot. The biomasses of understory plants and forest litter (including leaves and sexual organs and twigs (<10 mm diameter)) in the sampling plots were harvested and weighed as fresh weight using an electronic balance and taken to the lab to be oven-dried at a temperature of 70°C until a constant weight was attained. The dry weights of understory plants and forest litter were determined, and the biomasses of understory plants and forest litter quantity per unit area were obtained.

Five soil profile pits (1 m long × 1.5 m wide × 1 m deep) were dug from the center of each plot and at its four corners. Samples were collected from each soil profile at depths of 0-20, 20-40, 40-60, 60-80, and 80-100 cm using a soil drilling sampler (5 cm inside diameter). Soil samples of 500 g from the same depth layer in the same plot were composited evenly to produce a mixed sample for each depth per plot, and subsequently, all samples (5 ages × 3 replicate sample plots for each forest stand age × 5 soil depths) were transferred to the lab for analysis. The soil samples were air-dried and passed over a 2 mm sieve to eliminate roots and other coarse debris and then ground to pass via a 0.25 mm mesh to measure multiple indexes (i.e., soil organic C (SC), total nitrogen (SN), and total phosphorus (SP)).

**Soil sample analysis**

The *SC* concentration was determined using the $H_2SO_4$-$K_2Cr_2O_7$ oxidation procedure (Nelson and Sommers 1982). SN and SP were estimated by referring to our recently published study (Cuong et al. 2022). The SN concentration was derived using the Kjeldahl procedure after digestion with a mixture of $C_7H_6O_3$ and $H_2SO_4$. The SP content was measured using the colorimetric method after the sample was digested with $H_2SO_4$ and $HClO_4$. The SC, SN, and SP contents were reported as g$\cdot$ kg$^{-1}$ on a dry weight basis. Soil stoichiometric ratios were computed using the mass ratios of SC, SN, and SP, which were C/N, C/P, and N/P, respectively (Ma et al. 2020; Wang and Zheng 2020).

**Table 1.** Basic characteristics of the five *Acacia* hybrid forests

| Measured factors | Forest age (years) | | | | |
|---|---|---|---|---|---|
| | **2** | **4** | **6** | **8** | **10** |
| Slope (°) | 3 | 3 | 5 | 4 | 7 |
| Elevation (m a.s.l.) | 83 | 86 | 85 | 95 | 93 |
| Average DBH (cm) | 6.30±0.36$^a$ | 12.40±0.40$^b$ | 16.13±0.32$^c$ | 17.80±0.26$^d$ | 19.93±0.40$^e$ |
| Average tree height (m) | 6.17±0.29$^a$ | 13.90±0.36$^b$ | 17.77±0.64$^c$ | 20.50±0.50$^d$ | 22.63±0.35$^e$ |
| Stand density (Plants$\cdot$ ha$^{-1}$) | 1620±35$^e$ | 1247±42$^d$ | 980±20$^c$ | 807±12$^b$ | 620±20$^a$ |
| 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 biomass (Mg$\cdot$ 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$^c$ |
| Litter biomass (Mg$\cdot$ 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$^c$ |
| Main understorey plant species | *Chromolaena odorata* (L.) R.M. King & H. Rob., *Mallotus apelta* (Lour.) Müll. Arg., *Tetracera scandens* (L.) Merr., *Lophatherum gracile* Brongn. (*L. gracile*), *Mimosa pudica* var. *tetrandra* (Willd.) DC., *Saccharum arundinaceum* (Retz.), and (*Chrysopogon aciculatus* (Retz.) Trin.) | | | | |

Note: Values are mean±Standard Deviation (SD). Means in a row, different lowercase letters are significantly different at p<0.05. DBH, diameter at breast height (1.3 m)

### Data processing and analysis

All statistical analyses were performed with R version 4.2.0 (R Core Team 2022) and SPSS version 25.0 (IBM Corp. 2017) statistical software programs. The mean SC, SN, and SP contents as well as their ratios were determined for each forest stand age. The results were presented as mean±standard deviation. Two-way Analysis of Variance (ANOVA) was applied to analyze the impacts of plantation age, soil depth, and their interactions on soil SC, SN, and SP contents and their stoichiometry. One-way ANOVA followed by Fisher's least significant difference test was used to examine the differences in soil nutrient concentrations and stoichiometry among the three plantations and four soil depths. Prior to ANOVA, data normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene's test) were tested. Pearson correlation analysis was employed to assess the correlations among C, N, and P contents in the soil. A *p-value* of <0.05 was considered statistically significant.

## RESULTS AND DISCUSSION

### Variations in soil nutrient concentrations with stand ages and soil depths

Soil nutrient parameters (SC, SN, and SP) significantly altered with stand ages ($p$<0.001), soil depths ($p$<0.001), and interactions between these two ($p$<0.001), except for SN and SP ($p$ = 0.649 and $p$ = 0.863, respectively) (Table 2). Except for *SC* between 6- and 4-year-old stands at the soil depth of 0-20 cm ($p$>0.05, Figure 2A) and SP among 8-, 6-, 4-, and 2-year-old stands at soil depths of 0-20, 20-40, 40-60, and 60-80 cm ($p$>0.05, Figure 2B), significant variations were observed in SC, SN, and SP among different stand ages at various soil depths ($p$≤0.05, Figures 2A-2C). The SC, SN, and SP concentrations appeared to increase with forest age. The respective maximum and minimum SC, SN, and SP values were detected in the 10- and 2-year-old plantations for the five sampled soil depths (i.e., 0-20, 20-40, 40-60, 60-80, and 80-100 cm).

Soil depth is a parameter that regulates nutrient concentrations in the soil (Figures 2A-2C). The maximum SC, SN, and SP concentrations were observed in the upper 0-20 cm layer for all five stands, which illustrates that these contents are primarily stocked in the topsoil layer. Furthermore, for all five stand ages, these contents showed declining trends as the soil depth increased. The concentrations of *SC* and *SN* decreased significantly at the 0-100 cm soil depth for all five stands ($p$≤0.05). However, the SP concentration decreased rapidly for all five stands at the depth of 0-40 cm ($p$≤0.05) and then more slowly at the depth of 40-100 ($p$>0.05).

### Variation in C:N:P stoichiometry with stand ages and soil depth

A two-way ANOVA illustrated that forest ages and soil depths significantly affected soil nutrient indicators ($p$<0.001) but did not have significant effects on soil nutrient stoichiometry (C/N, C/P, and N/P) ($p$=0.190, $p$=0.477, and $p$=0.924, respectively) (Table 2).

The ratios of soil C/N, C/P, and N/P at the five soil depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm) increased across stand ages (Figures 3.A-3.C). The highest C/N, C/P, and N/P ratios for the various stand ages were observed in 10-year-old stands, whereas the lowest was noted in 2-year-old stands. Along the forest stand ages, the soil C/N, C/P, and N/P ratios within the 0-20 cm soil layer increased from 11.42 to 12.94, 22.85 to 51.47, and 2.00 to 3.98, respectively; the 20-40 cm soil layer increased from 9.48 to 10.35, 15.38 to 41.37, and 1.61 to 4.01, respectively; the 40-60 cm soil layer increased from 7.08 to 9.81, 9.84 to 37.22, and 1.38 to 3.79, respectively; the 60-80 cm soil layer increased from 5.18 to 9.80, 5.25 to 32.91, and 0.99 to 3.39, respectively; and the 80-100 cm soil layer increased from 5.79 to 8.45, 3.45 to 25.00, and 0.60 to 2.97, respectively. Irrespective of stand age, soil nutrient stoichiometric ratios decreased as the soil depth increased. Nonetheless, there was no discernable difference in soil C/N, C/P, and N/P ratios among various soil depths for any of the stand ages ($p$>0.05), except for the C/N ratio in the 4- year-old stand and the C/P and N/P ratios in the 4- and 2-year-old stands ($p$≤0.05).

### Pearson correlation coefficients of soil nutrient contents and stoichiometry

Figure 4 depicts the correlation analysis between soil nutrient contents and ecological stoichiometry. The SC, SN, and SP exhibited an extremely significant positive correlation ($p$<0.001). *SC* displayed a highly significant positive correlation with soil C/N, C/P, and N/P ratios ($p$<0.001). Furthermore, SN showed a strong positive correlation with soil C/N, C/P, and N/P ratios ($p$<0.001). Moreover, *SP* exhibited a significant positive correlation with soil C/N, C/P, and N/P ratios ($p$<0.001). Additionally, extremely significant positive correlations ($p$<0.001) were noted among the ratios of soil C/N, C/P, and N/P ($p$<0.001).

**Table 2.** Interactive effects of stand age and soil depth on soil nutrient concentrations

| Variables | *F (p)* value | | |
|---|---|---|---|
| | **Stand age** | **Soil depth** | **Stand age × Soil depth** |
| *SC* | **516.357 (<0.001)** | **437.813 (<0.001)** | **6.402 (<0.001)** |
| *SN* | **305.835 (<0.001)** | **126.974 (<0.001)** | 0.828 (0.649) |
| *SP* | **43.360 (<0.001)** | **56.486 (<0.001)** | 0.607 (0.863) |
| *C/N* | **14.095 (<0.001)** | **58.07 (<0.001)** | 1.380 (0.190) |
| *C/P* | **212.920 (<0.001)** | **142.857 (<0.001)** | 0.995 (0.477) |
| *N/P* | **184.806 (<0.001)** | **47.043 (<0.001)** | 0.520 (0.924) |

Note: SC: Soil organic Carbon concentration, SN: Soil total Nitrogen concentration, SP: Soil total Phosphorus concentration. Bold fonts indicate extreme significance (p<0.001)

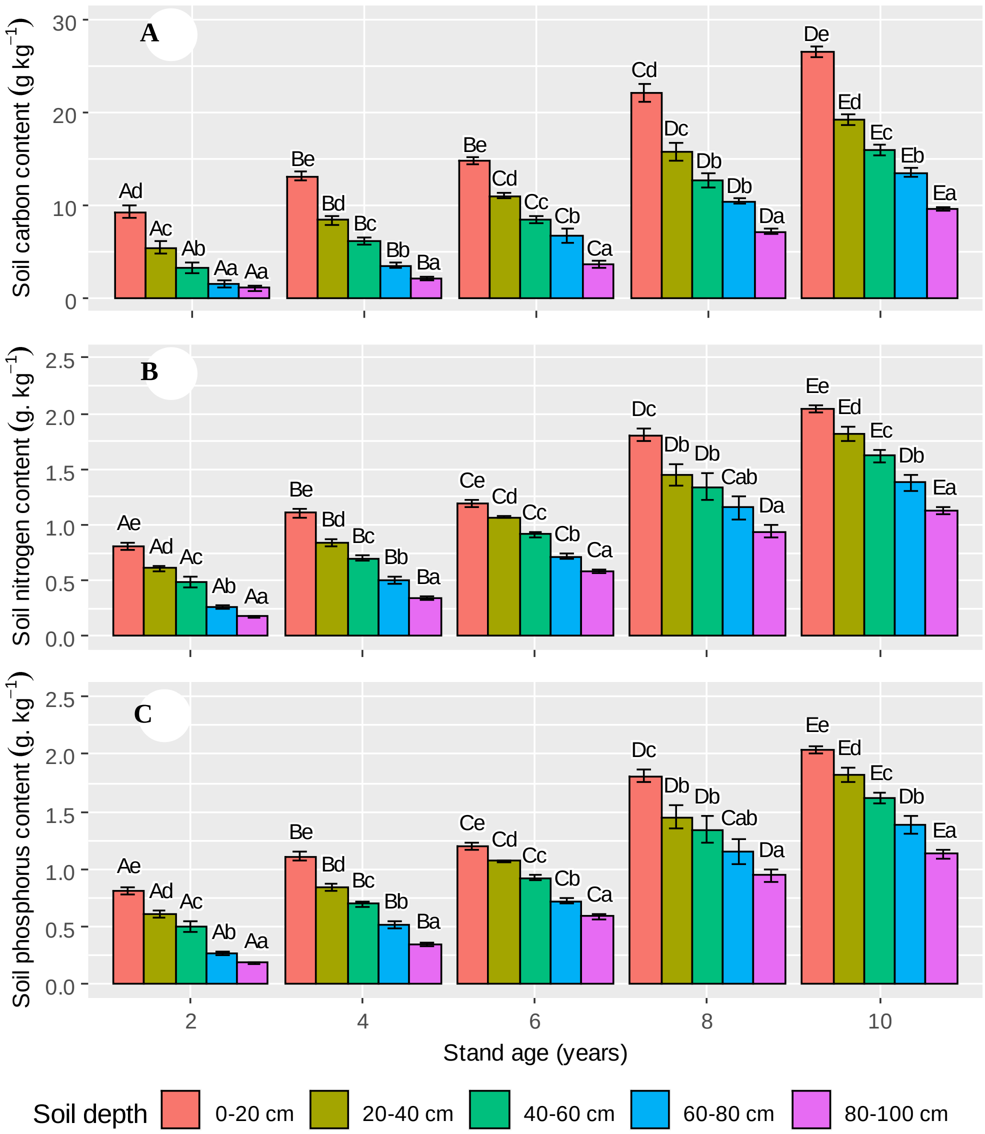


**Figure 2.** Soil nutrient concentrations at various soil depths in *Acacia* hybrid forests. Note: Different uppercase letters represent significant differences between the same soil depths in various stand ages ($p<0.05$). Different lowercase letters represent significant differences between the sampled soil depths within the same stand age ($p<0.05$). Error bars represent mean±standard deviation (n=3)

## Discussion

*Impact of forest age and soil depth on soil nutrient content*

C, N, and P are the predominant chemical elements in the soil, and their concentrations and distributions exert an important effect on plant growth and development (Jiang et al. 2021). The findings from this study indicated that soil nutrient concentrations (SC, SN, and SP) increased significantly with increasing age in *Acacia* hybrid plantation. These results agree with those from earlier studies (Zhao et al. 2014; Liu et al. 2016; Cuong et al. 2023). These findings may be explained by a significantly greater plant litterfall production and fine-root turnover in older plantations and a larger amount of root exudates entering the soil (Cuong et al. 2023). Plant biomass parameters (involving understory plant biomass and litter biomass) are positively correlated with soil nutrient concentrations (Table 1), illustrating the accumulation of soil nutrient contents with increasing plant biomass, which is due to the important regulation of plant biomass on soil nutrient concentrations. Nutrients from plant roots and litter that are returned to the soil are the primary components of forest biogeochemical cycling (Zhu et al. 2019). Moreover, as the stand age increases, soil microbial and enzymatic activities are increased (Lu et al. 2022), thereby enhancing soil nutrient transformation and storage (Lei et al. 2023). However, there are still controversies regarding the effects of forest age on soil nutrient contents (e.g., decrease gradually with age increment (Lee et al. 2015; Wu et al. 2015); first increase and then decrease (He et al. 2022), or show no significant variation with forest age (Yang et al. 2018a). One possible description for this divergence is that, besides forest age, numerous other parameters influence soil nutrients, such as the difference in species planted, soil characteristics, previous land use, climate, and management practices (Cuong et al. 2023).

Soil depth is a vital factor that influences the contents of soil nutrients (SC, SN, and SP) (Xu et al. 2019). Several previous investigations have shown that *SC* and *SN* contents were relatively greater in the top layer than those in the deeper layer, while SP concentrations did not significantly differ among soil depths, resulting in marginal variations in their stoichiometric ratios (Luo et al. 2020; Li et al. 2021). This contradicts the present study. Our study data established that SC, SN, and SP decreased considerably with increasing soil depth in all plantations and were present predominantly in the surface layer (0-20 cm). These findings are similar to those from previous reports (Fan et al. 2015; Yin et al. 2021; Cuong et al. 2023). This observation could be attributed to the rich distribution of plant aboveground litter and underground roots in the upper soil layer (0-20 cm). The decomposition of plant aboveground litter and belowground roots enriches the humus in the topsoil with a distinct surface aggregation (Gao et al. 2014; Abdullah et al. 2022). In addition, an abundance of plant litter and roots, high humidity, plentiful microorganisms, and the continuous disturbance in the topsoil promote the accumulation of soil nutrients (Deng et al. 2015). With increasing soil depth, inputs from the plant's underground roots and aboveground litter are restricted by the permeability of the soil. Furthermore, there is a gradual decrease in microbial decomposition activity and litter, root residues, and secretions, which results in the striking stratification features of soil nutrient contents (Berger et al. 2002; Liu and Wang 2020; Rahman et al. 2022).

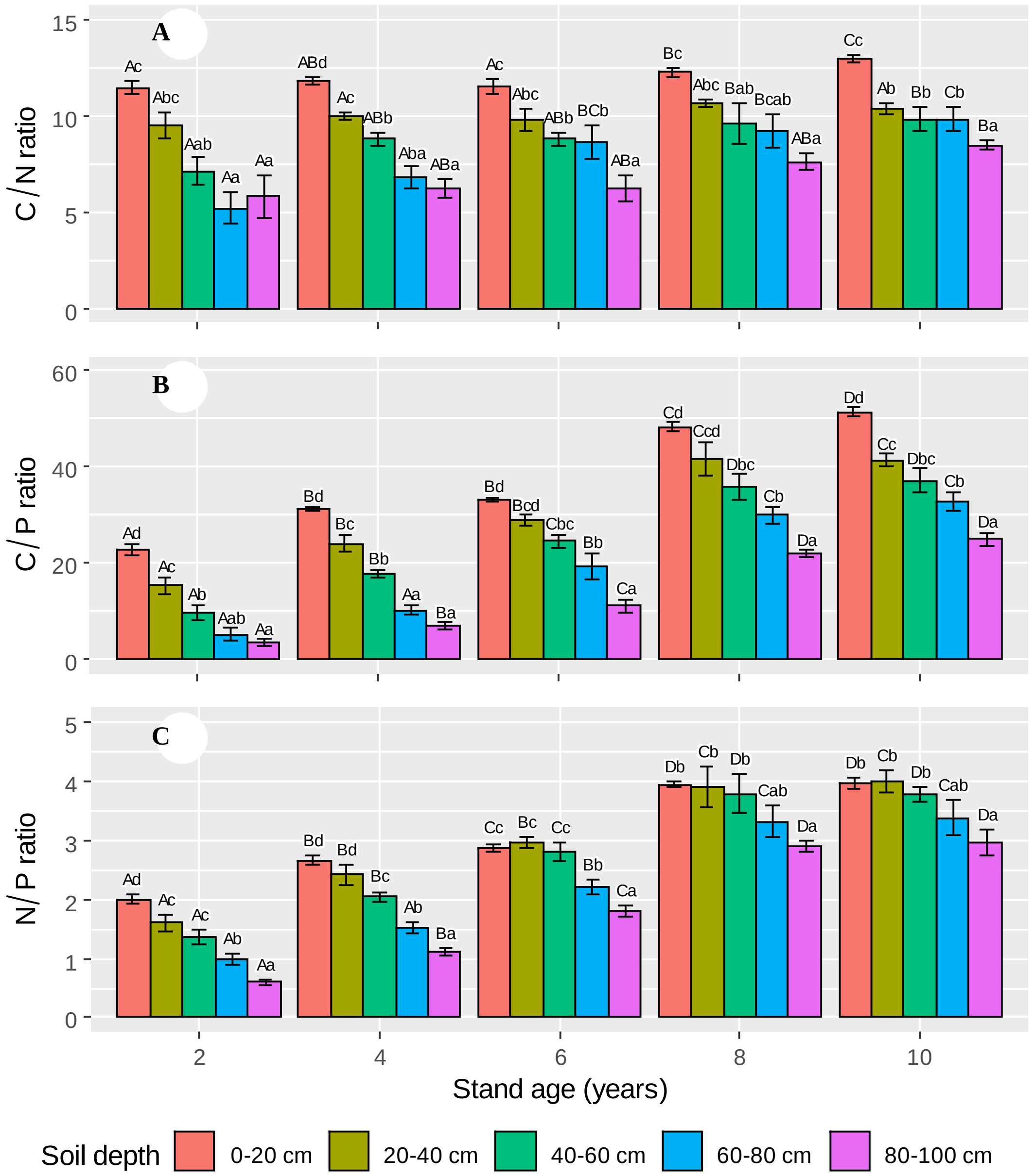


**Figure 3.** Soil nutrient stoichiometric ratios at various soil depths in the *Acacia* hybrid forests. Note: Different uppercase letters represent significant differences between various stand ages within the same soil depth (p<0.05). Different lowercase letters represent significant differences between various soil depths within the same stand age (p<0.05). Error bars represent mean±standard deviation (n=3)

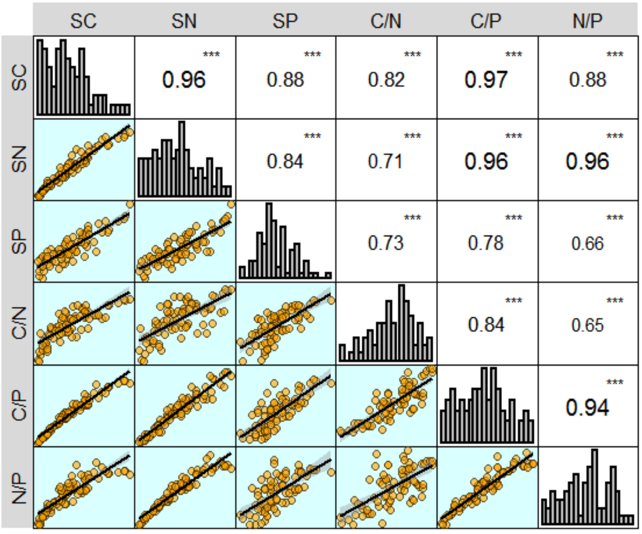


**Figure 4.** Pearson correlation coefficients of soil nutrient contents and ecological stoichiometry. ***show significant effects at p<0.001

*Effects of stand age and soil depth on soil nutrient stoichiometry*

The soil nutrient stoichiometry ratio is a critical index that reflects soil quality and organic matter composition. The C/N ratio is an indicator that determines the C and N nutrient equilibrium and is often employed as a sensitivity index of soil quality (Wang and Zheng 2020). The average soil C/N ratio across different stand ages and soil depths was 9.12 in this study, which was much lower than the global average of 14.30 reported by Cleveland and Liptzin (2007). Previous studies have reported that the soil C/N ratio is inversely related to the decomposition rate of soil organic matter and that a lower ratio signifies a more rapid rate of decomposition (Wang and Zheng 2020; Wang et al. 2021). Thus, the results from this research demonstrate that soil nutrient accumulation, organic matter decomposition, and mineralization rates at this site are higher than the global average. There was an increasing trend of soil C/N ratio as the stand age increased. Overall, SC and SN concentrations increased with plantation age, and the rate of increase of SC was greater than that of SN; therefore, the C/N ratio increased.

Soil C/P ratio is used to determine the phosphorus release potential from microbially mineralized organic matter in the soil, which exerts a significant impact on plant growth and development (Yang et al. 2018b). A lower C/P strengthens the soil's available phosphorus by stimulating microbial organic matter decomposition. In contrast, a higher C/P limits the amount of available phosphorus as a result of microbial organic matter degradation; these microbes compete with plants for soil phosphorus, which is detrimental to plant growth (Wang et al. 2014). In our study, the mean C/P ratio in the soil (25.23) was substantially lower than that for global forest soils (186) (Cleveland and Liptzin 2007), which indicates that the mineralization rate of phosphorus is relatively high at this site. The ratios of soil C/P and N/P showed a similar tendency in response to forest age. The soil C/P ratio increased as the stand age increased and reached the maximum in the 10-year-old stand. Our findings signify that phosphorus is a restricting factor during the development of *Acacia* hybrids. These results can be explained by the low amounts of phosphorus in the soils of tropical Vietnam as well as phosphorus absorption by rapidly growing tree species (Sam et al. 2006). Furthermore, previous investigations have reported that phosphorus limitation increases with forest development (Huang et al. 2013).

Nitrogen and phosphorous are vital determinants of plant growth and development (Lu et al. 2023). The soil N/P ratio is often used to diagnose soil nutrient-limiting indicators and assess nutrient restriction thresholds (Batjes 1996; Jiang et al. 2021). The average soil N/P ratio (2.60) at this site was much lower than the average of global forest soils (13.10) (Cleveland and Liptzin 2007). As the plantation age increased, the rate of increase of SN was greater than that of SP, which led to an increase in the soil N/P ratio. Previous studies have reported significant correlations between plant growth rate and soil N/P ratio (Zhong et al. 2019). In this study, the soil N/P ratio was lower in the early period and higher in the later periods of trees. This observation implies that nitrogen may be a limiting factor during the early periods of tree development (Ren et al. 2016). Other researchers have also documented that as forests aged, nutrient limitation in the soil ecosystem altered, shifting from nitrogen restriction in the early periods of tree growth to phosphorus restriction in the later periods (Huang et al. 2013; Fan et al. 2015).

In line with the findings of former studies, soil C/N, C/P, and N/P ratios demonstrated a decreasing tendency with soil layers in various forest ages of *Acacia* hybrid, which could be attributed to the same change dynamics in SC, SN, and SP (Li et al. 2013; Qi et al. 2020; Qiao et al. 2020). Other possible reasons are the soil surface layer being easily impacted and nutrient return from the litterfall (Feng et al. 2017). Soil nutrients are often initially concentrated on the top surface layer and then transported to deeper layers via water or soil animals (Qi et al. 2020).

In conclusion, these findings suggest that forest ages and soil layers have substantial impacts on soil nutrient contents and their stoichiometric characteristics. The SC, SN, and SP contents as well as C/N, C/P, and N/P ratios increased with increasing forest age. The concentrations of SC, SN, and SP tended to decrease as the soil depth increased, displaying the phenomenon of soil "surface accumulation". These results show that the application of nitrogen fertilizer can promote tree growth in the earlier period and that phosphorus application can eliminate phosphorus limitation during the later period. The outcomes from this study aid in understanding the SC, SN, and SP interactions and nutrient limitations and serve as an important scientific reference for the sustainable management of *Acacia* hybrid plantations.

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