SOIL NITROGEN STORAGE AND ASSOCIATED REGULATION FACTORS IN AN *ACACIA* HYBRID PLANTATION CHRONOSEQUENCE IN SOUTHERN VIETNAM

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Abstract. The study was designed to quantify the soil total nitrogen (*STN*) storage (*SNS*) and its controlling factors in *Acaci*a hybrid *(Acacia auriculiformis* × *A. mangium*) plantations in five different ages (2-, 4-, 6-, 8-, and 10-years-old) in Langa - Dongnai Forestry Company, Southern Vietnam. A total of 75 soil samples were taken at five different soil depths from 0–100 cm. The *STN* concentration, *SNS*, soil properties, and plant biomass features (i.e., understorey vegetation biomass and litter biomass) were estimated. The *STN* concentration significantly increased with increasing forest stand age, whereas significantly decreased with increasing soil depth in all stand ages. The *SNS* in the uppermost 1 m soil layer in 2-, 4-, 6-, 8, and 10-year-old stands was 6.83, 9.50, 12.30, 17.15, and 19.41 Mg ha^{-1}, respectively. The *SNS* was focused mainly on the topsoil layers (0–40 cm). The *SNS* in the upper 0–40 cm soil layer accounted for over 50% of the total soil N stocks and the accumulation revealed decreasing tendencies with an increase of soil depth in all five stands. The soil organic carbon concentration and soil particle size fractions (i.e., soil silt concentration) were detected as the leading environmental parameters modulating the *SNS* variance. Our findings illustrate that considerations of N sequestration potential in *Acacia* hybrid plantations must take stand age into account and offer significant information for a better comprehension of the key environmental parameters driving *SNS* in Southern Vietnam.

Keywords: *forest plantations, soil properties, plant biomass features, stand age, soil depth*

Abbreviations used: *PCA* (principal component analysis); *SAP* (soil available phosphorus); *SBD* (soil bulk density); *SMRA* (stepwise multiple regression analysis); *SNS* (soil total nitrogen storage); *SOC* (soil organic carbon); *STN* (soil total nitrogen); *STP* (soil total phosphorus); *SWC* (soil water content); *TOC* (tolerance); *VIF* (variance inflation factor)

Introduction

Increasing carbon dioxide (CO_2) contents and other greenhouse gas emissions into the atmosphere are becoming a crucial global threat; thus, posing serious environmental issues (Deng et al., 2017). Finding some strategies to mitigate the atmospheric concentrations of

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greenhouse gases is an urgent issue (Li et al., 2019; Cuong et al., 2020). Globally, soils are the largest carbon (C) pools of the terrestrial C cycle, constituting approximately thrice the amount of C stocked in vegetation and twice the amount stocked in the atmosphere. Worldwide the upper 100 cm of soil contains 1500 Pg C (Lal, 2018). Particularly, forest soil C is a crucial component of the global C reservoir, occupying 70-73% of all soil organic C (SOC) globally (Six et al., 2002). Carbon and nitrogen (N) are essential elements for preserving soil structure, ecological function, nutrient cycling, and forest ecosystem stability (Wang et al., 2019). Soil N also plays a prominent role in C reservoirs because it interacts with C to promote ecosystem productivity and C sequestration (Ngaba et al., 2020). The dynamic change of soil N is the fundamental parameter governing C sequestration potential in forest ecosystems; for example, rising N inputs result in sustainable C sequestration (Deng et al., 2016; Wang et al., 2019). Therefore, accurate quantification of soil total N (*STN*) storage (*SNS*) and its main driving parameters in various stand ages is essential for forest sustainable management and predicting the variations of future soil C and N cycles.

Shifts in *SNS* after afforestation and stand age have been documented by a number of field studies. Several studies have indicated that *SNS* are age-independent (Sartori et al., 2007), increase with age increment (Dou et al., 2016), decrease with stand age (Smal and Olszewska, 2008; Zeng et al., 2014), or demonstrate an initial decline subsequently followed by an increase with forest stand age development (Ritter, 2007). The contradictory results distinctly reveal the necessity for mechanistic knowledge of how soil ecosystems alter with stand development in plantation ecosystems.

Acacia hybrid (*Acacia mangium* × *Acacia auriculiformis*) is a major plantation species in the Southeastern region of Vietnam due to its excellent timber, rapid growth, and high timber production. It plays a pivotal role in forestry production in Vietnam and is currently cultivated across an area of 1.5 million ha in Vietnam, accounting for approximately 32.8% of total plantation forests in the country (MARD, 2021). Apart from manufacturing wood products for industries, *Acacia* hybrid plantations contribute significantly to offering environmental services such as C and N capture and storage. Hence, a deeper knowledge of the *N* dynamics and its governing mechanisms in *Acacia* hybrid forest soils is of great importance for improving the *C* storage of soils, formulating sustainable forest management measures and strategies, and understanding their role in climate change adaptation and mitigation. Numerous researches have been conducted on biological and growth characteristics (Ngoan and Bao, 2019), wood quality (Jusoh et al., 2014), biomass and C sequestration (Hai et al., 2009), soil physicochemical features (Hung et al., 2017), biological nitrogen fixation (Dong et al., 2014) in *Acacia* hybrid forests. Information on soil N sequestration by *Acacia* hybrid plantations in Southern Vietnam, nevertheless, is limited. Thus, the study was evaluated to examine soil N in a chronosequence of five different aged *Acacia* hybrid forest stands (2-, 4-, 6-, 8-, and 10- years old) in Southern Vietnam. The particular objectives of this research were to: (i) estimate the soil total N content and storage; and (ii) ascertain the key factors controlling soil total N storage variability in *Acacia* hybrid forests over five different ages in Southern Vietnam.

Material and methods

Site characteristics

The study sites were located in Langa - Dongnai Forestry Company (11°00′00″ to 11°23′00″N and 107°00′00″ to 107°22′00″E), Dongnai Province, Vietnam (*Fig. 1*). The area belongs to a tropical monsoon climate zone that has defined rainy and dry seasons. The rainy season extends from May to November and the dry season from November to the following April. The mean annual precipitation is 3293 mm, mostly occurring from August to October. The mean annual temperature is 25°C, and the average annual relative humidity is 85% (Ngoan et al., 2023). The elevation of the research area ranges from 80 to 93 m above sea level, with slope angles ranging from 2 to 7°. Based on the FAO-UNESCO soil classification system, the primary soil type in the research area is yellowish-brown ferralitic soil, derived from shale rocks (Sam et al., 2006). The dominant woody plants are *Tectona grandis* L.f., *Sindora siamensis* Tejsm. ex Miq. var. *siamensis*, *Dipterocarpus obtusifolius* Teijsm. ex Miq., and *Hopea odorata* Roxb. Approximately 62.4% of the total forest area is made up of plantations. *Acacia* hybrid accounts for about 33.5% of all plantations in this region and is critical in the production of pulp and timber. The study site consists of a chronosequence *Acacia* hybrid stands with ages of 2-, 4-, 6-, 8-, and 10-year-old (hereafter called AH2, AH4, AH6, AH8, and AH10, respectively). All the stands were on the second rotation and were fertilized with NPK 16-16-8 fertilizer once a year for the first three years. The initial planting density of the experimental stands was recorded as 3 m × 2 m (1667 trees$\cdot$ ha^{-1}), and thinning operations were only carried out for the stands after 4 years with thinning intensity not exceeding 30% of the standing volume. The diversity and abundance as well as the growth of understory vegetation were well-developed, especially for the 8- and 10-year-old plantations. The predominant understorey shrub and herb plant species include *Lophatherum gracile* Brongn., *Mimosa pudica* var. *tetrandra* (Willd.) DC*.*, *Tetracera scandens* (L.) Merr., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Saccharum arundinaceum* Retz., *Mallotus apelta* (Lour.) Müll. Arg., and *Chrysopogon aciculatus* (Retz.) Trin.

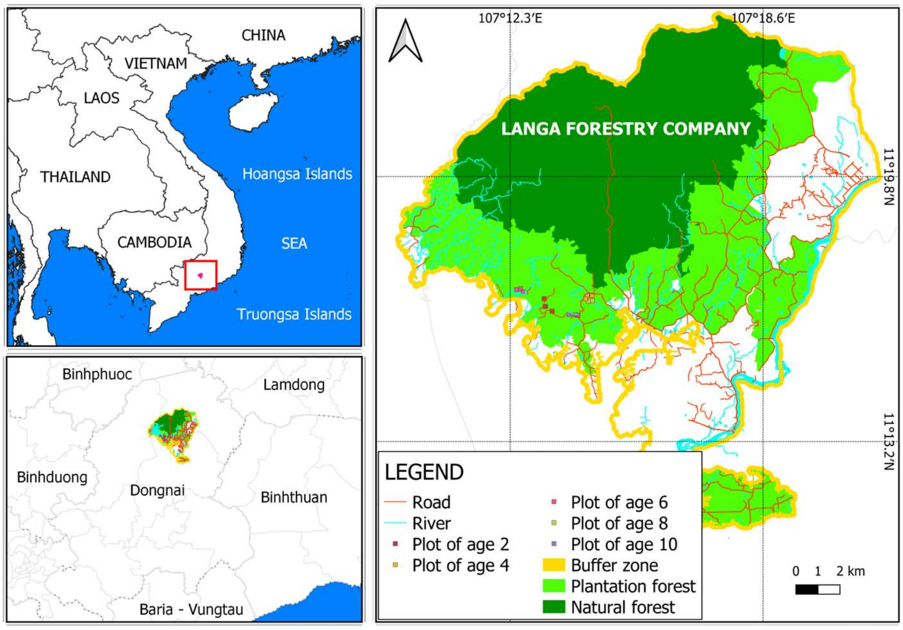


Figure 1. *The location of the research sites Langa - Dongnai Forestry Company at Vietnam*

Field sampling and measurements

During 10th December to 30th January in 2022, three sample plots (25 m × 20 m) were established in each *Acacia* hybrid stand (i.e., a total of 15 plots were established) (*Fig. A1 in the Appendix*). All five stands were no more than two km apart (*Fig. 1*). The tree density, height, and stem diameter at breast height (*DBH*) of trees in the sample plots were measured. Canopy closure was estimated using a smartphone application (Gap Light Analysis Mobile Application software), and 10 points were established in each plot. More detailed information on the sampling sites is described in *Table 1*.

Table 1. *Characteristics of five different aged Acacia hybrid forest stands*

Measured variables	Stand age (years)				
	2	4	6	8	10
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· 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· 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· 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}
Elevation (m a.s.l.)	83	86	85	95	93
Slope (°)	3	3	5	4	7

Values are means ± standard deviation (SD). Different capital letters demonstrate a significant difference between different stands ($p < 0.05$)

In each plot, the understorey biomass (including shrubs and herbs) was measured by a destructive sampling of five 2 m × 2 m quadrates. In each plot, the litter contribution was estimated by selecting five quadrates (1 m × 1 m) from each of the four corners and the plot center. All understorey biomass and litter in the samples were collected and weighed as fresh weight, taken to the laboratory, and put in a 70°C oven to dry to a constant weight. After weighing, the dry weight of understorey and litter biomass in the samples was measured, and the understorey and litter biomass amount per unit area was estimated.

Five soil pits were dug to 1-m depth from the four corners and the centre of each plot, and soil samples were collected at five depth layers (0–20, 20–40, 40–60, 60–80, and 80-100 cm) using a soil drilling sampler (5 cm diameter). Soil samples from the same depth layer in the same plot were mixed in equal volume proportions, air-dried naturally, and stored at room temperature. In total, 75 soil samples were collected (5 ages × 3 replicate plots for each age × 5 soil depths). All soil samples were sieved through a 2-mm screen before soil property analysis, and soil animals, plant roots, and other debris were removed. The soil bulk density (*SBD*) of each layer in all sampling plots was extracted using a stainless-steel cylinder with a volume of 100 cm^3 of undisturbed soil samples.

Soil sample analysis

Basic soil characteristics were assessed using standard methods. *SBD* for each soil depth was measured by drying the core soil samples at 105°C for more than 24 hours until constant weight (Blake and Hartge, 1986). Soil particle size fractions, including clay content (<0.002 mm), silt content (0.02–0.002 mm), and sand content (0.02–2 mm) were measured by the pipette method (Van Reeuwijk, 2002). Soil water content (SWC, %) was determined gravimetrically using 20 g soil samples dried in an oven at 105 °C for 24 hours (Cuong et al., 2022b). The H_2SO_4-$K_2Cr_2O_7$ oxidation procedure was used to measure soil organic carbon (*SOC*) concentration (Nelson and Sommers, 1982). The determination and calculation of soil total nitrogen (*STN*), total phosphorus (*STP*), and available phosphorus (*SAP*) concentrations were referred to Vietnam National Standard procedures (TCVN 6498:1999; TCVN 8940:2011; and TCVN 5256:2009) adopted by Cuong et al. (2022b). In particular, as follows: *STN* concentration was digested by a mixture of $C_7H_6O_3$ and H_2SO_4, and then the modified Kjeldahl procedure was used to measure *STN* content; *STP* content was tested using the colorimetrically after the sample was broken down with $HClO_4$ and H_2SO_4; *SAP* concentration was extracted with $NaHCO_3$ and measured using the molybdenum antimony colorimetric method. Soil *pH* was assessed with a pH meter at 1:2.5 soil water suspension (Cuong et al., 2022b).

Computation of soil total nitrogen storage

Soil nitrogen storage was computed from the *STN*, *SBD,* and soil horizon thickness. In the soil samples, coarse fractions (>2 mm) were very rare. Thus, the study used the following equation to compute *SNS* at each soil depth (Wang et al., 2019; Cuong et al., 2022a):

$$SNS = STN \times SBD \times SHT \times 10^{-1} \quad \text{(Eq.1)}$$

where *SNS* denotes soil total nitrogen stocks ($Mg \cdot N \cdot ha^{-1}$); *STN* denotes the total nitrogen concentration ($g \cdot kg^{-1}$); *SBD* denotes the soil bulk density ($g \cdot cm^{-3}$); and *SHT* denotes the soil layer thickness (cm).

Statistical analysis

We used the SPSS 25.0 (IBM Corp, 2017) and R version 4.2.0 (R Core Team, 2022) software programs to perform all statistical calculations. All of the data were tested for normality of distributions and homogeneity of variances before analysis. Comparisons of *STN*, *SNS*, and soil features among various stand ages and soil depths were conducted using a one-way analysis of variance (ANOVA) followed by the LSD test ($p < 0.05$). Pearson's correlations analysis was conducted to identify the relationships between *SNS* and measured environmental factors, including plant biomass features parameters (i.e., understorey vegetation biomass, and litter biomass), and soil physical (i.e., *SBD*, *SWC*, and soil texture) and chemical (i.e., *pH*, *SOC*, *STP*, and *SAP*) characteristics factors. The environmental parameters with high weighted parameter loadings were identified by minimizing the dimension of environmental parameters using Principal Component Analysis (PCA); the outcome of a possible linear correlation between variables was also eradicated (Fan et al., 2018; Cuong et al., 2022b). It should be noted that only principal components (*PCs*) having eigenvalues greater than 1 (i.e., >10% of the total variance explained) and parameters having highly weighted parameter loading (i.e., eigenvectors > ± 0.7) were retained for stepwise multiple regression analysis (*SMRA*) (Fan et al., 2018; Cuong et al., 2022b). We conducted *SMRA* using the filtered variables as inputs to figure out the significant variables that affect *SNS*. The data were all expressed as means ± standard deviation (SD) (n = 3).

Results

Soil physical properties in Acacia hybrid plantations

The soil textural feature parameters in the study area demonstrated that the sand content decreased while clay and silt contents increased with soil depth in stands of all ages (*Fig. 2a-c*). There were no statistically significant differences (p>0.05) in soil clay, silt, or sand fractions between different soil layers in the same forest age. AH2 showed the highest sand percentage for each soil depth (p<0.05), whereas AH10 had the highest percentages of clay and silt for all soil depths (p<0.05).

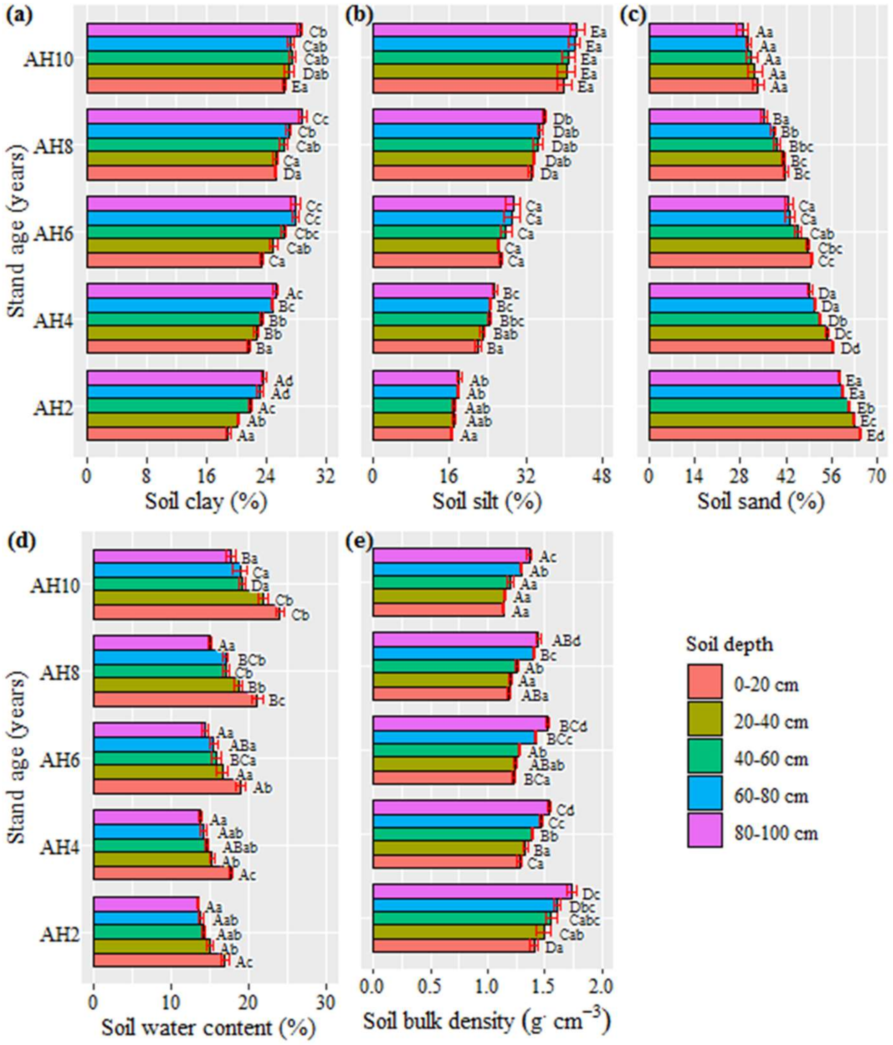


Figure 2. *Soil clay (a), silt (b), sand (c), water content (d) and bulk density (d) in different soil depths Acacia hybrid forests. * Error bars represent standard deviation (SD). Different capital letters indicate significant differences between the same soil layers in the different stand ages (p<0.05). Different small letters indicate significant differences between the sampled soil layers within the same stand age (p<0.05)*

The *SWC* was observed to decrease with increasing soil depth over the five stand ages, with the maximum found in 0–20 cm depth (p<0.05), ranging from 16.82% to 23.98% along forest stand ages (*Fig. 2d*). The *SWC* in AH10 was the highest among all stand ages

($p<0.05$), whereas AH8, AH6, AH4, and AH2 did not differ significantly ($p>0.05$), and this tendency was recorded at all soil depths.

The *SBD* changed in the opposite sense with both stand age and soil depth (*Fig. 2e*). The *SBD* value was significantly higher ($p<0.05$) at the 80–100 cm depth than at the 0-20, 20–40, 40–60, and 60–80 cm depths for all stand ages. The *SBD* values at the AH2 were significantly greater ($p<0.05$) than those at the other four stand ages for all soil depths. However, there was no significant distinction ($p>0.05$) in *SBD* among stand ages (i.e., AH10, AH8, AH6, and AH4) at the five soil depths.

Soil chemical properties in Acacia hybrid plantations

Figure 3 displays the statistical comparison of soil chemical properties (soil *pH*, *SOC*, *STP*, and *SAP*) between five different aged stands at five soil depths. Soil nutrient concentrations (*SOC*, *STP*, and *SAP*) decreased with rising soil depth along the five stands, with the superficial soil depth (0-20 cm) being larger ($p<0.05$) than in the other four deeper soil layers (20–40, 40–60, 60–80 cm, and 80–100 cm) (*Figs. 3b-d*). Statistically significant differences ($p<0.05$) in soil nutrient values were found among various soil depths in the different aged stands, with the exception of *SOC* between the AH6 and AH4 at the 0–20 cm soil depth ($p>0.05$), and the *STP* between the AH8, AH6, AH4, and AH2 at the 0–20, 20–40, 40–60 and 60–80 cm soil depths ($p>0.05$). The concentrations of soil nutrients increased with stand age, being the highest in AH10 and the lowest in AH2, and this tendency was apparent at the five soil depths. Contrary to the patterns detected in soil nutrient contents, soil *pH* value decreased across the forest stand ages for all soil layers (*Fig. 3a*). Nevertheless, there was no significant variability ($p>0.05$) in soil *pH* across forest stand ages. Soil *pH* values increased with increased soil depth for all ages. However, there was no statistically significant ($p>0.05$) difference among different soil depths at the same forest age, except for the between soil depths 40-60 and 60-80 cm at the 2-year-old stand, and the between soil depths 0-20 and 20-40 cm, 40-60 and 60-80 cm at the 10-year-old stand ($p<0.05$).

Soil nitrogen content in Acacia hybrid plantations

The *STN* concentration in the different soil layers increased significantly along forest stand ages ($p<0.05$; *Fig. 4a*). At depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm, *STN* concentrations in AH2 were 0.81, 0.61, 0.49, 0.26, and 0.23, respectively, and *STN* concentrations in AH10 were 2.04, 1.82, 1.62, 1.38, and 1.16, respectively. The *STN* concentration of the surface soil layer (0-20 cm) was the greatest in all five stands, with values of 0.81, 1.11, 1.19, 1.81, and 2.04 $g\cdot kg^{-1}$, respectively (*Fig. 4a*). In all five stands, the results also demonstrated a significant decreasing trend of *STN* concentration with rising soil depth ($p<0.05$).

Soil nitrogen storage in Acacia hybrid plantations

Figure 4b displays trends in the soil layer *N* stocks across the age sequence of *Acacia* hybrid stands. An apparent accumulation of *SNS* was detected ranging from 6.83 Mg ha^{-1} in AH2 to 19.41 Mg ha^{-1} in AH10. Soil N storage was significantly higher in all layers along with the age gradient ($p<0.05$). Soil N storage decreased with soil layers deepen in five forest stand ages, with the maximum value measured in 0-20 cm depth, ranging from 2.26 Mg ha^{-1} to 4.64 Mg ha^{-1} along forest stand ages. Over 50% of *SNS* was stored at the deepening upper soil layer of the 0-40 cm depth and the accumulation revealed decreased tendencies with increasing soil depth in the five stands.

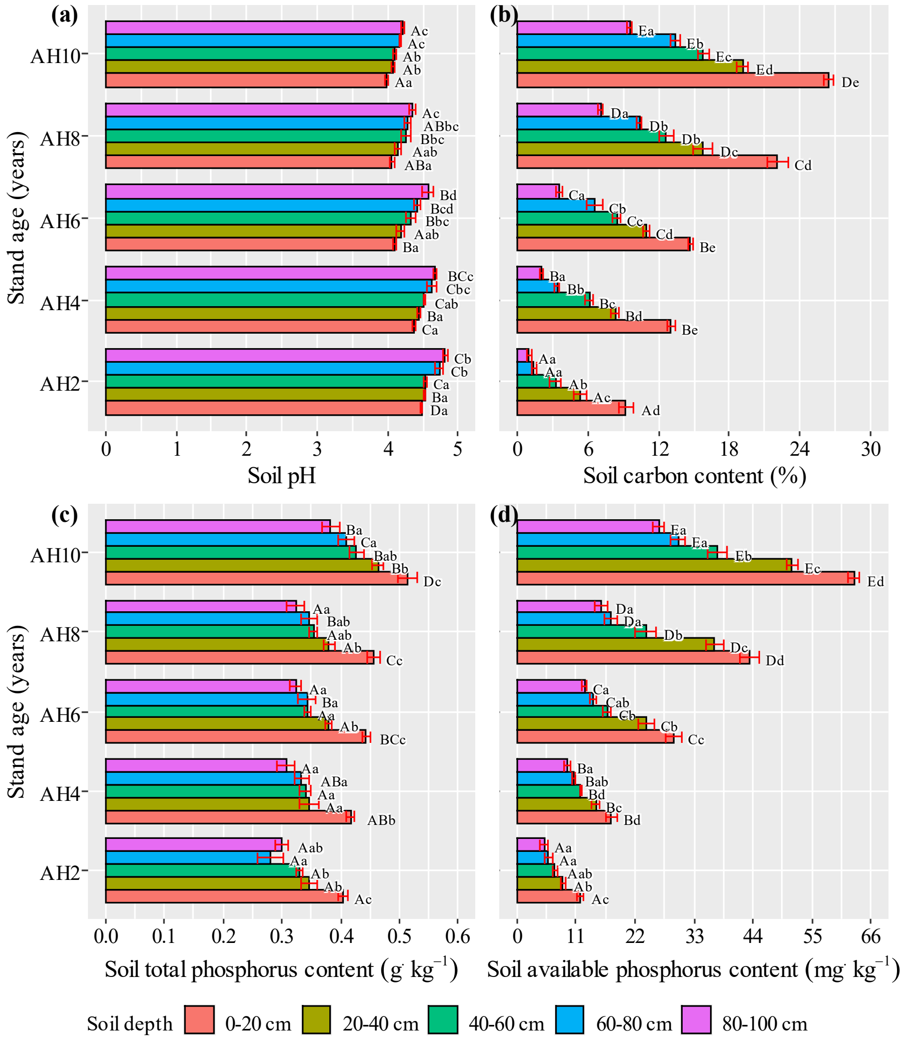


Figure 3. *Soil pH (a), carbon (b), total phosphorus (c), available phosphorus concentrations in different soil depths Acacia hybrid forests. * Error bars represent standard deviation (SD). Different capital letters indicate significant differences between the same soil layers in the different stand ages ($p<0.05$). Different small letters indicate significant differences between the sampled soil layers within the same stand age ($p<0.05$)*

Effect of environmental factors on soil total nitrogen storage

The analysis of the correlation between the *SNS* and the numerous environmental parameters (*Fig. 5*). Soil total N storage substantially and positively associates with soil clay (r = 0.43, $p<0.001$), silt (r = 0.76, $p<0.001$), *SWC* (r = 0.89, $p<0.001$), *SOC* (r = 0.95, $p<0.001$), *STP* (r = 0.79, $p<0.001$), *SAP* (r = 0.96, $p < 0.001$), but is significantly negatively associated with *SBD* (r = -0.86, $p < 0.001$), *pH* (r = -0.94, $p < 0.001$) and sand (r = -0.72, $p<0.001$). Soil total N storage is also significantly positively related to biomass of plant components, including UVB (r = 0.82, $p < 0.001$) and litter biomass (r = 0.85, $p < 0.001$).

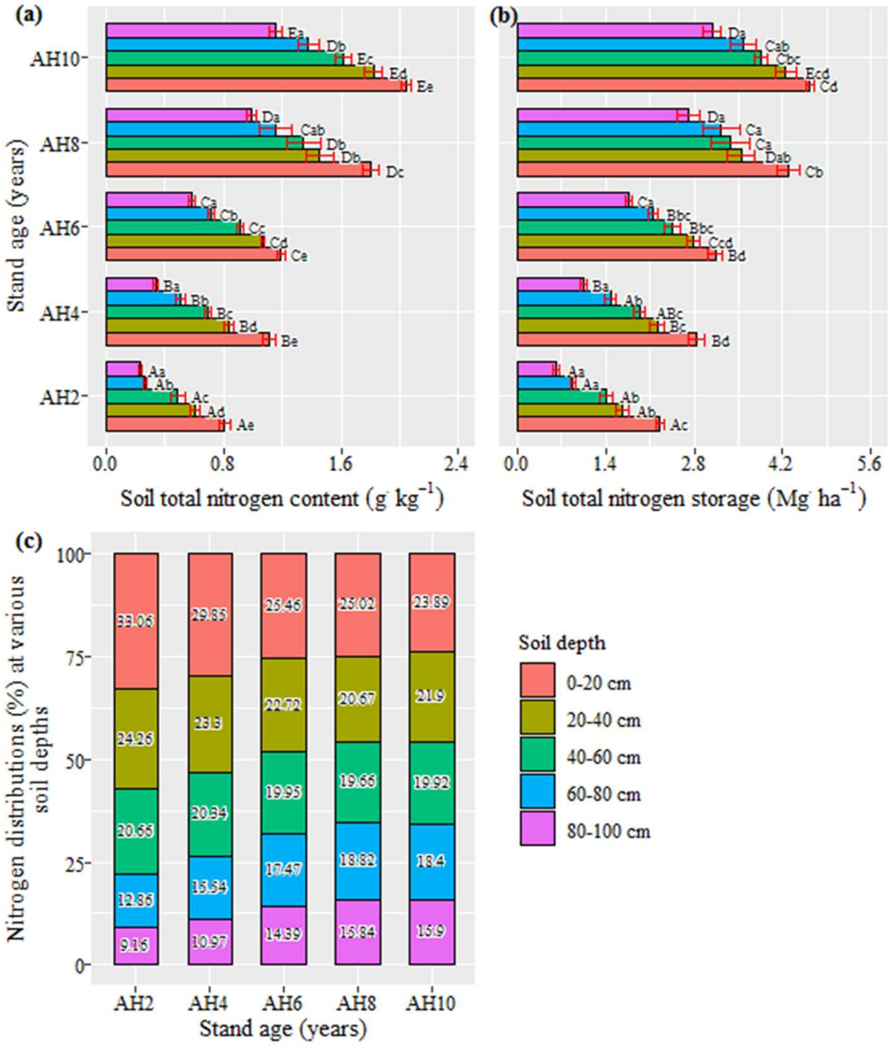
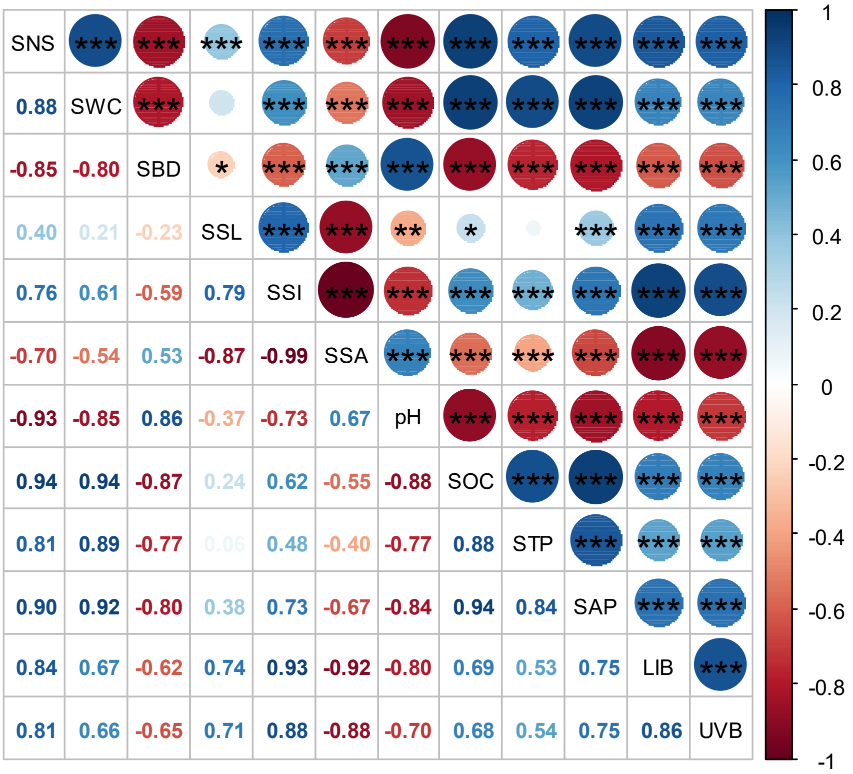


Figure 4. *Soil total nitrogen concentration (a), soil total nitrogen stocks (b), and soil total nitrogen storage distribution (c) in different soil depths Acacia hybrid forests. * Error bars represent standard deviation (SD). Different capital letters indicate significant differences between the same soil layers in the different stand ages ($p<0.05$). Different small letters indicate significant differences between the sampled soil layers within the same stand age ($p<0.05$)*

The PCA results illustrated two *PCs* with eigenvalue >1, representing 91.02% of the variance (*Fig. 6*). The first *PC1* explained 72.85% of the total variation, whereas the *PC* interpreted 18.18% of the variation. The varimax rotation factor loadings revealed that *SOC*, *STP*, *SWC*, *SAP*, *SBD*, and *pH* were the factors under *PC1*. However, multivariate correlation values indicated *SOC* was strongly related to *STP*, *SWC*, *SAP SBD*, and *pH* (*Fig. 5*). Hence under *PC1*, *SOC* with 0.938 loading value was remained as the indicator parameter for *SMRA* to avoid redundancy. Under *PC2*, soil clay, silt, and sand are all significantly correlated ($p<0.01$) with each other but only the soil clay with the highest loading value (0.937) is selected for *SMRA* (*Fig. 5*).



SNS	***	***	***	***	***	***	***	***	***	***	***
0.88	SWC	***		***	***	***	***	***	***	***	***
-0.85	-0.80	SBD	*	***	***	***	***	***	***	***	***
0.40	0.21	-0.23	SSL	***	***	**	*		***	***	***
0.76	0.61	-0.59	0.79	SSI	***	***	***	***	***	***	***
-0.70	-0.54	0.53	-0.87	-0.99	SSA	***	***	***	***	***	***
-0.93	-0.85	0.86	-0.37	-0.73	0.67	pH	***	***	***	***	***
0.94	0.94	-0.87	0.24	0.62	-0.55	-0.88	SOC	***	***	***	***
0.81	0.89	-0.77	0.06	0.48	-0.40	-0.77	0.88	STP	***	***	***
0.90	0.92	-0.80	0.38	0.73	-0.67	-0.84	0.94	0.84	SAP	***	***
0.84	0.67	-0.62	0.74	0.93	-0.92	-0.80	0.69	0.53	0.75	LIB	***
0.81	0.66	-0.65	0.71	0.88	-0.88	-0.70	0.68	0.54	0.75	0.86	UVB

Figure 5. *Correlation analyses between soil total nitrogen stocks and environmental parameters in Acacia hybrid forest stands. SNS, soil total nitrogen storage; SWC, soil water content; SBD, soil bulk density; SSL, soil clay; SSI, soil silt; SSA, soil sand; SOC, soil organic carbon; STP, soil total phosphorus; SAP, soil available phosphorus; UVB, understorey vegetation biomass; LIB, litter biomass. *** Correlation is significant at the 0.001 level; ** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level*

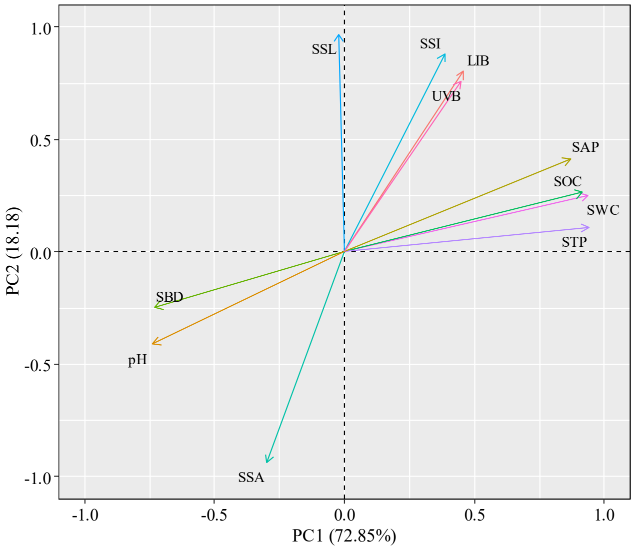


Figure 6. *Principle component analysis (PCA) of the environmental parameters. * SWC, soil water content; SBD, soil bulk density; SSL, soil clay; SSI, soil silt; SSA, soil sand; SOC, soil organic carbon; STP, soil total phosphorus; SAP, soil available phosphorus; UVB, understorey vegetation biomass; LIB, litter biomass*

To detect the greatest predictive parameters that impact *SNS*, we performed *SMRA* with *PC1* (*SOC*), and *PC2* (Clay) as independent parameters and *SNS* as the dependent parameter. Results by multiple linear regressions revealed that the *SOC* and soil clay were the two most predominant parameters governing *SNS* and both factors had a substantial positive influence (*Table 2*). The tolerance (*TOL*) of these 2 variables was all greater than 0.1, and the variance inflation factor (*VIF*) was all less than 10, demonstrating that there is no multicollinearity between the two environmental variables.

Table 2. *Results of stepwise multiple linear regression analyses demonstrating the relationship between soil total nitrogen storage and environmental factors*

Dependent variable	Explanatory variable	Coefficient estimate	SE	t-value	p-value	R^2	TOL	VIF
SNS	Constant	-0.859	0.370	-2.322	0.023	0.911		
	SOC	0.153	0.006	24.725	0.000		0.944	1.059
	Soil silt	0.077	0.015	5.122	0.000		0.944	1.059

SNS, soil total nitrogen storage; *SOC*, soil organic carbon; SE, standard error of the coefficient estimate; TOL, tolerance; VIF, variance inflation factor. The values of TOL > 0.10 and VIF < 10 denote there is no multicolinearity to the research data

Discussion

Changes in soil total nitrogen content and storage

Soil depth is a prominent factor influencing *STN* distribution (Xu et al., 2019). Our data revealed that the *STN* concentration in the mineral soil decreased with an increase in soil depth (*Fig. 4a*). Previous findings about *STN* content with soil depth obtained were the same to our results (Zhang et al., 2018a; Wang et al., 2019; Cuong et al., 2022a; Xu et al., 2023). This could be interpreted by the decreasing inputs of soil organic matter (i.e., plant litter and roots) with increasing soil depth from both above- and below-ground litterfall (Cuong et al., 2022a; Rahman et al., 2022), particularly by the declining impact of the humus layer on the soil surface (Xu et al., 2019) and the reduction activities of soil animals and microbes (Houlton and Morford, 2014). As soil depth increases, the soil permeability and root absorption reduce, and the *SBD* increases, inhibiting the input of dissolved soil organic matter by leaching (Berger et al., 2002). This suggests that the surface soil participates most actively in N sequestration (Wang et al., 2021). The N concentration in the mineral soils significantly increased with the stands age, perhaps due to the increasing litter productivity and slow decomposition in older forest stages with the development of forest stands (Wang et al., 2019). This finding was in accordance with the previous investigations (Zhang et al., 2019; Ngaba et al., 2020; Cuong et al., 2022b). These changes could be explained by the continuous N inputs from above-ground litterfall, root exudates, and root turnover outweighing N decomposition along with the forest stand development. Our study revealed that *SNS* was significantly positively correlated with the plant biomass variables (i.e., understory biomass and litter biomass) (*Fig. 5*), demonstrating *SNS* accumulation with increased plant biomass as a result of nutrient biological cycling through forest litter production (Liu et al., 2020). Several studies have indicated that litter and roots are the two main sources of soil N input by plants, which are the foundation of biogeochemistry and nutrient cycling in forest ecosystems (Zhou et al., 2015; Cao et al., 2020). As the afforestation time increases, soil microbial and enzymatic activities are enhanced (García de León et al., 2016), thereby advocating soil N transformation and storage. Yet, there still exists a great deal of divergences among previous research findings regarding the impacts of forest stand age on SNS (Markewitz et al., 2002; Smal and Olszewska, 2008; Mao et al., 2010; Noh et al., 2010; Li et al., 2018; Wang et al., 2019). These controversial results may result from various kinds of parameters that are interpretable for restoring *SNS* after afforestation, such as soil physicochemical properties features, tree species planted, site management practice, disturbances, N_2 fixation, climate, land cover change, all of which may overshadow the impact of forest stand age on *SNS* (Mao et al., 2010; Cuong et al., 2022a). Besides the intricate relationships among soil N storage and plantation age, in terms of the vertical distribution of *SNS*, more than 50% of the *SNS* was recorded in top 40 cm of the mineral soil horizon in all five stands (*Fig. 4c*), illustrating that larger amounts of *SNS* were stored in the topsoil layer. This suggests that, despite being sensitive to human disturbance activities, soil natural erosion, and extrinsic factors, the surface soil in the research site is the prominent N pool. Therefore, the current findings suggest that focus research on the vertical variability of *SNS* and preservation of N in the surface soil from human disturbances, soil natural erosion, and extrinsic factors are required in the context of N sequestration.

Main environmental factors controlling soil total nitrogen storage

Soil physical and chemical characteristics and plant biomass parameters are principal controls of *SNS* (Li et al., 2019; Cuong et al., 2022a). The findings from this study revealed that biomass, soil physical soil chemical features significantly affected the *SNS* in *Acacia* hybrid plantation ecosystems (*Fig. 5*), with *SOC* and soil texture (soil clay content) being the most crucial controlling factors of *SNS* among the eleven factors tested (*Table 2*). Some researchers have demonstrated that *SOC* is a major index that has substantial impacts on *SNS* in earlier studies because soil organic matter is a crucial N sink pool and N accumulates rapidly in soil organic matter (Lewis et al., 2014). Decomposition and accumulation of organic matter in soil are critical pathways for soil N accumulation (Nie et al., 2020), which correspond with the positive relationship found between *SNS* and *SOC* (*Fig. 5*). As one of the most important parameters of soil physical factors, soil texture plays a significant role in modulating *SNS*. In the current study, the noticed variability in *SNS* in stands of different ages was positively correlated to both clay and silt content, while *SNS* was negatively correlated to sand content (*Fig. 5*). Other studies have revealed that *SNS* was highly positively linked to the clay and silt contents of soils (e.g., Hassink, 1994; Zhou et al., 2019) because clay and silt particle fraction and micro-aggregates help to absorb soil organic matter and protect it from soil microbial degradation in an anaerobic environment to varying degrees (Zhou et al., 2019). Furthermore, soil mechanical constitution could also indirectly impact *SNS* by regulating soil particle agglomeration, hydrology, aeration, water retention, and temperature (Saxton and Rawls, 2006). Additionally, other soil characteristics parameters (e.g., soil P, *SWC*, *SBD*, and soil *pH*) were the major environmental factors with high factor loadings, which may be used to explain *SNS* variability to some extent (*Fig. 6*). Our results revealed that *SNS* was significantly positively related to soil P concentrations (*STP* and *SAP* concentrations) (*Fig. 5*), demonstrating the significant role of soil nutrients in affecting the change in *SNS* at a local scale (Sam et al., 2006; Liu et al., 2012). Previous investigations discovered that soil P limitation might constrain N accumulation, where the connection between phosphorus and iron or aluminum oxides alleviates P availability for microbial growth and activities (Cleveland et al., 2002; Liu et al., 2012). *Acacia* hybrid is a leguminous plant species with a high symbiotic biological N fixing capacity due to its symbiotic association with nodule-forming bacteria (Cuong et al., 2022a), and it is likely to maintain the N input sources in our areas. Meanwhile, it has been reported in earlier studies that P deficiency in the soil might affect symbiotic N_2 fixation activity (Augusto et al., 2013), ultimately affecting *SNS*. Schleuss et al. (2019) illustrated that the increase in *STP* was beneficial to the acquisition of P by plants, which can increase plant productivity and therefore strengthen the input sources of *STN*. Soil water content is another dominant soil physical indicator that has had significant effects on *SNS* because it can strongly adjust soil organic matter decomposition via soil microbial biological activity. Our findings indicated that *SWC* had a considerable positive impact on the *SNS* (*Fig. 5*), which is congruent with the findings from prior reports (Zhang et al., 2018c; Duan et al., 2020). That may be due to *SWC* may alter during stand development, which in turn leads to the improvement of soil biological activity (microbial biomass and enzyme activities) linked with nutrient decomposition and cycling (Zhang et al., 2019), thereby enhancing soil N transformation and storage. For example, increasing soil microorganisms and enzymes can stimulate the decomposition of soil organic (Zhang et al., 2018b). Furthermore, exogenous N derived from plant decomposition and atmospheric deposition can also be fixed in the soil by microbes (Ren et al., 2017). The *SNS* at the study site was also significantly affected by *SBD*. Our findings showed that *SBD* was significantly negatively correlated with *SNS* (*Fig. 5*). Previous researchers demonstrated that soils with lower *BD* accumulated more *STN* concentrations because it can be mobilized via the pores inside the soil constitution. Soils with low *BD* have more macro-pores and macro-aggregates, which can stimulate soil microbe activity, tree root development, and below-ground biological activities, consequently enhance the formation of organic matter and N content in soils (Duan et al., 2020). Soil *pH* is regularly referred to as a critical environmental element that governs the distribution of the soil microbial community involved in N cycling (Lauber et al., 2009). Our study also discovered a strong negative association between soil *pH* and *SNS* (*Fig. 5*). Similar findings were reported by several earlier reports (Kemmitt et al., 2006; Duan et al., 2020). Studies have pointed out that soil acidification has probable to slow soil organic matter turnover in some acid soils by changing the composition of microorganisms, hence conducive to the accumulation of *SNS* (Schmidt, 1982; Wang et al., 2018). Additionally, alternative N sources and processes may also have an influence on *SNS*. For example, atmospheric N deposition (Mao et al., 2010), and biological N fixation (Li et al., 2019) are frequently used to clarify *SNS* increase during the development process of forest. Furthermore, the stand characteristic features (e.g., stand density, canopy closure, *DBH*, and *H*) may assist in elucidating the alteration in *SNS* across various age forests (*Table 1*).

Conclusions

The current study revealed the storage and dynamics of soil N in differently aged *Acacia* hybrid plantations in Southern Vietnam. Soil total N concentration significantly increased with the increase in stand ages, and considerably reduced with increased depth of soil layers across all stand ages. The mineral soil stocks of total N exhibited continuously increasing trends across stand development, and the upper 0–40 cm soil depth held more than 50% of the total soil N stocks at five stand ages. Soil organic C concentration and soil particle size fractions (i.e., soil silt concentration) were the two most important environmental parameters modulating the *SNS*, and both parameters had a positive impact. Results from this study revealed that *Acacia* hybrid plantations had considerable soil N sequestration potential during stand development. The findings highlighted the significance of stand age in forest soil N storage assessment for policymakers when modelling global climate change scenarios.

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REFERENCES

[1] Augusto, L., Delerue, F., Gallet-Budynek, A., Achat, D. L. (2013): Global assessment of limitation to symbiotic nitrogen fixation by phosphorus availability in terrestrial ecosystems using a meta-analysis approach. – Glob Biogeochem Cycles 27(3): 804-815.

[2] Berger, T. W., Neubauer, C., Glatzel, G. (2002): Factors controlling soil carbon and nitrogen stores in pure stands of Norway spruce (*Picea abies*) and mixed species stands in Austria. – For Ecol Manag 159(1): 3-14.

[3] Blake, G. R., Hartge, K. H. (1986): Bulk density. – In: Klute, A. (ed.) Methods of soil analysis part 1: Physical and mineralogical methods. 2nd edition, Am Soc Agron, Madison, WI, USA, pp: 363-375.

[4] Cao, J., Pan, H., Chen, Z., Shang, H. (2020): Dynamics in stoichiometric traits and carbon, nitrogen, and phosphorus pools across three different-aged *Picea asperata* Mast. plantations on the Eastern Tibet Plateau. – Forests 11(12): 1346.

[5] Cleveland, C. C., Townsend, A. R., Schmidt, S. K. (2002): Phosphorus limitation of microbial processes in moist tropical forests: Evidence from short-term laboratory incubations and field studies. – Ecosystems 5(7): 0680-0691.

[6] Cuong, L. V., Hung, B. M., Bolanle-Ojo, O. T., Xu, X., Thanh, N. M., Chai, L., Nebiyou, L., Wang, J., Thang, B. V. (2020): Biomass and carbon storage in an age-sequence of *Acacia mangium* plantation forests in Southeastern region, Vietnam. – Forest Syst 29(2): e009.

[7] Cuong, L. V., Sang, T. V., Bolanle-Ojo, O. T., Bao, T. Q., Ngoan, T. T., Tuan, N. T., Hung, N. X., Long, L. V., Duong, D. T. T., Phu, N. V. (2022a): Soil nitrogen content and storage in age sequence *Acacia mangium* plantations in the Southeastern region of Vietnam. – Malays J Soil Sci 26: 120-132.

[8] Cuong, L. V., Thang, B. V., Bolanle-Ojo, O. T., Bao, T. Q., Tuan, N. T., Sang, T. V., Niu, X. X., Thanh, N. M. (2022b): Enhancement of soil organic carbon by Acacia mangium afforestation in Southeastern region, Vietnam. – Agric For 68(2): 133-155.

[9] Deng, L., Wang, G. L., Liu, G. B., Shangguan, Z. P. (2016): Effects of age and land-use changes on soil carbon and nitrogen sequestrations following cropland abandonment on the Loess Plateau, China. – Ecol Eng 90: 105-112.

[10] Deng, L., Han, Q. S., Zhang, C., Tang, Z. S., Shangguan, Z. P. (2017): Aboveground and belowground ecosystem biomass accumulation and carbon sequestration with *Caragana korshinskii* Kom plantation development. – Land Degrad Dev 28(3): 906-917.

[11] Dong, T., Doyle, R., Beadle, C., Corkrey, R., Quat, N. (2014): Impact of short-rotation Acacia hybrid plantations on soil properties of degraded lands in Central Vietnam. – Soil Res 52(3): 271-281.

[12] Dou, X., Xu, X., Shu, X., Zhang, Q., Cheng, X. (2016): Shifts in soil organic carbon and nitrogen dynamics for afforestation in central China. – Ecol Eng 87: 263-270.
[13] Duan, B., Man, X., Cai, T., Xiao, R., Ge, Z. (2020): Increasing soil organic carbon and nitrogen stocks along with secondary forest succession in permafrost region of the Daxing’an mountains, northeast China. – Glob Ecol Conserv 24: e01258.
[14] Fan, H., Zhao, W., Daryanto, S., Fu, B., Wang, S., Wang, Y. (2018): Vertical distributions of soil organic carbon and its influencing factors under different land use types in the Desert Riparian Zone of Downstream Heihe River Basin, China. – J Geophys Res Atmos 123(14): 7741-7753.
[15] García de León, D., Moora, M., Öpik, M., Neuenkamp, L., Gerz, M., Jairus, T., Vasar, M., Bueno, C. G., Davison, J., Zobel, M. (2016): Symbiont dynamics during ecosystem succession: co-occurring plant and arbuscular mycorrhizal fungal communities. – FEMS Microbiol Ecol 92(7): fiw097.
[16] Hai, V. D., Trieu, D. T., Tiep, N. H., Bich, N. V., Duong, D. T. (2009): Research on carbon sequestration potential and commercial value of some major types of plantation forests in Vietnam. – Final Project Report No. VAFS2009, Vietnamese Academy of Forest Sciences, Hanoi, Vietnam, 190p.
[17] Hassink, J. (1994): Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. – Soil Biol Biochem 26(9): 1221-1231.
[18] Houlton, B., Morford, S. (2014): A new synthesis for terrestrial nitrogen inputs. – Soil Discuss 1(1): 497-540.
[19] Hung, T. T., Doyle, R., Eyles, A., Mohammed, C. (2017): Comparison of soil properties under tropical Acacia hybrid plantation and shifting cultivation land use in northern Vietnam. – South For: a Journal of Forest Science 79: 9-18.
[20] IBM Corp. (2017): IBM SPSS Statistics for Windows, Version 25.0. – Armonk, NY: IBM Corp.
[21] Jusoh, I., Abu Zaharin, F., Adam, N. S. (2014): Wood quality of Acacia hybrid and second-generation *Acacia mangium*. – BioResources 9(1): 150-160.
[22] Kemmitt, S. J., Wright, D., Goulding, K. W. T., Jones, D. L. (2006): pH regulation of carbon and nitrogen dynamics in two agricultural soils. – Soil Biol Biochem 38(5): 898-911.
[23] Lal, R. (2018): Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. – Glob Chang Biol 24(8): 3285-3301.
[24] Lauber, C. L., Hamady, M., Knight, R., Fierer, N. (2009): Pyrosequencing-based assessment of soil pH as a predictor of soil bacterial community structure at the continental scale. – Appl Environ Microbiol 75(15): 5111-5120.
[25] Lewis, D. B., Castellano, M. J., Kaye, J. P. (2014): Forest succession, soil carbon accumulation, and rapid nitrogen storage in poorly remineralized soil organic matter. – Ecology 95(10): 2687-2693.
[26] Li, G., Zhang, X., Huang, J., Wen, Z., Du, S. (2018): Afforestation and climatic niche dynamics of black locust (*Robinia pseudoacacia*). – For Ecol Manag 407: 184-190.
[27] Li, Q., Yang, D., Jia, Z., Zhang, L., Zhang, Y., Feng, L., He, L., Yang, K., Dai, J., Chen, J., Zhao, X. (2019): Changes in soil organic carbon and total nitrogen stocks along a chronosequence of Caragana intermedia plantations in alpine sandy land. – Ecol Eng 133: 53-59.
[28] Liu, L., Gundersen, P., Zhang, T., Mo, J. (2012): Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. – Soil Biol Biochem 44(1): 31-38.
[29] Liu, Y., Fang, Y., An, S. (2020): How C:N:P stoichiometry in soils and plants responds to succession in *Robinia pseudoacacia* forests on the Loess Plateau, China. – For Ecol Manag 475: 118394.

[30] Mao, R., Zeng, D. H., Hu, Y. L., Li, L. J., Yang, D. (2010): Soil organic carbon and nitrogen stocks in an age-sequence of Poplar stands planted on marginal agricultural land in Northeast China. – Plant Soil 332(1): 277-287.

[31] MARD (2021): Promulgation of the state of National forests. No. 2860/QĐ-BNN-TCLN. – Ministry of Agriculture and Rural Development (MARD), Hanoi, Vietnam.

[32] Markewitz, D., Sartori, F., Craft, C. (2002): Soil change and carbon storage in Longleaf pine stands planted on marginal agricultural lands. – Ecol Appl 12: 1276-1285.

[33] Nelson, D. W., Sommers, L. E. (1982): Total carbon, organic carbon, and organic matter. – In: Page, A. L., Miller, R. H., Keeney, D. R. (eds.) Methods of soil analysis, Part 2. Am Soc Agron, Madison, WI, USA, pp: 539-579.

[34] Ngaba, M. J. Y., Ma, X. Q., Hu, Y. L. (2020): Variability of soil carbon and nitrogen stocks after conversion of natural forest to plantations in Eastern China. – PeerJ 8: e8377.

[35] Ngoan, T. T., Bao, T. Q. (2019): Growth of Acacia hybrid plantations (*Acacia auriculiformis* × *Acacia mangium*) on different site indexes in Dongnai Province. – Journal of Forest Science and Technology 6: 25-35.

[36] Ngoan, T. T., Cuong, L. V., Ha, N. T., Phu, N. V., Toan, N. V. (2023): Soil carbon stocks under canopy of Acacia hybrid plantations in Dinhquan district, Dongnai Province, Vietnam. – Journal of Forest Science and Technology 2: 76-85.

[37] Nie, X., Wang, D., Yang, L., Zhou, G. (2020): Controlling soil total nitrogen factors across shrublands in the three rivers source region of the Tibetan Plateau. – Biogeosciences and Forestry 13(6): 559-565.

[38] Noh, N. J., Son, Y., Lee, S. K., Seo, K. W., Heo, S. J., Yi, M. J., Park, P. S., Kim, R. H., Son, Y. M., Lee, K. H. (2010): Carbon and nitrogen storage in an age-sequence of *Pinus densiflora* stands in Korea. Science China. – Life Sciences 53: 822-830.

[39] R Core Team (2022): R: A language and environment for statistical computing. – R Foundation for Statistical Computing, Vienna, Austria.

[40] Rahman, M., Wang, Y., Zhang, K., Ahmad, B., Ali, A., Ahamd, A., Muhammad, D., Afzaal, M., Zhang, Z., Bohnett, E. (2022): Variations in soil C, N, P stocks and stoichiometry with soil depth and forest types in Qilian Mountains of Northwest China. – Front Environ Sci 10: 21.

[41] Ren, C., Chen, J., Deng, J., Zhao, F., Han, X., Yang, G., Tong, X., Feng, Y., Shelton, S., Ren, G. (2017): Response of microbial diversity to C:N:P stoichiometry in fine root and microbial biomass following afforestation. – Biol Fertil Soils 53(4): 457-468.

[42] Ritter, E. (2007): Carbon, nitrogen and phosphorus in volcanic soils following afforestation with native birch (*Betula pubescens*) and introduced larch (*Larix sibirica*) in Iceland. – Plant Soil 295(1): 239-251.

[43] Sam, D. D., Que, D. N., Siem, T. N., Binh, N. N. (2006): Forest soils, nutrition, and management. – Hanoi Agriculture Publishing House, Vietnam, 143p.

[44] Sartori, F., Lal, R., Ebinger, M. H., Eaton, J. A. (2007): Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. – Agric Ecosyst Environ 22(3): 325-339.

[45] Saxton, K. E., Rawls, W. J. (2006): Soil water characteristic estimates by texture and organic matter for hydrologic solutions. – Soil Sci Soc Am J 70(5): 1569-1578.

[46] Schleuss, P. M., Widdig, M., Heintz-Buschart, A., Guhr, A., Martin, S., Kirkman, K., Spohn, M. (2019): Stoichiometric controls of soil carbon and nitrogen cycling after long-term nitrogen and phosphorus addition in a mesic grassland in South Africa. – Soil Biol Biochem 135: 294-303.

[47] Schmidt, E. L. (1982): Nitrification in soil. – Nitrogen in Agricultural Soils 22: 253-288.

[48] Six, J., Callewaert, P., Lenders, S., De Gryze, S., Morris, S. J., Gregorich, E. G., Paul, E. A., Paustian, K. (2002): Measuring and understanding carbon storage in afforested soils by physical fractionation. – Soil Sci Soc Am J 66(6): 1981-1987.

[49] Smal, H., Olszewska, M. (2008): The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen, and phosphorus. – Plant Soil 305(1): 171-187.

[50] Van Reeuwijk, L. P. (2002): Procedures for Soil Analysis. – Technical Paper No. 9, 6th Edition, FAO/ISRIC, Wageningen, the Netherlands, 120p.

[51] Wang, C., Lu, X., Mori, T., Mao, Q., Zhou, K., Zhou, G., Nie, Y., Mo, J. (2018): Responses of soil microbial community to continuous experimental nitrogen additions for 13 years in a nitrogen-rich tropical forest. – Soil Biol Biochem 121: 103-112.

[52] Wang, Y., Liu, L., Yue, F., Li, D. (2019): Dynamics of carbon and nitrogen storage in two typical plantation ecosystems of different stand ages on the Loess Plateau of China. – PeerJ 7: e7708.

[53] Wang, X., Li, Y., Duan, Y., Wang, L., Niu, Y., Li, X., Yan, M. (2021): Spatial variability of soil organic carbon and total nitrogen in Desert Steppes of China's Hexi Corridor. – Front Environ Sci 9: 761313.

[54] Xu, H., Qu, Q., Li, P., Guo, Z., Wulan, E., Xue, S. (2019): Stocks and stoichiometry of soil organic carbon, total nitrogen, and total phosphorus after vegetation restoration in the Loess Hilly region, China. – Forests 10(1): 27.

[55] Xu, H., Hu, C., Zhang, H., Peng, B., Hu, G. (2023): Ecological stoichiometric characteristics of leaf, litter, and soil in Eucalyptus plantations with different ages in subtropical, South China. – Applied Ecology and Environmental Research 21: 3755-3765.

[56] Zeng, X., Zhang, W., Cao, J., Liu, X., Shen, H., Zhao, X. (2014): Changes in soil organic carbon, nitrogen, phosphorus, and bulk density after afforestation of the "Beijing–Tianjin Sandstorm Source Control" program in China. – Catena 118: 186-194.

[57] Zhang, H., Duan, H., Song, M., Guan, D. (2018a): The dynamics of carbon accumulation in Eucalyptus and Acacia plantations in the Pearl River delta region. – Ann For Sci 75(2): 40.

[58] Zhang, W., Qiao, W., Gao, D., Dai, Y., Deng, J., Yang, G., Han, X., Ren, G. (2018b): Relationship between soil nutrient properties and biological activities along a restoration chronosequence of *Pinus tabulaeformis* plantation forests in the Ziwuling Mountains, China. – Catena 161: 85-95.

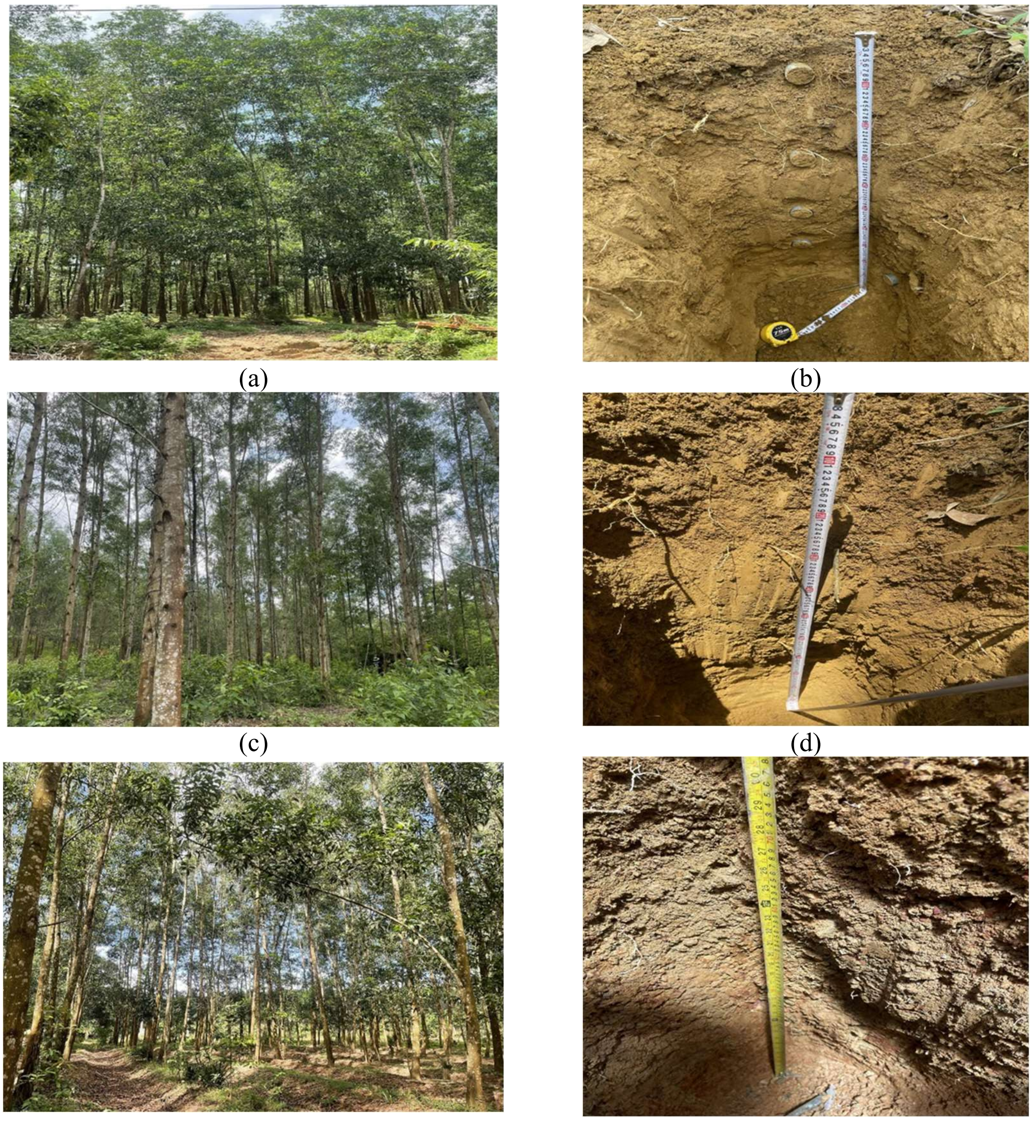
[59] Zhang, X., Sun, Z., Liu, J., Ouyang, Z., Wu, L. (2018c): Simulating greenhouse gas emissions and stocks of carbon and nitrogen in soil from a long-term no-till system in the North China Plain. – Soil Tillage Res 178: 32-40.

[60] Zhang, W., Liu, W., Xu, M., Deng, J., Han, X., Yang, G., Feng, Y., Ren, G. (2019): Response of forest growth to C:N:P stoichiometry in plants and soils during *Robinia pseudoacacia* afforestation on the Loess Plateau, China. – Geoderma 337: 280-289.

[61] Zhou, W. J., Sha, L. Q., Schaefer, D. A., Zhang, Y. P., Song, Q. H., Tan, Z. H., Deng, Y., Deng, X. B., Guan, H. L. (2015): Direct effects of litter decomposition on soil dissolved organic carbon and nitrogen in a tropical rainforest. – Soil Biol Biochem 81: 255-258.

[62] Zhou, W., Han, G., Liu, M., Li, X. (2019): Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land uses in Mun River Basin, Northeast Thailand. – Peer J 7: e7880.

APPENDIX



(a) (b)

(c) (d)

(e) (f)

Figure A1. *Some pictures of the 4-year-old (a-b), 6-year-old (c-d), and 8-year-old (e-f) Acacia hybrid stands*

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