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Influence of Short-cycle Acacia on Soil Quality

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ABSTRACT

Although short-cycle Acacia plantation has caused negative impacts on the mountainous soil environment, the understanding of these impacts is still unknown in Vietnam. Therefore, this study evaluated the effects of short-cycle Acacia plantation on soil properties under successive seven-year cycles in some areas of Vietnam. A total of 182 soil samples randomly stratified by the Acacia cycles were collected at the topsoil depth of 30 cm to analyse the effects of Acacia cycles on changes in the soil properties. Non-parametric Kruskal-Wallis & Mann-Whitney tests were used to assess the differences in soil properties under different Acacia cycles and natural forest. Then, the Analytical Hierarchy Process (AHP) was applied to combine the soil properties into the soil quality index for assessing soil quality in the different cycles. The results showed that changes in the soil properties among the Acacia cycles and the natural forest were statistically different ($p<0.05$). The AHP-based soil quality assessment shows clearly the varying levels of soil deterioration in the successive cycles. It was also found that the indicators of OM, TN, and pH were more closely correlated with the SQI; therefore, soil conservation measures are indispensable for the Acacia soils. The study is a practical contribution to the understanding of

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soil quality change in short-cycle Acacia plantation areas that are common in many parts of the world, especially in the tropics.

Keywords: AHP; Soil Quality Index; Short-Cycle Acacia

INTRODUCTION

Currently, Vietnam's planted forests are about 4.7 million hectares, of which 30% of the total area is Acacia forests. Planted forests have made a great contribution to the Vietnamese economy and created jobs for rural forestry communities. However, planted forests have also caused environmental consequences, especially soil degradation. The effects of planted forests on soil properties reported in previous studies may be negative or positive. On the negative side, the conversion of natural forests to monoculture plantations changes the amount of litterfall and the physicochemical properties of soils (Krashevska et al., 2015; Monkai et al., 2018). A decrease in litterfall has resulted in reduced organic matter, biodiversity, and especially soil microorganisms (Cai et al., 2018; Fox et al., 2020; Liao et al., 2012; Wardle et al., 2004). Similarly, other studies also reported that fast-growing tree species have resulted in decreased macronutrients, reduced biodiversity, increased soil erosion, and reduced soil fertility (Bouillet & Bernhard-Reservat, 2001; Liu et al., 2018; Marais et al., 2012; Mensah, 2016). The key causes of soil nutrient depletion and reduced pH are timber logging after short-rotations of monoculture plantation partly due to erosion (Guillaume et al., 2015; Guo et al., 2022). When the wood is harvested, nutrients are also removed from the planting sites. Several case studies reported that plantations resulted in removals of soil macronutrients due to timber logging (Evans, 2022, Jurgensen et al., 1997; Santos et al., 2017; Turner & Lambert, 1986; Weetman & Webber, 1972). Logging also removes the cations of Ca and Mg from the topsoil, thereby increasing soil acidity (Oostra et al., 2006).

On the positive side, several studies have reported supportive effects of planted forests on soil properties. Wall et al., (2005) revealed that soil pH, soil organic matter, and nitrogen contents increase, but soil bulk density decreases in planted forests. In addition, planted forests showed a positive correlation between biomass and soil properties, such as increased soil organic matter, nitrogen, phosphorus, and reduced bulk density (Sang et al., 2012; Sitters et al., 2013; Tchichelle et al., 2016). In particular, the total nitrogen and total organic carbon concentrations were significantly found to be higher when compared with shifting cultivation systems (Hung et al., 2016), and abandoned lands (Dong et al., 2014).

Although the effects of planted forests on soil properties have been investigated in many parts of the world, the effects of short-cycle consecutive Acacia plantations are currently unknown in Vietnam. Therefore, the purpose of the study is to assess the effects of short-cycle Acacia plantation on soil physical and chemical properties. The study began with an assessment of soil property changes over the seven-year cycles in the study area. The soil properties were then combined into an AHP-based soil quality index to facilitate comparison of the Acacia soil quality among the cycles. The soil quality index not only facilitates comparison of the soil quality over successive Acacia cycles, but it also facilitates spatial comparisons at different scales (Glover et al., 2000; Karlen et al., 2003). The soil quality index can be generated by Boolean logic (Hoseini & Kamrani, 2018), weighted linear combination (WLC) (Silva-Gallegos & Aguirre-Salado, 2017), weighted overlay (WO) (Hassan et al., 2020), multiple linear regression (Khoi, 2024; Leroux et al., 2019), (Akpoti et al., 2019), multi-criteria evaluation (MCE) (Malczewski, 2004, 2006), fuzzy logic (Feng et al., 2017; Zabel et al., 2014), machine learning algorithms (Ebrahim, 2007; Mockshell & Kamanda, 2018; Phillips et al., 2009). In this study, the Analytic Hierarchy Process (AHP) method (Saaty, 1980) is chosen because it is a highly reliable method (Kihoro et al., 2013). It can be used as a consensus mechanism for decision analysis that requires group work (Yalew et al., 2016). AHP considers the evaluation based on the set of criteria and alternative options, from which the optimal decision is made. It also allows estimating the weight of the number of evaluation criteria by the decision maker's pairwise comparison method (Rodcha et al., 2019).

MATERIALS AND METHODS

Location Selection

The study areas were located in the state-owned forestland of Tuyen Quang’s Yen Binh & Yen Son forestry companies; Phu Tho’s Yen Lap forestry company; Nghe An’s Song Hieu forestry company; and Gia Lai’s Quy Nhon forestry company (Figure 1). At each study area, the soil sample sites were randomly stratified by the seven-year Acacia cycles, along with nearby natural forest plots on the slope of 8 - 12° and Ferrosols. Acacia tree density in the study areas is from 1,600 to 2,000 trees per hectare. The average annual temperature and rainfall in the northern regions of Vietnam are 22-27 degrees Celsius and 1,500 to 2,000 mm per year, respectively. The average annual temperature and rainfall in Quy Nhon are 27-28 degrees Celsius and 1500-2,500 mm per year, respectively.

Soil Sampling

The management goal is to sustain Acacia timber yield, minimum soil dataset should be chosen in relation to the Acacia timber yield. The study selected organic matter (OM), total nitrogen (TN), total phosphorus (TP), total potassium (TPO), pH, bulk density (BD), and soil porosity (P) because they are related to sustaining Acacia timber productivity. A total of 182 composite soil samples were randomly stratified by the cycles of the Acacia plots of 25m × 25m and nearby natural forest plots. Of which, 34 Acacia’s soil samples were collected in the cycle 1; 32 Acacia’s soil samples were collected in the cycle 2; 32 Acacia’s

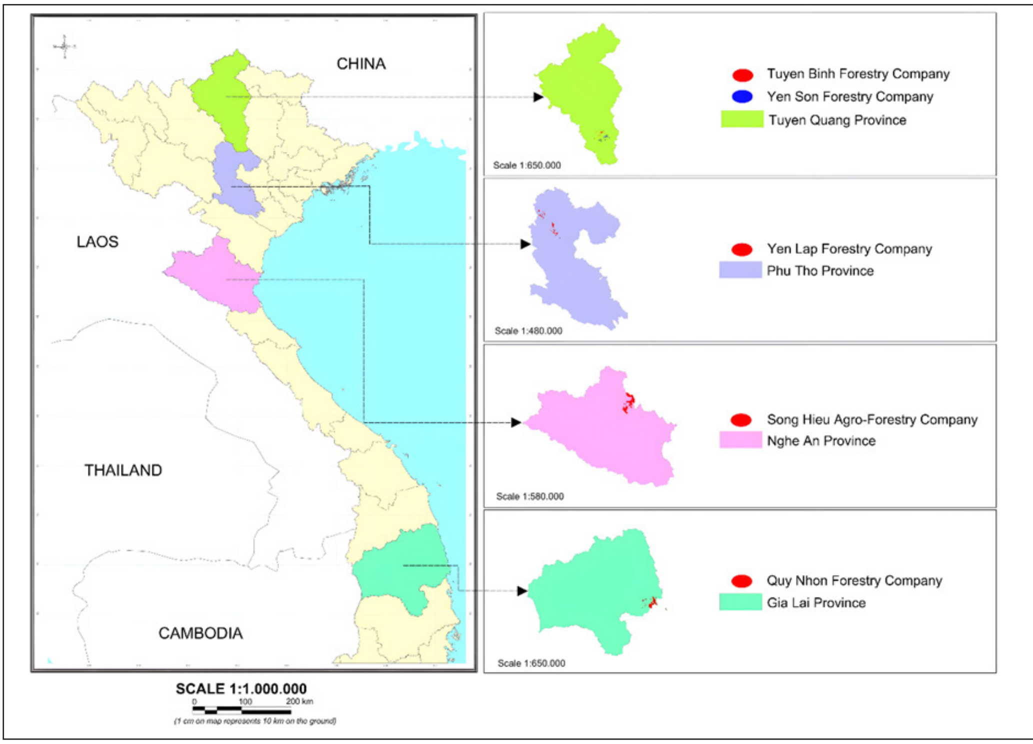


Figure 1. Locations of the study area

soil samples were collected in the cycle 3; 22 Acacia's soil samples were collected in the cycle 4; and 22 Acacia's soil samples were collected in the cycle 5; and 40 natural forest's soil samples were collected in nearby sites of the Acacia plantation areas. At each plot, 18 subsamples were taken along two diagonals of the plot, then mixed into a composite sample. The composite samples were contained in a nylon bag that records the coordinates and other details of the samples, then transported to the laboratory.

Soil Physical Measurement

Soil bulk density and soil porosity were measured by the Vietnamese standard TCVN 11399: 2016 at the soil depth of 30 cm. Soil bulk density was determined from the mass of dry soil per unit volume of a soil sample collected with a cylindrical metal tube with a known volume (100 cm^3) in undisturbed soils. Soil porosity was calculated based on the soil bulk density and particle density using the following equation (Mtyobile et al. 2020):

$$\text{Soil porosity } \% = (\text{soil bulk density}/\text{particle density}) * 100$$

Soil Chemical Analysis

The composite samples were air-dried and sieved through a 2 mm sieve, and any fragments were removed. The soil samples were analysed for the soil chemical indicators by the Vietnamese standards (TCVN). Soil pH was measured by the standard TCVN 5979: 2007, similar to the ISO 10390:2005. Total organic carbon was determined through wet oxidation with potassium dichromate, as outlined in TCVN 4050:1985. For total nitrogen, the Kjeldahl digestion method was specified in the standard TCVN 6498:1999. Total phosphorus was analysed using the spectrophotometric method after acid digestion described in the TCVN 4052:1985. Total potassium was analysed by flame photometry as described in TCVN 8660:2011. All analyses were conducted in triplicate to ensure data reliability, with appropriate quality control measures, including the use of certified reference materials and blank samples. The analytical procedures were performed under controlled laboratory conditions with calibrated equipment to maintain measurement accuracy and precision throughout the study.

Statistical Analysis

Descriptive statistics were determined for the soil properties, and they were checked for normality by the Shapiro–Wilk test. The study revealed that the soil properties of the Acacia cycle samples did not show a normal distribution; therefore, the non-parametric Kruskal–Wallis and Mann-Whitney test were used to compare the differences under different Acacia cycles and with natural forest at 5% significance level.

Soil Quality Assessment

The soil quality index was aggregated to evaluate soil quality change among the continuous cycles of Acacia. Soil properties were measured in different units, and linear conversion functions were applied to convert the raw values of the soil property to the common scale of 1-100 (Andrews et al., 2004; Karlen et al., 2003).

For OM, TN, TP, TPO and P, the conversion function is given as:

$$\text{Rescaled Score} = \left(\frac{X - Xmin}{Xmax - Xmin}\right) * 100$$

For soil bulk density (BD), the conversion function is given as:

$$\text{Rescaled Score} = \left(\frac{Xmax - X}{Xmax - Xmin}\right) * 100$$

where x = the measured value of a soil property; x_{max} = the maximum value of a soil property; x_{min} is the minimum value of a soil property.

For pH, if the pH value < 7, the first formula is used for the conversion, and if pH > 7, the second formula is used for the conversion. Each soil property has a different degree of relative importance on soil quality. This importance was incorporated into the assessment through the weighting of the soil property. The pairwise comparison method in the AHP framework was applied to estimate the weights of soil properties (Saaty, 1980). The soil quality index was calculated as follows:

$$SQI = \sum_{i=1}^{n} SiWi$$

Si represents the score of a soil property i, and Wi represents the relative weights of a soil property i.

RESULTS AND DISCUSSION

The Soil Properties under the Acacia Cycles

The results of the descriptive statistical analysis are presented in Table 1. Table 1 shows the mean, median and standard deviation (SD) of the soil properties under the Acacia cycles and natural forests in the study areas. Table 1 shows the Kruskal-Wallis test results of successive cycles in the study area. In general, there are statistically significant differences between the Acacia cycles and natural forests ($p < 0.05$) (Table 1). The post-hoc analysis by the Mann-Whitney test showed that all soil properties were clearly different among the Acacia cycles ($p< 0.05$). In addition, the Mann-Whitney test also shows that all soil properties of the Acacia cycles are clearly different from those of natural forests ($p<0.05$).

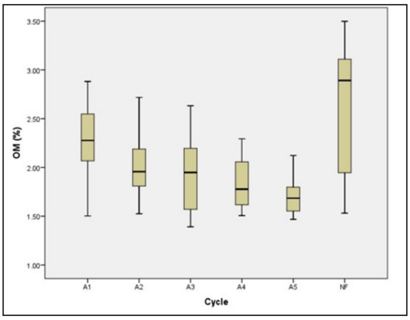
The soil analysis results indicate that OM and TN tended to be stable from the first to the fifth cycles of Acacia. Compared with the natural forest, OM and TN decreased slightly over the consecutive cycles. The TP, TPO, and pH showed a clear decreasing trend over the consecutive cycles. The Acacia showed a clear decline compared to the natural forest. The BD showed a clear increase, indicating the hardening of the surface soil in the study areas. In contrast, soil porosity (P) showed a decrease due to the operation of machinery during timber harvesting, planting and tending Acacia forests after each new planting cycle. Comparing our study results with previous studies, some studies have similar results; however, some studies have opposite results. For example, some studies reported that Acacia increased soil pH, TN and TP (Lee et al., 2015), increased fertility (Koutika et al., 2019; Machado et al., 2017; Tchichelle et al., 2016). Similarly, a case study in Central Vietnam (Dong et al., 2014) reported that Acacia had an impact on soil improvement on infertile soils. However, the study by Huong et al. (2015) showed that continuous planting of Acacia from the 2^{nd} cycle caused a decrease in soil nutrients, especially N, P, Ca, and K. Abu Seri and Abd Rahman (2021) reported the results of the investigation on the influence of the age of Acacia on the soil properties of the soil. The results showed that the soil pH, N, P, K, Ca, and soil density also decreased; however, OM and N remained stable.

Table 1
The soil properties under hybrid Acacia cycles in the study sites

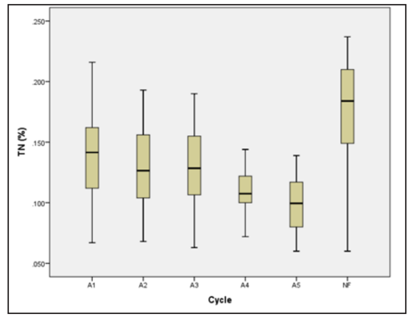
Planting cycle	OM (%)	TN (%)	TP (%)	TPO (%)	pH	BD (g/cm^3)	P (%)
Cycle 1 of the Acacia (A1), n = 34							
Mean	2.27	0.140	0.090	0.918	3.87	1.39	41.46
Median	2.27	0.141	0.095	1.180	3.90	1.32	40.33
SD	0.35	0.037	0.028	0.576	0.54	0.27	5.74
Cycle 2 of the Acacia (A2), n = 32							
Mean	2.02	0.128	0.078	0.663	3.58	1.42	40.38
Median	1.95	0.126	0.090	0.770	3.43	1.43	39.10
SD	0.35	0.035	0.029	0.410	0.42	0.23	5.63
Cycle 3 of the Acacia (A3), n = 32							
Mean	1.92	0.128	0.080	0.480	3.49	1.49	37.87
Median	1.94	0.128	0.080	0.240	3.45	1.45	38.15
SD	0.35	0.034	0.034	0.440	0.32	0.23	5.68
Cycle 4 of the Acacia (A4), n = 22							
Mean	1.83	0.109	0.075	0.094	3.25	1.52	40.28
Median	1.77	0.107	0.072	0.093	3.25	1.56	39.81
SD	0.25	0.018	0.023	0.027	0.15	0.24	6.38
Cycle 5 of the Acacia (A5), n = 22							
Mean	1.70	0.099	0.073	0.090	3.10	1.62	36.56
Median	1.68	0.099	0.071	0.093	3.11	1.59	35.90
SD	0.17	0.023	0.014	0.026	0.06	0.09	3.21
Natural Forest (NF), n = 40							
Mean	2.66	0.169	0.117	0.501	3.78	1.29	52.71
Median	2.89	0.184	0.120	0.154	3.71	1.15	52.87
SD	0.60	0.057	0.016	0.530	0.48	0.33	3.19

Note. OM -organic matter, TN -total nitrogen, TP -total phosphorus, TPO -total potassium, pH -soil acidity, BD -bulk density, P -soil porosity. Variation in the soil properties under Acacia cycles and natural forests were tested by Kruskal-Wallis: OM (ʎ^2= 22.94 df = 5, $p < 0.05$), TN (ʎ^2= 27.54, df = 5, $p < 0.05$), TP (ʎ^2= 26.06, df = 5, $p < 0.05$), TPO (ʎ^2= 46.36, df = 5, $p < 0.05$), pH (ʎ^2= 61.33, df = 5, $p < 0.05$), BD (ʎ^2= 27.54, df = 5, $p < 0.05$), P (ʎ^2= 48.99, df = 5, $p < 0.05$). All pair comparisons of the Acacia cycles and natural forest were tested by Mann-Whitney. All soil properties among Acacia cycles are statistically significant ($p<0.05$)

The results of our soil analysis show that there is a clear distinction between each property among the continuous replanting cycles. The OM and TN indicators at boxplots (a) and (b) of Figure 2 are stable from the second cycle to the third cycle, then show signs of a slight decrease in the fourth and fifth cycles. Comparing the OM and TN of Acacia and natural forest shows differences ($p < 0.05$). The TP content showed signs of decrease in the later cycles compared to the first cycle and natural forests in the boxplot (c) of Figure 2. However, TPO and pH had the strongest decrease, as shown in the boxplots (d) and (e)



(a)



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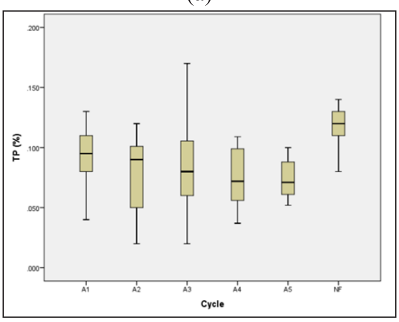

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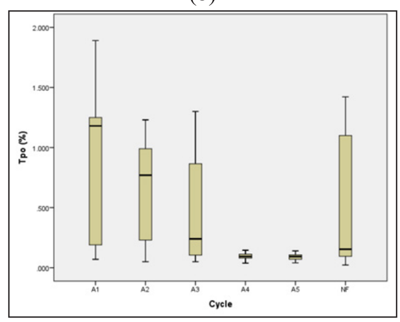
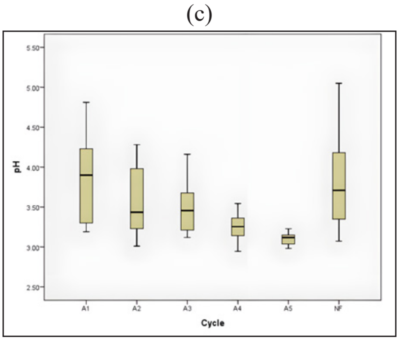
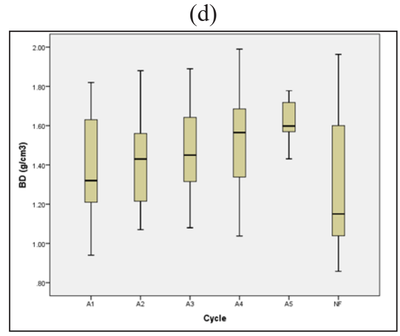


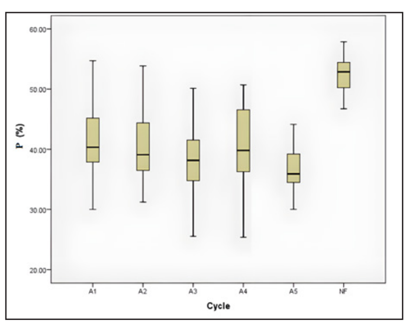
(d)



(e)



(f)



(g)

Figure 2. Variation in soil properties under Acacia cycles and natural forest
Note. All pair comparisons of Acacia cycles and natural forest at the boxplots (a), (b), (c), (d), (e), (f), (g) were tested by the Mann-Whitney. All soil properties among the Acacia cycles are statistically significant ($p<0.05$). A1- Acacia cycle 1, A2 - Acacia cycle 2, A3 - Acacia cycle 3, A4- Acacia cycle 4, A5 - Acacia cycle 5, NF -natural forest

of Figure 2. The soil bulk density at boxplot (f) of Figure 2 shows an increasing trend, indicating that the topsoil shows signs of hardening as an inevitable result of short-cycle Acacia plantation, caused by logging machinery and removal of the surface litterfall. Soil porosity index generally decreased slightly in the first 3 cycles of Acacia rotation but showed a sharp decrease in the 5th cycle due to mechanical logging activities, soil erosion and removal of forest surface litterfall, as showed at the boxplot (g) of Figure 2.

Weighting Soil Properties

From the perspective of agriculture and forestry, farmers as well as land managers often evaluate the relative importance of physical and chemical indicators, which contribute to the overall soil quality. Therefore, the estimation of the relative importance of each physical and chemical soil indicator was essential. The relative role or priority of each soil property can be consulted with soil experts as well as farmers. In this study, soil experts were consulted to build a pairwise comparison matrix of the soil properties in the study based on the AHP method (Karlen et al., 2003; Saaty, 1980). The results of the pairwise comparisons of the soil properties are presented in Table 2.

The weight estimation results show that OM has the highest weight, followed by pH, TN, TP, TPO, soil porosity, and soil bulk density. The computed consistency ratio is at 0.012, which is in the consistent level of less than 0.1. This ensures that the computed weights are logical in expert judgments (Saaty, 1980). From Table 2, OM has the highest weight, 0.326, meaning that OM is the most important factor affecting soil quality. Soil acidity (pH) plays the second most important role in overall soil quality (0,208). Soil acidity is a fundamental chemical parameter because it is related to most of the chemical properties of the soil as well as the activities of soil organisms. Chemical weathering

Table 2
Pairwise matrix of the soil quality parameters using the Analytic Hierarchy Process

Soil Properties	OM	pH	TN	TP	TPO	BD	P	Weights (W)
OM	1.0	2.0	2.0	4.0	4.0	6.0	5.0	0.326
pH	1/2	1.0	1.0	3.0	3.0	5.0	4.0	0.208
TN	1/2	1.0	1.0	3.0	3.0	5.0	4.0	0.208
TP	1/4	1/3	1/3	1.0	1.0	3.0	2.0	0.086
TPO	1/4	1/3	1/3	1.0	1.0	3.0	2.0	0.086
BD	1/6	1/5	1/5	1/3	1/3	1.0	1.0	0.040
P	1/6	1/4	1/4	1/2	1/2	1.0	1.0	0.047

Note. OM -Soil Organic Matter, pH -soil pH, TN -tota nitrogen, TP -total phophorus, TPO -total potassium, BD -soil bulk density, P -soil porosity; maximum eigenvalue (λmax) = 7.083; n = 7; consistency index (CI) = (λmax–n)/(n–1) = 0.014; random index (RI) = 1.36; consistency ratio (CR) = CI/RI = 0.012, accepted in tropical climates often causes natural soil acidity. However, farming activities such as afforestation also add to acidity because farming stimulates pyrite oxidation. Total nitrogen plays an important role in protein biosynthesis and photosynthesis of plants, so the presence of sufficient nitrogen content ensures good plant growth. The weight of total nitrogen estimated from the pairwise comparison matrix is 0.208, which is equal to the weight of the pH. Phosphorus and potassium are essential macronutrients for plant growth. However, their roles in influencing soil quality are considered less important than organic matter and nitrogen, as well as soil pH. The weights of phosphorus and potassium are the same and equal to 0.086. Soil porosity and bulk density are two physical properties that influence soil moisture and soil aeration. However, they are considered the least important because they are usually more stable than soil chemical properties. The weights of bulk density and soil porosity are 0.040 and 0.047, respectively.

Soil Quality Index

The results of assessing the soil quality from seven soil physical and chemical indicators show that, in general, the soil quality in both the natural forest and the Acacia forest at the research sites is at the moderate soil quality level, the total soil quality score of all Acacia and natural forest sites is less than 70 on the scale of 100 (Figure 3 and Table 3). The natural forest sites have a higher soil quality level than Acacia sites. Acacia forest plots in the 3rd to 5th cycles show clear signs of soil quality decline compared to the natural forest sites. It is noted that all the study sites were Acacia forests managed by a state-owned forestry company, and all monitoring plots implemented the same forest management practices without fertiliser addition; therefore, there was no differential influence of fertilisers on soil quality among the selected study sites.

It is noted that soil quality is a concept that is subject to points of view, so the selection of soil quality assessment criteria depends on the preferred concept (Soil Science Society of America, 1995; Anderson & Gregorich, 1984; Larson & Pierce, 1994). In this study, the two groups of soil chemical and soil physical properties were selected; however, the group of soil biological properties was not involved in the assessment because biological property data have not been measured yet. Therefore, the results of the soil quality assessment with this Acacia only reflect an important part of soil quality, but are not completely comprehensive. Therefore, further studies are necessary to supplement soil biological properties. In our view, no chemical fertilisers or pesticides were applied to the Acacia soil and the reference natural forest at the study sites; therefore, the soil ecosystem was not negatively impacted and maintained a relatively stable state over a long period. Under these conditions, the physical and chemical indicators of the Acacia soil reflected the major soil quality properties, helping to maintain the sustainable development of the forest ecosystem. Therefore, although lacking biological indicators, the soil quality index still has significance for comparing soil quality across the selected study sites.

Another issue with the AHP-based SQI assessment is the sensitivity of the soil quality index. Although the AHP method is an effective tool for synthesising the soil properties into a single composite index, allowing for effective comparisons across plots, farms, and even regional or national scales, the determination of the role of each soil property depends on the subjective opinion of the expert. Therefore, in estimating factor weights from the pairwise comparison matrix, it is necessary to check the consistency of the comparison matrix, ensuring that the consistency index CR < 0.1. Furthermore, taking the opinions of many experts as well as expert groups helps to minimise biased opinions.

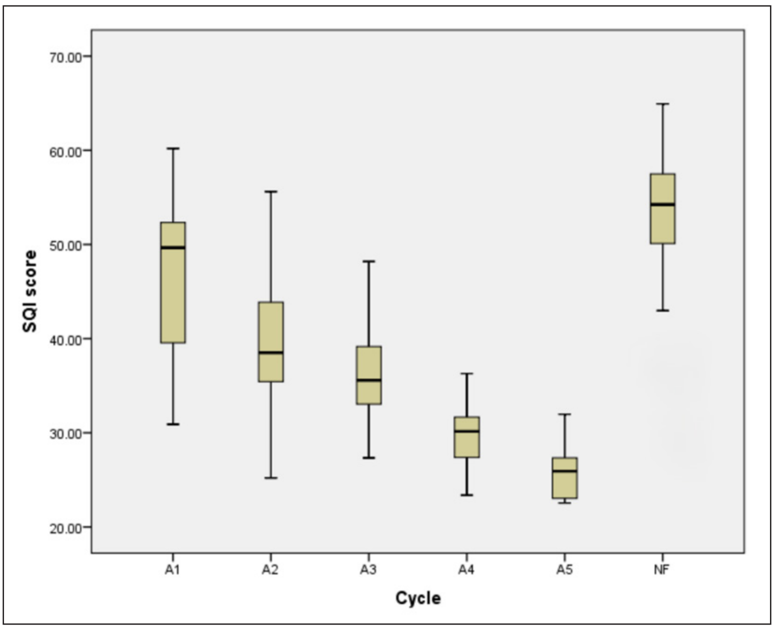


Figure 3. Soil quality index score under different Acacia cycles and natural forest

Table 3
The SQI score under the Acacia cycles and reference natural forest

SQI Statistics	Natural Forest Score	SQI Score under the Acacia Cycles				
		A1	A2	A3	A4	A5
Max	64.94	60.20	55.62	48.19	36.29	31.97
Min	28.73	30.89	25.20	27.33	23.37	22.54
Mean	52.05	46.78	39.20	36.37	29.96	25.87
SD	9.03	8.31	7.15	5.79	3.44	2.76

Pearson's correlation between the soil quality index and the individual soil properties was analysed to indicate which properties have a major influence on the soil quality. The correlation coefficients between the SQI and the soil properties of OM, TN, TP, TPO, pH, BD, and P were 0.75, 0.729, 0.42, 0.55, 0.65, -0.46, 0.50, respectively. The two-tailed Pearson's correlation coefficient was statistically significant ($p<0.05$). The OM and TN had a stronger correlation with the soil quality index, followed by pH ($r = 0.65$), TPO ($r = 0.55$), TP ($r = 0.42$), BD ($r = -0.46$), and P ($r = 0.50$). From the correlation analysis, it implies that the conservation of the soil quality of the Acacia requires maintaining OM, TN, and TPO in the Acacia areas. In particular, it is necessary to implement measures to maintain the soil quality level by returning the biomass of Acacia branches and leaves after harvesting Acacia timber. Forest owners should avoid burning Acacia leaves and branches as an effective measure to return organic matter and mineral nutrients to the soil.

CONCLUSION

The findings of the study indicate that changes in the soil properties among Acacia cycles and natural forests are statistically significant in the selected areas of Vietnam. The results imply that the initial cycle of the Acacia commonly yields a higher SQI score; however, subsequent cycles indicate a decline in soil quality level, owing to changes in individual chemical and physical properties. Apparently, the decline of soil quality is caused by changes in the physical and chemical properties under the Acacia forest. Organic matter, pH, total phosphorus, total potassium, and soil porosity decrease with the consecutive cycles. Only total nitrogen remains quite stable due to the nitrogen fixing of Acacia. Soil bulk density increased in the 3rd to 5th cycles of Acacia, indicating an increase in the ability to harden the topsoil layer. By analysing the Pearson's correlation between the SQI and the individual soil properties, it was found that OM, TN, and pH were more closely correlated with the SQI. This is an indication that soil improvement measures should focus more on protecting and improving these chemical properties. This study is a practical contribution to the understanding of soil quality change in short-cycle Acacia plantation areas that are common in many parts of the world, especially in the tropics.

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