Effects of successive rotations on stand growth and soil properties of monoculture Acacia plantations across ecological regions in Vietnam

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Ảnh hưởng của các chu kỳ kinh doanh liên tiếp đến sinh trưởng và tính chất đất của rừng trồng keo thuần loài ở các vùng sinh thái khác nhau của Việt Nam

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ABSTRACT

Several studies have reported that successive rotations of fast-growing plantations may lead to soil degradation and productivity decline, particularly under short-rotation management and intensive harvesting practices. However, information on how changes in soil properties influence the growth and productivity of major Acacia plantation species in Vietnam, including Acacia mangium, Acacia auriculiformis, and Acacia hybrids, across successive rotations in different ecological regions remains limited. To address this knowledge gap, this study used data collected from 54 sample plots established in Tuyen Quang, Nghe An, and Binh Dinh Provinces, Vietnam, during the period from 2023 to 2024. The results showed that: (1) The growth and productivity of Acacia plantations varied considerably among successive rotations and site conditions. The mean annual volume increment reached its highest values in the second rotation and declined in the third rotation, particularly in Tuyen Quang Province; (2) Soil organic carbon, total nitrogen, and total phosphorus tended to decrease, whereas soil bulk density increased under higher plantation rotations; (3) Pearson correlation analysis indicated that soil organic carbon, total nitrogen, total phosphorus, and pH(KCl) had no significant relationships with stand growth indicators; (4) Soil bulk density showed significant negative correlations with the stand's mean breast-height diameter, height, volume, and mean annual volume increment (r = -0.462 to -0.483; p < 0.01), indicating that soil compaction was an important limiting factor affecting the growth of Acacia plantations. These findings highlight the important role of soil physical properties in maintaining the productivity of Acacia plantations across successive rotations in Vietnam.

Keywords:
Acacia plantation,
plantation productivity,
soil properties,
stand growth,
sucessive rotations.

TÓM TẮT

Nhiều nghiên cứu cho thấy rừng trồng sinh trưởng nhanh qua nhiều chu kỳ kinh doanh có thể dẫn đến suy thoái đất và suy giảm năng suất, đặc biệt chu kỳ ngắn và khai thác với cường độ cao. Tuy nhiên, thông tin về ảnh hưởng của sự biến động tính chất đất đến sinh trưởng và năng suất của các loài keo trồng chủ yếu ở Việt Nam, bao gồm Acacia mangium, Acacia auriculiformis và keo lai, qua các chu kỳ kinh doanh kế tiếp tại các vùng sinh thái khác nhau vẫn còn hạn chế. Để góp phần bổ sung khoảng trống nghiên cứu này, nghiên cứu đã sử dụng số liệu thu thập từ 54 ô tiêu chuẩn được thiết lập tại các tỉnh Tuyên Quang, Nghệ An và Bình Định trong giai đoạn 2023–2024. Kết quả nghiên cứu cho thấy: (1) Sinh trưởng và năng suất rừng trồng keo biến động đáng kể theo các chu kỳ kinh doanh và điều kiện lập địa. Giá trị tăng trưởng thể tích bình quân năm đạt cao nhất ở chu kỳ kinh doanh thứ hai và giảm ở chu kỳ thứ ba, đặc biệt rõ tại tỉnh Tuyên Quang; (2) Hàm lượng carbon hữu cơ, nitơ tổng số và phospho tổng số trong đất có xu hướng giảm, trong khi dung trọng đất tăng lên theo các chu kỳ rừng trồng; (3) Phân tích tương quan Pearson cho thấy carbon hữu cơ, nitơ tổng số, phospho tổng số và pH(KCl) của đất không có mối quan hệ có ý nghĩa thống kê với các chỉ tiêu

Từ khóa:
Chu kỳ kinh doanh,
năng suất rừng trồng,
rừng trồng keo,
sinh trưởng lâm phần,
tính chất đất.

sinh trưởng lâm phần; (4) Dung trọng đất có tương quan nghịch có ý nghĩa thống kê với $D_{1.3}$, Hvn, thể tích và tăng trưởng bình quân chung thể tích của lâm phần (r = -0,462 đến -0,483; p < 0,01), cho thấy hiện tượng nén chặt đất là một trong những yếu tố ảnh hưởng đến sinh trưởng rừng trồng keo. Những kết quả này nhấn mạnh vai trò của các tính chất vật lý đất trong việc duy trì năng suất rừng trồng keo qua nhiều chu kỳ kinh doanh ở Việt Nam.

1. INTRODUCTION

Plantation forests currently play a crucial role in sustainable forestry development worldwide, as well as in Vietnam. In the context of the ongoing decline of natural forest areas, planted forests are considered a major source of timber supply, while also contributing to carbon sequestration, ecosystem restoration, and the enhancement of local livelihoods [1, 2]. Fast-growing species such as Pine, Eucalyptus, and Acacia are widely used in production forests due to their broad adaptability, short successive rotations (SRs), and high timber productivity [3, 4].

In Vietnam, production plantations play a strategic role in forestry economic development and the livelihoods of mountainous communities. Currently, Acacia plantations cover approximately 2.5 million hectares, mainly concentrated in the Northeast, North Central, and South Central Coastal regions. Commonly planted Acacia species include *Acacia mangium* Willd*, Acacia auriculiformis* A. Cunn. ex Benth*, and Acacia hybrid (Acacia mangium x Acacia auriculiformis)* due to their rapid growth, wide adaptability, and high economic value [5, 6]. The prevailing characteristics of current Acacia plantation models are monoculture, intensive management, and short SRs to support pulpwood and woodchip production for export [5, 7]. However, the repeated establishment of SRs on the same sites is posing significant challenges to maintaining soil quality and sustaining forest productivity in the future.

Numerous studies worldwide have shown that monoculture plantations under SRs may lead to declines in soil organic carbon, total nitrogen (N), and total phosphorus (P), while simultaneously increasing soil bulk density and reducing soil porosity [8-10]. Practices such as clear-cut harvesting, slash burning, and whole-tree biomass removal are considered major factors contributing to site degradation and increased soil erosion [11, 12]. Although Acacia plantations can improve certain soil properties during the early stages through biological nitrogen fixation and the addition of organic litter, many long-term studies have still reported declining organic matter content and increasing soil bulk density under repeated rotations [13, 14].

In addition to their effects on soil properties, many studies have demonstrated that forest growth and productivity are closely associated with site condition and soil quality. Declines in organic matter, increases in soil bulk density, and nutrient imbalances can reduce the capacity of trees to absorb water and nutrients, thereby directly affecting tree diameter, height growth, and biomass accumulation. Several studies have indicated that soil bulk density has a clear negative relationship with forest growth and productivity indicators, highlighting the important role of soil physical properties in sustaining long-term forest productivity.

In Vietnam, studies on Acacia plantations have mainly focused on growth performance, productivity, ecological–technical factors affecting plantation development, economic efficiency and livelihoods, environmental impacts, and sustainable management solutions such as large-timber production, species diversification, and soil conservation [5-7, 15, 16]. However, research on the relationships between SRs of Acacia plantations and soil properties remains limited, particularly under different ecological conditions in Vietnam. In addition, there is still a lack of cross-regional studies assessing the overall impacts of SRs on soil quality and plantation growth. In particular, the role of soil physical properties, especially soil bulk density, in influencing the growth and productivity of Acacia plantations has not yet been comprehensively evaluated.

Based on these issues, the study was conducted to: (1) evaluate the effects of successive rotations on the growth, productivity, and soil properties of monoculture Acacia plantations across different ecological regions of Vietnam; and (2) analyze the relationships between soil properties and plantation growth in order to identify the key soil factors influencing plantation productivity. The study provides a scientific basis for improving soil management practices, reducing soil degradation risks, and enhancing the long-term sustainability of Acacia plantation productivity in Vietnam.

2. RESEARCH METHODS

2.1. Study Area

The study was conducted in three representative ecological regions of the major Acacia plantation areas in Vietnam, including Tuyen Quang (Northeast), Nghe An (North Central Coast), and Binh Đinh , currently Gia Lai (South Central Coast). These regions contain large areas of Acacia plantations, diverse site conditions, and represent the characteristic climatic, topographic, and soil conditions of Vietnam.

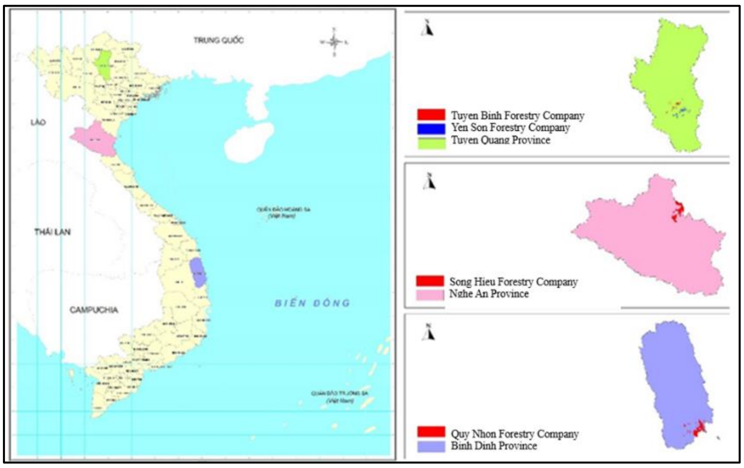

Figure 1. Study areas

Tuyen Quang is characterized by a humid tropical climate, low mountainous terrain, and ferralitic soils developed on shale and metamorphic rocks [17]. Nghe An has a tropical monsoon climate with hot dry seasons, medium mountainous terrain, and red-yellow as well as ferralitic soils derived from different parent materials [16]. In contrast, Gia Lai, located in the South Central Coastal region, has a hotter and drier climate, low hilly terrain, and nutrient-poor soils that are highly susceptible to erosion [18].

Acacia plantations in the study areas are mainly monoculture plantations managed under intensive silvicultural practices and short rotation cycles (RCs) for pulpwood and woodchip production for export. Acacia plantations in Nghe An and Binh Dinh mainly consisted of *Acacia auriculiformis*, whereas those in Tuyen Quang included A*cacia mangium, Acacia auriculiformis,* and *Acacia hybrids*. Clear-cut harvesting is commonly applied between rotations, and post-harvest residues are often burned before replanting [5]. The differences in natural conditions, plantation species, and management practices among the study areas provide an important basis for evaluating the effects of successive rotations on soil property variations and the growth performance of Acacia plantations.

2.2. Research objects

The study objects were monoculture production Acacia plantations under different RCs, including the first rotation (R1), second rotation (R2), and third rotation (R3). The plantations mainly consisted of Acacia auriculiformis in Nghe An and Binh Dinh Provinces, and Acacia hybrid and Acacia mangium in Tuyen Quang, which are the dominant species used for production plantations in these regions. The selected plantations were established using relatively similar silvicultural practices, including planting method, planting density, site preparation, weed control, and clear-cut harvesting systems. Within each study site and rotation cycle, the selected stands mainly differed in topographic position and elevation conditions (e.g., foot slope, middle slope, and hilltop), while other site and management conditions were kept as comparable as possible.

Due to the lack of long-term monitoring under the same forest stands over extended periods, the study applied a space-for-time substitution approach by comparing stands under different RCs to assess trends in soil property variation and plantation growth. In each ecological region, two plantation areas were selected to better represent the variability of site conditions within the region, thereby improving the representativeness and reliability of the study results.

2.3. Sample plot establishment and soil sampling

A total of 54 sample plots (SPs) were established during the period 2023–2024, with 18 SPs arranged in each study Province, to evaluate stand growth and selected soil physical and chemical properties. In each Province, two study areas were selected as replicates based on typical site conditions and common Acacia plantation management practices. Within each study area, three RCs were identified, including R1, R2, and R3. For each rotation cycle, three SPs were established corresponding to three topographic positions. Consequently, each study area contained nine SPs, resulting in a total of 18 SPs per Province.

Following this plot arrangement, each SP covered an area of 500 m². The selected stands were mainly between 4 and 8 years old, with priority given to stands close to harvesting age in order to clearly reflect the effects of SR on soil property variations and Acacia plantation growth. Within each SP, common plantation growth indicators were measured, including stand density, plantation quality, diameter at breast height (DBH), total tree height (Hvn), bole height (Hdc), and Canopy diameter.

Soil bulk density was determined in each SP using a soil core sampler at the 0–10 cm surface soil layer. The collected samples were preserved, transported, and analyzed in the laboratory following standard procedures for bulk density determination.

For soil chemical analyses, composite soil samples were collected from 12 systematically distributed sampling points arranged along diagonal transects within each SP using a soil auger at a depth of 0–30 cm. The collected composite samples were preserved and transported to the laboratory for chemical analysis.

2.4. Data analysis and processing methods

**** Methods for calculating stand growth and productivity indicators***

Descriptive statistical analyses, including mean values, and ranges of variation, were calculated for growth variables such as DBH (cm), Hvn (m), V (m³/tree), M (m³/ha), and ΔV (m³/tree/year).

Growth and stand productivity indicators of Acacia plantations were calculated as follows:

The stand density (N/ha) were determined using the following formulas:

$$\boldsymbol{N} = \frac{\mathbf{10.000} \times \boldsymbol{N_{0tc}}}{\mathbf{500}} \quad (1)$$

The basal area of an individual tree was calculated as follows:

$$gi = (\Pi^*(DBH/2)^2)/10.000 \quad (2)$$

The total basal area of the SP was calculated follows:

$$G_{otc}=\sum gi \quad (3)$$

The stand basal area per hectare was determined as follows:

$$G\ (m^2/ha) = \frac{\mathbf{10.000} \times \boldsymbol{G_{0tc}}}{\mathbf{500}} \quad (4)$$

The tree volume was calculated using the following formula:

$$V= G.Hvn.f \quad (5)$$

G is the basal area at 1.3 m height (m²);

Hvn is the total tree height (m);

f is the form factor of the tree stem (f=0.5 for Acacia plantations).

The standing volume of each SP was calculated as follows:

$$\mathrm{Motc} = \sum \mathrm{Vi}(m^3/ha) \quad (6)$$

The stand volume per hectare was then determined as follows:

$$\mathrm{M}\ (\mathrm{m}^3/\mathrm{ha}) = \frac{10.000 \times M_{0tc}}{500} \quad (7)$$

The mean annual increment was calculated as follows:

$$\Delta_{\boldsymbol{t}} = \frac{\boldsymbol{T_a}}{\boldsymbol{a}} \quad (8)$$

Δt is the mean annual increment of variable t;

T_a is the investigated variable at age a.

In this study, ΔV represents the mean annual increment in stand volume.

**** Soil Analysis***

Soil samples collected from the field were preserved, processed, and analyzed in the laboratory following current Vietnamese standard methods to ensure data accuracy and consistency. Soil pH(KCl), total organic carbon, total nitrogen, total phosphorus, and total potassium were determined according to TCVN 5979:2007, TCVN 8941:2011, TCVN 6498:1999, TCVN 8940:2011, and TCVN 8660:2011, respectively.. The analytical results provided the basis for evaluating variations in soil properties across successive rotations and their relationships with the growth and productivity of Acacia plantations.

**** Testing differences in mean annual volume increment within each rotation cycle***

The growth indicator (∆V) was tested using the non-parametric Kruskal–Wallis test for K independent samples. In cases where significant differences among SP were detected, pairwise comparisons were further conducted using the Mann–Whitney U test for two independent samples. When no significant differences were found among the SPs, the data were pooled to evaluate ΔV for the different study sites under each rotation cycle.

**** Relationships between stand growth and soil properties in Acacia plantations***

To evaluate the relationships between soil properties and the growth and productivity of Acacia plantation stands, Pearson correlation analysis was applied to determine the strength and direction of linear relationships between soil variables and stand growth indicators. The soil variables included organic carbon content, total nitrogen, total phosphorus, total potassium, soil pH(KCl), and soil bulk density, while the stand variables included DBH, Hvn, V, ΔV, and stand volume (Motc). SPSS 20 software was used to perform the correlation analysis using Pearson's correlation coefficient (r). Statistical significance was determined at $p < 0.05$ and $p < 0.01$.

3. RESULTS AND DISCUSSION

3.1. Stand growth and productivity of Acacia plantations in the study areas

The survey results from the three representative ecological regions showed that the growth and productivity of Acacia plantations varied considerably according to rotation cycle, stand age, and site conditions. Major growth indicators such as DBH, Hvn, V, G, M/ha, and ΔV clearly reflected the trends in productivity changes of Acacia plantations across SR.

**** Tuyen Quang province***

The stand growth and productivity of monoculture Acacia plantations in Tuyen Quang are summarized in Table 1.

Table 1. Stand growth and productivity of Acacia plantation in Tuyen Quang Province

RC	Age	Stand density (trees/ha)	DBH (cm)	Hvn (m)	V (m^3/tree)	ΔV (m^3/tree/year)	M (m^3/ha)
1	4	680–1000	11.55–12.43	9.00–10.84	0.0576–0.0596	0.0144–0.0149	39.17–59.58
1	8	660–940	13.45–15.61	12.37–13.19	0.1001–0.1347	0.0125–0.0168	82.09–117.25
2	5	660–900	12.42–13.29	11.34–11.94	0.0713–0.0881	0.0143–0.0176	58.16–64.21
2	6	700–1100	13.07–13.41	12.95–13.45	0.0912–0.0972	0.0152–0.0162	68.06–100.28
3	6	860–980	10.54–12.22	10.92–13.06	0.0511–0.0850	0.0085–0.0142	50.13–83.31
3	7	620–840	12.79–14.75	10.47–12.20	0.0751–0.1092	0.0107–0.0156	63.10–83.00

** Note: Growth variables are presented as the minimum–maximum values of the SPs within the same RCs.*

The results reveal that Acacia plantation growth varied considerably with stand age, rotation cycle (RC), and site conditions. Stand density ranged from 620–1,100 trees/ha, DBH from 10.54–15.61 cm, Hvn from 9.00–13.45 m, and individual tree volume from 0.0511–0.1347 m^3/tree. In general, older stands (7–8 years old) tended to show higher DBH, height, and tree volume than younger stands. However, plantations under R3 generally exhibited lower ∆V and stand productivity compared to previous rotations.

The non-parametric Kruskal–Wallis test showed no significant differences in volume growth among the three SPs representing different topographic positions within the same RC and study site under R1 and R2 ($p > 0.05$), indicating relatively uniform stand growth between foot-slope, mid-slope, and hilltop positions. However, significant differences were detected under R3 at both study sites, suggesting greater growth differentiation among topographic positions under higher RCs.

**** Nghe An province***

The stand growth and productivity of monoculture Acacia plantations in the SPs in Nghe An are presented in Table 2.

Table 2. Stand growth and productivity of Acacia plantation in Nghe An Province

RC	Age	Stand density (trees/ha)	DBH (cm)	Hvn (m)	V (m³/tree)	ΔV (m³/tree/year)	M (m³/ha)
1	6	1040–1380	15.11–15.43	10.84–11.04	0.1032–0.1082	0.0172–0.0180	107.31–149.33
1	7	1260–1640	13.76–14.58	10.64–10.77	0.0822–0.0955	0.0117–0.0136	113.49–143.46
2	5	2000	14.15–14.31	10.93–11.03	0.0899–0.0938	0.0180–0.0188	179.84–187.67
2	6	700–1000	13.24–13.61	10.67–11.10	0.0756–0.0849	0.0126–0.0142	52.91–84.93
3	5	2000	11.61–11.89	9.14–9.41	0.0505–0.0540	0.0101–0.0108	101.00–107.90
3	6	640–900	13.83–14.59	10.29–10.98	0.0837–0.0935	0.0140–0.0156	59.11–84.16

** Note: Growth variables are presented as the minimum–maximum values of the SPs within the same RCs.*

The results indicate that Acacia plantation growth in Nghe An varied with RCs, stand age, and stand density. Stand density ranged from 640–2,000 trees/ha, DBH from 11.61–15.43 cm, Hvn from 9.14–11.10 m, and individual tree volume from 0.0505–0.1082 m³/tree. In general, plantations under R1 and R2 showed better growth and productivity than those under R3. The highest values of individual tree volume (0.1032–0.1082 m³/tree) and mean annual volume increment (ΔV = 0.0172–0.0188 m³/tree/year) were recorded in the 6-year-old stands under R1 and the 5-year-old stands under R2. In contrast, the lowest growth values were observed in the 5-year-old stands under R3, with DBH of 11.61–11.89 cm and V of 0.0505–0.0540 m³/tree. High-density stands (2,000 trees/ha) under R2 also exhibited high stand productivity, with stand volume ranging from 179.84–187.67 m³/ha.

The Kruskal–Wallis test showed no statistically significant differences in ΔV among topographic positions within the same rotation cycle ($p > 0.05$), indicating relatively uniform growth among sample plots. Therefore, the sample plots within each rotation cycle were pooled to calculate representative ΔV values for comparisons among RCs.

**** Binh Dinh province***

The stand growth and productivity of monoculture Acacia plantations in the SPs in Binh Dinh are presented in Table 3.

Table 3. Stand growth and productivity of Acacia plantation in Binh Dinh Province

RC	Age	Stand density (trees/ha)	DBH (cm)	Hvn (m)	V (m³/tree)	ΔV (m³/tree/year)	M (m³/ha)
1	5	460–1100	10.48–13.46	7.92–10.98	0.0390–0.0856	0.0078–0.0171	17.94–77.05
2	5	420–1200	11.77–21.38	9.98–22.71	0.0607–0.4275	0.0121–0.0534	66.81–179.55
2	8	440–560	19.46–21.95	22.29–22.59	0.3452–0.4619	0.0432–0.0577	193.32–203.23
3	5	1000–1460	11.95–12.32	10.41–10.77	0.0634–0.0680	0.0127–0.0136	68.02–92.62
3	8	520–640	16.86–18.86	19.80–20.87	0.2327–0.3005	0.0291–0.0376	142.62–156.27
1	5	460–1100	10.48–13.46	7.92–10.98	0.0390–0.0856	0.0078–0.0171	17.94–77.05

** Note: Growth variables are presented as the minimum–maximum values of the SPs within the same RCs*

The results indicate that Acacia plantation growth in Binh Dinh varied considerably with rotation cycle, stand age, and stand density. Stand density ranged from 420–1,460 trees/ha, DBH from 10.48–21.95 cm, Hvn from 7.92–22.71 m, and individual tree volume from 0.039–0.462 m³/tree. In general, 8-year-old stands under R2 and R3 showed substantially better growth and productivity than 5-year-old stands, with the highest values of V, △V, and stand volume recorded under R2. In contrast, some 5-year-old stands under R1 exhibited relatively low growth performance, with stand volume ranging from 17.94–21.93 m³/ha.

The Kruskal–Wallis test showed no statistically significant differences in △V among topographic positions within the same rotation cycle at most study sites ($p > 0.05$), indicating relatively uniform growth among sample plots. Only R3 at one study site showed significant differences, suggesting localized growth variation under higher RCs .

3.2. Variations in soil properties across RCs

The results of analyses of several basic soil chemical and physical properties under Acacia plantations in the SPs in the study areas are summarized in Table 4.

Table 4. Soil properties across successive rotations of Acacia plantations

Province	Rotation Cycle	Organic C (%)	Total N (%)	Total P (g/kg)	Total K (g/kg)	pH(KCl)	Bulk Density (g/cm³)
Tuyen Quang	1	1.95 ± 0.51	0.178 ± 0.054	0.251 ± 0.085	5.44 ± 1.29	3.60 ± 0.33	1.35 ± 0.08
	2	2.31 ± 0.73	0.179 ± 0.051	0.415 ± 0.062	5.71 ± 1.30	3.41 ± 0.30	1.28 ± 0.11
	3	1.66 ± 0.37	0.132 ± 0.013	0.230 ± 0.059	3.09 ± 1.42	3.96 ± 1.01	1.43 ± 0.13
	Total	**1.98 ± 0.59**	**0.163 ± 0.047**	**0.299 ± 0.107**	**4.75 ± 1.75**	**3.66 ± 0.64**	**1.35 ± 0.12**
Nghe An	1	1.52 ± 0.08	0.114 ± 0.014	0.453 ± 0.054	9.27 ± 1.22	3.96 ± 0.32	1.38 ± 0.18
	2	1.33 ± 0.22	0.106 ± 0.018	0.539 ± 0.132	7.16 ± 2.55	3.57 ± 0.42	1.34 ± 0.11
	3	1.23 ± 0.30	0.087 ± 0.020	0.404 ± 0.080	6.03 ± 1.91	3.60 ± 0.27	1.34 ± 0.12
	Total	**1.36 ± 0.24**	**0.102 ± 0.020**	**0.465 ± 0.106**	**7.49 ± 2.31**	**3.71 ± 0.37**	**1.35 ± 0.13**
Binh Dinh	1	0.47 ± 0.07	0.035 ± 0.005	0.218 ± 0.134	8.37 ± 2.14	4.34 ± 0.41	1.60 ± 0.30
	2	0.48 ± 0.04	0.037 ± 0.003	0.154 ± 0.037	6.68 ± 0.95	4.05 ± 0.38	1.42 ± 0.27
	3	0.63 ± 0.17	0.048 ± 0.013	0.213 ± 0.048	9.14 ± 2.36	4.03 ± 0.29	1.61 ± 0.16
	Total	**0.53 ± 0.13**	**0.040 ± 0.010**	**0.195 ± 0.085**	**8.06 ± 2.09**	**4.14 ± 0.37**	**1.54 ± 0.25**

Note: Values are presented as Mean ± SD (mean value ± standard deviation).

The summarized results indicate that soil properties under Acacia plantations differed markedly among ecological regions and RCs. Organic carbon content in Tuyen Quang was considerably higher than in Nghe An and Binh Dinh, with mean values ranging from 1.66–2.31%, whereas values in Nghe An ranged from 1.23–1.52% and in Binh Dinh only from 0.47–0.63%. Similarly, total nitrogen content in Tuyen Quang ranged from 0.132–0.179%, which was higher than in Nghe An (0.087–0.114%) and Binh Dinh (0.035–0.048%). These results indicate that soils in Tuyen Quang had a greater capacity for organic matter and nitrogen accumulation, while soils in Binh Dinh showed a much stronger tendency toward nutrient depletion.

For total P, Nghe An recorded the highest values, ranging from 0.404–0.539 g/kg, exceeding those in Tuyen Quang (0.230–0.415 g/kg) and Binh Dinh (0.154–0.218 g/kg). In contrast, total P content was highest in Binh Dinh and Nghe An, where several RCs recorded values above 8 g/kg; in particular, R3 in Binh Dinh reached an average of 9.14 g/kg. Meanwhile, Tuyen Quang exhibited substantially lower potassium content, especially under R3 where the value declined to approximately 3.09 g/kg. These findings reflect considerable differences in soil conditions and nutrient retention capacity among the studied ecological regions.

Soil bulk density tended to increase under higher RCs, particularly in Binh Dinh, where average bulk density reached 1.60–1.61 g/cm³ under R1 and R3, higher than in Tuyen Quang (1.28–1.43 g/cm³) and Nghe An (1.34–1.38 g/cm³). Soil pH(KCl) values in all three regions were generally low, ranging mainly from 3.4–4.3, indicating strongly acidic soils; however, Binh Dinh showed relatively higher pH values compared with the other two provinces.

Considering the trends across RCs, several nutrient indicators, including organic carbon, total N and total P, tended to decline in R3, particularly in Tuyen Quang where organic carbon decreased from 2.31% in R2 to 1.66% in R3, while total P declined from 5.71 to 3.09 g/kg. At the same time, soil bulk density increased from 1.28 to 1.43 g/cm³. These trends suggest that repeated harvesting and replanting cycles may degrade soil quality, reduce organic matter accumulation, and increase soil compaction over SR.

3.3. Relationships between soil properties and the growth and productivity of Acacia plantations

The results of the Pearson correlation analysis indicated that most soil chemical properties, including organic C, total N, total P, and pH(KCl), showed no clear relationships with the growth and productivity indicators of Acacia plantation stands. The correlation coefficients between organic carbon and DBH, Hvn, V, and ΔV were very low (|r|=0.03–0.17) and not statistically significant (p>0.05). Similarly, total N and total P exhibited very weak correlations with growth indicators, with |r| < 0.20. These results suggest that, under the study conditions, total soil nutrient contents did not directly reflect the growth performance of the plantation stands.

Table 5. Pearson correlation coefficients between selected soil properties and growth indicators of monoculture Acacia plantations in the three study areas

Soil Property	DBH	Hvn	V	∆V	Motc	Statistical Significance
Organic C	0.053	0.173	0.133	0.030	-0.091	p > 0.05
Total N	-0.010	0.201	0.082	0.012	-0.158	p > 0.05
Total P	0.195	-0.023	0.140	0.122	0.143	p > 0.05
Total K	-0.122	-0.442**	-0.236	-0.107	0.204	p < 0.01 with Hvn
pH(KCl)	-0.019	-0.040	-0.004	-0.046	0.193	p > 0.05
Bulk Density	-0.462**	-0.483**	-0.473**	-0.483**	-0.308*	p <0.01 and p < 0.05

Note: **: Statistically significant at p < 0,05; **: Statistically significant at p < 0,01*

Among the analyzed soil properties, soil bulk density showed the clearest relationship with the growth and productivity of Acacia plantation stands. The results indicated that bulk density was negatively correlated with DBH (r = -0.462), Hvn (r = -0.483), V (r = -0.473), and ∆V (r = -0.483), all of which were statistically significant at p < 0.01. These findings indicate that as soil bulk density increases, meaning the soil becomes more compacted, the growth performance of Acacia trees declines markedly. From an ecological perspective, high bulk density reduces soil porosity, restricts gas exchange, limits water retention capacity and root development, consequently affecting nutrient uptake and stand growth.

In contrast, the stand growth indexes exhibited very strong positive relationships with one another. DBH showed a very strong correlation with individual tree volume (V) (r = 0.942; p < 0.01), and was also highly correlated with ∆V and Motc, indicating that diameter growth plays a decisive role in determining productivity and biomass accumulation in Acacia plantations.

3.4. Discussion

The results from this study showed that the growth and productivity of Acacia plantations varied considerably according to rotation cycle, stand age, and site conditions, which is consistent with many international studies on tropical Acacia plantations. In Tuyen Quang and partly in Nghe An, ∆V increased from R1 to R2 but declined under R3, indicating signs of growth reduction after SRs of harvesting and replanting. Similar trends were reported by Huong et al. [19] for *Acacia auriculiformis* plantations in southern Vietnam and in long-term studies on *Acacia mangium* plantations in Indonesia [20].

Previous studies by Mackensen et al. [11] and Mendham & White [12] also showed that repeated harvesting over SRs may reduce plantation productivity due to nutrient depletion and site degradation. Similarly, studies by Dong et al. [13] and Hung et al. [14] indicated that although Acacia plantations may improve soil conditions during the early stages through biological nitrogen fixation and litter accumulation, long-term rotations still tend to reduce soil organic matter and increase soil bulk density. In the present study, organic carbon content in Tuyen Quang decreased from 2.31% in R2 to 1.66% in R3, while soil bulk density increased from 1.28 to 1.43 g/cm³. Repeated harvesting operations, machinery traffic, and reductions in organic residue inputs may further accelerate soil compaction and structural degradation under successive plantation rotations.

Comparisons among ecological regions showed that soils in Tuyen Quang had higher organic carbon and total N contents than those in Nghe An and Binh Dinh, whereas Binh Dinh had lower nutrient contents but higher soil bulk density. These results reflect differences in site conditions and organic matter accumulation among ecological regions. These differences may reflect variations in climate, soil texture, moisture availability, topography, and plantation management intensity among ecological regions. Previous studies have also suggested that soils in drier tropical regions or under intensive management are more susceptible to soil compaction and rapid organic matter depletion after repeated harvesting cycles [8, 9].

The Pearson correlation analysis showed that most soil chemical properties, including organic carbon, total nitrogen, total phosphorus, and pH(KCl), had weak and non-significant relationships with plantation growth indicators $|r| < 0.20$, $p > 0.05$. In contrast, soil bulk density showed significant negative correlations with DBH ($r = -0.462$), Hvn ($r = -0.483$), V ($r = -0.473$), and $\triangle V$ ($r = -0.483$) at ($p < 0.01$). These findings indicate that increased soil compaction can markedly reduce Acacia growth by decreasing soil porosity, restricting gas exchange, and limiting root development and nutrient uptake. Similar results were reported by Kasongo et al. [8], Zhu et al. [10] và Zhou et all. [9].

Overall, the study results indicate that the growth and productivity of Acacia plantations are influenced by the combined effects of RCs, site conditions, and soil properties, among which soil physical properties, particularly soil bulk density, play a more important role than total soil chemical indicators. These findings suggest that sustainable management of Acacia plantations should focus on maintaining soil structure, minimizing soil compaction, and conserving organic residues after harvesting in order to sustain forest productivity across future RCs.

This study was based on a space-for-time substitution approach and mainly focused on several basic soil physical and chemical properties. Therefore, other important factors affecting plantation productivity, such as available nutrient forms, soil microbial activity, litter decomposition, and long-term hydrological processes, were not fully evaluated.

4. CONCLUSIONS

The growth and productivity of Acacia plantations varied considerably across successive rotations and ecological regions. Mean annual volume increment tended to increase in the second rotation and decline in the third rotation, while soil organic carbon, total nitrogen, and total phosphorus generally decreased under higher RCs .

Pearson correlation analysis showed that soil bulk density had significant negative relationships with DBH, Hvn, V, and $\triangle V$, indicating that soil compaction is an important limiting factor affecting the growth and productivity of Acacia plantations. These findings highlight the importance of maintaining favorable soil physical conditions and reducing soil compaction to support the sustainable management of Acacia plantations across successive rotations in Vietnam.

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