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Sustainable Management of *Acacia auriculiformis* Plantations for Wood Production over Four Successive Rotations in South Vietnam

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Received: 31 March 2020; Accepted: 9 May 2020; Published: 13 May 2020

Abstract: Vietnam's forestry sector is facing rising demands for wood to support national and rural economies, and rural livelihoods. A feasible option to meet this demand is to improve productivity in the current plantation estates, especially in those owned by thousands of small growers. Growers have invested in short-rotation acacia plantations primarily for the woodchip market, but are being urged through government policies and pressured by certification bodies and some NGOs to shift to longer rotations, preferentially, for growing saw logs. In this context, we examined the productivity of an *Acacia auriculiformis* plantation in South Vietnam, over four successive rotations, spanning 25 years. We show that it is possible to increase and sustain wood production in the long term, by applying simple but integrated management practices, recognizing that the conservation of site resources is critical for sustainability. Practices which depleted site organic matter and nutrients lead to a hidden, but high, cumulative loss of production. Given the site and soil damaging practices prevalent in the country, it is likely that production foregone in those sites may be equivalent to the yield from one in every four or five rotations harvested. With sound management including the conservation of site resources, planting the best germplasm, appropriate stocking and judicious use of herbicide, total wood production and the proportion of saw logs (50–70% of the commercial wood at about 7 years of age) can be increased substantially. At the same time, these practices also can promote understory development and diversity in the stand. Such holistic benefits are possible without extending the rotation length and/or thinning, which are likely to raise the levels of risks for small growers, who are not covered by any insurance. Investments and support for small growers to enable higher productivity and value per unit area in their holdings, through sustainable management, would offer practical and low-risk options for the benefits of growers, processors and ecosystems.

Keywords: acacia; sustained production; four short rotations; saw logs; understory

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1. Introduction

The forestry and wood products sectors play a key role in the national economy and rural development in Vietnam. It is a leading hardwood chip exporter; it exported 10 million tons (bone dry) in 2018 [1] and produced at least one million tons for the domestic market. It also manufactures plywood, particle board, flooring and furniture for the domestic and export markets. The value of exports was $9.38 billion in 2018, was estimated to reach $11.0 billion in 2019 and is targeted, by the government, to grow to $18–20 billion by 2025 [2].

Many of the plantations are in the hands of more than 300,000 small growers, individually managing 1–5 ha holdings; these resources contribute 50–60% of the domestic wood supply (estimated from various sources) and the rest comes from state or private enterprises managing 2000–10,000 ha units. Most of the wood processing enterprises are small units, estimated from various sources to be about 4500 or more. The sale of wood is a reliable source of income for small growers [3,4]. The growing, processing and related services employ about 500,000 people directly [4] and many more indirectly.

Log harvest from native forests has been illegal in Vietnam since 2019, and hence domestic wood production is totally dependent on plantation forests and farm trees. Plantation resources include acacias, eucalypts, pines, melaleuca and a few native species. The current wood demand is 35 million $m^3 \cdot y^{-1}$, of which 28 m^3 are met from local suppliers and the rest by log imports [4]. Acacias (*Acacia. auriculiformis, A. mangium, A. mangium X auriculiformis* hybrids, and *A. crassicarpa)* are the most important plantation species [5], estimated to be 2.1 M ha in 2019, supplying 20.6 M m^3 y^{-1} round wood [4].

Acacias are grown under diverse conditions, ranging from deltaic soils in low lying flat land in Mekong in the south to eroded and degraded soils on steep slopes in the north. Growth rates over 5–7 year cycles range from 10 to 25 m^3 ha^{-1} yr^{-1}, with many low productivity stands [6–8]. Many field observations indicate that in many holdings, productivity is low, is limited by site factors, poor management practices and low investments.

Small growers can cope with only low levels of risk, and they strongly prefer short rotations of five to six years, seeking an early return and primarily aiming for woodchip market. Government agencies are trying to influence the growers to shift their management and economic goals through a policy which mandates, in some regions, a reduction in woodchip exports and promotes saw log production to strengthen the processing sector (Ministry of Agriculture and Rural Development-MARD- Policy Decision 5115, [9]). Some NGOs and certification bodies also push growers for longer rotations, even to 12 years, with the expectation that if growers followed unspecified "longer rotations" and/or stand thinning, more saw logs will be produced. However, there is little evidence demonstrating that, by following these paths and facing higher concomitant risks, small growers would receive higher returns, based on prices paid at their farm gate. A detailed evaluation of the productivity and sustainability of plantation forestry in SE Asia, including Vietnam [5,6,10], concluded that productivity is impaired by site-damaging inter-rotation management practices including the removal of slash and litter with heavy equipment, repeated ploughing throughout the rotation to control weeds (instead of judicious use of herbicides or periodic hand-weeding), the deployment of genetically unreliable planting stock, overstocking or understocking and poor stand tending. On the other hand, there are also opportunities and options for increasing productivity and product value and maintaining soil properties, even on degraded soils [6,10,11].

The Forest Science Institute of South Vietnam partnered with an international network project for the sustainable management of sub-tropical and tropical plantation forests (1995–2008; [11]). The main aim was to study the long-term management options for improving the productivity of successive rotations of *A. auriculiformis,* plantations, a species widely grown and used for a range of products in Vietnam. A previous paper described the results from the first phase [12]. This paper focuses on the following interrelated long-term sustainability objectives, which are:

- describe the stand growth pattern from one year of age to the end of the rotation, including total wood production, current annual increments (CAI) and mean annual increments (MAI) as a basis for management decisions on the length of rotation and end products;
- examine the sustainability of wood production across successive rotations (over 25 years) and the effects of long-term site organic matter (soil fertility) management on stand growth;
- assess the impacts of inter-rotation management practices that use herbicide over rotations on the development and diversity of the understory;

- examine the relationships between stand development, stem growth rates and product divergence (pulp wood and saw logs), a key issue for growers in terms of the current market and policy directives by the government.

We discuss how the results can be applied to support sustainable management practices that are adoptable by small growers, for improving productivity, promoting understory development and diversifying product streams to meet the current market.

2. Materials and Methods

2.1. Location, Climate and Soils and Previous Land Use

The site is located in Phu Binh, Binh Duong Province (11.3° N, 106.8° E), South Vietnam. The region has a sub-equatorial, seasonally dry climate. The long-term rainfall and temperature for the duration of four rotations from 1995 to 2019 are shown in Figure 1. The mean annual maximum temperature was 33.9 °C and mean minimum temperature was 23.3 °C. From 2010 to 2016, mean maximum temperatures were higher than in other times, with correspondingly lower minimum temperatures (Figure 1). The rainfall (from July to June) ranged from 1964 to 3460 mm y^{-1}, but the means for the first three rotation periods were very close (2539–2594 mm y^{-1}). Most of the rain falls between May and November (Figure 1), peaking at about 712 mm in July and 656 mm in September. Rainy seasons are typically followed by a dry season from December to April, when tree diameter increments decline and may reach zero during January–February, when the rates of litter fall are high. The number of months that received less than 50 mm $month^{-1}$ rainfall varied from one to four during the years from the first to the third rotation.

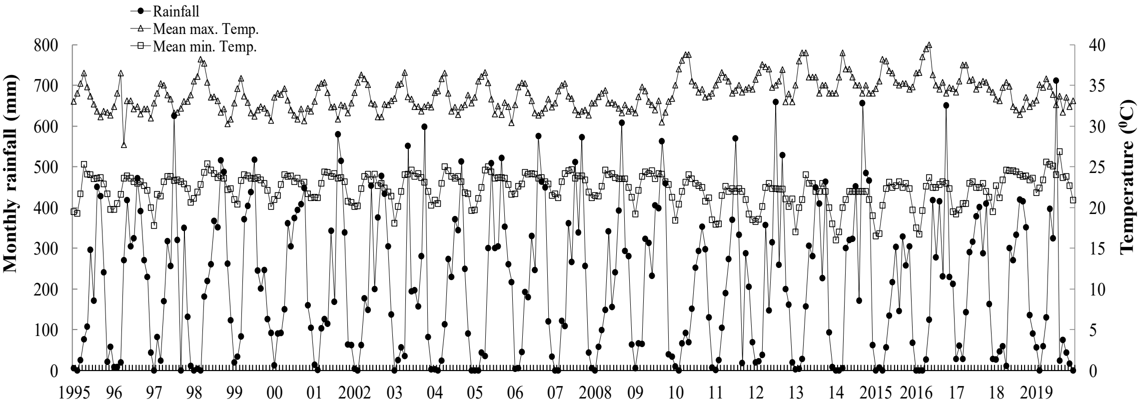


Figure 1. Mean monthly rainfall and temperatures (minimum and maximum) over the course of the four successive rotation cycles (1995–2019). Source: Dong Xoai Meteorological station located 20 km from the experimental site.

The soil type was chromic Acrisol. The A horizon (0–19 cm) comprised of a grey, brown and yellow (10 YR 6/2) sandy clay loam with a subangular blocky structure, followed by the BA horizon (19–45 cm), with properties similar to A, but a more blocky structure, and then the B horizon (10 YR 5/3), extending to 120 cm depth with a sandy clay composition. There was evidence of root growth throughout the profile, which decreased with depth. Properties in the 0–10 cm horizon were: sand 57%, silt 18%, clay 18%, $pH_{(H20)}$ 4.8, $pH_{(KCl)}$ 4.0, soil organic carbon 16.7 g kg^{-1}, total nitrogen 1.2 g kg^{-1}, Bray-1 extractable phosphorus 10.8 mg kg^{-1} and CEC 14.3 c mol kg^{-1}. The bulk density increased slightly with depth from 1.4 g cm^{-3} in the 0–10 cm layer to 1.5 g cm^{-3} at 30–50 cm, which decreased slightly at the end of the second rotation [12].

2.2. Treatments

The first rotation *A. auriculiformis* stand (planted in 1995) was harvested at seven years of age and treatments were applied in the following three rotations. The treatments represented different biomass harvesting intensities and inter-rotation site management, consistent with the network objectives [11,12]. These were then coded as BL0, BL1 and BL2 to be consistent with the network. The treatments BL0 and BL1 continued throughout all rotations. The treatment BL2 was revised, based on early results from phase one [11,12] and all three treatments were relabeled to represent a gradation in the long-term soil properties as fertility low (F_L), medium (F_M) and high (F_H), respectively.

BL0 (F_L): The whole tree was harvested and then all aboveground biomass, including litter and understory, was removed. This was repeated at every rotation.

BL1 (F_M): Only merchantable stem wood (≥3 cm in diameter with bark) was harvested; all slash and litter retained. This treatment was reapplied at every rotation.

BL2 (F_H): Wood was harvested as in BL1. In the second rotation, the slash alone from BL0 plots was transported, replication wise, and distributed evenly over the existing slash and litter (double slash). In the third and fourth rotations, double slash was discontinued. Instead, in the BL1 regime, each tree received superphosphate at 20 g tree^{-1} P (~30 kg ha^{-1} P) mixed with soil at the bottom of the planting holes before planting. This change was based on the evidence of decline in extractable soil P in the second rotation here [12] and in a study on *A. mangium* in Sumatra [13], and growth response to added P in related studies. All harvests and other operations associated with treatment application were done manually, ensuring minimum soil disturbance.

The experiment was a randomized complete block design with five replications and three treatments. Each plot was 1152 m^2 (12 rows × 16 trees in a row) and had two buffer rows, giving 96 trees in the net measured plots. All plots were arranged in a contiguous block with tracks for access. Additional plots treated as F_M were set up in the adjacent area for sequential harvests for developing allometric relationships. Hereafter, treatments are referred to as F_L, F_M and F_H.

2.3. Management

Rotation 1 (R-1): Planted in July 1995 and harvested at seven years of age. The site was originally occupied by overcut, degraded native vegetation. It was cleared with a bulldozer, biomass was burnt and it was then disc-ploughed twice. The spacing was 3 × 4 m (833 trees ha^{-1}). A small doze of fertilizer was added in the planting hole. After planting, inter-row spaces were disc-ploughed twice every year during the first three years for weed control. Accordingly, the site was ploughed at least eight times during this rotation, as was commonly practiced at that time. With this practice a span 1.5–2.0 m wide along the tree rows remained under the weeds. No herbicide was used.

Rotation 2 (R-2): Planted in July 2002 and harvested at six years of age. The spacing was 3 × 2 m (1666 trees ha^{-1}). All trees received 50 g of 16-16-8 NPK fertilizer at planting, according to the local practice. Treatments were carried out as described earlier.

Rotation 3 (R-3): Planted in July 2008, and the end of rotation measurements were done in July 2015 at seven years of age. The spacing and weed management were as per R-2. Weeds were controlled as in R-2. Trees did not receive basal fertilizer.

Rotation 4 (R-4): An unforeseen contract issue delayed the final harvest of R-3 to the end of the rainy season in 2015. Therefore, the planting of R-4 was postponed to July 2016. The spacing, weed management and basal fertilizer were as per R-3.

In all rotations, the trees with multiple stems were cutback to one dominant stem before one year of age. In addition, in R-3 and R-4, a few lower branches, typically to a height of 1.0–1.5 m from the ground, were pruned during the first two years. Beginning with the harvest of the first rotation, the zero-tillage principle was followed.

2.4. Weed Management

In the first rotation, weeds were reduced by repeated disc-ploughing of the inter-row space, which left behind weeds along tree rows. For R-2, glyphosate at 1.9 kg ha^{-1} was sprayed once before planting, followed by applications at the same rate three and 10 months after planting. This was repeated twice during the second and third year; timings were based on the duration of the rainy season and the regrowth of vegetation. In between, weeds (especially woody species and tree climbing vines) were slashed manually, which promoted new shoots and improved the efficiency of herbicide spray. After three years, there was little or no weed control. This regime was repeated in R-3. In the current rotation, some weeds were slashed manually, and herbicide was sprayed thrice, the last application being 27 months after planting.

2.5. Genetics of Planting Stock

The first rotation was planted with seedlings raised from seeds collected from a local plantation. For R-2, seedlings were raised from seeds collected from a stand at Dong Nai province. It was a provenance trial in which trees with poor form and low growth were culled earlier. R-3 and R-4 were planted with equal proportions of two clones developed by the Vietnam Academy of Forest Science and approved for commercial planting by government authorities.

2.6. Understory Vegetation

The occurrence and diversity of the understory vegetation was assessed in September 2019, 10 months after the last herbicide application.

Ground cover: This assessment was done by three trained staff. After the clarification of the objective and cross validating each other's results for consistency through trial runs, they assessed all plots with no further comparison or discussion between them; each person commenced the work from a different location in the experiment and walked in opposite directions. The data across all replications were used.

The percentage ground cover is a visual estimate of the percentage of the area of a plot occupied by the understory if all the patches of understory were assembled in one formation (continuum) within that plot. In another assessment, each assessor stood at the center of the plot and notionally subdivided the total plot area into four equal quarters. For each quarter, a score was given between one (zero or little understory) and 10 (nearly full cover). The means of scores per plot were used for analysis. The trends in the effects of treatments on understory, assessed by two methods, were consistent and identical; a linear regression between the plot results from two methods (score vs. % cover) had an R^2 value of 0.99, $n = 15$ (data not shown). Given this close agreement, the results from one method (% cover) only are reported (Table 1).

Table 1. Tree size, ground cover and diversity of understory during August 2019 (rainy season) below the three-year-old fourth rotation *A. auriculiformis* plantation in Phu Binh, South Vietnam.

Treatment	Height (m)	Dbh (cm)	LAI (m^2 m^{-2})	Understory Ground Cover (%)	Understory Plants (plants ha^{-1})
F_L	12.4	9.6	3.0	22	90,000
F_M	12.6	9.8	3.1	58	309,900
F_H	12.8	10.3	3.3	64	334,700
p-value ($\alpha = 0.05$)	<0.001	0.001	0.03	0.03	<0.001
LSD ($p = 0.05$)	0.2	0.3	0.2	32.1	113,745

To measure the diversity and abundance of the understory, five 4 m^2 sub-plots per main plot were located, one at the center of the main plot and the others representing different radial positions from the center towards the plot corners. In each sub-plot, all plants were counted and species were identified as woody species, shrubs and grasses, and a number of species were converted to the plot level for analysis.

2.7. Leaf Area Index

The leaf area index (LAI) and understory were assessed at the same time. Photographs were taken from 10 fixed positions in two parallel lines, diagonal to the center of each plot. The digital photographs were analyzed using Fuji-win 32 image analysis software to estimate LAI. These estimates of LAI were calibrated against the plant area index (PAI) measured at the same position and time using a Li-Cor LAI-2000 Plant Canopy Analyzer.

$$\mathrm{PAI} = 0.07\ \mathrm{LAI}_{\mathrm{camera}} + 0.18\ (R^2 = 0.98;\ n = 36;\ p < 0.01) \tag{1}$$

PAI was converted to *LAI* using an equation [14]:

$$\mathrm{LAI} = 1.54\mathrm{PAI} - 0.11\ (R^2 = 0.99) \tag{2}$$

2.8. Tree Growth and Sawlogs

The diameter at breast height (Dbh-D) was measured annually throughout the study. Tree heights (H, m) at harvest were estimated using equations derived from destructive sampling at each rotation.

$$\text{Rotation-1: } \mathrm{H} = 14.53\log\mathrm{D} - 1.13\ (\mathrm{R}^2 = 0.92\ n = 30) \text{ at 7 years of age} \tag{3}$$

$$\text{Rotation-2: } \mathrm{H} = 24.54\log\mathrm{D} - 10.25\ (\mathrm{R}^2 = 0.71\ n = 60) \text{ at 6 years of age} \tag{4}$$

$$\text{Rotation-3: } \mathrm{H} = 33.67\log\mathrm{D} - 17.4\ (\mathrm{R}^2 = 0.90\ n = 18) \text{ at 7 years of age} \tag{5}$$

where D is Dbh in cm. All R^2 values were significant ($p < 0.01$).

Standing volumes were calculated as:

$$\mathrm{V} = \pi\left(\frac{\mathrm{D}}{200}\right)^2 * \mathrm{H} * \mathrm{F} \tag{6}$$

where V is the stem volume in m^3, D is Dbh in cm, H is total height in m and F is a form factor (0.475). We developed and tested this form factor by felling and assessing 210 trees representing all diameter classes (Dbh) across three rotations. By testing rotation as a grouping factor in the regression analysis, we found no significant difference between rotations. For estimating merchantable (commercial) volume, the top end diameter was set at >3 cm, as practiced in the local wood markets. These were 2–3% less than the total volume.

For the fourth rotation, tree heights were measured directly. Volume at seven years of age was predicted by the Shumacher formula, using the software STATGRAPHICS Centurion XV.I. (STATGRAPHICS TECHNOLOGIES, INC., The Plains, VA, USA) and measured volumes for 1–7 years from R-3 and measurements from 1 to 3 years from R-4. This method is used in Vietnam to predict the growth of individual trees and stands, including volumes, and to understand growth patterns in relation to stand age and management [15].

Volumes in each treatment were predicted through the application of equation:

$\mathrm{V} = \mathrm{m}^*\exp(-\mathrm{b}^*\mathrm{A}^{\wedge -\mathrm{c}})$, where V is volume in m^3; m, b, c are coefficients and A is age in years.

$$\mathrm{V}\ (\mathrm{F_{L}}) = 321.0\exp(-8.27\mathrm{A}^{\wedge -1.52}) \text{ with } \mathrm{R}^2 = 99.9;\ \mathrm{SE} = 1.8 \tag{7}$$

$$\mathrm{V}\ (\mathrm{F_M}) = 344.1\exp(-8.62\mathrm{A}^{\wedge -1.56}) \text{ with } \mathrm{R}^2 = 99.9;\ \mathrm{SE} = 2.1 \tag{8}$$

$$\mathrm{V}\ (\mathrm{F_H}) = 472.0\exp(-6.61\mathrm{A}^{\wedge -1.23}) \text{ with } \mathrm{R}^2 = 99.9;\ \mathrm{SE} = 3.4 \tag{9}$$

In Vietnam, stem logs from plantations are categorized (Decision 27/2018/TT BNNPTNT-MARD) as pulp wood (V_{PW}) if logs are within ≥ 3–10 cm D, and as saw logs if they have a small end D ≥ 10 cm.

Saw logs are further categorized as: small saw logs ($V_{SSL,}$ D 10.0 ≤ 14.0 cm), medium saw logs ($V_{MSL;}$ 14.0 < D ≤ 18.0 cm) and large saw logs ($V_{LSL,}$ D >18.0 cm).

To develop allometric relationships between D and stem-log types, 18 trees (7 to 20 cm diameter) were sampled. For each tree, log components were estimated as a percentage of total volume according to the following rules:

Pulp wood (PW):

if D < 10 cm, V_{PW} = 100% V

$$\begin{gathered}\text{If D10.0 cm} \leq \text{D} < \text{20.0 cm, } \mathrm{V}_{\mathrm{PW}}\ (\%\ \mathrm{V}) = 610.23\ \exp^{\wedge(-0.22 \times D)}\ (R^2 = 0.93,\ n = 18,\ p < 0.01), \\ \text{and if D} \geq \text{20 cm } V_{\mathrm{PW}} = 8.2\% \text{ of V.}\end{gathered} \tag{10}$$

Small saw logs (SSL):

$$\begin{gathered}\text{If D 10.0 cm} \leq \text{D} < 20.0\ \mathrm{V}_{\mathrm{SSL}}\ (\%\ \mathrm{V}) = -1.17\mathrm{D}^2 + 33.08\mathrm{D} - 184.9\ (R^2 = 0.76,\ n = 18,\ p < 0.01); \\ \text{and if D} > \text{20 cm, } \mathrm{V}_{\mathrm{SSL}} = 7.6\% \text{ of V.}\end{gathered} \tag{11}$$

Large saw log (LSL):

$$\text{if D} < \text{15 cm, } \mathrm{V}_{\mathrm{LSL}} = 0\% \text{ of V} \tag{12}$$

$$\text{if D } 15 \leq 20 \text{ cm, } \mathrm{V}_{\mathrm{LSL}}\ (\%\ \mathrm{V}) = (10^{\wedge-10})\mathrm{D}^{\wedge 8.79}\ (R^2 = 0.88,\ n = 9,\ p < 0.01) \text{ and} \tag{13}$$

if D > 20 cm, V_{LSL} = 45% of V

After calculating the volumes of pulp wood and large saw log, medium saw log volumes were estimated as:

$$\mathrm{V}_{\mathrm{MSL}} = \mathrm{V} - \mathrm{V}_{\mathrm{LSL}} - \mathrm{V}_{\mathrm{SSL}} - \mathrm{V}_{\mathrm{PW}}. \tag{14}$$

2.9. Statistical Analysis

A one-way analysis of variance (ANOVA) was applied to test the treatment effects on stand growth at each annual measurement and at harvest for R-2 and R-3. Growth data for R-4 was estimated as described earlier. Similarly, one-way ANOVA was used to examine treatment effects on understory and stand attributes (Table 1). When the ANOVA indicated a significant difference between means ($p < 0.05$), the least significant difference (LSD) in a multiple range test (Tukey's HSD) was used to assess which treatment means were different from each other ($\alpha = 0.05$). The statistical analysis was conducted using Genstat 13th Edition (VSN International 2011).

2.10. A Supporting Experiment

To corroborate some results reported here, we re-examined the data from another experiment that represented a contrasting ecosystem (site and genetics), on war-damaged and eroded (stony and shallow) ferralitic Acrisol soil in Dong Ha, central Vietnam [7]. The first rotation *A. mangium* × *A. auriculiformis* hybrid stand (MAI, 17 m^3 ha^{-1} yr^{-1}) was harvested, stem wood was removed manually, and all slash, litter and understory biomass were retained on site. A second rotation experiment examined the effects of some weed control practices, fertilizers and the slope of the land on the growth of a mix of six *Acacia* hybrid clones. A total of 1428 trees ha^{-1} were planted; however, by harvest, mortality reduced this to 1056 trees ha^{-1}. At the end of the second rotation, the mean MAI was 19.8 m^3 ha^{-1} yr^{-1} compared to 32.4 m^3 ha^{-1} yr^{-1} in this study. The saw log criterion was cut lengths with a diameter above 12 cm (local standard). Overall, the plot level data (five treatments and four replications spread across the sloping site gave $n = 20$ plots) represented a range of intra-site variations and associated growth rates.

3. Results

3.1. Stand Growth

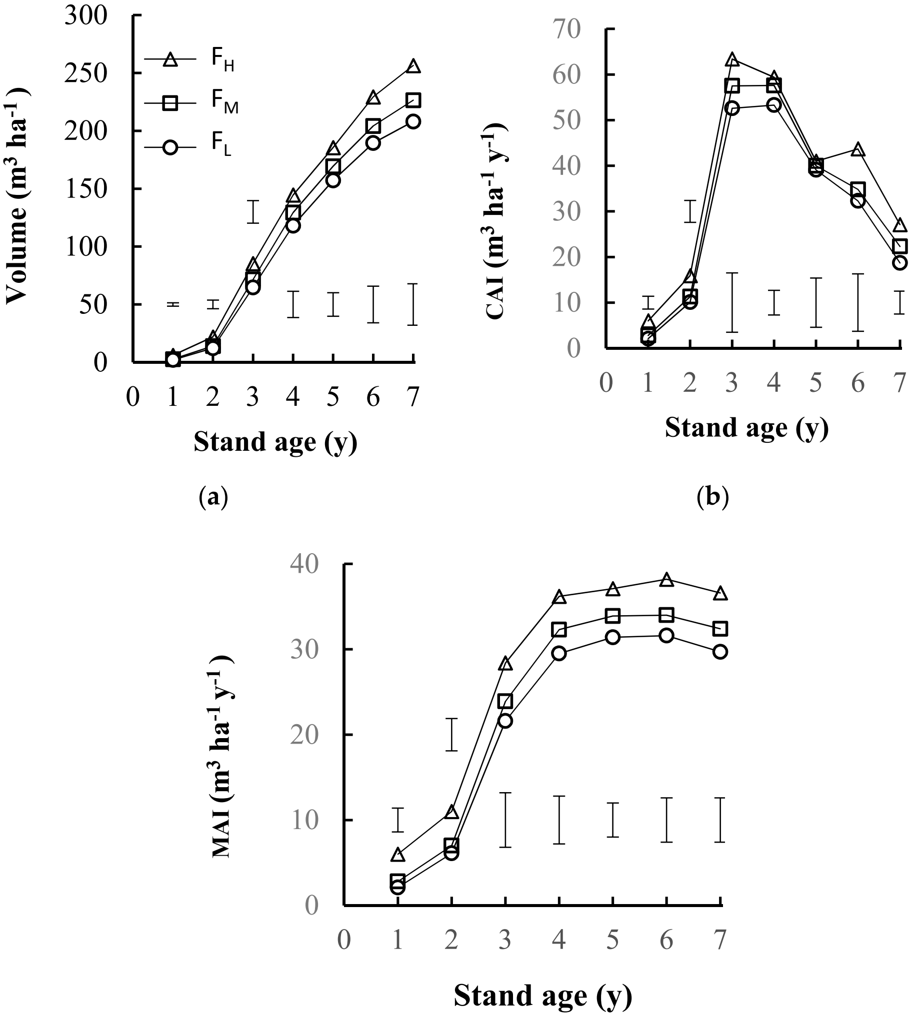
The photos (Figure 2) show, strikingly, how management interventions had transformed the stand features, productivity, stem form and stand uniformity from the first to fourth rotation. The first rotation (R-1) was managed according to practices typical of that period (e.g., bulldozing, repeated ploughing, low-quality seedlings, low stocking) and hence was the baseline for our research. Out of about 833 trees planted, 658 ha^{-1} survived to harvest. Tree heights ranged from 4 to 16 m and Dbh from 6 to 25 cm. Stand had low amounts of commercial wood, but carried a large amount of aboveground biomass, including weeds (Figure 2a).The second rotation (R-2) examined the effects of a set of inter-rotation management practices. The management regime including improved seedlings and higher stocking (planted at 1660 trees ha^{-1}, 1400 trees ha^{-1} at harvest), resulted in a faster growth rates and substantially higher wood production. However, many stems had a poor form, double/multiple leaders and heavy branches, which diminished the log quality (Figure 2b). In the third rotation (R-3), site and stand management remained largely as in R-2, but the planting stock was changed to two clones, which were selected for their improved growth rates and stem form (straight, uniform, free of double leaders and lighter branching) (Figure 2c). These preferred stand attributes are also seen in the younger fourth rotation (R-4) (Figure 2d).

(**a**) (**b**)

(**c**) (**d**)

Figure 2. Stand structure and features for four successive rotations of *A. auriculiformis* grown under changing management regimes, over 25 years, in south Vietnam. (**a**) First rotation (planted 1995) at seven years of age, (**b**) second rotation (planted 2002) at an age close to six years; (**c**) third rotation (planted 2008) at 6.5 years of age and (**d**) fourth rotation (planted 2016) at three years of age.

Annual growth data were used to determine current annual increments (CAI) and mean annual increments (MAI) during the R-2 and R-3 rotation. Results for R-3 only are presented in Figure 3, because it was planted with improved clones, management treatments gave sustained growth response, it had good stocking (at harvest, 1500 trees ha^{-1}), and was managed for seven years, one year longer than the common local practice. Treatment effects on growth emerged from two years onwards (Figure 3).



(**a**) (**b**)

(**c**)

Figure 3. Stand volume (**a**), current annual increments (CAI) (**b**) and mean annual increments (MAI) (**c**) of *A. auriculiformis* plantation over the seven years in the third rotation and the effects of site management on growth attributes. Vertical bars are LSDs at $p < 0.05$.

Wood production ranked, throughout the rotation, in the descending order of long-term soil fertility management F_H–F_M–F_L, and the differences between treatments widened with stand age, reaching a maximum at harvest (Figure 3). Current annual increments peaked at three years of age at 57.8 m^3 ha^{-1} y^{-1} (mean of treatments), and then declined rapidly. MAI peaked close to age four at 32.7 m^3 ha^{-1} y^{-1} (mean of treatments), remained steady at that rate to age six and then, regardless of the significant effects of treatments, began to decline. For example, MAI decreased from 34.6 m^3 ha^{-1} y^{-1} at age six to 32.9 m^3 ha^{-1} y^{-1} at seven years, consistent with the decline in CAI. Similar trends in growth attributes were found in R-2 (data not given). In general, in this environment, MAI peaked between ages three and four years and would decline beyond age six years with CAI declining at fast rates from ages as early as three years. This type of information on growth attributes, if developed for major sub-regions/sites and species, would provide valuable guidance for making decisions on rotation length and product options, and for evaluating the growth trajectory in response to management.

3.2. Productivity of Four Successive Rotations

Figure 4 shows the stem wood volume over four successive rotations, spanning nearly 25 years, and the responses to management treatments applied/re-applied at each inter-rotation phase. The mean height of trees at harvests were: R-1, 11.7 m, R-2, 17.0 m and R-3, 21.0 m. Overall wood production increased from 74.3 m^3 ha^{-1} in R-1 to 174.8 m^3 ha^{-1} in R-2 (2.4-fold over R-1) and then to 229.9 m^3 ha^{-1} in R-3 (threefold over R-1). At a common age of six years, production in R-2 was 174.8 m^3 ha^{-1} compared to 212.9 m^3 ha^{-1} in R-3, an increase of 38.1 m^3 (21.7%) and the corresponding MAIs were 29.1 and 34.6 m^3 ha^{-1} yr^{-1}. The overall mean growth rate in R-3 is higher than in R-2, partly due to the response to P added in F_H (Figure 4). A stricter comparison between rotations can be made using treatment F_M (no P fertilizer), which was common to both rotations at the common age of six years. In that case, R-2 grew at 28.3 m^3 ha^{-1} yr^{-1} yielding 169.7 m^3 ha^{-1} and R-3 at 32.4 m^3 ha^{-1} yr^{-1} yielding 226.5 m^3 ha^{-1}; this represents 56.8 m^3 extra wood, or a 33.4% increase. This gain is attributable partly to the improved genetics of the planting stock (Figure 2), and higher survival (final stockings were 1400 and 1500 trees ha^{-1} in R-2 and R-3, respectively).

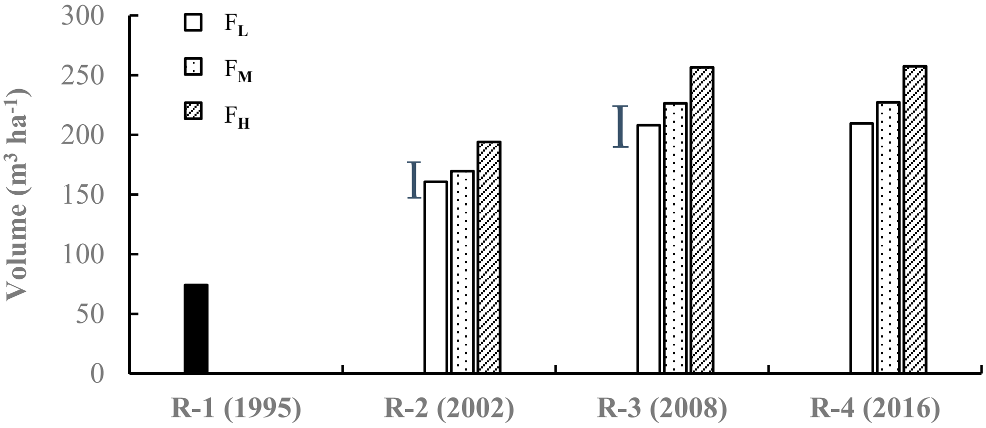


Figure 4. Wood production at harvests over four successive rotations of *A. auriculiformis* in relation to repeatedly applied site management practices; volumes in R-4 were projected to seven years. Numbers in brackets are years of planting. Vertical bars are LSDs at $p < 0.05$ for R-2 and R-3.

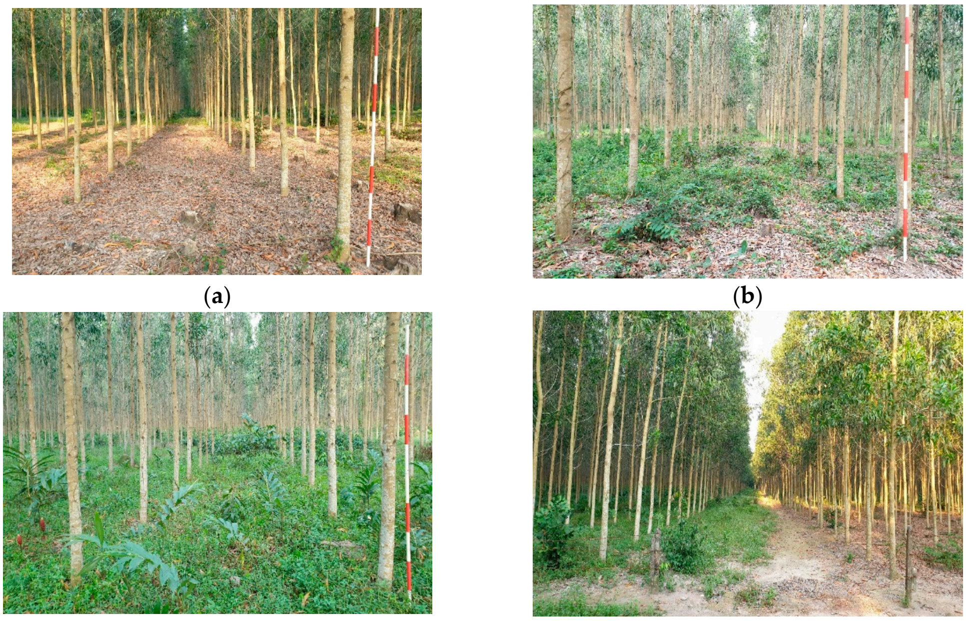
The conservation of slash and litter at every rotation (after the first) increased productivity consistently compared to the removal of those resources (Figure 4, see Table 1 for early response in R-4). For example, in R-2, the doubling of slash and litter increased production by 20.7% over F_L. In R-3, the F_H treatment (long-term conservation of organic matter and P fertilizer) produced the highest MAI, 38.2 m^3 ha^{-1} yr^{-1} at age 6 and 36.6 m^3 ha^{-1} yr^{-1} at 7 years of age. The CAIs (although they declined sharply beyond three years (Figure 3b) were higher under improved soil fertility; between age 6 to 7 years, the rates for F_L, F_M and F_H were 18.7, 22.3 and 27.1 m^3 ha^{-1} yr^{-1}, respectively.

Significant amounts of wood production were lost (forgone) by management practices that depleted organic matter and nutrients from the site in every rotation when compared to the best production achievable in the same rotation (Figure 4). These losses, cumulatively over three rotations, amounted to 130 m^3 ha^{-1}, of which 60–70% would be saw logs.

At harvest, mean annual increments (MAIs) for R-1, R-2 and R-3 were 10.6, 28.3 and 32.4 m^3 ha^{-1} y^{-1}, respectively. The stem height and diameter of trees in R-4 at three years of age (Table 1) are very close to those found in R-3 at that age, and we estimate that R-4 will be on par with R-3 at seven years of age (Figure 4). The growing environments (e.g., rainfall, soil available water and temperature) across rotation periods (Figure 1) can influence growth rates. The annual rainfall patterns (Figure 1) and total rainfall received over the rotation period do not show any major differences between R-1 and R-3. There was a relatively higher mean maximum and correspondingly lower mean minimum temperature for a 6–7 years' period (Figure 1). The ambient CO_2 concentration in the mid-1990s was around 354 ppm compared to the current level of about 390 ppm. Thus, the potential impacts of seasonal variations in soil available water and other climatic changes on growth cannot be discounted here. Nevertheless, the results highlight the high scope for improving the productivity, sustainably, and efficiency of resource use by adopting relatively simple practices that conserve site resources, maintain soil fertility and deploy the best germplasms in this ecosystem.

3.3. Development of Understory

In this experiment, the vegetation management regime was tailored to reduce competition by weeds for site resources and to ensure that trees achieve good survival and early growth. We did not aim to create a weed-free plantation throughout the rotation. Some understory species regrew after two years during the rainy months and the foliage of most (except some woody shrubs) died back during the dry season. These changes led to a striking difference in the understory structure and ground cover in the fourth rotation under three-year-old 12–14-m-tall stands (Figure 5, Table 1).



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Variations in understory developed in a fourth rotation *A. auriculiformis* stand at three years: (**a**) F_L (**b**) F_M (**c**) F_H; (**d**): F_H *versus* F_L with access path in the middle.

In plots from where all above ground biomass was removed repeatedly (F_L), there was only a sparse understory with many irregular patches, largely devoid of understory compared to the vigorous and diverse understory in plots where slash and litter were retained (F_M), and even more so in those with slash and litter retention plus P fertilizer (F_H). There was a strong legacy effect of treatments on the understory. Under F_L, the percentage ground cover was 22%, in contrast to 64% under F_H, confirming the pattern in Figure 5. Improved soil fertility (F_H) promoted three times more ground cover and four times more plant abundance than in those where organic matter was depleted and soil fertility was lower, and also produced the highest tree growth (Table 1).

At the end of the first rotation in 2002, the understory had 52 species, comprising 29 woody species, 17 shrub species and five grass species. Dominant species were *Panicum maximum*, *Imperrata cylindrica*, *Bauhinia cadinale*, *Memecylon* sp. and *Cratoxylon formosum*. In 2019, in the fourth rotation, there were 45 species comprised of 12 woody species, eight shrubs and 25 grasses. None of the species that dominated in R-1 were dominant in R-4 and some were absent. In R-4, the dominant species included *Aganonerion polymorphum* Pierre, *Ageratum conyzoides, Dioscorea persimilis, Hedyotis uncinella* Hook. f., *Lycopodium obscurum, Markhamia stipulata* var. *pierrei* Sant, *Holarrhena pubescens, and Zingiber* *zerumbet* (L.) J.E. Sm. There were also some differences between treatments in the mix of dominant species, although some species were common. Noteworthily, although there were 25 grass species in the current stand, *Imperrata cylindrica,* a very invasive grass in plantations in parts of Vietnam and widely in Indonesia, which was dominant in the first rotation, was absent in all treatments. Moreover, the species *Panicum maximum* was nearly absent.

3.4. Product (Pulp Wood and Saw Log) Options from Short-Rotation Acacia

In the methods section, we showed strong correlations between Dbh and the standing volumes and saw logs. Therefore, the dynamics of Dbh class distribution as the stand grows should provide a guide to the production of saw logs and pulp wood at harvest.

The changes in stem classes with increasing age in rotations two and three are shown in Figure 6. These stands were managed similarly, but differed in the genetics of planting stock, which influenced stem form, growth rates and saw log yield (Figure 2b vs. Figure 2c). Up to three years of age, stems in <10 cm Dbh accounted for 55–60% of the total. That proportion declined sharply as trees grew and, beyond four years of age, accounted for only 5–10% of the total. The proportion of classes in 12–14 and 14–18 cm is notably higher in R-3 than in R-2. The higher growth rates, better germplasm and the extra age contributed to the greater proportion of larger Dbh classes in R-3. The trend of a continuous drop in the frequency of 10–14 cm class from age 4 to 7 years clearly matched the trend in progressive recruitment into the higher 14–18 cm class. This was especially evident in R-3, where about 80% of the stems reached the 10–14 cm class by 5 years of age. At 5 or 6 years of age, a good proportion of stems were suitable for saw logs, and even more were suitable by 7 years of age. The saw log yields estimated from both rotations showed similar trends reflecting the diameter classes, and hence only mean treatment results from R-3 are presented (Table 2). The amounts of pulp wood largely remained the same, but saw log yield increased with age. For example, the medium saw log volume increased from 43.8 m^3 ha^{-1} at age 5 to 83 m^3 ha^{-1} at 7 years of age, which was consistent with the sharp rise in corresponding Dbh class (Figure 6). At 6 years of age, 72% of the volume (151 m^3 ha^{-1}) was within the saw log category and a further 21 m^3 ha^{-1} was by 7 years of age, accounting for 75% of the commercial volume. The commercial volumes for F_L and F_H were 204 m^3 ha^{-1} and 251 m^3 ha^{-1}, respectively, and the corresponding saw log volumes were 157 and 200 m^3 ha^{-1}, respectively, at 7 years of age. These results show that if growers managed their sites (improving soil productivity) and stands well, planted suitable germplasm, and achieved proper stocking, they would be able to harvest higher volumes of both saw logs and/or pulp wood within the currently common range of rotation length.

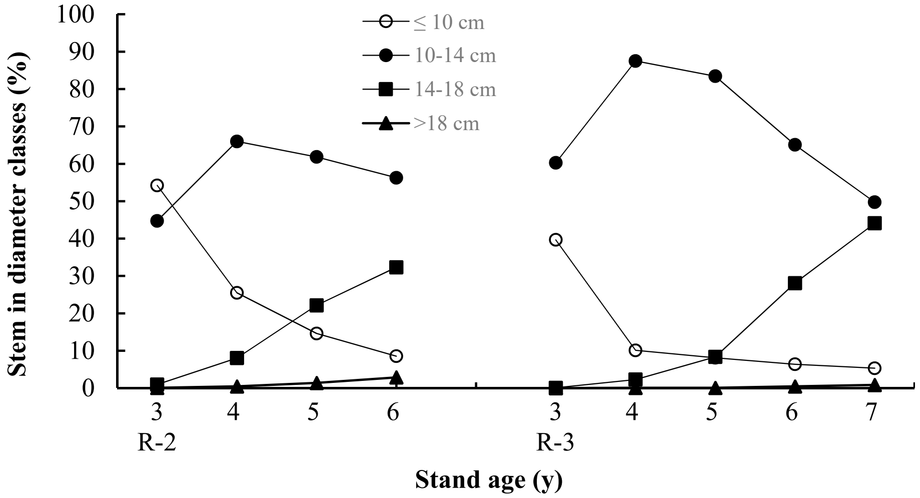


Figure 6. Changes in frequency distribution of diameter at breast height (Dbh) classes with stand age in the second and in the third rotations of *A. auriciliformis*. Each data point is a mean of three management treatments.

Table 2. The total volumes of commercial wood produced and estimated amounts in different log classes (products) in the third rotation stand from age four to harvest.

Stand Age (y)	4	5	6	7
Volume		(m^3 ha^{-1})		
Standing volume	130.7	170.7	207.9	230.5
Commercial volume	128.1	167.3	203.7	225.9
Pulp wood	53.3	50.3	50.6	49.7
Saw logs				
Small	42.0	64.4	80.7	89.4
Medium	32.8	52.2	70.6	83.1
Large	0.0	0.4	1.8	3.7

3.5. Early Stand Growth and Wood Production at the End of Rotation

Figure 7 illustrates that there were strong relationships between the basal area at early ages and the amounts of commercial wood and saw log components at harvest in two contrasting ecosystem–genotype combinations. Similarly, the relationship was significant for saw logs with *A. auriculiformis* in South Vietnam ($R^2 = 0.85$ $p < 0.01$, $n = 20$) and for *A.* hybrid in Central Vietnam ($R^2 = 0.55$ $p < 0.01$, $n = 20$). The correlations with pulp wood were poor in both cases (data not presented). The results show that in Dong Ha (low MAI), with *A.* hybrid, and in Phu Binh (high MAI), with *A. auriculiformis*, significant amounts of saw logs suitable for local markets can be produced in short rotations. Furthermore, information on growth rates measured at about the mid-rotation age may be a reliable guide to product outcomes at harvest.

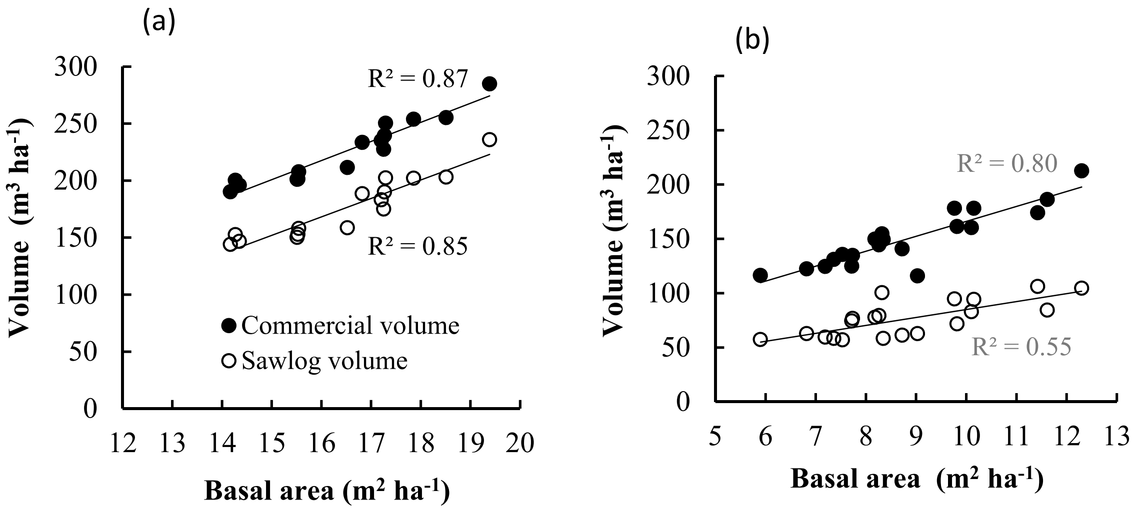


Figure 7. Relationships between basal area and wood production: (**a**) *A. auriculiformis* clones in Phu Binh, South Vietnam, basal area at age four and wood volumes at seven years, (**b**) *A. mangium* × *A. auriculiformis* hybrid clones in Dong Ha, Central Vietnam, basal area at 3.2 years and volume at 7.6 years.

4. Discussion

4.1. Managing for Sustainable Production

The application of sustainable management practices at the inter-rotation phase and the deployment of good germplasm can substantially improve the productivity and value of successive short rotations of *A. auriculiformis* plantations (Figure 4). We demonstrated a threefold increase in wood production from the first to the following rotations and a substantial revival of understory diversity, by continuous improvements in management practices, including the conservation of slash and litter and zero-tillage, which improved soil fertility.

Conversely, practices including whole tree harvest and the depletion of organic matter (F_L) resulted in a loss of production at every rotation (Figure 4). In the F_L at this site, between the first and second rotation [12], 61.5 Mg ha^{-1} organic matter was removed along with 284.8 kg N ha^{-1}, 42.9 kg P ha^{-1}, 157.8 kg K ha $^{-1}$ and 46.9 kg Ca ha^{-1}. When only commercial wood with bark was harvested, smaller amounts were removed: 115.2 kg N ha^{-1}; 29.0 kg P ha^{-1}; 81.5 kg K ha^{-1} and 21.8 kg Ca ha^{-1}. On the other hand, even after removal of slash and litter, in the 0–10 cm soil layer organic carbon increased from 16.7 g kg^{-1} at the end of the first rotation to 22.8 g kg^{-1} at the end of the second, with a corresponding increase in soil nitrogen by N-fixation by acacia and cycling. The conservation of slash and litter increased both soil C and N [12]. In *A. mangium* plantations in Sumatra, N fixation over the first 18 months after planting ranged from 26 to 142 kg N ha^{-1}, depending on the addition of P, weed control and genotypes planted [16]. These inputs to the soil would have helped to sustain tree growth at lower rates, even after the removal of aboveground organic matter.

In rotations one and two, trees were supplied with a small dose of fertilizer containing P at planting. In the second rotation, the double slash treatment added 26.7 kg P ha^{-1} over and above the amount in the single slash [12], and there would have been further buildup of P in the topsoil–litter layer via nutrient cycling during subsequent rotations. Despite this, the application of P at planting increased production by 30 m^3 ha^{-1} at harvest in R-3, and produced the highest growth in R-4 (Table 1). In contrast, at a second rotation site in central Vietnam, the early response to P in *A.* hybrid was not sustained until harvest [7]. Studies in Sumatra, Indonesia, showed a significant response to P applied at planting *A. mangium* between 2 and 3 years of age [17] and in young *E. pellita* [18] at sites where slash and litter of the previous one or two rotations of *A. mangium* (which had received P fertilizer) were conserved. The growth rates, the consequent uptake (demand) rates and low and declining levels of extractable P over the rotations [12,13] are factors to be studied for the further refinement of nutrients, especially P, for acacia. So far, experiments have not shown a response to nutrients other than P for acacia in Vietnam (e.g., [7,19]).

The consistent drops in production from the F_H to F_L treatments at every rotation shown here are the results of differences in management (Figure 4). Such losses are encountered in several other studies—for example, *A. mangium* in Sumatra [13], and 16 sites/species combinations of acacia, eucalypts, pines and Chinese fir in subtropics and tropics (see reviews [10,20]). Repeated harvest residue removal led to serious losses in the production of eucalypts, even in highly productive sites, in Australia [21] and Brazil, where the loss could not be ameliorated by the addition of a high dose of fertilizer [22]. This is partly because, beyond the effects on total nutrient stock, management practices have critical and long-lasting legacy effects on the dynamics of carbon and nutrient pools and their key functions [21,22].

In our experiment, all operations were done manually with minimum soil disturbance. This is not the case in operations by growers; many of them resort to windrowing (which mostly displaces some topsoil) and/or burning to create bare soils even on sloping/steep land, leading to soil losses, and then plough inter-rows, repeatedly, to control weeds ([5,21,23]; also several field observations by the authors). The low growth of the first rotation, due to weak management (Figures 2 and 4), is comparable to those in many sites in Vietnam, and many sites are located on previously degraded soils (e.g., [7]), or on steep slopes (where risks from organic matter loss are high), growing at MAI as low as 13 m^3 ha^{-1} yr^{-1} [24]. The losses (production forgone), over three rotations (Figure 4) amounted to 130 m^3 ha^{-1}, of which 60–75% would be saw logs. To see this is in perspective, this amount is equivalent to the yield from an additional rotation from a stand grown for six years at MAI close to 22 m^3 ha^{-1} yr^{-1}. The contrasting sites, genotypes and management practices (e.g., Figures 2 and 7) discussed here are representative of many sites in Vietnam. For many growers, losses, as discussed above, may equal to one lost rotation for every four/five rotations harvested. The losses in production of this nature are not readily visible in the appearance of stand features and canopy; they are a “hidden loss” to all parties. Therefore, these results and the discussion here have long-term implications for wood supply in Vietnam and income for small growers.

There is a view among some growers that harvest residue retention increases the risk of fire and this is one reason why they remove residues. Typically, there would only be small amounts of wood, less than 3–4 cm in diameter, left at the site after harvest at the growth rates in their plantations. Commonly, local communities collect some of these materials for domestic fuel. If trees are harvested in time for replanting in June–July (rainy months), the rates of mass loss (decomposition) of slash are rapid: nearly 50% of leaf mass was lost in the first month and the remaining was lost in three months, and nearly 60% of small branch mass was lost in nine months (in press [25]). It seems unlikely that the retention of slash per se would increase the risk of fire broadly during the inter-rotation phase. Nevertheless, the threat of fire can be high during the dry months in some regions and the concern of the growers warrants examination to encourage sustainable practices. The losses in production due to management discussed here can be avoided by encouraging the implementation of simple management steps, including the conservation of site organic matter and topsoil (and avoiding soil damage), deployment of improved and appropriate planting stock, judicious vegetation management and simple stand tending during the inter-rotation phase and the next one to two years after planting.

4.2. Vegetation Management and Understory

The application of management practices that gave the highest tree growth also promoted the abundance and diversity of the understory within 10 months after the herbicide application ceased and when the stand was at age three years (Figure 5, Table 1). This is a preferred attribute for long-term ecosystem functions. What are the possible explanations? When herbicide is sprayed over the slash and litter layers (e.g., F_H), a proportion of the spray volume is intercepted by layers of organic matter, and hence a part of it may not have contacted the weeds, whereas, in the absence slash and litter (F_L), spray droplets may be more effective. Under the organic matter layer, plants may re-sprout from underground rhizomes or germinate from seeds. The fate of glyphosate at this site is not known. Glyphosate is strongly absorbed by the soil and has a low mobility. It is degraded by soil microbes and its half-life is dependent on soils and the environment; a typical field half-life of 47 days has been suggested (Wikipedia, glyphosate, http://en.wikipedia.org/wiki/Glyphosate, accessed 28/11/19). In the high fertility treatment, trees were taller and had higher LAI (3.3 m^2 m^{-2}) than in F_L (3.0 m^2 m^{-2}) (Table 1). The higher cover and abundance of the understory in F_H over F_M is surprising because the main difference between them is the application of P in $F_{H.}$ Fertilizer P application, although highly localized, stimulated understory development throughout the plots. The amounts of P taken by the above- and below-ground tree biomass from the fertilizer and soil would have been recycled through the slash, litter and root turnovers away from the points of application, and this may have influenced the P distribution beyond the planting hole more generally.

At a nearby site with *A. auriculiformis,* strip weed control (one-meter-wide weed-free strip spanning tree rows by herbicide application) was compared with total weed control [19]. At four years of age, there was no difference in survival (95%) between treatments and growth under total weed control was only 5–7% higher than in weed strip control [19]. Weeds tend to strongly compete with trees for water and nutrients and, in some cases, light in the first one or two years after planting, but there after the competition declines, depending on the site. It is not necessary to keep plantations totally weed free for the best outcomes in this environment [19]. Repeated ploughing to control weeds during a rotation is common in Vietnam (as it was in the first rotation in this study) and elsewhere in SE Asia [5]. Small companies report that they avoid herbicides for fear of losing certification from the Forest Stewardship Council (FSC) (E.K.S.N. personal observations and discussions with managers), although plantations elsewhere (e.g., Australia, Brazil, Chile) which use herbicides, routinely, are FSC certified. Repeated ploughing is undesirable for maintaining soil organic matter; it mutilates the roots in the 20–25 cm topsoil each time, which is costly, and the practice retains competing weeds in (approximately) a 1–2-m-wide strip along tree rows. However, the overarching conclusion from this study is that management practices that included the conservation of organic matter, which improves nutrient cycling and soil properties, and the judicious use of herbicides, improved wood production in successive rotations and concomitantly promoted the resurgence of previously suppressed vegetation as a diverse understory, at a stage in stand development when trees face little or no risk from competing vegetation (Figure 5). The need for adaptive research and effective technology transfer to growers to promote better weed management practices and organic matter retention for supporting productivity and ecosystem processes is obvious. There has been little research on weed management in plantation forestry in Vietnam.

4.3. Saw Log and Pulp Wood Balance in Production

As noted in the introduction, growers are being urged by the government and pressured by interest groups, including international certification agencies, to adopt "longer rotations" and thinning to increase the saw log yield from plantations. Therefore, the question is: can judicious management practices aimed at improving productivity also deliver economically viable amounts of saw logs and pulp wood from short rotations with minimum stand interventions beyond the early stage? In Vietnam, the processing units utilize straight logs cut to 1.0–2.0 m length with diameters upwards of 10 or 12 cm; their price at the mill gate is graded by diameter. Their uses for value-added products are enabled by new technologies. The trends in Dbh class distribution (Figure 5) and the saw log yield (Table 2) show that even if the local markets were to raise the minimum diameter criteria for saw logs by one or two cm, about 60–70% of the commercial volume from the third rotation would suit the saw log category at seven years of age. As shown in Figure 7, in an *A*. hybrid stand on an eroded site, growing at significantly lower MAI than the present study, 46% of the commercial volume was in saw log category over 12 cm in diameter [7]. In contrast, in the nearby properties of small holders, because of the nature of their management, the scope for harvesting saw logs was low [7,26]. It is clear that substantial amounts of saw logs and pulp wood can be produced in well-managed, short rotations without thinning or additional investments in fertilizer and weed control beyond the early years. Similar outcomes are being achieved on a large scale with short-rotation eucalypt plantations in southern China [27]. The relationships shown in Figure 7 emphasize the importance of ensuring good survival, early canopy development and fast growth, aimed at realizing the best possible productivity at a site for the best outcomes from short rotations for growers. Further developments of these types of relationships into simple models, validated across a range of commercial plantations, could provide practical tools targeted for small growers in order to aid their decisions on rotation length and product options to suit their livelihood needs. Their decisions can be guided by real time information on the performance of candidate stands at about four years of age, in order to select the best option for future management.

Outputs from economic modelling used to promote long rotations (e.g., [28]) based on limited data from the State Forest Company, log prices quoted at the mill gate, and ignoring of the well-known risks to growers are irrelevant in relation to the conditions of small growers and the price paid to them at the farm gate. Growers face several constraints and risks, biophysical and economical, including higher vulnerability to natural hazards such as typhoons, when shifting management to "longer saw log rotations" [23,29,30]. No research has so far produced reliable evidence that small growers receive premium prices for large diameter logs at the farm gate and make larger profits. Therefore, it is not surprising that very few, if any, small growers have been willing to risk their investments and labor for longer rotations and/or thinning, as they are not protected by any insurance cover. These issues are also clouded by false, generalized statements such as "In general, short rotation plantations have poor environmental records than that of long rotations" (e.g., [28]). Some certifiers (e.g., WWF–FSC alliance) and some European NGOs (e.g., [31]) also advocate longer rotations based on their preference and beliefs, without any experimental evidence. The sustainability of plantation forestry has little to do with the length of rotation per se; it is governed by overall conservative site management, soil and environmental care, planting appropriate germplasms and due benefits to investors.

There will be significant benefits to growers by strengthening the adaptive research on *A. auriculiformis*, starting with developing a better understanding of the site soil conditions under which the species can grow well. Its wood is used for products including plywood, floorings and furniture. Currently its saw logs (of the same diameter) fetch a 20% higher price than the more widely grown *A*. hybrid at the *mill gate*. It is reported to have a higher tolerance to wind storm damage, and denser and more durable wood than *A. magnum* and *A*. hybrid. Recent research suggests that it has a higher resistance to stem-wilt canker than *A. mangium* and *A. mangium* × *A. auriculiformis* hybrid [32,33], a crucial consideration for the future of acacia forestry, given the severe impacts of diseases on *A. mangium* plantations in Indonesia [34].

There are many sites in Vietnam where the productivity and log value of acacia plantations per unit area can be improved substantially. Strategies for prioritizing research and application towards sustainable management and benefits have been suggested [23]. To pursue those opportunities, small growers need not necessarily lengthen the rotation unduly and/or thin the stand. It may be counterproductive to pressure them to go for an undefined "long rotation" and, thus, higher risks. Woodchip export remains an opportunity for small growers who seek early returns with low risks; this is not to be discouraged. For the benefit of growers and processors, the focus should be on improving productivity and product value through sustainable management to fully realize the site/genotype potential, which would also help to improve ecosystem values, including soil carbon, nitrogen gains [12,16] and understory development (Figure 5). All these outcomes would improve the livelihood opportunities of small growers, rural development and environmental services [26].

5. Conclusions

Our research on managing the productivity of four successive short rotations of *A. auriculiformis* plantations in south Vietnam over 25 years demonstrates a threefold increase in wood production from the first to following rotations, by applying management practices, such as the conservation of organic matter and nutrients on sites, which improves soil fertility, and the planting of improved genetic stock. Furthermore, with conservative site management and judicious herbicide use, it is possible to foster diverse understory development. Some of the management practices prevalent now, which damage the productive capacity of site and soil, are likely to lead to hidden losses in wood production. For growers, such losses may be equal to the yield from one rotation for every four/five rotations harvested. By improving productivity, both saw logs and pulp wood can be sustainably produced in short rotations, without thinning or other additional investments, at many sites in Vietnam. This approach would be more practical and manageable for small growers than longer rotations aimed largely at producing saw logs, which lead to higher risks. For the benefits of small growers and to increase the wood supply for processing, the focus should be on assisting growers to improve productivity and product value per unit area with environmental care, via integrated and sustainable management.

Author Contributions: Project conceptualization, design and measurement protocols, E.K.S.N. and V.D.H.; experiment management, data collection and analysis, V.D.H., N.X.H., K.M.H., N.V.D.; interpretation E.K.S.N. and V.D.H.; writing E.K.S.N. and V.D.H.; review, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: The first phase of this study received support from the Center for International Forest Research (CIFOR), the Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia) and the Office of Development Assistance, Japan. Long-term support for the project was given by the Ministry of Agriculture and Rural Development (MARD), the Vietnamese Academy of Forest Sciences (VAFS), the Forest Science Institute of South Vietnam (FSIS) and the Center of Application for Forest Technology and Science (SCAFTS). Sadanandan Nambiar, Australia, provided long-term support with personal funds.

Acknowledgments: We thank leaders and colleagues from the Forest Science Institute of South Vietnam for encouragements, various assistance in data collection and long-term maintenance of the field experiment. Chris Harwood and Daniel Mendham (CSIRO) reviewed the drafts and provided valuable suggestions for improvements. We thank the two journal reviewers for their helpful comments regarding improvements.

Conflicts of Interest: The authors declare no conflict of interest.

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